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Multihop Wireless Networking with RF Wake-up Enabled Intermittently-powered Nodes

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Abstract

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Wireless sensors and devices already form an integral part of modern society, but they are constrained by their battery life and the need to be recharged and replaced. To remove the need for batteries and the associated problems of recharging, energy harvesting (EH) can provide power from ambient energy in the environment, meaning large storage is not required as energy is continually replenished. However, the very low harvesting power of small harvesters means it is challenging to operate these devices. Existing work can split computation tasks in conditions where the power supply is intermittent, however, communication in these conditions has only been demonstrated with a nearby high capability device to communicate with. Alternatively, research has demonstrated that EH can power peer-to-peer mesh networked devices, but requiring higher capacity storage and fails with intermittent EH sources. Therefore, in this thesis I demonstrate how to achieve mesh networked communication of intermittently-powered devices.

First the specific challenges of intermittent devices are looked at and why these conditions make communication difficult. In order to communicate in spite of this, I examine how wake-up receivers (WuRxs), rectifying antennas (rectennas) and industrial, scientific and medical (ISM) Band transceivers can be used to achieve point-to-point links. Resulting from this, higher power communications from 10 dBm to 15 dBm are shown to generally achieve better performance, due to greater transmitter efficiency and enabling lower power WuRx to effectively extend listening time.

Once nodes are deployed, optimal real time operation is important in order to maximize the utility from the harvested energy, where wasteful transmitting or listening leads to suboptimal performance. I generalize the energy consumption for an EH node, including the consumption from each radio wake-up, in an analytical and simulated model to see how different parameters affect the resultant goodput, a measure of throughput. Consequently, splitting the energy equally between transmitting and receiving is shown to maximize performance, but the wake-ups reduce throughput and affects the optimum energy split.

Whilst the theoretical analysis is helpful for shaping initial decisions, simulation is required for analysing network behaviour over multiple hops. Therefore, new routing methods for low duty cycle networks are implemented and measured in an intermittent scenario. Specifically, the existing protocol, routing protocol for low power and lossy networks (RPL), is analysed

under scarce EH conditions, where the intermittency caused by insufficient EH results in a collapse in multihop routing capability. Comparably, an alternative protocol opportunistic RPL (ORPL), can utilise the network without specifying potentially unavailable forwarders and instead dynamically utilizing available forwarders. This allows it to operate over multiple hops in spite of intermittency.

Finally, combining both the benefits of ORPL and WuRx leads demonstration of multihop routing in intermittent networks with minimal EH requirements. By modelling several configurations of WuRx, the experiments investigate the trade-off between neighbour count and neighbour availability, as well as the number of hops to reach the destination. The highest range shows the greatest performance when considering routing to a fully powered root node. However, when the root node is intermittent, or when routing data to other intermittent destinations, the cost of the high power radio leads to lower delivery rates. Instead a balance is found, to reach sufficient forwarders to ensure packet delivery, but without compromising the duty cycle too much.

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Definitions and Abbreviations

RF radio frequency

EIRP equivalent isotropic radiated power

WSN wireless sensor network

WuRx wake-up receiver

EH energy harvesting

PA power amplifier

PPP Poisson point process

IC intermittent computing

IoT Internet of Things

MAC medium access control

SWIPT simultaneous wireless information and power transfer

WPT wireless power transfer

OOK on-off keying

RI receiver initiated

TI transmitter initiated

TPC transiently powered computing

TSCH time slotted channel hopping

OR opportunistic routing

NVM non-volatile memory

WPAN wireless personal area networks

MCU microcontroller unit

TDMA time division multiple access

CRS candidate relay set

AODV ad hoc on-demand vector routing

DYMO AODVv2

ARP address resolution protocol

TTL time to live

UDP unacknowledged datagram protocol

DTN delay tolerant networks

RPL routing protocol for low power and lossy networks

SoA state of the art

ETX expected transmissions

EDC expected duty cycles

DODAG destination oriented directed acyclic graph

DIO DODAG information object

DAO DODAG advertisement object

ORW opportunistic routing for WSN

ORPL opportunistic RPL

PDR packet delivery ratio

WBAN wireless body area network

LPL low power listening

ISM industrial, scientific and medical

UHF ultra high frequency

Declaration of Authorship

I declare that this thesis and the work presented in it is my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as: Edward Longman et al. "Wake-up Radio-Enabled Intermittently-Powered Devices for Mesh Networking: A Power Analysis". In: *2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC)*. IEEE. 2021, pp. 1–6. DOI: 10.1109/CCNC49032.2021.9369557

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   Edward Longman, Mohammed El-Hajjar and Geoff V. Merrett. "Multihop Networking for Intermittent Devices". In: 10th International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems (ENSsys '22). Boston, MA, USA: ACM, 6th Nov. 2022. DOI: 10.1145/3560905.3568104

Signed:.. Date:..................

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Personally, and most significantly I thank my family; my wife Olivia to whom I cannot give enough credit and who labours to raise the next generation long before it bears fruit. Thank you for listening to me and engaging in my excitable musings of unnecessary scientific or pedantic detail, often over dinner. Thank you also for embracing my idiosyncrasies and bizarre interests, and even taking them on yourself. Thank you to my parents and sister who provided me with opportunities and adventures, to help me understand the world and learn so much long before I started my research, and for bringing so much fun throughout all of it.

Finally, all of this rests upon the foundation of my God, who provides all I need, gives life to all and is my salvation. Nothing I do can repay what He gives, and no height of endeavour or weight of gold nor silver can surpass His greatness.

To Olivia, It's so special to share the journey with you.

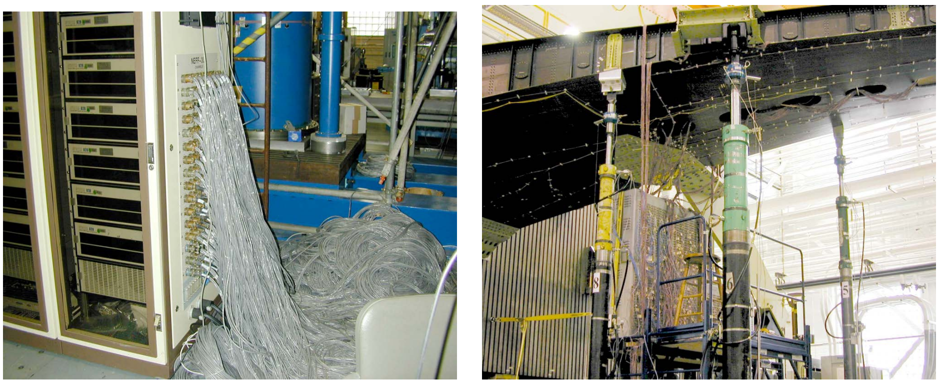
1 Introduction

Modern industrial and environmental management is using increasing amounts of autonomous sensing to more efficiently manage assets, whilst simultaneously reducing the need for human intervention. Such devices constitute up the Internet of Things (IoT) and device numbers are expected to grow considerably [5]. This necessitates better ways to perform sensing and monitoring, by reducing the cost and maintenance of devices, whilst still meeting the long term connectivity requirements. Nodes in IoT networks tend to be battery powered or tethered to a mains supply, but it is often more complicated to install and maintain these where, for low power devices, the battery lifetime is the determining factor in device lifespan [6, 7].

For IoT devices to achieve such longevity without periodic maintenance, energy harvesting (EH) has emerged as an alternative to batteries in numerous applications, such as low rate feedback control, and infrastructure management [8], and structural health monitoring [9]. Ambient energy harvesting sources, such as mechanical, thermal, and radiant energy, can be exploited to create electricity, so energy storage is replenished without human intervention. However, such sources typically are low density and subject to environmental variation, which constrains the power generation and hence the communication performance. Therefore, to enable new applications and enhance existing ones, I implement networking under these highly constrained conditions.

One application of IoT networks is in feedback systems, for example in aircraft control systems or building management systems. In modern systems they have many sensor inputs to increase the controllers efficiency and ability to provide more appropriate control actions [10]. This can include reporting back to an operator for preventative maintenance or highlighting sub-optimal parts of the system. These systems are classified into: devices to a controller (Machine to Machine, M2M) or to an end user (Machine to Human, M2H) [11]. To increase fault tolerance, more recent efforts have been focused on distributed computing, so networked devices do not rely on infrastructure nodes, single points of failure. As part of this, sensor fusion, combining many coarse measurements to get more accurate and precise results, is employed and enables low cost redundant systems [12, 13].

For this increased autonomy of distributed systems but with reduced reliance on high cost infrastructure, new challenges in connectivity must be met which cannot simply be solved with more wiring. If the new sensors are connected with wires, it results in increased complexity of construction and weight [14, 10], as shown in Figure 1.1. Also, some applications of sensors cannot be wired if moving relative to other parts of the system, like in inflatable structures, if communicating in harsh environments or if blocked by a physical barrier [15]. The nature of wireless devices is that they have a limited power budget, which determines their size and cost, when considering storage and energy generation. It also determines their capability, like reducing activity when energy is limited. This does rule out high performance applications but by maximizing the productivity with a given amount of energy, the proportion of sensors that can work wirelessly is increased. Next is a detailed look at the advantages of moving away from battery technology and how that changes the approaches to operate devices and the network.



(A) (B)

FIGURE 1.1: Photographs showing (a) the cabling required to connect 466 foil strain gauges to (b) the stitched/resin film infused graphite-epoxy wing box, a test article as part of an aircraft design process. Reproduced from [16].

1.1 Motivation for EH Sensing

In order for IoT devices to have a useful capability, batteries have been used to provide wireless capability, however there are several disadvantages of using batteries as a power source. First, battery powered deployments have a lifetime that is determined by the capacity and ageing of the battery, where both the consumed power and the natural ageing limits such devices to a ten year life [17]. Secondly, with increasing numbers of devices being manufactured, there is increasing awareness of the environmental impact of batteries, through their whole lifecycle from production to disposal. Thirdly, where rechargeable batteries are used, manual intervention is required to recharge the devices and with large increases in the number of devices this becomes an implementation barrier. Given the ambition for greater numbers and autonomy of IoT devices, alternatives to battery power sources are needed.

Ambient energy harvesting (EH) sources can exploit mechanical, thermal, and radiant energy sources to create electricity, so energy storage is replenished without human intervention increasing the lifetime of IoT devices. It also means capacitors can replace the batteries to mitigate the lifetime and environmental concerns. Although the capacitors have significantly smaller energy storage capacity, they do not experience chemical degradation nor is there high environmental harm in production or disposal. Since the storage is being replenished by the energy harvester, the device can still operate with a lower energy storage capacity and so long as EH continues can operate beyond the lifetime of batteries. However, EH sources typically are low density, like thermo-electric generators producing 100 µW, and subject to environmental variation, such as a kinetic harvester on animals, which limits the power generation and hence the device performance [18].

1.2 Motivation for Intermittent Operation

A typical solution to overcome this challenge is to use a large secondary energy storage source or to increase the energy harvester size to maintain connectivity, but this leads to an increase in the size and cost of the nodes. Considering the foreseen scale of IoT networks [5], it is important to reduce the size and cost of devices. This motivates using the simplest devices with nearly zero energy storage and small harvesters, while still being resilient to power failures [19].

Given the variability and output power of energy harvesters compared with the power consumption of a low-power microprocessor around 5 mW [20], it is not sufficient to assume that nodes can operate continuously since the energy storage capacity cannot sustain long periods of scarce EH supply. This leads to devices operating *intermittently*, i.e., consuming power for a short period, before the energy storage is depleted and then shutting down to replenish the stored energy. Hence, these devices spend a large proportion of time off and unable to respond to events.

There has been considerable research on intermittent computing (IC) to ensure computation can make progress in these conditions, by splitting their tasks across consecutive power cycles [21]. This enables the devices to operate despite energy and storage scarcity, continuing to sense and respond to the environment.

1.3 Motivation for Intermittent Networking

In addition to managing computation across operational cycles, devices need to operate together, communicating their results and receiving updates from other devices [22]. This requires networking solutions that allow connectivity to be maintained with intermittent devices in spite of the large proportion of time they spend off. A particular challenge is point-to-point communication between intermittently-powered devices, where existing solutions rely on a centralized entity/coordinator communicating to a low power receive node [23, 24]. However, this higher capability node limits the required increase in autonomy as it needs intervention for energy replenishment of an external continuous supply. Therefore, techniques that do not require the simultaneous deployment of higher capability devices are important, because such devices increase the overall complexity of deployment without adding sensing capability.

Mesh networking allows peer nodes to communicate without the need for higher capability devices communicating over multiple hops between end nodes. Routes depend on the location of the source and destination and the availability of intermediate nodes, where routes taken by data varies widely, and does not need to pass through a few core nodes or via a hub. Particularly suited to this are distributed decision-making and sensor fusion applications where sufficient global system accuracy can be achieved from a larger number of lower accuracy devices [25, 12], which simultaneously increases redundancy. Intermittency poses new challenges to mesh networking, since timekeeping is impossible across power outages, consecutive transmissions are limited due to the small energy storage and there are high amounts of route changes. Such challenges currently limit the adoption of intermittently-powered homogeneous mesh networks and motivates this investigation and are discussed more in Chapter 3.

1.4 Research Justification

With growing demand for IoT devices solutions are required to avoid the associated maintenance burden and to minimize the environmental impact. Intermittent computing (IC) research has shown that forward progress can be made with state retention across power outages, allowing devices to be powered from energy harvesters with minimal energy storage. However, the subsequent communication of the collected data or inferences has been neglected [26].

Previous research has investigated EH networking solutions to allow for workload differences according to EH variation across the network. They also allow for transmission control to reduce the load to guarantee nodes remain available and the network does not collapse [27]. These approaches rely on energy storage only achievable with batteries and, in order for the control communication overhead to be sufficiently small, variation in node availability must also be small.

Additionally, various communication approaches have been created to maximize the available communication from limited energy storage. Due to the characteristics of intermittent power supplies, any communication protocols cannot rely on time information to synchronize protocols as is required with time division multiple access (TDMA) amongst others [28] as timing information is not preserved through power outages. Alternatively, asynchronous approaches require increasing the idle listening time to reduce latency and increase throughput, so techniques such as Low Power Listening, radio frequency (RF) wake-up, wake-up receivers (WuRxs) and simultaneous wireless information and power transfer (SWIPT) reduce the power consumption of idle listening. The first three techniques reduce the time the main radio is active and in turn greatly reduce the power consumed overall. All but the first approach rely on harvesting RF power and using it for some part of decoding or a wake-up. These approaches all rely heavily on higher capability devices, to listen with very high sensitivity, to provide powerful wake-ups or to deliver RF power for the receiver. Whilst, these solutions provide low-power receive functionality, the impact on the initiator has not been accounted for, as existing research relies on a high capability sink. However the cost of communication initiation is very important in mesh networks where nodes act as both receiver and transmitter.

Another factor that needs to be considered is the organisational behaviour of the network protocols across power outages and how to process messages saved to non-volatile memory (NVM) while off. Current implementations of wake-up methods [29, 30, 31, 32, 33, 34] do not use NVM, rather they transmit information to a coordinator node immediately after receiving a wake-up signal, and do not store the state of neighbouring nodes. Intermittent nodes may not be able to acknowledge a wake-up, but may still be able to receive, instead storing into NVM. However, this will affect the network organization as the transmitter will not receive an acknowledgement. Instead, nodes can rely on overheard forwarding that needs to be processed when the node power supply is restored. Additionally, methods to operate where the optimum forwarding node may be off are required, not assuming its presence but also not removing all routing data on restart.

Finally, due to the focus on homogeneous intermittently-powered devices, when considering multihop networking the transmission cost for forwarders must be taken into account, where existing solutions rely on a centralized entity/coordinator communicating to a low power receive node [23, 24]. Furthermore, this transmission cost must be balanced with the capability of receiving nodes, maintain connectivity in spite of the intermittency. This is because current solutions do not adapt to the high variability or send so many control messages that the network collapses.

The multihop requirement ties across many layers and aspects of intermittently-powered devices. It means that nodes cannot be considered in isolation but the small energy storage limits the communication, so the network operation cannot be decoupled from the lower level physical interactions. Specifically it requires considering the multinode communication with scarce EH resources, and also considering energy consumption of communication radios. By modelling the node communication operation the performance can be measured for various configurations more realistically than just isolating network analysis from physical characteristics. By precisely modelling energy consumption this research aims to progress to enabling the high degree of autonomy demanded by IoT applications with increased fault tolerance, lifetime, and sensing coverage.

1.5 Research Aims

Given the possibilities of EH to power computing in the IoT but the lack of communication methods to collect data created by such devices, this thesis addresses the following aims:

- A1 *Assess the appropriate hardware for transmitting and receiving wireless information between EH devices.* - Nodes require communication hardware that maximizes the lifetime from a small energy storage, but not at the expense of the energy required to initiate communication at the transmitter. Therefore a suitable combination of hardware must be found.
- A2 *Explore tradeoffs for the node-to-node communication rate when limited EH and energy storage causes intermittency.* - When the nodes are intermittent, each time the high power main radio is used it directly reduces the time spent listening, therefore the balance of transmission and receiving must be found.

A3 *Determine the performance of routing protocols when nodes are intermittently-powered* - Several multihop routing protocols exist for duty-cycled wireless sensor network (WSN), but this thesis determines the performance with regard to asynchronous, intermittent behaviour.

A4 *Demonstrate multihop point-to-point routing with minimal EH supplying a network of nodes.* - Combining the benefits of low power communication hardware and routing protocols that withstand intermittency to show the potential for the envisioned IoT networks.

1.6 Contributions

This thesis reports results to address the research aims, where the following contribution points correspond to the stated numbered research aims:

C1 *Study of power consumption of low power transceivers for and the effective range to a low power wake-up device* - Chapter 3 considers how the power consumption, instead of just power output, for the transmitter affects what range it can reach and why the transmitter efficiency is important.

Edward Longman et al. "Mesh Networking for Intermittently Powered Devices: Architecture and Challenges". In: *IEEE Network* (2022). DOI: 10.1109/MNET.105.2000782

C2 *Modelling of the energy consumption of a small number of nodes for measuring message throughput* - Chapter 4 addresses the lack of knowledge of communication between WuRx nodes and gives an equation for the optimum load in a fully connected network, demonstrating the tradeoffs involved.

Edward Longman et al. "Wake-up Radio-Enabled Intermittently-Powered Devices for Mesh Networking: A Power Analysis". In: *2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC)*. IEEE. 2021, pp. 1–6. DOI: 10.1109/CCNC49032.2021.9369557

C3 *Whole network analysis of opportunistic RPL (ORPL) to prove operation under scarce EH conditions* - The experiments in Chapter 5 have demonstrated the suitability of opportunistic routing to the new application of multihop networking in EH WSN with homogeneous intermittently-powered nodes.

Edward Longman, Mohammed El-Hajjar and Geoff V Merrett. "Intermittent Opportunistic Routing Components for the INET Framework". In: 8th OMNeT++ Community Summit. Virtual Summit, 2021. DOI: 10.48550/ARXIV.2109.12047

The intermittent variant of the ORPL protocol was implemented in OMNeT++ alongside the new cross-layer interfaces and medium access control (MAC) overhearing capability. Additionally, energy consumption models of the data radio and WuRx were created to model the effect of sensitivity on consumption.

Edward Longman. *INET Intermittent Routing Components*. 2022. URL: https://github.com/UoS-EEC/INET-opportunistic-routing

C4 *Combination of ORPL with WuRx demonstrating cross network communication throughout intermittency* - Extending contribution C3 demonstrates how WuRx minimise the EH requirements, demonstrating connectivity with an intermittent hub and a spread of destination nodes.

Edward Longman, Mohammed El-Hajjar and Geoff V. Merrett. "Multihop Networking for Intermittent Devices". In: 10th International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems (ENSsys '22). Boston, MA, USA: ACM, 6th Nov. 2022. DOI: 10.1145/3560905.3568104

1.7 Thesis Structure

In this thesis, first a review in Chapter 2 of intermittently-powered devices is presented, including very low power communication methods and routing methods for mesh networks of wireless devices. This is to assess what technologies are available to create intermittently-powered networks. Following this in Chapter 3, the vision for mesh networked intermittently-powered devices is explored with four receiver types for maximizing the capability of intermittently-powered devices. As part of this I analyse the power consumption required to transmit to each receiver type, and present the collected power consumption values from several radio chips that could be used. From the hardware available, the next Chapter 4 details the resultant communication capability when nodes are intermittently-powered and use wake-up radios to listen, with the associated overhead of each wake-up included. A mathematical model of how the energy consumed after harvesting is created using the energy consumption of the radios in the previous chapter and the wake-up radios from Chapter 2. Next in Chapter 5, I present an implementation of opportunistic RPL (ORPL) for intermittently-powered devices in OMNeT. This covers design decisions determining how energy should be spent and how data should be prioritised. The implementation is then used for comparison with routing protocol for low power and lossy networks (RPL) in intermittent scenarios as well as testing WuRx in a large scale scenario requiring multihop communication across intermittent nodes.

Cricket is a game which the English, not being a spiritual people, have invented in order to give themselves some conception of Eternity.

Stormont Mancroft

2

Communication Techniques for EH and Networked Sensor Nodes

In order to enable distributed systems described in Section 1.3, powered only by minimal EH sources and energy storage to enable unlimited operation, there are many important components to be considered, where all are required in order to make the systems functional in spite of the intermittency. Each of the sections of the review are a result of the physical requirements of the batteryless EH network envisioned, as illustrated in Figure 2.1.

First, the EH batteryless constraints are a results of removing the battery energy storage, and instead using a capacitor. This results in research in the field of intermittent computing (IC) providing methods to enable computational progress, where state saving techniques mean that in the case of a power outage, the computation can be continued when the power is restored. However, devices must also be able to communicate where unpredictable EH motivates the review of point-to-point low power radio hardware (wake-up receiver (WuRx)) to improve connectivity between EH devices. This is by increasing the time listening from a small energy store, but coming at a cost of reduced range, and where combined with the limited EH they are intermittently-powered. The wireless connectivity constraints also motivate the review of channel modelling to determine how the frequency, medium loss and power levels influence the range and received power by devices.

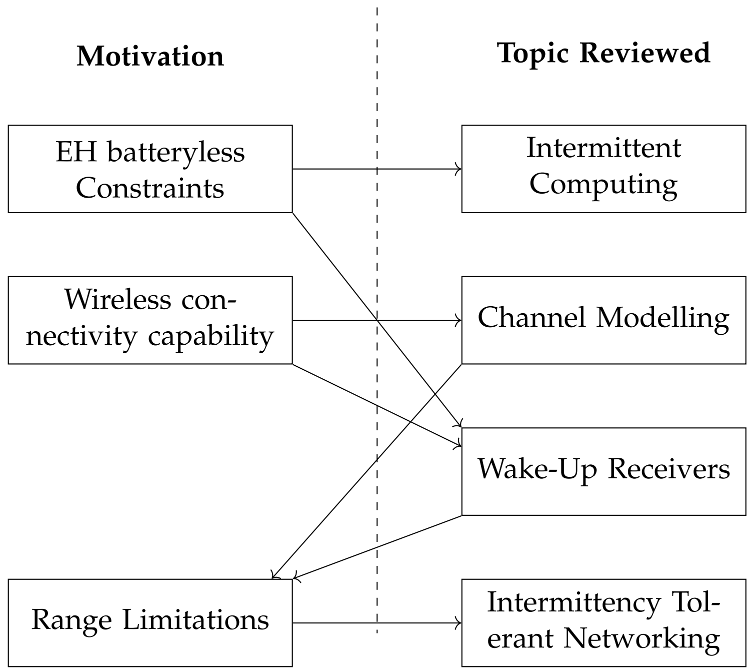


FIGURE 2.1: Structure of communications technologies review showing how within the context of wireless sensor networks enabled by EH, the constraints of intermittency with the need for connectivity further leads to the intermittent networking review.

The resultant range limitations and the intermittency caused by the minimal EH prevents communication between nodes using conventional networking methods. As shown in Figure 2.1, this leads to researching intermittency tolerant networking methods, first to overcome the range limitations by using several hops and using networking approaches that overcome the node intermittency. Routing methods such as opportunistic forwarding, delay tolerant networks (DTN) and selective flooding are considered, where they use multiple nodes as potential routes, overcoming individual node outages. In this chapter a detailed review into each of these components takes place, to discuss the consequences of intermittency and their ability to meet the requirements of networking, and enable networks that can operate beyond the conceivable life of existing battery powered networks.

2.1 Intermittent Computing

Intermittent computing (IC) is a program execution pattern required to allow processors to complete computation tasks where the batteryless system cannot sustain power over longer duration tasks [36]. IC, also referred to as transiently powered computing (TPC), executes programs over successive power cycles, enabled by advances in low power storage, where partial task progress can be stored and resumed when sufficient power can be provided to the processor [37]. For example, a processor

Citation	Year	Approach	Key Contribution
Ransford et al. [36]	2011	Static	Code checkpointing routines for correct execution restoration on restart.
Jayakumar et al. [37]	2014	Dynamic	Integration of FRAM module for better memory flexibility and lower shutdown energy.
Balsamo et al. [38]	2015	Dynamic	Dynamic memory saving to NVM at shutdown voltage threshold.
Rodriguez Arreola et al. [39]	2015	Review	Review and quantitative comparison of checkpoint and reactive IC approaches.
Van Der Woude and Hicks [40]	2016	Static	Energy Storageless operation with compile time checkpoint insertion.
Bhatti and Mottola [41]	2016	Static	Backup size reduction with access tracking and Copy-if-changed.
Sliper et al. [42]	2019	Dynamic	Page level access tracking for checkpoint size reduction.
Rheinländer and Wehn [43]	2019	Dynamic	Whole system using harvester tracking for early shutdown detection.

TABLE 2.1: Collated key publications on IC highlighting the differentiating contribution in each.

taking an accelerometer reading and performing a Fourier Transform may consume 10 mW for 1 ms. If the energy harvester produces 0.1 mW then the remaining power must come from energy storage, however if the storage can only provide 1 µJ then the node will shut down before ten percent of the computation is complete. In another example, consider the same sensing and computation but where an EH source is used that provides short bursts of 12 mW harvesting, hence the node can be powered entirely from EH but there is no guarantee about how long the supply will last, so if the burst is shorter than 1 ms the computation will be lost. Without saving of the intermediate results the whole operation is reset and must begin again. IC enables applications with more sophisticated requirements to be implemented, and aims to perform deferral and continuation of the program without significant, time-consuming programmer effort whilst maintaining correct execution outcomes [37]. The key works in the field of IC are summarized in Table 2.1.

In order to save the intermediate state there are two main execution schemes. Static checkpointing schemes [40, 36] divide the computation into small tasks that have a high probability of succeeding, due to the short duration each takes to complete. Dynamic or reactive schemes monitor the storage level and save the state just before power failure [43]. For both schemes progress is dependent on memory state that has to be saved and the size of the largest atomic task, that must be completed in a single execution cycle. Additionally, IC approaches need to ensure execution consistency so that regardless of where in a program execution is stopped, the result is the same.

Static checkpointing approaches insert code into the program when compiled to divide the program into small chunks. To ensure execution consistency, each section is idempotent [40], so that should execution fail, reverting to the checkpoint will not change the result. The disadvantage is that checkpoints add an average overhead of 60 %, significantly reducing the execution progress. Alternatively, by measuring the energy level before the checkpoint, premature checkpoints are skipped [36] which results in reduced overhead. There are more small scale improvements from reducing the size of the state saved, removing write-after-read and incremental checkpoints but these are not covered here.

Reactive schemes do not add any overhead *during* the execution of the program, instead the state is saved in a single action as the final step before shutdown. Initially in Hibernus [38] the whole state is saved. However, by tracking the memory allocated the data saved each time can be reduced [41]. Furthermore, when the execution duration is further reduced, and few allocated sections are read or modified each run, further savings can be made [42].

Given the availability of a small amount of energy storage, sufficient to save the whole state, and a low power comparator to track the voltage level, reactive schemes perform better [39]. Also for shorter execution times, tracking memory access outperforms whole state saving and whole allocated state saving techniques. Since devices need a small energy storage for communication scenarios discussed later, reactive approaches are better for communication scenarios.

These schemes enable computation when energy is scarce and the storage limitation causes short maximum execution duration. However, as described in Section 1.3, it must also be considered how these devices can communicate with each other, in challenging conditions of intermittency. Transmitting and receiving packets are atomic tasks and IC provides no help in this regard. Therefore, I now review models of the wireless communication channel before considering the energy consumption and capability of different low power listening techniques.

2.2 Industrial, Scientific and Medical (ISM) Band Wireless Characteristics

The first factor affecting the node to node communication ability are generic wireless communication characteristics. This affects basic considerations of range as well as how the communication channel is modelled. Additionally, the appropriate industrial, scientific and medical (ISM) frequency band for the analysis should be determined.

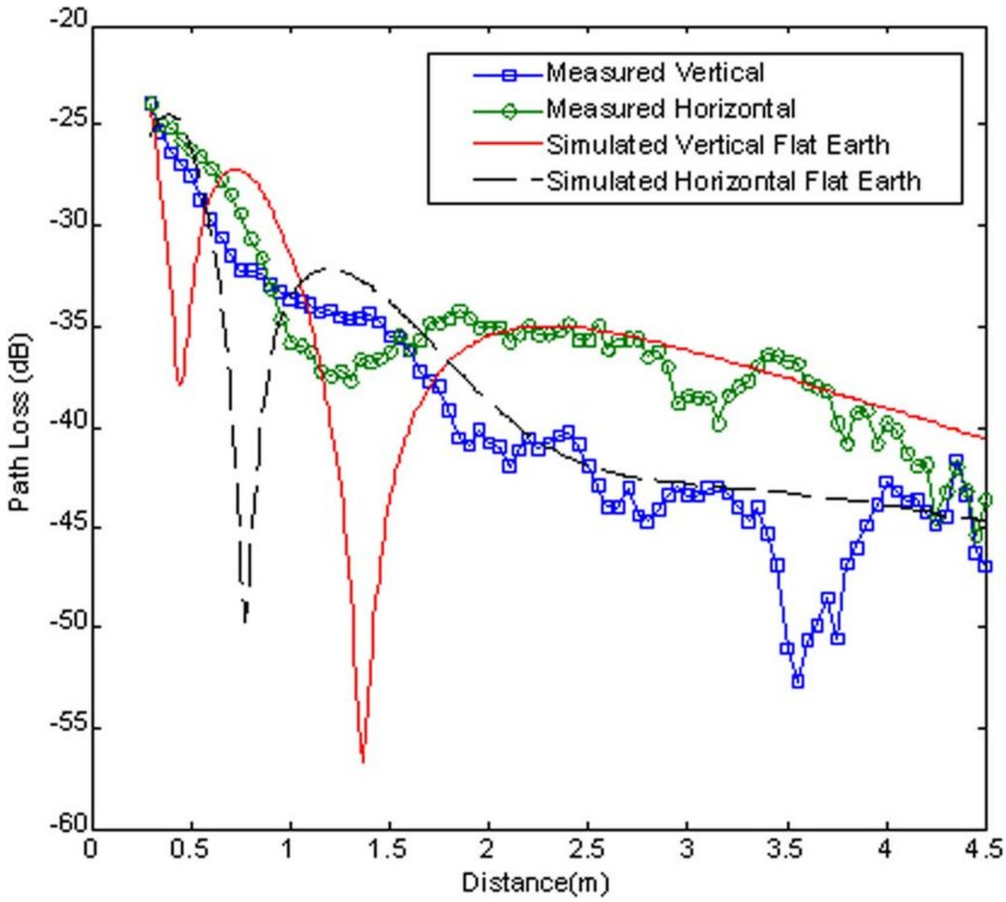


FIGURE 2.2: Path loss variation with distance when simulated and measured with a multi-path propagation model. Reproduced from [44].

The available power at a distance, d, from a transmitter is given by the Friis equation (2.1) which uses the most basic path loss model to estimate the loss due to dispersion of a signal, with no reflection or fading included [44]. The antenna gain of the transmitter and receiver, a measure of directivity and aperture, can be lumped together into a single gain G. Multipath propagation can cause destructive interference effects where there is reduced power at certain distances if there are simple few sources of reflection, as shown in Figure 2.2. The effect of multi-path path loss is largest when the transmitter and receiver are close to ground planes [44].

$$
\begin{aligned}
P_{Rx,\mathrm{dBm}} &= P_{Tx,\mathrm{dBm}} + G - L_P \\
L_P &= 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 20\log_{10}(d)
\end{aligned}
\tag{2.1}
$$

2.2.1 Non-ideal propagation characteristics

The Friis equation models propagation of RF signals in an ideal free space situation. However, obstacles, the transmission medium and reflections all reduce the power received in practical situations. Importantly, it is observed that the path loss coefficient is higher at greater distances, which changes the trade off between utilizing more communication hops and using higher range devices, considered in Chapter 4. The ITU-R model [45] considers the effects of reflections and obstacles for indoor environments and could be used to estimate the path loss. However, it is more applicable to case study scenarios since it includes consideration for the number of floors a signal passes through. On the other hand, it is useful to note the power loss coefficient recommended for an office area is 3.3.

The two-slope path loss model modifies the Friis equation to use different path loss coefficients below and above a breakpoint distance, r_b, as in (2.2). Balancing complexity and model accuracy, the two slope model is easy to implement, but provides a sufficiently accurate model of propagation characteristics if the breakpoint distance and slopes are chosen correctly [46]. The value of L_{01} is the received signal strength at 1 m and is only dependent on the transmission frequency, f and propagation speed, c (approximately $2.997 \times 10^8\,\mathrm{m\,s^{-1}}$). It can be calculated with the equation $L_{01} = 20\log_{10}\left(\frac{4\pi f}{c}\right)$. The value for L_{02} is calculated from the final value of the first slope at the breakpoint distance, $L(r_b)$.

$$L(r) = \begin{cases} L_{01} + 10n_1 \log_{10}(r), & r \leq r_b, \\ L_{02} + 10n_2 \log_{10}(r/r_b), & r > r_b, \end{cases} \tag{2.2}$$

The IEEE 802.15.4-2006 Specification [47] provides a estimated two slope model for 2.4 GHz with a breakpoint distance of 8 m. It also specifies how to calculate the model for 900 MHz. An experimental study [46] measures the path loss at ground level in several different environments and then fits breakpoint values and slopes to the experimental readings. They also verify their two-slope model with a real-world mica-Z deployment, which demonstrates how the model is realistic at estimating links between neighbouring nodes, whereas the one slope model significantly overestimates. It evaluates model parameters for different scenarios including a courtyard and a park.

This model is only experimentally validated up to 50 m, but another study [48] provides a model beyond this range, also using a two slope model between 50 m and 2 km. It considers antennas placed over 2 m above ground level and also validates the theoretical path loss model with experiments.. Since the study considers a larger range, it only considers a single, more varied, suburban environment. Despite the study only considering antenna heights above 2 m, you can see that the resultant path

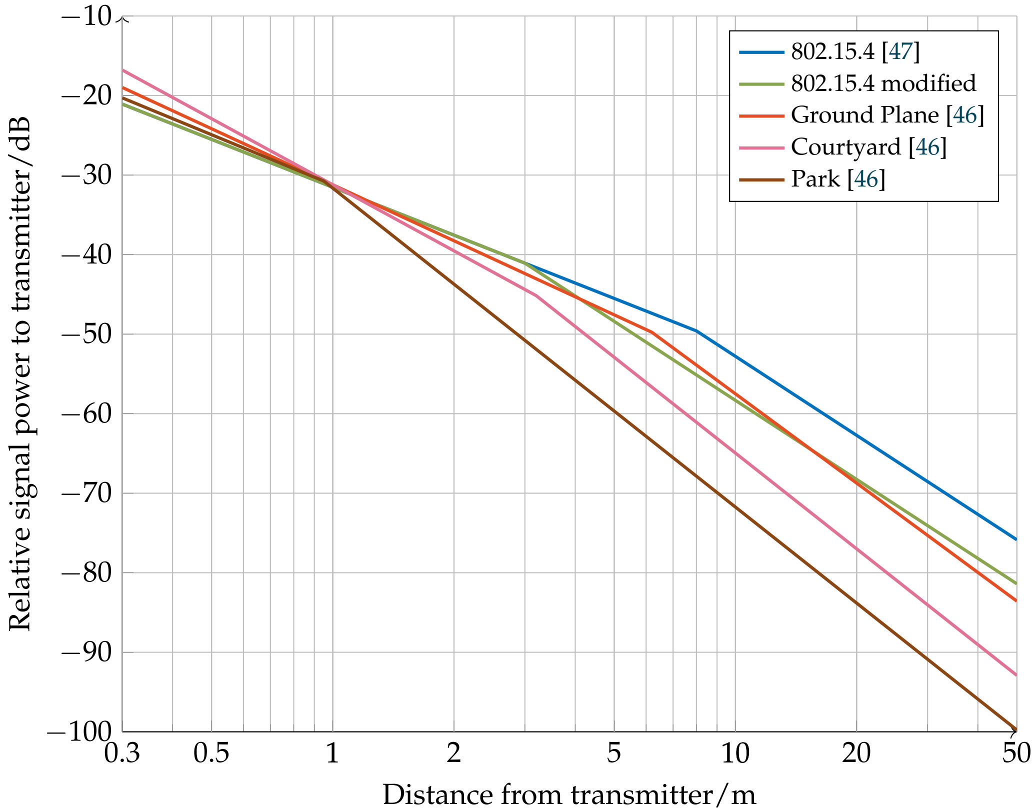


FIGURE 2.3: Two slope path loss model comparison at 900 MHz with a significant difference in received power and effective range with different models and environments. This only shows path loss and does not consider transmitter efficiency or antenna gains.

loss slope would be similar to if extrapolated with the shorter range ground plane model slope of 3.73. Additionally, it provides (2.3) to estimate the breakpoint distance, where the breakpoint distance is inversely proportional to wavelength, where h_{tx} and h_{rx} describes the height of the transmitter and receiver respectively.

$$r_b \approx \frac{4h_{tx}h_{rx}}{\lambda} \tag{2.3}$$

The IEEE 802.15.4 model does not alter the breakpoint between 2.4 GHz and 900 MHz as specified in (2.3), which explains why it is so different from experimental data [46]. Figure 2.3 shows that using (2.3) to reduce the breakpoint brings the IEEE 802.15.4 model close to the experimentally verified models for the ground plane, courtyard and park also shown in Figure 2.3. For a range under 1 m the loss is irrelevant for the scenarios considered. Between 1 m and 4 m there is only a small difference between the different IEEE 802.15.4, the ground plane and courtyard models of less than 5 dBm. Beyond this there begins to be more and more significant deviation. Depending on the sensitivity of the receiver, the difference in range modelled and the potential error in range becomes very high. For example, at −60 dBm the IEEE 802.15.4

specification models the range as 3× the Martinez-Sala park model, and 1.5× the ground plane model. This would make a significant difference to the practical range and also, because of the higher path loss coefficient at higher range, n_2, it reduces the effect of increasing the transmit power, where quadrupling the power will only increase the range by 50 % instead of the range doubling with the Friis model.

Certain frequency bands within the ultra high frequency (UHF) range are available for license free use, which mean a broader range of results from implemented devices are available. Additionally, it would be a requirement for most sensor networks to operate within these license free bands. In these license free ISM bands there are still restrictions on power and duty cycle that must be considered, for calculating the range of available power, to analyse the range and power consumption.

2.2.2 ISM Band Regulatory Constraints

The ISM frequency bands considered are around 433 MHz, 900 MHz and 2.4 GHz, have restrictions to ensure different devices can interoperate with fair access to the medium. The three bodies that set the relevant regulations are the FCC, ETSI and ITU, which governs the power and duration of transmissions. In the next section the possibility of RF power transfer is considered and therefore frequencies which allow high power of transmission are required [49]. There are differences in the specific frequencies and the duty cycle of the limits, however, it can be summarized as follows. For the 900 MHz band, a maximum of 100 mW equivalent isotropic radiated power (EIRP), averaged over a transmission duty cycle [50]. For the 2.4 GHz band in the US, under specific circumstance 4 W are allowed for a short period otherwise 1 W. Whereas only 100 mW are allowed in Europe, but this is a continuous (not duty-cycled) value [51].

Finally, for IoT deployments the antenna must remain small, <10 cm, to keep the size of the devices small. At 900 MHz the quarter wavelength antenna size is still small (9 cm) as calculated by (2.4).

$$l = c/4f \tag{2.4}$$

There are similar limits to 900 MHz on power in the 433 MHz band, however the size will be over double that of an equivalent antenna [52]. Given the limitations of the above regulations, the propagation and antenna characteristics to get the best range, the 900 MHz band should be used, even though it has to be duty cycled, as it has high permitted peak power, but also has better transmission characteristics, as shown in Figure 2.4.

No transmitter is isotropic, so there will always be higher power radiated in some dimensions, at the expense of reduced radiation in others. If assume a transmitter and receiver gain of 3 dB is assumed, so $G = 6$ dB, then the maximum available

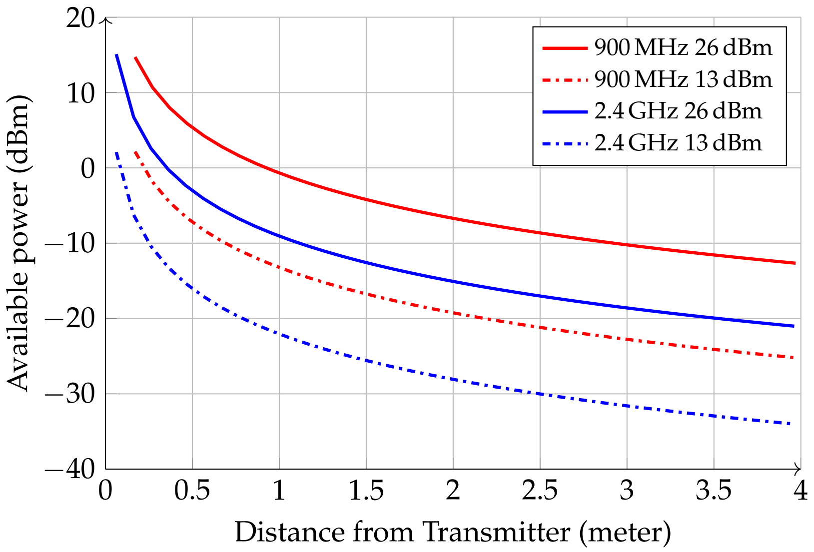


FIGURE 2.4: Power available at distance from transmitter using the basic Friis transmission equation with combined antenna gain of 5 dB.

power, for the 900 MHz and 2.4 GHz ISM bands, when transmitting at maximum power is shown in Figure 2.4 produced using (2.1). Due to the reduced aperture as frequency increases [52], the 2.4 GHz antenna results in lower received power when an equivalent quarter wavelength antenna is used. A larger antenna could be used with higher gain but this would reduce the omni-directionality, which is an important consideration when devices cannot be aligned manually with each other in WSNs.

These characteristics help to constrain the set of possible receive and transmit technologies to a single frequency band, but with suitable experimentally verified models to base range calculations on. In this frequency band the model demonstrates how at short range the path loss slope is smaller than a larger ranges, which significantly affects the efficiency of single-hop larger networks. Additional consideration of the efficiency of transmit hardware at different frequencies is given in Section 4.1.1 where this is balanced with the required energy storage to complete an atomic transmission or reception. Following the motivation for EH sensing in Section 1.1, and building on the wireless communication characteristics, the next section addresses communication initiation under energy scarce situations.

2.3 RF Wake-up with Rectennas and WuRx

RF wake-up uses the intrinsic power transmitted with a wireless communication to reduce the power consumed from the listening device's energy storage. Part or all of the incoming signal can be rectified and then the DC power can be used to power control or decoding circuitry. This removes the need for carrier generation, phase locked loop, and low noise amplifier circuitry in conventional radios. Conventional

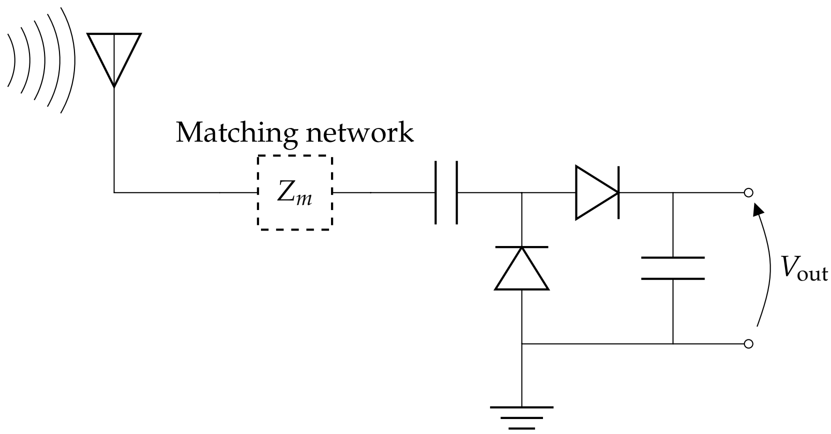


FIGURE 2.5: Simple rectenna circuit for generating DC from incoming RF signal using an antenna to receive the signal, combined with an optional lumped element network to match the antenna to the voltage doubling rectifier.

high sensitivity listening methods, when devices are powered from small energy storage, results in very short listening duration, even when the radio has a low duty cycle and the transmitter remains active for longer. The low power receive mode (low duty cycle listening) of a conventional radio consumes 150 µA for listening at 2 Hz where the transmitter consumes 750 µA for at least half a second to reach it [53, 54]. This means energy storage is determined by the communication cost [22] since computation takes place across several energy recharge cycles so can require smaller storage. Alternatively, I now cover the characteristics of rectifying antennas (rectennas) and WuRx to provide RF wake-up to reduce the listening consumption and the subsequent effect on the transmitter energy required.

2.3.1 Harvesting of RF Power

A rectifying antenna (rectenna) is an energy harvester that collects energy from incident RF signals and converts it to DC power, which can then be used to trigger or power a node. Rectennas are typically designed for specific frequency bands to maximize efficiency in bands where a higher level of signals is to be expected. There is a large variety of rectennas that have been designed for different frequency bands, but I focus here on devices between 868 MHz and 960 MHz which are the EU and US ISM bands with highest permitted power from a transmitter [51]. Rectennas where the antenna only uses off-the-shelf components are investigated because they are easier to validate and implement.

2.3.2 Antenna-rectifier Impedance Matching

A typical rectenna setup uses a voltage multiplier fed from an antenna, that can optionally be matched with a lumped element network, as shown in Figure 2.5, this

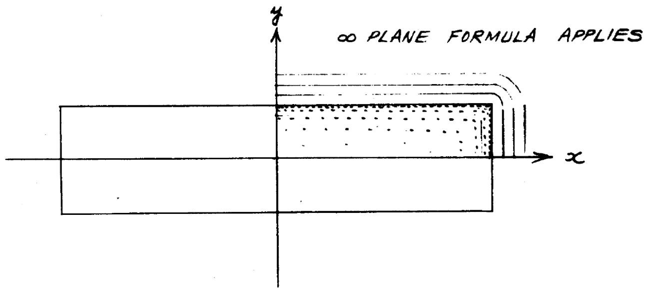


FIGURE 2.6: Current density and magnetic field looking along the axis of a strip conductor at high frequencies. Reproduced from [56].

generates a DC voltage dependant on the incoming RF signal. For maximum power transfer to be achieved the impedance of the antenna should be matched to the rectifier circuit [29]. This can be achieved with a lumped element matching network, which requires additional components and can introduce some additional losses due to the capacitor non-ideality [55], but has the advantage that the same antenna can be used for subsequent data transmission. Alternatively, tuned antenna shapes on printed circuit boards can be impedance matched where the shape and size of the antenna determines the impedance. The thickness of the copper traces, t, is not significant due to the skin effect. The thickness of the "skin" is calculated by (2.5) and the distribution of current, when δ is an order of magnitude smaller than t, is shown in Figure 2.6 [56]. At 868 MHz, $\delta = 2.2\,\mu\text{m}$, which is much smaller than the minimum trace thickness, $t = 17\,\mu\text{m}$. In this situation the resistance determined by surface current density.

$$\delta \triangleq \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \tag{2.5}$$

$$\mu \approx \mu_0 = \text{Vacuum permeability} = 4\pi \times 10^{-7}\,\text{H}\,\text{m}^{-1}$$

$$\sigma = \text{Conductivity (of copper)} = 5.8 \times 10^{7}\,\text{S}\,\text{m}^{-1}$$

The maximum available output power from a rectenna depends on the load where the voltage is always highest for an open circuit, but not the best power. An example of how the DC voltage varies for input power and load can be seen in Figure 2.7. This shows how in addition to matching the impedance of the antenna to the rectifier, to extract maximum DC power, the load should also be matched to the rectifier output [29].

2.3.3 State of the Art Rectifying Antennas Designs

To compare the capability of several rectenna designs six state of the art rectenna characteristics are plotted. Designs where there are only simulated results available have

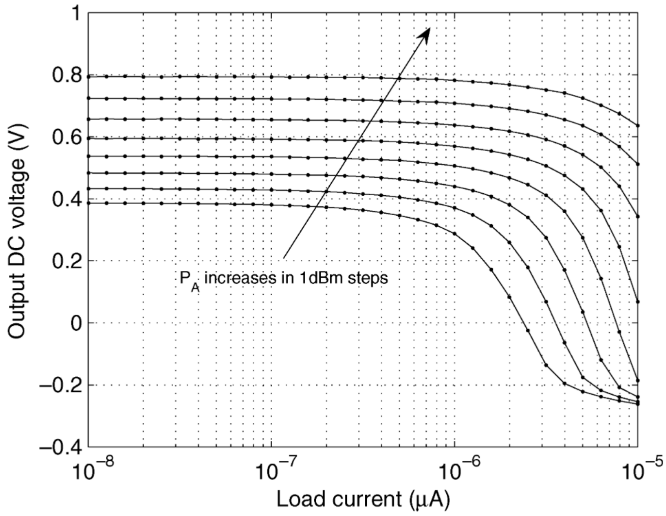


FIGURE 2.7: The effect of varying the load current on a rectenna for available power levels, P_A, between −24.7 dBm and −17.7 dBm. Reproduced from Mandal and Sarpeshkar [57].

not been included. All the designs plotted in Figure 2.8 used RF sources to test implemented designs at 868 MHz to 915 MHz, either at range or though an attenuating element. Several other rectennas have been investigated, but are not shown, as good characterization is not provided [58, 59] or it is designed for the wrong frequency band [60, 61, 62]. Only the designs that use off-the-shelf diodes have been considered here. Custom devices are considered by Valenta and Durgin [63], but most of them perform similarly to the designs highlighted in Figure 2.8, and the chips themselves are not available.

The rectenna by Visser et al. [29] is implemented as part of a sensor node [69] with an LCD that works up to 9 m from the transmitter. The conversion efficiency shown in Figure 2.8 gives the highest demonstrated efficiency from a practical implementation. Their transmitter is the 3 W EIRP Powercast, to show the potential distances achievable. It uses a transmitter over 7 times more powerful than the 26 dBm available from radios researched in Section 3.3, and also has a higher transmit antenna gain, so the range can be expected to be smaller with other power provisioner. It has the smallest form factor of all the rectennas with comparable performance.

This performance review of rectennas shows a consistent relationship between RF input power and conversion efficiency, over a range of different devices and topologies. It also shows how the impedance matched design by Visser et al. [29] achieves higher efficiency. This demonstrates the standard voltage that could be produced by the rectenna This enables an approximate model to be produced within the range of real devices to address what minimum range is achievable if using a fully-passive wake-up to trigger a device.

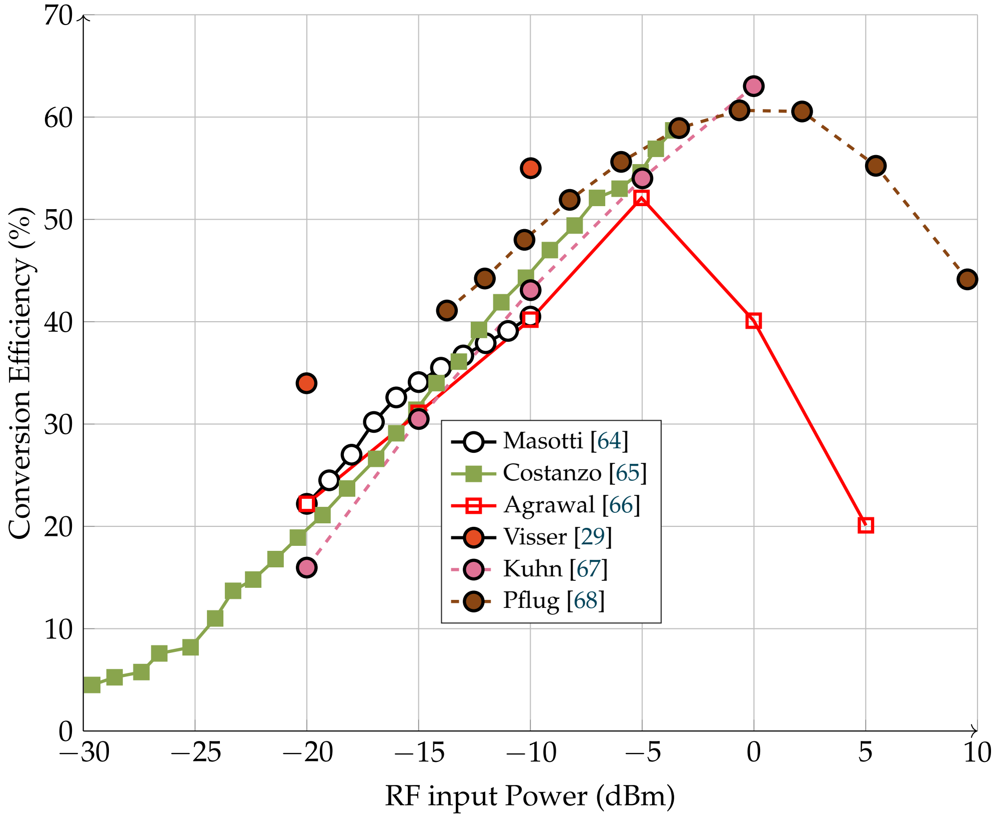


FIGURE 2.8: Comparison of state of the art UHF rectifier and rectennas from literature. Figure based off plot produced by Pflug and Visser [68]. The figure of merit is efficiency. Masotti et al. [64] would in practice have higher efficiency due to an antenna with Gain>1.

2.3.4 Wake-up receiver (WuRx) Technologies

Wake-up receiver (WuRx) (sometimes called wake-up radios) are low power devices that can perform more complex detection of radio signals compared with rectennas. WuRx rectify the incoming RF signal, just like a rectenna, but can operate from lower signal levels by using a nodes own power supply for amplification and decoding [55]. A WuRx consists of a band pass filter followed by a rectifier to demodulate the signal and then depending on the data encoded in the signal, it can emit a wake-up signal. WuRxs provide increased sensitivity and decoding capabilities, like a main radio, but consume orders of magnitude less power for listening closer to the leakage currents of other device components. Data collected by Wentzloff [70] gives an extensive overview of integrated CMOS state of the art wake-up radios (ULP radios). The highest performing works are reviewed in this section and are displayed in Table 2.2. Also, a couple of WuRx that are made with off-the-shelf components are reviewed. All the lowest power devices (Under 40 µW) use on-off keying (OOK) modulation, because it does not require running a local oscillator to decode, however it is much more susceptible to interference than other schemes and has lower data rates. Given the short duration, under 10 ms, of the wake-up signal this is not thought to be a significant issue because the range is limited so the probability of multiple low rate devices initiating a overlapping communication is small.

The state of the art ULP receiver is a 4.5 nW receiver [73] that combines and off chip transformer filter with a CMOS rectifier. A device with 10 dBm higher sensitivity is shown in [71] and [72], however, it has higher power consumption, 7.6 nW, and also a 33 % lower data rate (200 bps). This means a transmitter would have to spend more transmit energy to send the same wake-up signal. Both these chips are designed for the 115 MHz band.

Alternatively, relatively higher power consumption devices can be chosen, but still using less than 100 µW. At 2.4 GHz a design [80] achieves a sensitivity of −97 dBm with a power consumption of 99 µW. This is a much less power than a full radio with similar sensitivity, although it has the limitations of only matching a predetermined signal, and lower data rates. Likewise at 915 MHz a −87 dBm chip uses two stage approach [78], first for energy detection then address decoding to filter false wake-ups all keeping the power consumption below 52 µW. As it uses energy detection first, it requires a longer wake-up, but this allows for dynamic address decoding by feeding the received address to a microcontroller unit (MCU).

In the 915 MHz band, two CMOS solutions are reviewed here, both are made at the University of Michigan and their spin-out Everactive [74, 19]. The first, with 116 nW consumption, has sensitivity of −45 dBm, this has been commercialized into the PK1001 chip. This chip has a higher consumption, however, also has a higher data rate of 31 kbps.

An alternative CMOS implementation is the Austrian Microsystems AS393*x* correlator [32] using OOK Modulation to provide a 31 bit address, which triggers a micro-controller to decode the remainder of the incoming data, when correctly correlating the stored address. It uses 5.6 µW, most of which is to power the address correlator, and has a sensitivity of −50 dBm.

An alternative to using an integrated circuit is to construct the WuRx from off-the-shelf passive components. WuRxs of this kind are easier compare approaches since they can be replicated. Magno et al. [81] builds upon an earlier 270 nW design [75] without an address decoder, and instead uses a PIC micro-controller for address decoding, which takes the place of the AS393*x* chip. This means each false wake-ups (63 µW) costs a little more but it is not as high as with no decoding at all. If the main micro-controller is used the false wake-up uses 400 µW for the duration of the false wake-up. The power consumption at the same sensitivity is 1.2 µW. At lower sensitivities, the WuRx can achieve power consumption of 152 nW. Although this uses less power than Gamm et al. [32], the data rate is ten times smaller, meaning over long transmissions the cost to the transmitter would be higher.

Citation	Year	Type	Frequency band / MHz				Passive Sensitivity	Active Sensitivity (dBm)	Active Power
			115	433	900	2400			
Wentzloff [70]	-	Review	-						
Moody et al. [71, 72]	2018, 2019	WuRx	X	X				-71	7 nW
Jiang et al. [73]	2017	WuRx	X					-69	4.5 nW[a]
Oh et al. [74]	2013	WuRx		X	X	X		-43	116 nW[a]
Marinkovic and Popovici [75, 30]	2011, 2012	WuRx		X					270 nW
Hambeck et al. [76]	2011	WuRx			X			-71/-64	2.4 µW
Milosiu et al. [77]	2013	WuRx			X			-82	215 µW
Abe et al. [78]	2014	WuRx			X			-87	52 µW
Gamm et al. [32]	2012	WuRx			X			-52	2.7 µW
Moazzeni et al. [79]	2015	WuRx			X			-75	16.5 µW
Roy et al. [31]	2015	WuRx				X		?	116 nW?
Salazar et al. [80]	2016	WuRx				X		-97	99 µW
Magno et al. [81]	2016	WuRx						-32 to -55	0.19 nW to 1.2 nW
Fabbri et al. [55]	2019	Passive WuRx and Backscatter			X		-16	-17	-
Roberts and Wentzloff [82]	2012	Biased Rectenna			X			-42	98 nW
Shen et al. [83]	2016	Backscatter					n/a	-	-
Majid et al. [34]	2019	Backscatter			X		-25?	-25	2 mW
Liu et al. [84]	2013	RF EH and Backscatter		539			-24		540 nW (harvested)

TABLE 2.2: Broad range of publications of WuRx chosen from best performing WuRx in the review the review and backscatter devices in the 915 MHz band. A ? indicates where the figure is unclear from the publication.

[a] These devices achieve very low power but at the expense of a very low datarate under 300 bps

A couple of the studied WuRxs were integrated to make a wireless sensor. The first [30] took an approach that used a master node to send wake-up packets to connected nodes. A coin cell battery powered the node, with an MSP430, at the core. The MSP430 is a series of processors designed for very low power operation and it is used for decoding the SPI signal from the wake-up receiver. The wake-up receiver consumed 270 nW and the transmitter (at −10 dBm) consumed 47.7 nW. A second approach [31] has a master node (called an aggregator) that transmits signals to a EH node that transmits back on a different frequency. A solar panel is used to power the device, a fully integrated CMOS core, and the response transmission rate is determined by the power available to the device, however no information about sensitivity is available.

A third WuRx [32] was tested with two heterogeneous nodes where one provided the wake-up for the other, of the three implementations reviewed here this was the only one to do so. A range of 40 m was achieved from one node to the other and the battery life was claimed as 9 years, however this is not taking into account the degradation of the battery or other leakage currents.

To summarize, a number of WuRxs are available at low powers around 100 nW. Two commercial solutions exist: Everactive PK1000/1 and Austrian Microsystems AS393x. Alternatively, implementations with off-the-shelf components and custom decoding have power consumption around 1 µW. Applications studied implement star network topologies and do not consider mesh networking at all, but the characteristics measured here help to model the behaviour realistically in further simulations.

There is a very wide variety of WuRx available, and only a representative sample are considered here, to demonstrate the relationship between consumption and range. A more detailed presentation of WuRx in the 900 MHz band including some additional devices with the lowest power consumption at different levels of sensitivity is presented in Table 5.1. The low-power receivers provide one half of the story but also the response when a wake-up is received must be considered. Specifically, by reviewing technologies in the context of the ability to enable the low power receiver technologies discussed in Section 2.4.

2.3.5 Backscatter

Given the high transmit power consumption required to communicate, an alternative method called backscatter has been proposed [84]. This harnesses a wide-band signal which is reflected by changing the impedance of the device antenna with an RF switch. These solutions respond to a beacon to do immediate sensing, then transmitting back [34]. They do not offer any kind of state retention nor do they include intermittent power sources. Importantly, they employ techniques that prove the viability of RF power transfer at distances over 10 m from a high power beacon to a tag. A backscattering transmitter node then only consumes 250 nW, which is even smaller than the receiver consumption of 540 nW. However, since the nodes do not generate the radio signals, they require a separate RF source providing an ambient power level of −10 dBm with a resultant tag-to-tag range of only 50 cm.

Another implementation uses a custom matching circuit to split an incoming RF signal using a majority of the signal for power and a small proportion for a WuRx to decode a message [55]. The MCU powered by the RF then modulates the antenna impedance through an RF switch to respond. This implementation is able to operate down to −16 dBm which with their 8.5 dB directive 2 mW power source is able to communicate at 9.7 m.

The high transmission requirement required is also seen in subsequent tag-to-tag implementations [83, 34] where a 1 W transmitter is required within 2 m range. For their experimental setup the background RF power level is therefore similar at −9 dBm. Where there is not a high power ambient source, one would have to be provided and given the intended independence of IoT networks from such infrastructure this is unsuitable and has equivalent requirements to the star topology WuRx implementations. Next alternative networking topologies are considered without the infrastructure dependence of star topologies.

2.4 Link Layer Communication

Very low power link protocols for intermittent network should reduce the MAC power consumption for low data rate scenarios [85], maintaining sufficient listening capability with less EH. For example, reducing the receiver power consumption by 10× would allow 10× more listening from the same energy storage and also reducing the main radio 'on' time decreases the required energy storage.

The link layer determines medium access control (MAC), scheduling, framing, device addressing and frame acknowledgement. One of the most significant effects of intermittency on networking is the inability to use scheduled MAC protocols [86] because of the loss of synchronization with each power failure. Scheduled MAC enables large energy consumption savings by duty cycling power-hungry radios across the network. All nodes only spend a fraction of the time communicating, where adjacent nodes are synchronized to transmit and receive in the same time slot. Slotted techniques work using synchronization to only listen in scheduled slots.

To reduce the power consumption in wireless nodes, IEEE 802.15.4 [47] defines a MAC protocol to schedule the duty cycling of connected nodes, however it does not synchronize beyond one hop and would require relaying nodes to have always-on receivers. The time slotted channel hopping (TSCH) protocol [87] is created after realising the limits of IEEE.802.15.4(a) channel hopping and scheduling. It establishes routing slots across the whole network, to enable efficient multihop schedules, but is initially a centralized approach. The centralized approach also relies on a powered node that can manage the schedules of the entire network. Decentralized approaches have also been attempted [88], but a tightly coupled "micro schedule" must be maintained across the whole network. Also, in multihop networks as the number of hops increases the clock error is magnified, increasing the accuracy and power consumption requirements of the clocks, for successful synchronization.

If a node loses synchronization, for example in a power outage, then it must listen for the entire schedule period, and potentially also to several channels, to learn the operating cycle of neighbours. When synchronization losses are increasingly frequent compared to the data rate, as is the case with intermittent systems, the resynchronization energy consumption will be more than when random access is used; therefore, synchronized methods are impractical [89].

Alternatively, unsynchronized methods must be explored. To reduce the power consumption of listening, RF wake-up can be used as well as high power transmissions to counteract the reduced sensitivity. This is an analogous trade off to duty-cycling a receiver as in common low power listening (LPL) techniques, which requires longer transmission preamble [90, 91]. Additionally, considering a multi-hop scenario, an opportunistically enabled link-layer protocol can harness the broadcast physical layer to increase forwarding opportunities.

Next some aspects of link layer communication with wake-up radios are described in detail, starting with how communication with WuRx is initiated between two devices. Then the effect of radio initialization times is considered and the time taken for a received wake-up to active the device. Finally, I consider with respect to intermittently-powered devices whether the encounter probability can be increased even when there is limited information about the EH power of surrounding nodes.

2.4.1 Communication Initiation

The first aspect of MAC is whether the receiver or transmitter initiates communication as shown in Figure 2.9. With transmitter initiated (TI) methods, when a node has information to send it sends the message, then (optionally) waits for acknowledgements. In a receiver initiated (RI) protocol, when a node is ready to receive data, it broadcasts availability or directly addresses neighbours which, if waiting to transmit, can respond with a data packet.

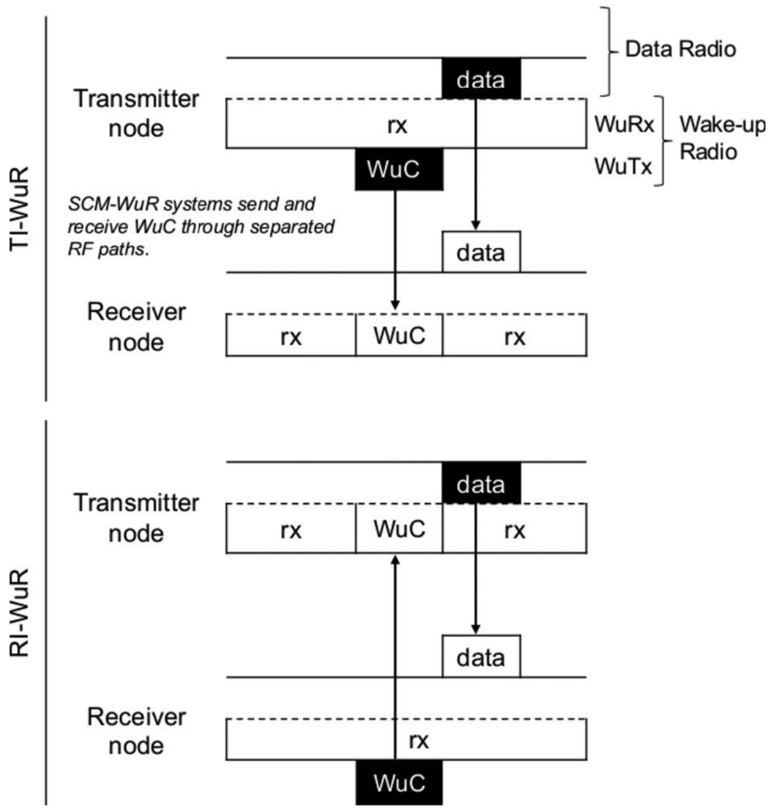


FIGURE 2.9: Comparison of TI and RI modes in WuRx enabled sensor nodes [92].

For star networks with a higher capability central hub and wake-up radios on other nodes, RI allows the hub to efficiently schedule the readings from sensor nodes. One example is a wireless body area network (WBAN) [30], where a sensor nodes fitted with WuRx send readings to the receiver in slots after the wake-up. Also, a comparison using OMNeT++ to compare MAC protocols [92] determines that RI protocols are beneficial in mobile sink scenarios, such as a vehicle driving around an area with sensor nodes. The sensor nodes need to listen with as little power as possible, but the mobile sink has no such restriction and sends the wake-up messages when near to the sensors. They quantify the benefit of using WuRxs in sensor network scenarios but only up to two hops and there is no direct comparison of RI to TI protocols.

In a comparison of PW-MAC (RI) and TI-WuR (TI) protocols [93] with IEEE 802.15.4, where the TI protocol generally performs better than the RI on most metrics, and both consume an order of magnitude less power than IEEE 802.15.4. The biggest improvement of TI over RI is when the wake-up interval is small. Also, when there is a high probability of packet failure both the latency and power consumption are not affected much in TI. In an error prone environment the RI protocol, PW-MAC, does show a small improvement over TI-MAC, however this comes at a larger power consumption, so for intermittently-powered devices the overall network performance would be resultantly worse.

A multi-hop RI protocol called RI-WuR [94] uses a forwarded wake-up from the base station over several hops to enable the end device main radio to transmit in a single hop. The wake-up takes several hops due to the decreased sensitivity of the WuRx whereas the data transmission takes place in a single hop. This RI method relies on all the hops being awake to be able to forward the wake-up, regardless of the realistic path availability. Also, it assumes that the data radios are also in range, where even with increased sensitivity, the data radio may not be able to send the data back in one hop.

Receiver initiated protocols require the sending node link layer to know in advance which receiver initiation requests to respond to. With fixed next hops in RPL and in a star topology [30] this is simple, because the network layer predetermines the next hop. However, for more dynamic routing additional negotiation between network layer and link layer must take place [95], and potential for contention between multiple senders is not generally considered, as the existing research is on the basis that the networks are very low traffic [96]. Additionally the network layer must judge the suitability of a potential forwarder with up to date information and potentially relax required minimum progress metrics as time elapses, or speculatively defer the transmission until more progress is available [97].

Additionally, a receiver must have enough energy to transmit when it receives an initiation message. The energy required to do the transmission will be several times that of just an acknowledgement due to the number of bits transmitted. This energy requirement of RI protocols rules out some fully passive reception methods discussed in Section 3.2, where TI protocols can still enable data progress even when the next hop does not have energy.

Given the receiver energy requirements of RI compared to TI methods, the TI communication is more appropriate for intermittently-powered multihop networking. Furthermore, considering the mechanism of opportunistic routing considered in the next section, only TI methods are considered in more detail.

2.4.2 Wake-up Scheduling

WuRx require two separate transmissions, the first is a wake-up, followed by the data transmission. There is a small amount of latency that must be considered while the neighbouring nodes start their radios, then the data transmission occurs. The data should not be transmitted until the data radio is ready, however the data radio consumes much more power than the WuRx, so having a guard time that is too high results in unnecessary energy wastage, as shown in Figure 2.10, and significantly effects the listening time.

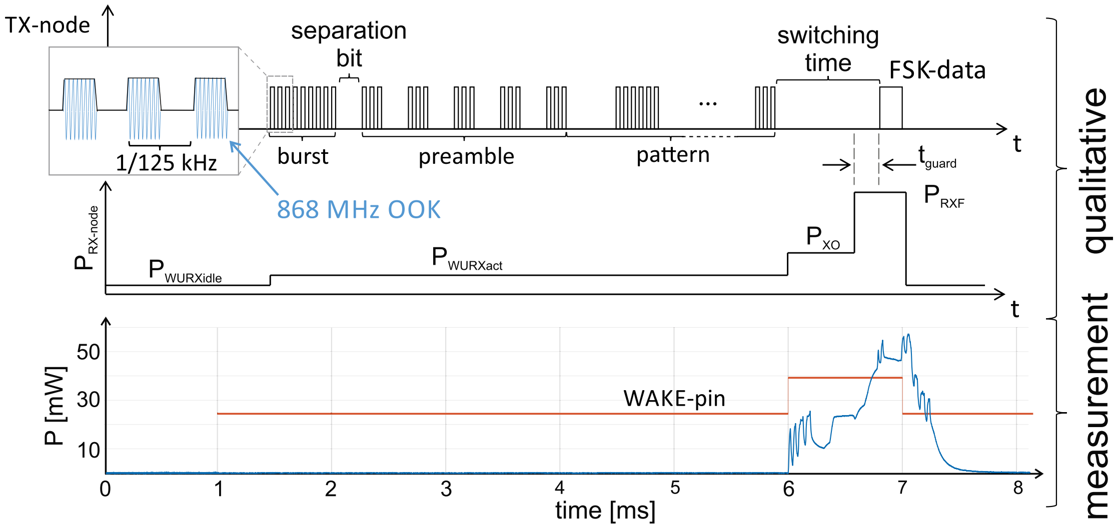


FIGURE 2.10: Demonstration of timing of wake-up and data communication showing power consumption and start up wait required before sending data [98]. P_{XO} is the power required in starting the radio oscillator and t_{guard} is the time allowing for variation in start-up delay.

This latency consists of the delay from the wake-up radio for preamble detection and address correlation, the start up time of the MCU and the start-up time of the radio [98]. The start up time of the MCU can take 2 µs to 3 µs [75], although wake up can be quicker if not in such a deep sleep mode. The startup of the radio is dominated by the crystal oscillator stabilisation and different models show different start-up performance which is discussed later in Chapter 4.

2.4.3 Improving Encounter Rate

Another important role for the link layer is establishing neighbouring nodes. This can be done by logging each neighbour encounter as well as recording overheard neighbours. The rate at which encounters occur determines parameters such as the network route timeout and what the routing capability is. Furthermore, optimising when beacons are sent is important to ensure there is not misalignment between transmissions and other node listening cycles.

If scheduling can maintained as in PW-MAC [93], the duration of wasted listening can be reduced by knowing when other nodes are likely to transmit. This leaves more energy for transmission or other processing. However, as soon as synchronisation is broken it will be more difficult to determine the status of the neighbours because of the shorter listening cycles. Additionally, with the very low power listening possible with WuRx, the additional cost of the clock may outweigh the saving achievable by reducing the already low listening energy consumption [99].

Alternatively, without such scheduling methods when neighbouring nodes have a similar EH source, there is a tendency for them to interleave, and have drastically reduced encounters, as described in Find+Flync [100]. Instead, maximising randomness of wake-ups is important to ensure there are not blind spots in the neighbour map of each node.

Link layer communication connects two neighbouring nodes when they are in range, and wake-up radios can help to lower the cost of this so that the availability is higher. However it does not consider how nodes advertise availability and how data can be communicated beyond one hop. This is essential if areas need to be monitored where it is impossible to have a data collection node or gateway in range. Additionally, the link layer attempts to move data from point to point but does not guarantee success of that communication, and may not provide any information about the link state, nor allow differentiation between data for different applications.

2.5 Networking

To manage aspects such as end-to-end application links and multihop links, networking is required. Networking allows for data to be communicated beyond immediate neighbours using intermediate nodes using multihop routes to pass messages from the source to the destination nodes. The key network topologies are peer-to-peer, star, mesh and tree networks.

In the simplest form, star networks have a central coordination node that can reach all the other nodes, and all messages pass through the central point. This increases the burden on this central node but makes network coordination simple and more easily achievable with WuRx, because it the central node has complete connectivity to the other nodes, and this is reviewed first. Then an alternative is reviewed, mesh networking, that allows for nodes to communicate over multiple hops, where data can take a more direct route and where it is not reliant on a single higher capability device. This can either be in a peer-to-peer manner, where all nodes have a comparable map of the network or in a tree, where nodes route relative to a designated route (upwards), or away from that route (downwards).

2.5.1 Existing Networked Intermittently-powered Nodes

Some existing IC and task based energy management research has considered the cost of wireless communication to a base station. All of the works considered here are for intermittent devices that rely on the harvested energy to transmit sensor readings, but where limited energy storage results in limits on the time spent idle listening and the transmission power. Given the intermittent-power and the small energy storage available, the networking solution chosen in all of these is star networking, using a powered base station to always listen or provide a carrier to modulate. This is because individual devices cannot sustain idle listening or provision power to other nodes. Where the base station is only for one node, I have called the topology point to point instead of star.

WISP [101] is a sensing platform that uses harvested energy from an RF source to power a microprocessor and sensor. Like the other devices that use backscatter as in Section 2.3.5, the main limitation is the power required at the RF transmitter and the very low device to device range.

Another implementation of networking in intermittently-powered devices is the remote camera sensing device called Camaroptera [102]. By monitoring the stored energy levels it can take a photo and then process and analyse the photo, and when there is enough stored energy, use a LoRa transmitter to send it to a base station. For the LoRa transmission accurate timekeeping is required with a consistent power supply, in addition to the burst energy required for camera operation.

Two point-to-point implementations both are based on the Hibernus++ approach to intermittent computing. The first [103] implements a wireless bicycle trip computer that communicates readings to another node when there is sufficient harvested energy. The second focusses on energy prediction from a solar panel [104] to determine whether the energy will be sufficient to power the communication and, if insufficient, communication is paused until there is enough stored energy.

The final example focusses on whether application sensing requirements can be met by transiently powered nodes. Although it aims to be “infrastructure-less” it relies on transmitted Bluetooth low energy (BLE) transmissions being received by mobile phones that randomly become available depending on the users mobility. Therefore, the devices form temporary star networks around the mobile receivers. Additionally, like the Cameraoptera node, this node requires a large energy storage to ensure there is accurate timekeeping.

These existing works have been summarized in Table 2.3 and a question mark is used to indicate values that are not clear from the literature. Some works have large storage values and it is debatable whether these are intermittent devices, given that they could possibly operate more efficiently in a duty cycled manner.

2.5.2 EH Multihop Networking

Multihop techniques enable information to be transmitted beyond the immediate neighbours of a node, but require nodes to share information about what nodes are

Author	Year	Radio	Consumption	Energy Storage	Range	Topology
Nardello et al. [102]	2019	SX1262	Tx: 350mW Rx: 70mJ	33 mF	500m	Star
WISP [101]	2008	Backscatter (4W RF source)	Rx & Tx: 0dBm incident power	10 µF	2.3m	Star
Senkans et al. [103]	2017	nRF24L01	Tx: 16 µJ	50 µF	2m?	Point to Point
Ahmed et al. [104]	2019	CC2500	Tx: 60 mW Rx: 60 mW	60 µF?	?	Point to Point
Sigrist et al. [105]	2020	BLE	Tx: 8.08 µJ	520 µF	?	Star (with many mobile receivers)

TABLE 2.3: Capability of Intermittently-powered device implementations incorporating wireless communication, where all works use star topologies for multi-node systems.

further afield to determine a good route. Multihop networking protocols enable appropriate forwarding for received information with two objectives: ensure the data is received at the intended destination, and do not overload irrelevant nodes.

The following sections contain broad classifications of multihop networking approaches. Starting with well established standards but recognising that these are not so applicable to the intermittently-powered environment, more niche protocols are studied that are less developed and limited by implementation.

2.5.3 On Demand Routing

On demand routing protocols implement route discovery whenever a transmission is made to a new unknown destination. Also, route discovery can be initiated whenever route errors are detected in order to find new routes. Once an end-to-end route is discovered, the data is transmitted and along the route to the destination.

Ad hoc on-demand vector routing (AODV) is one such protocol [106] which has been extended with AODVv2 (DYMO) [107]. It is designed for Mobile Ad Hoc networks and therefore once a route is formed it expects fairly static end-to-end behaviour until a node moves out of range. Route requests are broadcast messages that are flooded until a node knowledge of the destination sends a route reply message. Other nodes will continue to forward the original route request as they do not hear the reply. DYMO adds functionality to send multi-cast route reply messages which slightly reduces the route request burden.

On demand routing is not suitable for the intermittent devices I consider because this relies on end-to-end connectivity at the time of data transmission, which is assumed

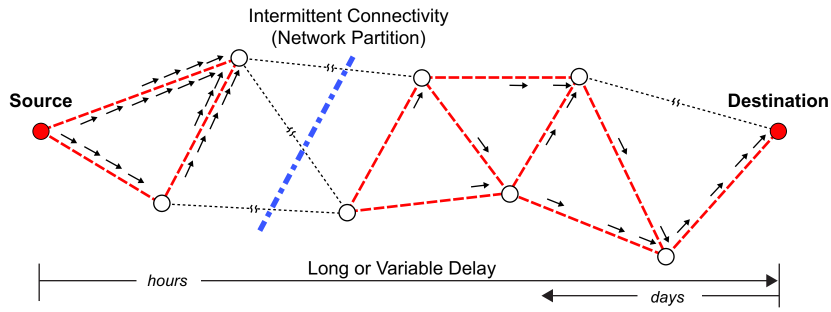


FIGURE 2.11: Intermittently connected network where a partition requires nodes to store messages for subsequent forwarding when reconnection occurs [109].

with typical internet devices but the exception with intermittent devices [108]. Additionally, when nodes have severely limited energy storage the process of the route request is likely to exhaust the supplies of the potential forwarding nodes.

2.5.4 Disruption Tolerant Networking

Given that the process of route finding may itself exhaust the supply causing a delay before the next transmission, methods that use the store and forward method are investigated. These have been called disruption/delay tolerant networks (DTN). For this purpose, the Bundle protocol has been proposed, where all delay tolerant nodes share a Bundle layer between the application and transport layers [109]. This has been applied to the Inter-planetary Internet where vast distances and orbital trajectories mean that conversational protocols, relying on round-trips and acknowledgements, may fail. The bundle protocol is not applicable to intermittently-powered networks because it relies on timing for time-to-live information as well as for calculating contact schedules, where the link availability is known ahead of time [109, 108].

Such a scenario is shown in Figure 2.11 where the bundle protocol can build up packets for sending across the intermittent connectivity gap when connectivity becomes available, called a custody transfer. Intermittently-powered devices do not have predictable contact schedules nor are they able to accurately keep track of time. Therefore, the proposed Custody Transfer to overcome delayed hops is not applicable since no guarantee about making progress within a contact schedule can be given.

While there has been considerable amounts of research related to DTN, there is limited research using them in the IoT environment [110]. Specifically, analysis with respect to the energy consumption of energy storage constrained devices, where device availability fluctuates more frequently than packets are transmitted. Examples of routing protocols that consider slow variation in stored energy to reduce the load on energy scarce nodes are LEACH [111], which aims to merge data and distribute energy dissipation according to energy availability. Another approach is Energy-opportunistic Weighted Minimum Energy where the routing algorithm relies on EH rate information to choose an optimal route. Since its nodes have slow variation in EH power, the resultant routing is effective at distributing the load but as storage decreases such routes cannot be relied upon. Given the different conditions of faster link variations in EH-WSN, I now consider some opportunistic routing protocols and the suitability to intermittently-powered mesh networks.

2.5.5 Opportunistic Networking

A significant factor in the energy consumption and delivery trade-offs of DTN is the routing. For this opportunistic routing (OR) provides a redundant tree of paths to route the information, which is well suited to low duty cycle networks, where links are intermittent [112]. This is more suitable than DTN protocols, designed for the Inter-planetary Internet and often relying upon predictable contact schedules.

Firstly, looking at OR used in a real world evaluation of different DTN [113]. Several routing protocols are considered which are all tailored towards mobile nodes that come in contact long enough to exchange lots of messages, before going separate ways to disseminate those messages. They consider Epidemic Routing, Spray and Wait and PROPHETv2 and also propose Distributed Forwarding Algorithm. An extension of Spray and Wait has been proposed in Volatile Spray and Wait [114] that uses the expected mobility to speed up the message spreading phase. These networks are all characterized by "store and carry" which does not fit the capability of most WSN installations which are static, so the reliance on large information transfers on meeting is unrealistic. All these protocols are a result of the trade-off of how many copies to forward identified in PROPHET [115], where too little forwarding results in low delivery ratios but over forwarding results in wastage of system resources, and long term reduction in network capability.

Smart Gossip [116] uses MAC broadcast to forward the messages to several listening devices which then retransmit the message based on a gossip parameter. To counter a broadcast storm, each transmission keeps track of the parent node and the gossip probability reduces based on the presence of siblings (neighbours with the same hops to the destination). Whilst there is consideration for node failures it only updates parent-sibling-child relationships and there is no consideration for the failure, and quick recovery experienced with intermittently-powered nodes. More appropriate for this problem is the proposed extension for packet loss, where nodes track transmission sequence numbers from each source node and request retransmissions when gaps in the sequence are detected. Since nodes keep a record of forwarded messages this may be recoverable in a single-hop, as long as all packets are taking the same route. Although retransmission requests add overhead it may be necessary when data

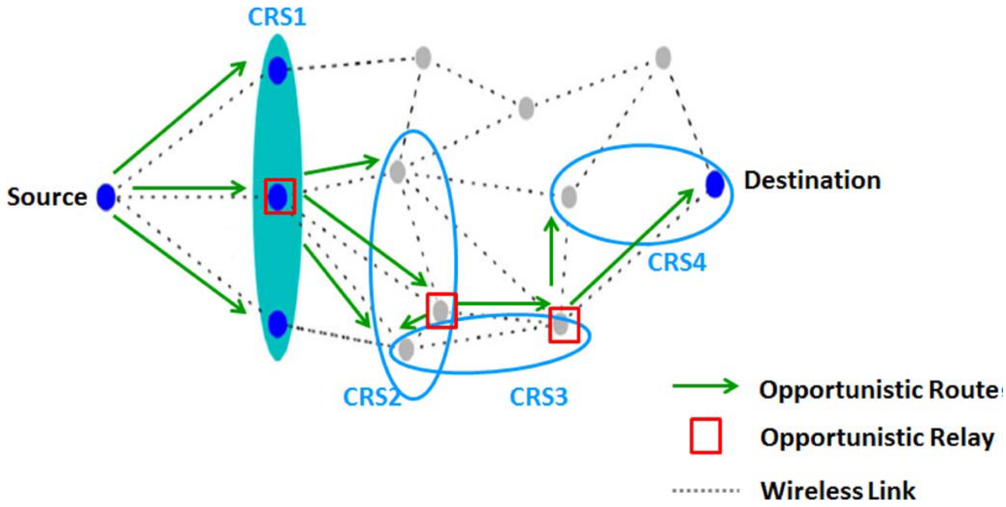


FIGURE 2.12: Demonstration of opportunistic routes to the candidate relay set (CRS) at each hop, only a single flow is considered here where one relay is chosen opportunistic relay at each hop [120].

delivery requirements are high since the gap in the sequence may be missing at subsequent hops also and it is not possible to determine if another route has been found. The analysis performed considers a high probability of node failures but only with slowly varying failures, when wireless losses are considered instead, only 20 % error rates are considered, whereas intermittently-powered devices exhibit a much faster varying on off rate.

A disadvantage of these protocols is that they only consider time slotted MAC protocols, designed to synchronize the radio on time between nodes and reduce overall listening time, instead asynchronous approaches must be considered. To improve the performance of EH-WSN where nodes are duty cycled but neighbour duty-cycle awareness is unrealistic, DCEB has been proposed [117]. This relies on close integration of the routing and MAC layer and also utilizes a RI communication. There are some other RI approaches that also implement broadcast transmissions ADB [118] and [119]. The limitations of this work are that only broadcast traffic is considered so will be wasteful in non-broadcast scenarios. Additionally, it specifies that a receiver initiated protocol must be used, however, with the increased listening that is possible with WuRx, a transmitter initiated method may also be possible. Of these flooding protocols, only ADB considers requests and repeat at the MAC layer, which is important to achieve greater coverage with low duty cycles. Whilst it achieves high coverage, it only uses unicast transmissions to allow acknowledgements and relies on immediate retransmission or acknowledgement.

An extensive review of over 50 opportunistic routing protocols [120] characterizes them based on their strategies for achieving reliable delivery and the optimizations they make for different application environments. An initial consideration is whether node to node transmissions are acknowledged, most are not but more recent cross-protocol attempts allow for implicit acknowledgement. All the protocols forward to nodes in the candidate relay set, shown in Figure 2.12, a subset of neighbours chosen to make progress towards the destination. Some protocols only consider choosing one forwarder each time, however, with intermittently-powered nodes unicast transmissions will be wasted so only those using multicast or broadcast methods are relevant. Additionally, only some protocols consider automatic repeats which may be necessary, especially at the source and destination where no other node can act in parallel, unlike where multiple relays are available. If multiple simultaneous flows are used by duplicating a message then the routing protocol must manage this to prevent it from flooding the network, this survey highlights several protocols that do this. Finally, the survey also looks at what different protocols seek to optimize. Whilst none of them consider how MAC wake-ups could be useful, EEOR (Energy Efficient Opportunistic Routing) [121] and CL-EE (Cross Layer Energy Efficient Routing) [122] consider the radio duty cycle or radio energy consumption and are highly applicable to the static but intermittent nodes considered.

Few comparisons of protocols are focused on the energy consumption however one such is SCAD [123]. Which has been evaluated and compared to other existing opportunistic protocols and is shown to outperform them. Unfortunately, the protocol relies on accurate timing information and the ability for immediate retransmission since other transmissions are suppressed by overhearing the first transmission. The nodes have to have the capability to transmit on demand because they use progress based backoff before forwarding. Therefore, separate mechanisms for suppressing surplus forwarding is required if this protocol is to work with intermittently-powered nodes.

Another approach considering energy consumption is Opportunistic Flooding [28], designed for a static network of duty cycled sensor nodes. Energy level, link quality and the knowledge of potential receiver schedules is used at each hop to determine the backoff before retransmission. It is compared against an improved naïve flooding approach that does not utilize lower latency hops that may require more energy. Both methods rely on accurate knowledge of the potential receivers listening schedule and use unicast MAC transmissions since the probability of multiple listening nodes each slot is very small. Given that high power radios are used and the storage is never fully depleted, the overhead of keeping accurate track of time is not significant for their study. The authors consider methods using multi-cast transmissions, but they disregard them since the schedule of neighbouring nodes is known and the probability of multiple listening at the same time is small. Therefore, a hybrid of both the asynchronous approaches harnessing the broadcast medium and also routing metrics considering energy are required.

Returning to CL-EE [122], the protocol is designed for quickly fading channels and where there are bounds on the number of retransmissions that are acceptable. It takes into account how varying the power transmission level may improve the number of hops, if there is a significant chance of a successful transmission. An in depth analytical analysis is presented that shows how the optimal forwarders can be chosen in a OR scheme. Their work demonstrates an improvement over early protocols but does not consider the energy consumption of non-ideal transmitters, and it needs to know the positions of all the hops to the sink to calculate the optimal power versus hop trade off. Whilst this may be possible in a network with data only travelling to the sink, if there are other network flows, the storage of all the routing information in the network becomes a problem on memory constrained devices. Furthermore, the exchange of information about position, signal strength and packet loss are all assumed to be at no cost, but in the intermittently-powered networks this is deemed non-negligible.

The opportunistic routing survey [120] considers many different possible metrics and highlights some suitable for WSN and energy constrained applications. First the expected duty cycles (EDC) metric is introduced to estimate the expected number of node duty cycles required to reach the destination, this is equivalent to an expected transmissions (ETX) metric for non-duty cycled networks.

Considering the limitations on routing complexity caused by the constrained nature of embedded devices, RPL has been designed to require minimal stored information but still enable node-to-node routing. RPL stores a list of preferred parents (upwards to the sink) forming a destination oriented directed acyclic graph (DODAG), and can similarly store a list of descendant nodes (downwards from the sink) in each branch. This information has a low overhead to store, but requires all cross branch messages to reach a common ancestor node before being routed down the tree. This has been adapted to for opportunistic routing for WSN (ORW) [124] which uses the EDC metric to dynamically choose the forwarding set. The protocol calculates the maximum value of EDC that any next hop contending to forward must have. Upon sending a transmission, nodes with a lower EDC value contend to become the forwarder with a light weight MAC protocol. Furthermore, by sharing the downward nodes set it allows for full upwards and downwards routing [125], but without the hard single node failure points of RPL.

2.6 Discussion

IC techniques allow for computation progress in harsh EH conditions but the information must be transmitted to build useful implementations of EH systems. The low power listening techniques that use rectennas and WuRx to harvest small amounts of energy from a transmitter are viable in dense networks where the transmitted power remains low but the low power listening devices can still detect the signal. Given the different ways in which devices would operate, research aim A1 is to explore the listening techniques in Chapter 3, to determine which are able to enable communication in the context of EH nodes.

Existing implementations rely on higher capability devices for a backscatter transmission system or for wake-ups to read back to the transmitter, which does not solve the problem of infrastructure dependence. Additionally, low power networks shown in Table 2.3 that use WuRx to implement a star network all have a small range. This motivates the investigation into multihop mesh networking, where nodes do not need to be all in range of a common forwarder. With a mesh network of intermittent EH nodes with small storage, individual point-to-point links, vary greatly in availability, which necessitates research aim A2, to determine how the trade offs of availability and transmission rate affect the link throughput addressed in Chapter 4. Even with the reduced link availability it is still possible for data to be successfully passed around the network because there is a large variety of possible routes.

Multi-hop techniques could allow networks of EH intermittently-powered devices to operate independently of high capability coordinators. Current implementations do not consider both delays caused by small energy storage and the asynchronous nature of node to node transmissions. There are many useful aspects that could be incorporated such as neighbour map sharing, in ADB [118] and energy level based back off in Opportunistic Flooding.

Additional analysis is required to measure the performance of networking protocols with the characteristic behaviour of WuRx where idle-listening is very low cost, and transmissions are costly to initiate but where large data transmissions and immediate acknowledgement are possible when the receiver is activated. However, there has been no simulation that considers the effect of intermittently-powered nodes. Specifically this concerns how the routing protocols respond to intermittency as stated in research aim A3. This aim is addressed by comparing ORPL protocol further in Chapter 5, because it fits the requirements of being lightweight enough for embedded devices, and does not require detailed information about several hops ahead in the route, due to its distributed nature. Additionally, it is able to route data downwards as well as to a sink node.

Given that WuRx are able to extend the active listening time of EH devices, but because current implementations only consider star networks the impact of reduced range is not considered. With the need for multi-hop networks, the effect of the reduced range that is a consequence of reducing power consumption must be evaluated to quantify the benefit and limitations of WuRx. This is the concern of research aim A4, where the behaviour of the routing must be measured alongside the comparison of range. The requirements of the simulation are accurate and fine-grained energy modelling, good models of transmission and interference, and implementation of multi-flow routing to reduce the required MAC retransmissions. Without simulation tools it is quite speculative comparing between methods therefore it is important to develop the simulation of this protocol including energy consumption of control packets.

Then I heard him speaking, and as I listened to him, I fell into a deep sleep, my face to the ground.
A hand touched me and set me trembling on my hands and knees. He said, "Daniel, you who are highly esteemed, consider carefully the words I am about to speak to you, and stand up, for I have now been sent to you.

Daniel 10:9-11

3

Wake-up Communication for Intermittently-powered Devices

In this chapter[1] techniques are proposed for node to node communication with intermittently-powered devices, incorporating aspects of intermittently-powered computing, low power communication methods like WuRx and routing methods for ad-hoc networks. The focus is on the prospective homogeneous mesh networks to enable the high degree of autonomy demanded by IoT applications for distributed computing and pervasive sensing [112]. Figure 3.1 shows a comparison between connectivity when considering previous implementations. Intermittent techniques in the bottom row allow devices to operate with a tiny energy storage buffer as covered in Section 2.5. Star connected techniques in the middle column use a higher capability node to coordinate EH powered nodes, where the wake-up assisted sink reduces the end node transmission required or wake-ups enables lower power sleep while listening end nodes [30]. The most connected, mesh networks, are currently only possible with large energy storage, whereas instead this research, highlighted in Figure 3.1, seeks to bring mesh networking to intermittently-powered devices.

The important distinction made is that nodes are homogeneous, that is with equal hardware for transmitting, receiving and harvesting energy, and in low EH conditions

[1] This chapter is based on a article published in the IEEE Network magazine April 2022 [3]. I produced all the figures and analysis of radios and wrote the text. The proposed receiver types were refined with Oktay Cetinkaya who also provided some text concerning wireless power transfer (WPT) and the work was supervised and revised by Mohammed El-Hajjar and Geoff V. Merrett

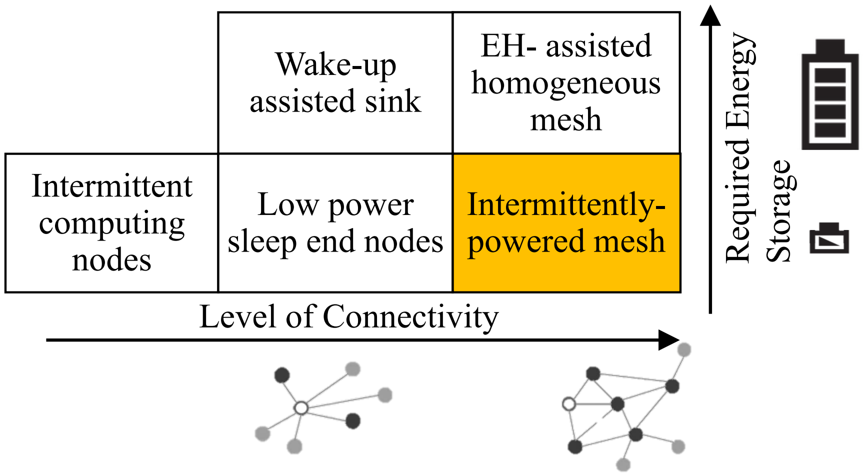


FIGURE 3.1: Domains of EH computing and networking with increasing energy storage requirement on the vertical axis and increasing connectivity on the horizontal axis, with this area of research highlighted.

the nodes become intermittently-powered. Intermittency poses new challenges to mesh networking, since timekeeping is impossible across power outages, consecutive transmissions are limited due to the small energy storage and there are high amounts of route changes. Such challenges currently limit the adoption of intermittently-powered homogeneous mesh networks and motivates this investigation.

First, a discussion is presented of some challenges faced by existing approaches that need to be addressed in order to achieve efficient mesh networking with intermittent nodes. Next, I consider what aspects of existing routing could benefit the network. Afterwards, four receiver types are studied that could be used to implement communication, when nodes must store data until enough energy is harvested. Finally, in this chapter the power consumption of transmitter hardware available is considered and the capability is analysed for each of the receive modes in light of this.

3.1 Intermittency Specific Challenges

To ensure routing is possible, the cost of transmitting and receiving must be less than the available power for the intermittently-powered nodes. Existing research for energy harvesting (EH) mesh networks helps specify the energy harvester and storage size to ensure there are very few node outages given a specified receiver listening power [24]. However, they still consider relatively large energy storage or reliable EH power, this is so they can reach the required reliability. This ultimately restricts the application domain, and does not meet the requirements of removing the need for energy storage and large EH.

From a whole network perspective, techniques are introduced to dynamically spread the load according to the EH and residual energy stored in nodes [28], where data is routed around or away from nodes with lower energy reserves, therefore reducing the EH power required. However, with intermittently-powered nodes, the node storage may only support a few transmissions or receptions before the storage is completely exhausted. This means the route lifetime is small, so information gathered about the best route becomes obsolete before it can be used. Additionally, the process of querying nodes may exhaust the energy supplies of hops along the route, given the very limited energy storage.

3.1.1 Synchronization of 'Off' Nodes

To reduce the EH power required, many techniques schedule active periods, so the receiver spends much less time listening and only listens when neighbouring nodes have a transmission slot. For example, by reducing the receiver on time by ten times would allow ten times more listening from the same energy store and also reducing the main radio 'on' time decreases the required energy storage. However, many such techniques rely on accurate time keeping which is lost during the power outages of intermittent devices.

This loss of synchronization is one of the most significant effects of intermittency on networking resulting in the inability to use scheduled MAC protocols [86]. Slotted MAC techniques work well when the medium is active for a small proportion of time, where listening energy consumed by power hungry radios is reduced by only listening in scheduled slots. All nodes only spend a fraction of the time communicating where adjacent nodes are synchronized to transmit and receive in the same time slot. If a node loses synchronization, for example in a power outage, then it must listen for the entire duty cycle period to learn the operating cycle of neighbours. When synchronization losses are increasingly frequent compared to the data rate, like with intermittent systems, the resynchronization energy consumption will be more than when random access is used, therefore synchronized methods are impractical. Furthermore, maintaining schedules of many nodes requires more resources and risks having disjoint groups of locally synchronized, but globally unsynchronized groups.

3.1.2 High Power Wake-up Transmissions

Alternatively, nodes can use pure wake-up based communication, which consists of using wake-up receiver (WuRx) consuming in the order of 100 µW triggered by wireless power transfer (WPT) from an initiator then enabling the main radio. This does not require synchronization but comes at an *increased cost to the transmitter*, since WPT must be used for lower sensitivity WuRxs. This presents several challenges to mesh networks: 1) How to dynamically allocate transmission energy, which affects the energy storage capacity and charging characteristics; 2) what communication hardware uses the harvested energy in the most efficient way; 3) when would higher transmission range outweigh lower listening cost. All of these require optimization based on density of the nodes, channel characteristics, hardware size limitations etc. Additionally, given that homogeneous nodes have to receive *and transmit* messages, the energy storage requirements for transmission must be considered including the subsequent listening ability in order to improve the connectivity across the network. These questions are looked at further in the next section.

Furthermore, fully intermittently-powered networking can occur when an off node, with zero energy stored, can receive information from a neighbour, via SWIPT, and then it can process and optionally forward it, when the node EH recovers. In this scenario, listening would be completely passive, and the energy storage is only required for transmitting. However, this faces similar power consumption challenges to wake-up communication. Next I consider the routing implications of intermittency.

3.1.3 Intermittently Hidden Forwarders

The network layer will decide whether to forward the data based on the destination and network model it holds. With conventional 'always-on' networks, the most naïve approach is selective broadcasting, where a message is forwarded once which will fail to reach intermittent nodes, since nodes can be off when the broadcasting happens. This is also incredibly wasteful of resources, since the data will be forwarded to completely irrelevant regions of the network. Unsurprisingly, there are many routing methods to prevent this and to prevent the network from being overloaded, by maintaining network state information in nodes for smart forwarding decisions. In a dynamic network, nodes must exchange control information to establish accurate records of neighbours and available routes. Due to the varying nature of EH, nodes and routes become unavailable immediately after discovery. Consequently, the overhead of the control messages presents a large burden that reduces the energy remaining for the core data communication. In the meantime, networking methods that *do not rely on implied future availability* are required.

In addition to the challenge of ensuring routing is not wasteful, receivers that are off cannot receive data forwarded to them. This receiver delay is mainly a problem at the final hop, so long as for other hops the specific forwarding node is not important, and the data makes progress. This means even if a selective broadcast routing is used, it does not provide sufficient guarantee that data will reach the intended destination, since the destination or immediate neighbours may be off when the broadcast occurs. Normally this is corrected by the transport layer in a networking model, whereas intermittent nodes need a more local solution, able to locally "gossip" the data to the intended destination is required. Additionally, if nodes are unable to receive when off, it is likely that multiple immediate forwarding neighbours of the destination node will retransmit data even after correct delivery, wasting their severely limited stored energy on redundant messages. 'Always on' networks experience the hidden node problem when nodes are out of range. This is a variation on the hidden node problem, where in this case the forwarding neighbours would benefit from overhearing the transmission or acknowledgement. But nodes may be unaware of other nodes forwarding before it, as such overhearing is at the MAC layer which will discard the message. If completely passive intermittent reception is enabled, then this becomes possible. The clear-to-send message is used to remedy this situation, which could be applied to intermittent networks for overhearing acknowledgements.

In response to these challenges, I propose four receiver types for intermittently-powered mesh networking nodes to exchange data for effective network operation. Whilst some components of the nodes are techniques demonstrated by previous work in a star configuration, the proposition is to use them to operate as homogeneous nodes communicating as peers. Furthermore, I propose types 3 and 4 which could be enabled by future radio technology and low power NVM, where data processing and acknowledgement sending can take place when the receiver EH supply is strong enough, without the need for energy storage to support immediate responses. In the next section, this operation of such devices is discussed where received messages can be stored in NVM until enough energy is harvested, alongside discussion of requirements for communication initiation.

3.2 Receive Types for Intermittently-powered Nodes

When nodes do not have sufficient energy to power a high power receive radio all the time, listening methods with even lower power consumption must be considered. This transfers some communication burden to the transmitter. In duty-cycled MAC this is by increasing the number or length of transmissions, to ensure each preamble is longer than a transmission. With RF wake-up as is considered here, this is through increasing the output power of the radio. Either method results in increased energy consumption per message, so nodes with EH sources must harvest longer per transmission and cannot retransmit immediately unless there is a sufficient stored energy buffer.

Nodes consist of a microcontroller powered from a small fixed capacity energy storage device, topped up by an energy harvester and used to listen and allow forwarding when there is enough stored energy. The node has a conventional radio, used for transmitting data packets and wake-up signals, and can be used as a high capability receiver, but at higher power consumption than alternatives. Nodes require different

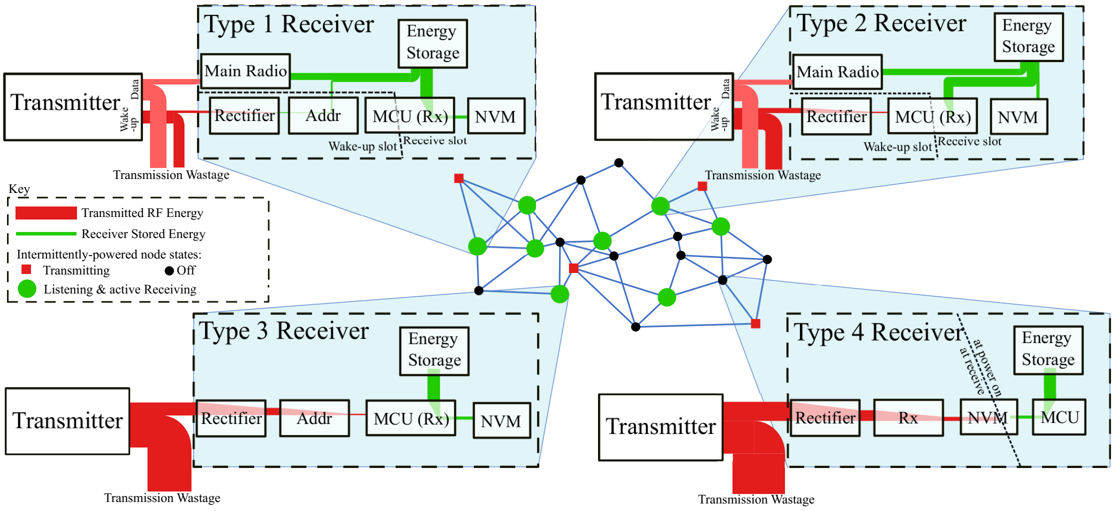
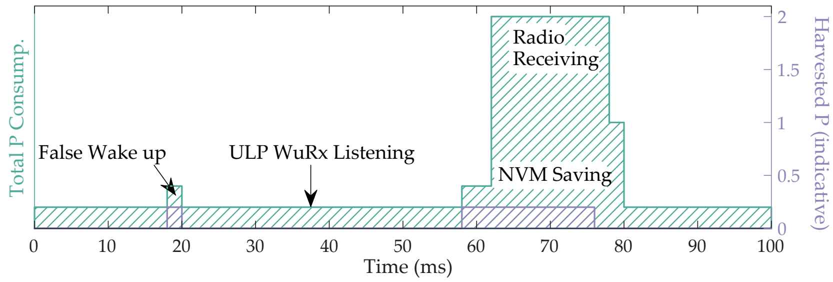


FIGURE 3.2: Energy flow from transmitter radio and receiver energy storage in network of intermittently-powered nodes. Four types of receiver with different receive chain blocks. The address decoder (Addr) block allows filtering of wake-ups, all blocks have NVM into which data is saved for reading from the microcontroller unit (MCU). Energy consumed during the wake-up and receive in separate time slots are indicated by dashed line within node. Please note the energy flows are not to scale and receiver types would not coexist within the same network.

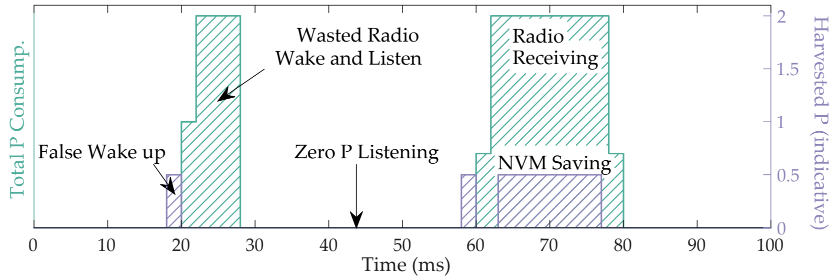
receiver hardware for each communication type, with reception from an active radio or fully passive data reception with simultaneous wireless information and power transfer (SWIPT) and optionally a passive or very low power radio wake-up source. Nodes have non-volatile memory (NVM) to store received data until there is enough energy to forward it to the next hop. I consider the effect of the consumption for wake-up at the transmitter and receiver further in Section 4.2.4, where Type 1 and 2 use existing technology but in a novel network architecture enabling multihop and where Type 3 and 4 are novel topologies that have not yet been realized in hardware. The configurations of these technologies to form different communication types are illustrated in Figure 3.2, to show how energy consumption and energy source differs for each configuration. Different receive types shift the energy burden from the receiver in Type 1 to the transmitter in Type 4. The energy for processing and saving to NVM in passive receive types comes from the transmitter which is shown in Figure 3.2. Due to the broadcast nature of radio transmissions, only a small proportion of the transmitted energy can be harnessed by the receiver. The energy harvested from the RF signals reduces the energy required at the receiver, as in Figure 3.3.

The different receiver types are as follows:

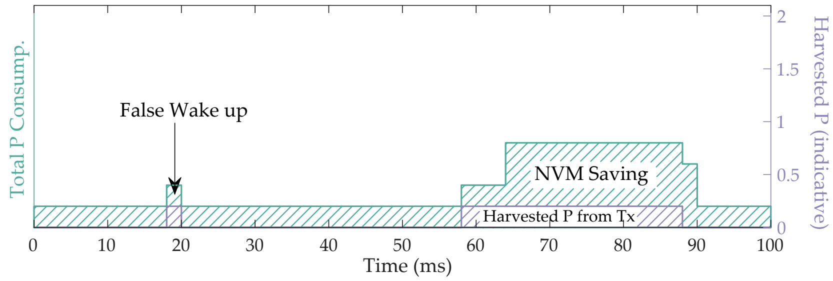
- **Type 1**: A WuRx triggers the node to wake-up and turn on the main radio. The WuRx consumes a similar amount of power to the micro-controller sleep mode, in order to filter false wake-ups like at 18 s in Figure 3.3a. The WuRx is powered from a small energy store that the node has reserved for listening. This small energy reserve also powers the node once it has received a wake-up signal for



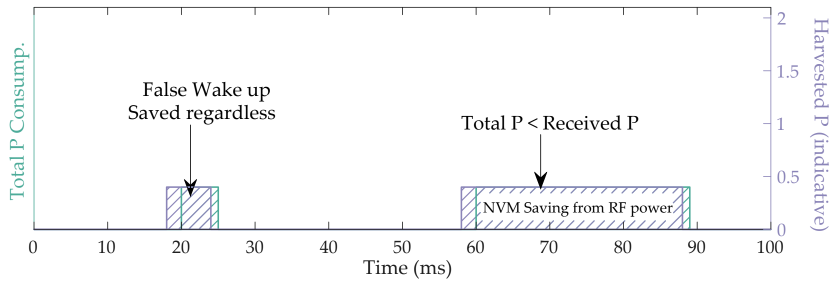
(A) Type 1



(B) Type 2



(C) Type 3



(D) Type 4

FIGURE 3.3: Power consumption of receive Types for intermittently-powered nodes to enable listening when the useful EH is insufficient to power main node. Where Harvested P represents energy received through RF power.

the receive event, as at 58 s in Figure 3.3a. The receiver sensitivity to wake-ups is −40 dBm.

- **Type 2**: The entirely passive device (consumes none of the receiver energy reserve) provides a wake-up signal from received RF energy. This means that the cost of sleeping the node whilst still being able to listen for messages is reduced to the near zero leakage through the power supply control circuitry. The main node and radio is subsequently powered by the energy reserve as shown by Figure 3.2. This can currently be achieved using a rectenna to detect activity in a certain frequency band and has a sensitivity of −15 dBm [126] as seen in Section 2.3.3, but the node will still have to turn on the whole radio for false wake-ups like at 18 s in Figure 3.3b.

- **Type 3**: The node wake-up is from an entirely passive device that can also decode a wake-up address, to reduce the false wake-ups. This is essentially a passive WuRx or selective rectenna which enables the main node and radio, powered by the energy reserve, to receive the data and store it for future retransmission. Since the power for the address decoding must come from the transmitter, a longer high power transmission is required, as shown in Figure 3.2. The advantage of passively decoding the address is the elimination of the effect of false wake-ups, shown at 18 s in Figure 3.3c.

- **Type 4**: The node can passively receive data and then the data can be stored in the NVM, while only consuming the incident RF power. The receiver does not need to filter out false wake-ups because any erroneous information received can be saved, as in Figure 3.3d, and be processed when the nodes own power supply is restored, so the cost of false wake-ups is negligible given a large enough NVM. The cost of computation to process the irrelevant messages is small compared to normal receive decoding. This is effectively SWIPT, where all the receive components are powered by the transmitted energy as in Figure 3.2; however, in mesh networks a proportion of the messages received will be for forwarding, unlike typical SWIPT implementations. The sensitivity is similar to Types 2 & 3, however the duration of the high power transmission is much longer, so the overall transmission consumption is higher.

The receiver power consumption for idle listening and receiving events is shown in Figure 3.3, where the power is from the transmitted RF signal. For Types 1 and 2, only the wake-up signal needs to be high power and the main radio for receiving enables high bandwidth and lower power data reception consuming the receiver's energy storage as shown in Figure 3.2. This reduces the transmitter energy consumed for each transmission and the energy storage required. Considering the possibilities for passive or semi-passive communication, the performance of the different communication types is dependent on the efficiency and minimum power requirements of hardware for radio communication and data processing.

3.3 Case Study of Off-the-Shelf Hardware Power Consumption

In this section, the performance of the available hardware in the different potential receiver types is analysed. Considering the EH supply and all the consuming components, there are several trade-offs: transmission cost, transmission rate, proportion of time listening and the listening and wake-up costs. It is important to recognize the links between these, because "improving" one factor may worsen the overall performance as less energy remains for other components. Therefore, the power consumption is analysed for the high power transmissions required for wake-ups within the context of a larger network.

First by collating the power consumption of several 868/915MHz band radios in Figure 3.4, it is demonstrated how range increases with increasing transmitter power *consumption*. There is a proportional increase in range up to 50 m (approximately 10 dBm output power) for radios within the same series, grouped by colour in Figure 3.4. With a Friis transmission medium model this shows the advantage of higher power transmissions in spite of the increased radiative losses because, in a uniform density network, the number of potential forwarders increases with the square of power consumed, since the radio is much more efficient at higher powers. When the number of candidate intermittently-powered forwarders is increased, it affects both the power consumption in those receivers but allows greater forward progress of the data. This is contrary to the consequence of assuming constant efficiency, like the coloured bands in Figure 3.4 or completely ideal radios, where the power consumed is proportional to the forwarders reached meaning shorter hops would be beneficial. If the radios were ideal, lower power transmissions that reach fewer nodes but with more selective forwarding reduces wasted receiving energy consumption across the network.

Considering the node operation, it is turned on when there is enough energy to transmit a wake-up signal and data packet, and also that all mesh network nodes follow the same operation/transmission policy. If the node does not transmit when turned on, it can perform other computing tasks and then turns off everything but the wake-up source, consuming quiescent listening power. For Type 1 equipped with a µW WuRx, nodes can listen for a long time using stored energy till the off threshold below which there is insufficient energy to receive a packet on the main radio. Each transmission reduces the proportion of energy (and time) that remains for listening, so a balance must be struck between more transmissions to attempt higher success rate and longer listening time for receiving data. In Chapter 4 this trade off is analysed in detail.

Thinking ahead to the mechanics of OR networking, the aim is to maximize the number of potential forwarding neighbour nodes. This increases the rate at which data makes forward progress towards the destination. Since increasing WuRx sensitivity to hear proportionally more neighbours decreases the listening time in the same proportion [24], changing this has a small effect, so long as the sensitivity allows all nodes to be connected to a few neighbours. Instead, you see that optimal transmitter consumption is a more significant factor. With SWIPT there is a combined penalty of both

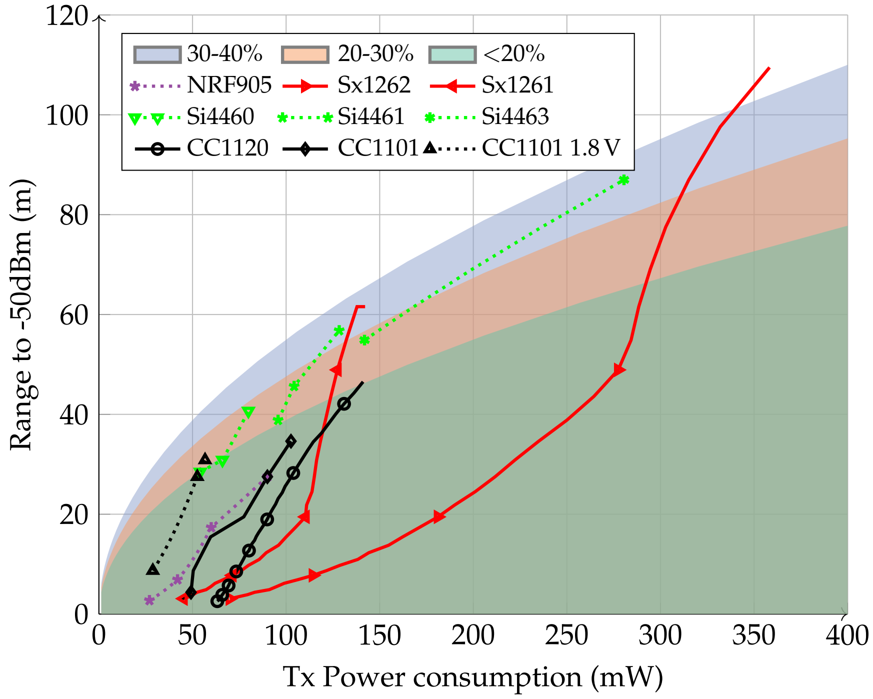


FIGURE 3.4: Power consumption of off-the-shelf radio transceivers at different radio ranges for fixed receiver sensitivity of −50 dBm against a background of transmitter efficiency regions. As the power increases, the efficiency also increases. Marks indicate values from datasheet tables, with lines interpolating between them.

reduced sensitivity, requiring higher transmit power, and reduced data rates, necessitating longer transmission. Therefore, the transmissions must be well over 20 dBm to achieve any sort of practical range. Consequently, the energy storage required on intermittently-powered nodes would need to be very large and the rate of transmissions prohibitively small.

Receiver Types 1 and 2, however show higher potential since the initial transmission is very short and subsequent power consumption is $\approx \frac{1}{5}$ of what would be required for SWIPT. Despite the necessary small consumption at the receiver, the huge reduction in consumption at the transmitter means that more transmissions can be made resulting in a net increase in throughput, by outweighing the reduction in listening time at receiving neighbours. Receiver Type 3 requires transmission power comparable to Types 1 and 2 and does not have to wait for the main radio to start. Type 3 therefore may outperform Types 1 and 2 depending on the size of data being transmitted and radio start time. Type 3 also has the advantage that it could operate when the node energy storage is below the level required for radio start up, but still above the MCU threshold.

3.4 Discussion

In this chapter, four receive types are proposed to enable intermittent devices to receive data with a minimum stored energy capacity. The proposed node topologies advance the state-of-the-art by showing how existing technology can enable homogeneous routing and how future node topologies could be used to make possible networking between nodes with even more scarce EH supplies. The lower the idle power consumption of the receiver, the more incident RF power is required to decode and save the information. The available transmitter hardware therefore directs the capability of homogeneous devices using such low power receiver types. Additionally, the efficiency characteristics of low power transmitters determine that it is beneficial to reach the greatest range possible in a mesh network.

The capabilities of Types 1 and 2 allow very low power listening, which improves the time that devices can listen for from a limited energy storage. Both Types 1 and 2 do not require the whole node to be powered from the incoming energy, which would place unreasonable energy requirements on a homogeneous transmitting node, with similar limited energy storage. Whilst Type 2 receivers have limited sensitivity, the potential to listen indefinitely could still be very beneficial in networks where a nodes are close enough to enable multihop transmissions, since the high power transmissions required for a rectenna a relatively short, so possible with the limited energy storage. From this, Types 1 and 2 show the highest potential for enabling intermittently-powered communication.

This does not show what the best policy of using this hardware is though, nor does it compare the effect of different datarates or wake-up address decoding available. Additionally, you cannot tell from a static analysis of nodes whether the higher power consumption of some wake-up radios and the resultant higher sensitivity is enough to provide a benefit of increased neighbours, providing routing options and potentially higher multihop reliability. Therefore, in the next chapter the optimum transmission rate is analysed and effect of each wake-up for a node with a semi-passive wake-up device and after that a network simulation is developed to directly evaluate different Type 1 and 2 devices against each other.

The role of listeners has never been fully appreciated. However, it is well known that most people don't listen. They use the time when someone else is speaking to think of what they're going to say next. True Listeners have always been revered among oral cultures, and prized for their rarity value; bards and poets are ten a cow, but a good Listener is hard to find, or at least hard to find twice.

Terry Pratchett, Pyramids

4

Semi-Passive Reception for Intermittently-powered Nodes

Working from the device hardware to the whole network, the next step is to address the links between nodes, and how the communication rate can be optimized considering the energy costs of transmitting and receiving and the cost of overhearing unnecessary messages. In this chapter[1] a simplified model of a node is built using a RF wake-up device and high-power transmitter to reach surrounding RF wake-up enabled nodes. Given the advantage of extended listening time with WuRx, but the need for autonomous operation of IoT networks, the focus is on communication in intermittent mesh networks-backed by WuRxs as shown in Figure 4.1, which is an area unexplored by existing research. The difference in being part of a mesh topology is that nodes must act as communication initiators with high transmission power consumption as well as responding to other nodes as receivers.

Previously, EconCast [127] considers intermittently connected mesh nodes and uses a Markov model to determine the broadcast throughput. However, it does not consider using WuRxs, nor the additional cost of each wake-up, with additional receiving and processing consumption, rather it only considers radios that have constant power consumption during the entire receive time (including listening). Whilst simulation

[1]This chapter is based on a paper presented at the IEEE Consumer Communication and Networking Conference (CCNC) 2021 [1]. I developed the mathematical model and simulation code used for this chapter and presented it at the conference. The paper was supervised and revised by Oktay Cetinkaya, Mohammed El-Hajjar and Geoff V. Merrett

results in Econcast are useful, an analytical form is needed to investigate a broader range of parameters; For example, using real power consumption and sensitivity data from commercial radios.

To address these shortcomings this chapter contributes an analytical node power consumption model to provide an equation to evaluate the goodput in intermittently-powered groups of homogeneous nodes. It additionally includes the specific characteristics of WuRx, and the transmission requirements to reach them, and the effect of an increased power reception level from multiple transmitters. This model is then evaluated with radio power consumption data to consider the effect of each transmission on the nodes energy level and listening, and to demonstrate the maximum goodput and the coupling to the transmission load.

Whilst other works in Section 2.5 consider communication with WuRx, they do not consider the mesh networking aspect that is included in this chapter. Instead they are star topologies where nodes are coordinated by a node consuming more power and potentially with higher EH capability or energy storage. They therefore neglect the significant effect of transmitting to a WuRx enabled node and how energy should be allocated in a homogeneous network.

The importance of correct energy allocation is illustrated in Figure 4.1 with the effect of allocating more energy for transmitting in a) compared with more energy for receiving in b), and by modelling it you can understand the consequences of allocating energy differently. When nodes are intermittent, with asynchronous transmitting and listening times and with low duty cycles, multi-hop communication can outperform single hops. Additionally, using WuRx in Figure 4.1b) illustrates how increasing listening time with WuRx must be considered in conjunction with the resultant reduction in range, requiring more hops.

The presented model allows for reasoning about the effect of radio sensitivity, given the need to transmit. The energy analysis is backed up by a MATLAB simulation model and, unlike existing work I consider the effect of transmitter efficiency which brings benefits to wake-up radios, compared to high sensitivity main radios.

4.1 Node Topology

I consider nodes using ambient EH to charge a small energy store and power a threshold based power controller, as shown in Figure 4.2. In order to enable wake-ups in a mesh topology, the nodes are equipped with WuRxs and primary radios. Nodes in transmitting states can pass messages to nodes in the listening state, incurring a wake-up cost, but nodes in the off state cannot receive or send, as shown in Figure 4.1. The node has a power controller that uses a threshold based on-off system and allows

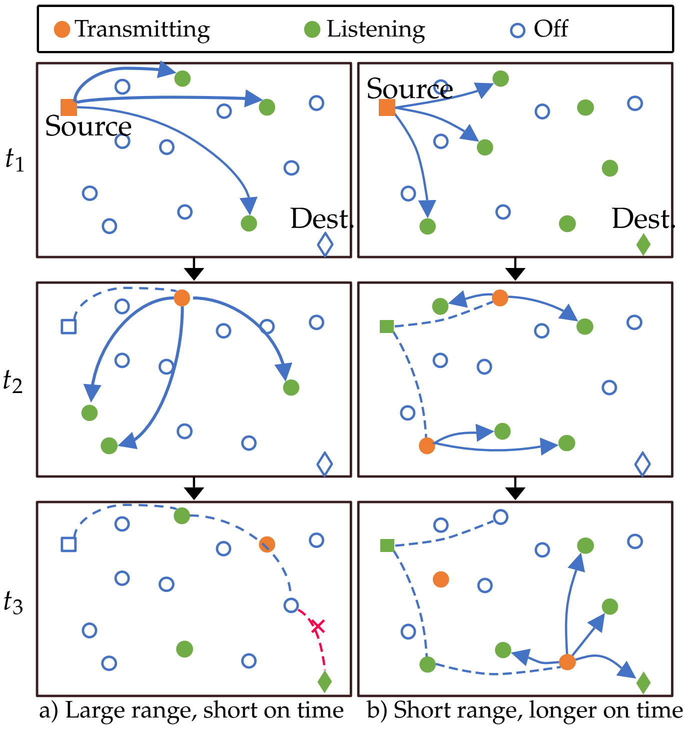


FIGURE 4.1: Comparison of intermittent homogeneous mesh configurations at consecutive periods, following a message from Source to Dest. for different range/-power priorities. Consecutive periods t_1, t_2, t_3 show links within the period and dotted lines show previous links. Network a) has higher power receivers extending the range. Network b) has reduced range, lower power receivers which enables a longer listening time, leading to correct reception at t_3.

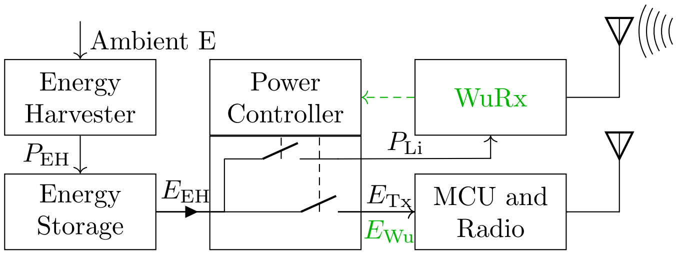


FIGURE 4.2: Components of a Type 1 EH wireless sensor node and flow of energy from storage when enabled by incoming wake-up signal (green).

the node to consume energy in bursts, which is the energy stored between the on and the off thresholds. When a node's supply is restored, termed an EH event, it can turn on and broadcast a wake-up signal followed by data transmission to its vicinity using a network ID for addressing [128], as presented in Section 3.2 Type 1. Listening nodes in the vicinity when a node broadcasts a wake-up can receive the transmission as in Figure 4.1. Wake-up throughout this section refers to received RF wake-up and not turning on when the energy storage is full, which is referred to as EH events.

Scarce EH conditions are provided, meaning that nodes cannot immediately forward or acknowledge data until the next EH event. This is because: 1) the relay node might use all of its energy during reception, and 2) the next hop might still be in the *off* state, as shown in Figure 4.1. Additionally, the assumption is made that the number of communicating nodes, i.e. *listening* or *transmitting*, is significantly lower than the *off* nodes. Which means using unicast transmissions for immediate MAC acknowledgement would result in many unnecessary repeat transmissions. Instead, the transmissions are of a multicast nature where acknowledgements must be negotiated between available forwarders, which is considered as part of the energy required for a wake-up.

4.1.1 Power Consumption When Transmitting

To estimate the transmission power consumption for the model the radios analysed in Section 3.3 are used. Other than the transmitter power amplifier (PA), the radio switching time is an important factor to consider for the model, since a slow turn on time also increases the energy used at the receiver but also the transmitter energy while it waits to transmit the data. Further discussion on this can be found in Section 3.3 and by Brini et al. [129].

A typical value for start up time is 2 ms, with power consumption of 5 mW [130, 53, 131]. For a 10 m range, a transmitter power consumption is required of 100 mW, for a packet of 150 bits, taking 0.7 ms, based on 300 kbit s^{-1} with 0.1 ms on and off switching either side. For this example this gives overall energy consumption of 80 µJ for each wake-up transmission.

4.1.2 Power Consumption When Listening

When a node is listening for wake-ups after an EH event the power consumption depends on both the wake-up device used and the power consumption of the node responding to each wake-up event. The WuRx affects the listening sensitivity, so is taken into account in the model, which is based off real power consumption of state-of-the-art WuRxs [70]. For example, comparing two 100 kbit s^{-1} 915 MHz devices, a 51 µW WuRx has a sensitivity of −75 dBm whereas the 98 nW device is less sensitive at only 41 dBm [82]. Whilst rectennas are also a wake-up source and are completely passive there is still leakage currents in the device power supply circuitry and given their low sensitivity, the model is still reasonable. I consider the energy used in different receiver types more in Section 3.2.

At each wake-up, the node must start the MCU and the radio to receive the imminent data packet. The radio is the limiting factor, where from a range of transceivers considered, the start-up time ranges from 0.9 ms to 15 ms [53, 130, 132]. This is illustrated by Figure 4.3 in 2.193 s to 2.195 s while the radio calibrates and initializes the receive chain. The other significant portion of the reception is the time spent in receive mode, 2.198 s to 2.200 s while the node waits for the transmission to start and decodes the data. The average power consumption is determined across these periods to determine the energy for each wake-up.

4.2 Node Performance under Uniform Load

In order to determine the number of messages that nodes can receive when the nodes are under uniform load, I now describe the model parameters of the intermittently-powered node, quantifying the harvested energy and energy consumption (shown in Figure 4.2), and communication parameters. The number of messages that nodes are able to receive is termed the Goodput, G, and forms the metric for assessing the performance as the load, density and communication hardware varies. A number of the key variables are closely linked to one another. Firstly, the node density, Λ, affects the transmission power required to reach neighbours, and also affects the wake-up rate and subsequent power consumption. Next, considering the energy used for each communication event, i.e. listen, transmit and receive, increasing the probability of transmitting at each EH event, $\mathrm{p}(Tx)$ will decrease the probability of listening at any moment, $\mathrm{p}(Li)$. The energy consumption model is used to find the optimum transmission rate, also incorporating the effect of wake-ups and the density of nodes.

4.2.1 System Model

The energy consumption is as follows: The energy harvester provides an average power, P_{EH} which is available to the node in discrete units, E_{EH}, that are termed energy bursts, equivalent to a threshold-based on/off system. Furthermore, the energy

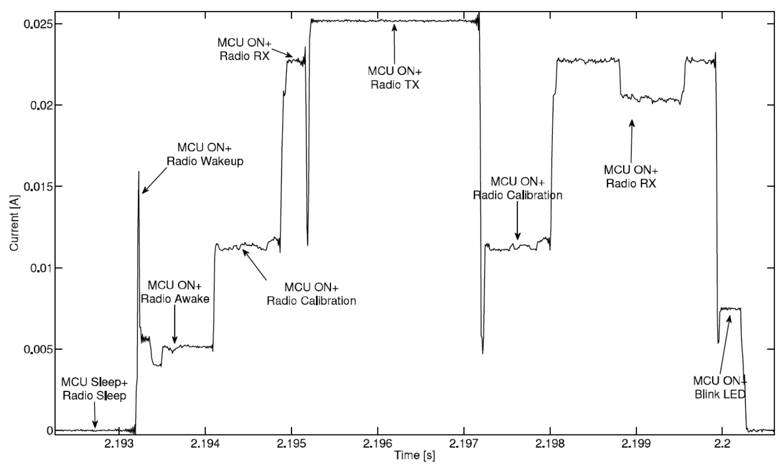


FIGURE 4.3: Consumption of power by a node when communicating and processing. Reproduced from [131].

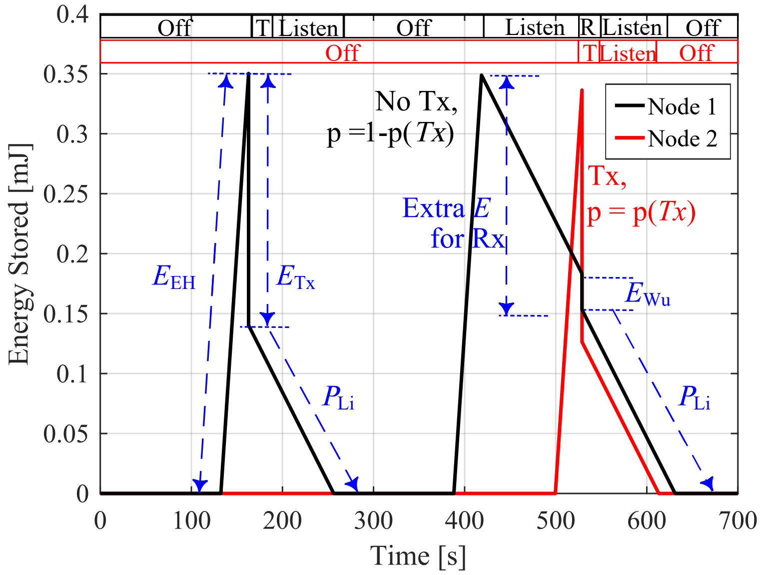


FIGURE 4.4: State and stored energy in two intermittent nodes using high power wake-up transmissions to a WuRx. The stored energy of Node 1 is annotated in blue, and T and R are Transmission and Reception events respectively.

TABLE 4.1: Parameters used in analysis and simulations of rate and goodput for intermittently-powered nodes with WuRx.

Symbol	Parameter	Value
P_{Li}	WuRx listening consump.	0.35 µW
E_{Wu}	Wake-up energy consump.	80 µJ or 0
E_{Tx}	Transmission energy consump.	400 µJ
λ_{EH}	Harvesting event rate	$6.66 \times 10^{-4}\,\text{s}^{-1}$
E_{EH}	Harvesting burst energy	$\mathcal{N}(\mu = 600\,\mu\text{J}, \sigma^2 = 40\,\mu\text{J}^2)$
P_{EH}	Average harvested power	0.4 µW
R	Transmission rate	0.66 to $6 \times 10^{-4}\,\text{s}^{-1}$
Λ	Node Density	0 to $5 \times 10^{-2}\,\text{m}^{-2}$
α	Path loss	2.6
$\frac{\eta P}{T}$	Link attenuation	35 dB

arrival rate is defined as $\lambda_{\text{EH}} = \frac{1}{\tau_{\text{EH}}}$, so $P_{\text{EH}} = \lambda_{\text{EH}} E_{\text{EH}}$. The considered node, as shown in Figure 4.2, has a primary radio and consumes E_{Tx} to transmit one wake-up signal and packet. The node has a WuRx with a fixed receive sensitivity, T, which consumes P_{Li} for listening. The node primary radio is used to receive the data after a wake-up, consuming E_{Wu}, shown for Node 1 in Figure 4.4, which includes forwarding negotiation if necessary.

The nodes operate as follows, when the harvested energy, E_{EH}, is higher than the transmit energy, E_{Tx}, the node transmits a packet from its queue, Q, depending on a load limiting probability, $\text{p}(Tx)$, to optimize the network performance. The remaining harvested energy after transmission, E_{Rx}, can be used to listen for wake-ups and receiving. Figure 4.4 shows this operation for a wasted transmission by *Node 1*, since

Node 2 is off, followed by a successful transmission by *Node 2*. *Node 1* listens and wakes up when the WuRx receives a signal I greater than the sensitivity T. Throughout this analysis the following notation is used: $\mathrm{p}(X)$ to denote the probability of X and P_Y to denote the power of Y. λ_Y refers to the rate of Y. The node transmit operation is limited by $\mathrm{p}(Tx)$, which is a function of $E_{\mathrm{EH}} > E_{\mathrm{Tx}}$, $|Q| > 0$, and a retransmission probability. The probability of a node being able to listen for wake-ups is denoted by $\mathrm{p}(Li)$. In Table 4.1, a summary is provided of parameters of the model, and their values used in simulation later in the chapter.

The parameters in Table 4.1 are chosen to represent reasonable values with currently available devices as follows: The wake-up power is taken as a representative value for a WuRx with a sensitivity of −40 dBm [82]. The transmission energy consumption is calculated from a 50 kbps 20 dBm wake-up transmission of 8 bytes followed by a 200 kbps 0 dBm data transmission. Since the transmitter is only about 40 % efficient, and the wake-up data rate is lower the wake-up transmission dominates, using approximately 320 µJ with the remainder used for the data transmission and switching. The harvested power is chosen to represent a small energy harvester such as a solar panel or vibration harvester [18]. The path loss coefficient is set at a value higher than 2 based on the more challenging characteristics of real radio environments over ideal propagation loss. Finally, the density of the nodes represents the distribution of nodes in a 2D plane where the highest density leads to a node spacing of about 5 m.

In order to maximize the performance of the network, nodes can adjust their transmission rate, R, with retransmission for higher delivery rate or by increasing the application sampling rate. Increasing R may increase wake-ups at other nodes, but simultaneously decreases listening time at the transmitting node. Therefore, given the homogeneous nature of mesh networks, R and corresponding energy allocated for communication events has to be optimized for the maximum G. For a mesh network, all nodes act to forward data around a network, a single node is considered where neighbour nodes exhibit the same transmission rate and listening time. The conditions/assumptions are summarized below:

(i) Nodes do not harvest enough to continuously listen.

(ii) EH events are uncorrelated and distributed as a Poisson point process (PPP).

(iii) A node's energy storage is large enough to store multiple EH events in short succession to ensure independence of the operation of each event.

(iv) If a wake-up is successful, the subsequent data communication will be also successful since the main radio has much higher sensitivity than the WuRx.

(v) The nodes are homogeneous, all having the same hardware and transmit/receive a similar number of packets.

4.2.2 Energy Consumption Analysis

Here, I analyse the consumption of E_{EH} following one EH event, based on (ii) and (iii) given in Section 4.2.1. E_{EH}, is used for transmitting in $\mathrm{p}(Tx)$ of cases. The remaining energy, E_{Rx}, is consumed for two things: E_{Li} for powering the WuRx for listening and E_{Wu} for each wake-up period at average active power P_{Li} and P_{Wu}, respectively. Once all E_{EH} is used, the node turns off and is unable to receive till the next energy burst, such as at 250 s and 610 s in Figure 4.4.

For wake-ups transmitted with probability $\mathrm{p(Wu)}$, P_{Wu} is only consumed if the receiver is listening, like at 525 s in Figure 4.4. This gives the expected time spent in wake-up per EH event, $\mathrm{p}(Li \cap Wu)\tau_{\mathrm{EH}}$, which is equal to $\mathrm{p(Wu)}\,\mathrm{p}(Li)\tau_{\mathrm{EH}}$ in consideration of (ii). From this, the average wake-up *energy* consumption per EH event can be calculated as $\mathrm{p(Wu)}\,\mathrm{p}(Li)P_{\mathrm{Wu}}\tau_{\mathrm{EH}}$. Hence, the E_{EH} consumption is summarized as:

$$E_{\mathrm{EH}} = \mathrm{p}(Tx)E_{\mathrm{Tx}} + E_{\mathrm{Li}} + \mathrm{p(Wu)}\,\mathrm{p}(Li)P_{\mathrm{Wu}}\tau_{\mathrm{EH}}. \tag{4.1}$$

Following this, to find $\mathrm{p}(Li)$, the average E_{Li} is derived:

$$E_{\mathrm{Li}} = E_{\mathrm{EH}} - \mathrm{p}(Tx)E_{\mathrm{Tx}} - \mathrm{p(Wu)}\,\mathrm{p}(Li)P_{\mathrm{Wu}}\tau_{\mathrm{EH}}. \tag{4.2}$$

Given the energy arrival rate $\times$ E_{Li} and constant P_{Li}, $\mathrm{p}(Li) = \lambda_{\mathrm{EH}} E_{\mathrm{Li}}/P_{\mathrm{Li}}$, which expands to

$$\mathrm{p}(Li) = \frac{[\lambda_{\mathrm{EH}} E_{\mathrm{EH}} - \lambda_{\mathrm{EH}}\,\mathrm{p}(Tx)E_{\mathrm{Tx}} - \mathrm{p(Wu)}\,\mathrm{p}(Li)P_{\mathrm{Wu}}]}{P_{\mathrm{Li}}},$$

and by rearranging, you get

$$\mathrm{p}(Li)\left[1 + \frac{P_{\mathrm{Wu}}\,\mathrm{p(Wu)}}{P_{\mathrm{Li}}}\right] = \frac{\lambda_{\mathrm{EH}}}{P_{\mathrm{Li}}}\left[E_{\mathrm{EH}} - \mathrm{p}(Tx)E_{\mathrm{Tx}}\right]. \tag{4.3}$$

To derive the goodput you can substitute the transmission rate, $R = \lambda_{\mathrm{EH}}\,\mathrm{p}(Tx)$. The transmissions at rate R are received in $\mathrm{p}(Li)$ cases, and goodput is defined as $G = \mathrm{p}(Li)R$. By multiplying both sides of (4.3) with R and using G accordingly, the analytical relationship between G and R is:

$$G\left[1 + \frac{P_{\mathrm{Wu}}\,\mathrm{p(Wu)}}{P_{\mathrm{Li}}}\right] = \frac{1}{P_{\mathrm{Li}}}\left[P_{\mathrm{EH}}R - E_{\mathrm{Tx}}R^2\right]. \tag{4.4}$$

4.2.3 Effect of Wake-up Probability

Since the node is part of a network, described by density Λ, it is subject to wake-up events from multiple transmitting nodes, like in Figure 4.1b) at t_3. Using the received signal strength, I, for a WuRx with sensitivity T, $\mathrm{p}(\mathrm{Wu})$ is defined as $\mathrm{p}(I \geq T)$. When Λ increases, $\mathrm{p}(I \geq T)$ increases and using PPP analysis from Kouzayha [133], $\mathrm{p}(\mathrm{Wu})$ can be modelled based on T as:

$$\mathrm{p}(\mathrm{Wu}) = \int_0^{\infty} \frac{1}{\pi u} \exp(-uT) \exp\left(-\frac{2\pi^2 \delta \Lambda}{\alpha \tan\left(\frac{2\pi}{\alpha}\right)} (\eta P u)^{\frac{2}{\alpha}} \right) \times \sin\left(\frac{2\pi^2 \delta \Lambda}{\alpha} (\eta P u)^{\frac{2}{\alpha}} \right) du, \tag{4.5}$$

P is the transmission power, T is the receiver sensitivity, η the antenna efficiency, and α is the path loss exponent. $\delta\Lambda$ is the transmitter density, where δ is the proportion of time nodes spend transmitting wake-ups, calculated from the beacon length and rate. $\mathrm{p}(\mathrm{Wu})$ in (4.5) can be used in (4.4) to calculate the maximum G based on Λ as well as the channel and radio parameters.

This then allows for the effect of wake-ups from the mesh network to be included in the goodput for the analysed link. It should be noted that $\tan\left(\frac{2\pi}{\alpha}\right) < 0$ for $\alpha > 2$ and this is evaluated in MATLAB where the upper limit of integration, ω, is chosen to be large enough for convergence. So rewriting the integral, for $\alpha > 2$, $\lim_{u\to\infty}$ integrand $= 0$, in a form to be numerically integrated gives

$$\mathrm{p}(\mathrm{Wu}) = \int_0^{\omega} \frac{1}{\pi u} \exp\left(-uT + \frac{K}{\tan\left(-\frac{2\pi}{\alpha}\right)} u^{\frac{2}{\alpha}} \right) \times \sin\left(K u^{\frac{2}{\alpha}} \right) du. \tag{4.6}$$

4.2.4 Hardware Configuration for Maximizing Throughput

Inspecting (4.4) and (4.5) reveals the interdependence of the primary radio and WuRx consumption with the output power and sensitivity respectively. In a WuRx-enabled mesh network, increased WuRx sensitivity corresponds to increased P_{Li} [70], while decreased sensitivity increases E_{Tx} for the same range [134], shown in Figure 4.5. Based on real radio characteristics, the energy used for a fixed-loss link is analysed in a network operating in the 868 MHz Band. The trade-off are considered between transmission energy requirements and receiver listening capability.

The Semtech SX1261/2 [132] is chosen as the node radio because it is efficient across a large range of output power levels and has a short start-up time which is important to minimize E_{Wu} as seen in Figure 4.3. Due to the lower efficiency of the PAs at lower power, the increase in range is approximately proportional to power consumed for powers up to 10 dBm, as discussed in Section 4.1.1. The WuRx model is formed by the relationship between listening power consumption and sensitivity (T) like in Section 4.1.2 [70] as:

$$10 \log(P_{\mathrm{Li}}) = -20 \log(T) + 60. \tag{4.7}$$

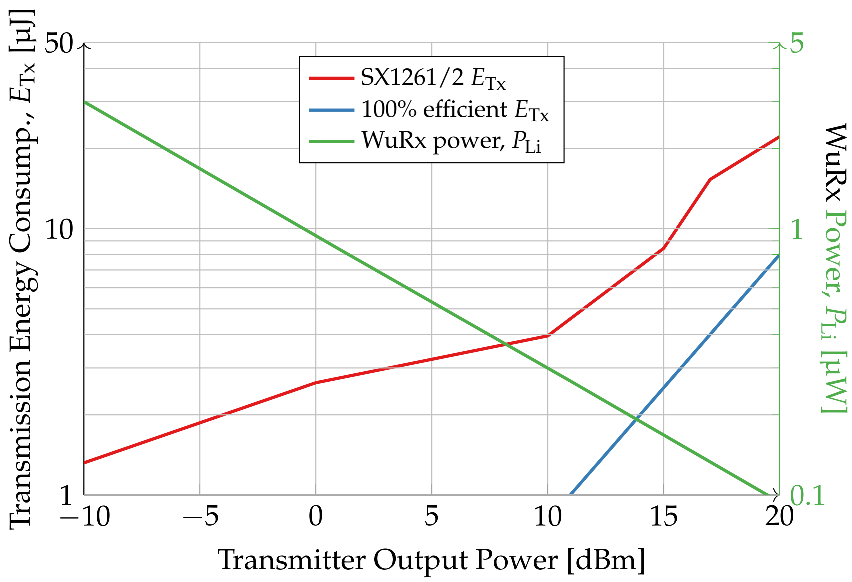


FIGURE 4.5: Model of energy consumption per transmission (including wake-up beacon), and the minimum consumption of a WuRx which can receive it after −50 dB link loss [132, 70].

By using the relationship in Figure 4.5, the G over a fixed-loss link can be analysed. Initially, the effect of wake-ups is not considered ($P_{Wu} = 0$) so the solution to (4.4) gives

$$G_{max} = \frac{P_{EH}^2}{2P_{Li}E_{Tx}}. \tag{4.8}$$

The maximum including the effect of wake-ups can be solved numerically, e.g. using the Newton Rapheson method, with G_{max} as a starting estimate. By using the parameters from Figure 4.5 in (4.4), the best transmitter power and WuRx configuration can be found.

4.3 Results

Using the analysis earlier in this chapter, the variation of goodput, G, is provided for the varying transmission load, R, different node densities, Λ, and primary radio and WuRx combinations. The overhead of wake-ups from a fixed number of neighbours is considered and validated with MATLAB simulations. Finally, the results from the analysis of realizable transmitters and receivers is presented.

The simulation consists of nodes modelled with components consuming power as specified in Table 4.1. The nodes operate as specified in Section 4.2.1 based on their value of stored energy. Each component consumes energy according to the operation and the resulting energy traces are shown in Figure 4.4. Information packets are generated at a fixed rate forming the load. For the multi-node case all nodes receive

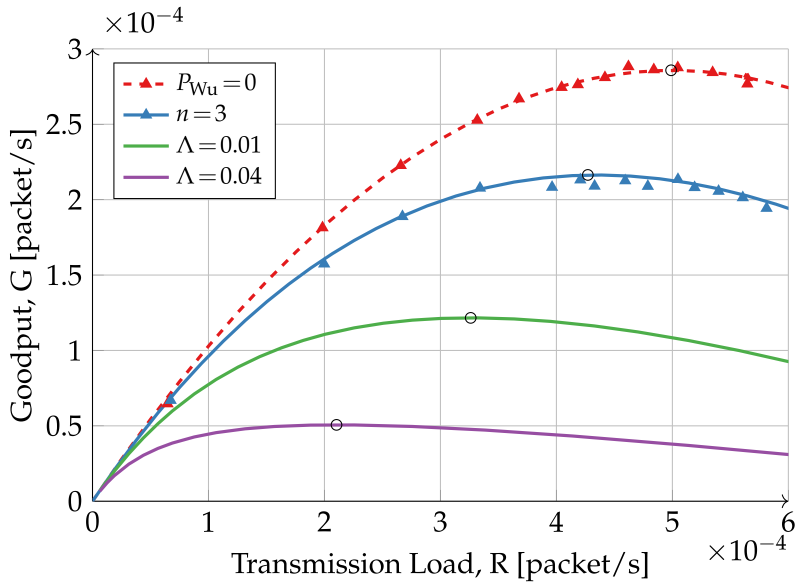


FIGURE 4.6: Transmission load and wake-up impact on goodput. Simulation results to validate the analytical solution marked by ▲ and maximum goodput by ○.

energy and information packets independently. Also, all nodes are within range of each other and a perfect channel model is assumed. The simulations are run for 10 Ms equivalent to 115 days of operation. Modelling with a more realistic channel model would reduce G due to data transmission failures but would have minimal effect on the wake-ups themselves.

4.3.1 Optimum Load for Maximum Goodput with a Fixed Number of Neighbours

Evaluating (4.4), when the node operates intermittently, gives increasing G as R is increased until G_{max}, beyond which G decreases. Figure 4.6 shows that, when the overhead of each wake-up is 0, the maximum G is achieved at $R_{\text{opt}} = P_{\text{EH}}/(2P_{\text{Li}}E_{\text{Tx}})$, when energy is split equally for transmitting and receiving. This result matches other authors simulation that does not consider the cost of waking up [127]. Above R_{opt}, the reduction in listening energy and time outweighs the extra transmissions.

P_{Wu} is included for three neighbouring nodes, $n = 3$, when evaluating (4.4). This is shown in Figure 4.6 where both the maximum G and R_{opt} are reduced as energy is instead used for the wake-ups. E_{Wu} is averaged across the transmission time in Section 4.1.1 for the value of P_{Wu}. Both zero overhead wake-ups and the fixed number of neighbours models have been verified with simulations with the parameters provided in Table 4.1, and the simulation points are marked on Figure 4.6. For a fixed number of neighbours, it is assumed that there is a perfect channel, and they are all within range of each other. The energy level is simulated over time (as in Figure 4.4) for EH events and radio consumption to validate the analytical function of G in (4.4).

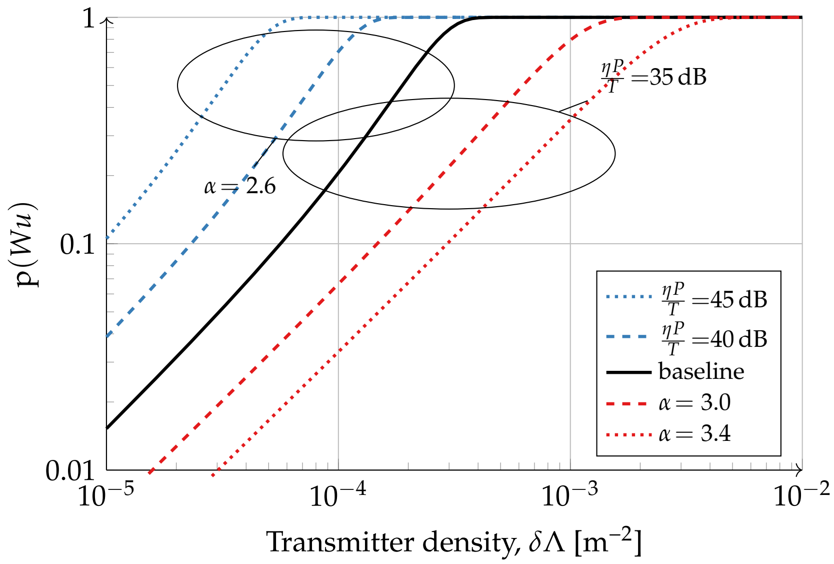


FIGURE 4.7: p(Wu) as a function of $\frac{\eta P}{T}$, α and $\delta\Lambda$, and baseline parameters of $\frac{\eta P}{T}$ =35 dB and $\alpha = 2.6$

4.3.2 Impact of Transmitter Density on Goodput

Beyond a fixed number of neighbours, the effect of Λ and transmission power is presented. When p(Wu) in (4.5) is included in the optimum load calculations (4.4), increasing p(Wu) reduces $G_{\max}$ because the energy is instead used to handle wake-ups. Since the impact of a wake-up increases E_{Rx}, the load must be decreased to ensure sufficient $\mathrm{p}(Li)$, as in Figure 4.6. If the load is not decreased for $\Lambda = 0.01$, G is then 10 % below $G_{\max}$ and 20 % below for $\Lambda = 0.04$. The variation in p(Wu) is calculated from (4.5) and shown in Figure 4.7 where increasing the ratio of $\frac{\eta P}{T}$ increases (proportionally to the power) the p(Wu), and increasing α decreases p(Wu).

Since wake-ups are not zero power, there is a small amount of energy consumed for each wake-up. Even if a higher level protocol determines that forwarding is not required, the MAC layer has no way to determine this so must wake-up regardless. Therefore, as the network density increases, so does the frequency of wake-ups, resulting in less energy remaining for listening and lower per node throughput, as shown in Figure 4.6 and Figure 4.8. As the density increases the proportion of failed wake-ups increases, i.e. 45 % at $\Lambda = 0$ but 90 % fail at $\Lambda = 0.05$. This corresponds to a higher proportion of retransmissions. Despite the per node throughput decreasing there may still be an increase in source to destination throughput because with greater density, each transmission has more potential forwarders. So long as the network does not become overloaded from unnecessary forwarding the greater density should increase the source to destination throughput from increased path diversity.

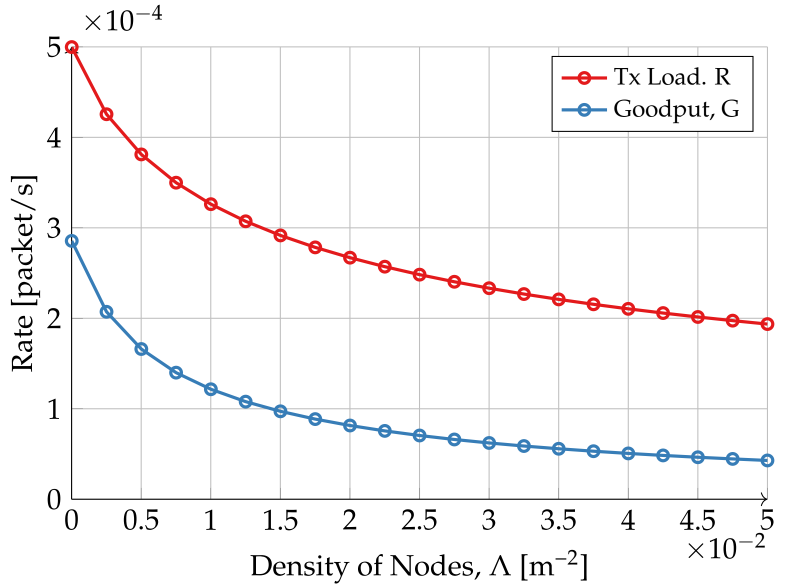


FIGURE 4.8: Optimum load and corresponding G for a mesh network of density Λ.

4.3.3 Choosing Tx and WuRx Combinations at Different Densities

The other factor affecting wake-ups is the combination of transmitter power and WuRx sensitivity and the associated power consumption. The model for $\mathrm{p(Wu)}$ and the transmitter/WuRx consumption can be combined with (4.4) to find the maximum G for varying WuRx sensitivity and average density. This is so that the best hardware combination can be chosen for a particular deployment. The transmit power is varied with both the density and the WuRx sensitivity, so that each node has a range of $2 \times$ average nearest neighbour distance, chosen to ensure 99 % of nodes are within range of at least two others. Therefore, the link loss affects the required transmit power which is derived from the Friis equation at each density. Figure 4.9 shows the benefit of using high power transmissions across a range of densities to achieve the highest goodput. Consequently, for dense networks, it is beneficial to use increased transmit power so long as E_{Li} reductions outstrip the increase in E_{Tx}. For the SX1261/2 radio this means transmit consumption stays relatively constant around 400 µJ. The WuRx can then be chosen based on the expected link loss.

The maximum G is a consequence of the E_{Tx} and P_{Li} trade-off, where after the inflection point at $P = 10\,\mathrm{dBm}$ in the transmitter model in Figure 4.5 there is reduced efficiency improvements as transmission power increases. Therefore, at higher transmission power, E_{Tx} increases faster than the decrease in P_{Li}, so the best transmitter power is where E_{Tx} begins to grow faster than E_{Li} falls, at each link loss. On the other hand, when E_{Wu} is included, the benefit of very low P_{Li} is reduced, since E_{Rx} remains constant, however, the effect of this is minimal and the transmitter radio characteristics still dominate.

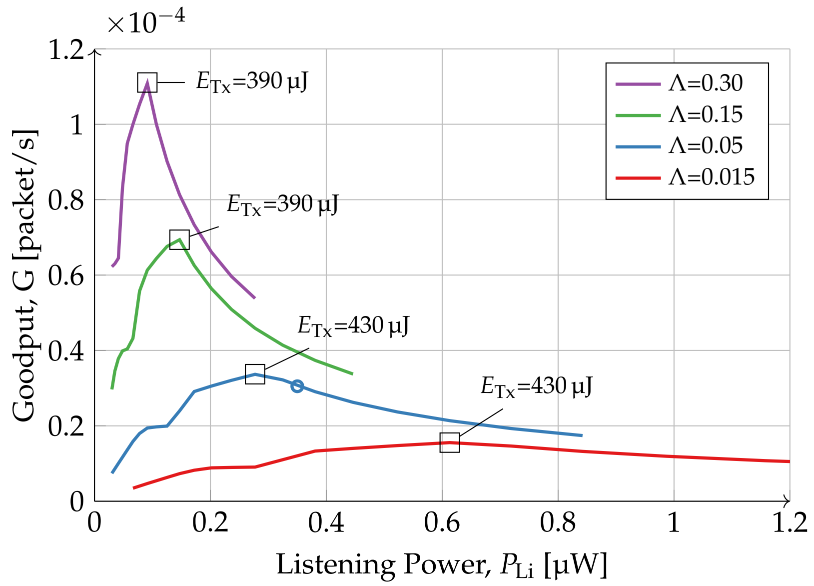


FIGURE 4.9: G_{max} when varying the density and required link budget. Transmitter consumption, E_{Tx}, at highest G annotated and Table 4.1 value circled.

The model was verified with the same simulation as Section 4.3.1 where the radio parameters were chosen to be close to the highest goodput at $\Lambda = 0.05$, as specified in Table 4.1. The result is circled in Figure 4.9. This model can be adapted for other hardware to understand both the achievable goodput in the intermittent network and also to choose primary radio and WuRx appropriately to improve network performance.

4.4 Conclusions

When purely considering the node to node communication between intermittently-powered devices you see that there is an important link between the transmission rate and the listening time. Consequently, intermittently-powered devices must be configured to limit their transmission rate to maintain sufficient energy to receive transmissions. In addition to the transmission rate, the cost of each wake-up to receive reduces the energy available for listening. Whilst this can be reduced by using WuRx to filter some false wake-ups, routing decisions remain at the network layer so only wake-ups from other systems can realistically be filtered out. The wake-ups reduce the overall goodput and the wake-up rate should influence how the transmission rate is limited in order to maximize goodput between nodes. Since the overall effect from this is small, highly accurate rate of wake-up calculations are not necessary, where coarse approximations will achieve close to optimal results.

The consideration of the behaviour of transmitter and receiver hardware has been omitted from previous literature, discussed in Section 2.5, whereas in mesh networked devices it must also consider the combined receive and transmit capability.

Given that the optimal hardware achieves at least a factor of 2 increase in goodput compared to a naïve approach of just minimizing listening power, and subsequently requiring increased transmit consumption, it has been shown that the best hardware combination is highly dependent on the efficiency of the transmitter radio at different output power levels. The required WuRx sensitivity can then be chosen to ensure that nodes have sufficient point to point range to support the routing of data across a multihop network.

The results shown in this chapter support the proposed mesh networking with intermittently-powered nodes, showing the possible throughput at each node. This shows how device hardware should be chosen to maximize goodput for a given EH rate and also forms a benchmark for future intermittently-powered communication. This analysis is not able to inform whether the reduced goodput with higher densities is outweighed by the routing effect of greater forwarder availability. Since the focus is on device-to-device communication, the characterization of networking protocols is required to determine the range and subsequent throughput, with the routing diversity available in mesh networks but with delays caused by intermittency.

Alice: Would you tell me, please, which way I ought to go from here?
The Cheshire Cat: That depends a good deal on where you want to get to.
Alice: I don't much care where.
The Cheshire Cat: Then it doesn't much matter which way you go.
Alice: ...So long as I get somewhere.
The Cheshire Cat: Oh, you're sure to do that, if only you walk long enough

Lewis Carroll, Alice in Wonderland

5 Opportunistic Routing for Intermittently-powered Networks

Following the investigation of point to point communication techniques, multiple hop communication must be considered to enable scenarios where nodes are not within range of each other [1]. For example in an environmental monitoring network, where ground topology blocks signals between nodes and where the distances are large. Also, within buildings, even with higher sensitivity devices, thick structural elements block signals and floors significantly attenuate signals limiting connections across more than 1 floor [135]. Multi-hop networking for Intermittently-powered devices has requirements that differ from battery or mains powered wireless sensor networks. Most significantly, any routing protocol must not rely on predictable availability of a specific forwarding node, whether scheduled or asynchronous. Secondly, end to end routes cannot be established before data is sent, because the end to end route may be only intermittently available, or become unavailable during transit along a route.

The first section begins by providing the model of the networks that are investigated and why the motivation leads to this model. Given the provided network model considered the justification and suitability of the chosen RPL and ORPL protocols is described. Following this, the approaches used to route data towards or away from a routing hub are compared and discussed. Finally in this section, the behaviour when

[1] Parts of this chapter were presented at ENSsys 2022 [4]. I wrote the simulation code, performed the experiments and analysed the results. The work was supervised and assisted by Mohammed El-Hajjar and Geoff V. Merrett

faced with limited EH that causes intermittency is explored to support the theory that opportunistic routing will be beneficial in an intermittent scenario.

This chapter then makes the following contributions. First the ORPL protocol [125] is implemented in the OMNeT Simulator, taking a extensible and modular approach which demonstrates the interfaces required for cross-layer operation of intermittent protocols. The implementation allows for comparison with other routing protocols and under different EH conditions. Second, using the OMNeT Simulator, the RPL protocol performance is demonstrated under scarce EH conditions that cause intermittency. This determines the operation when there is minimal stored energy and EH cannot sustain continuous operation, whereas previous implementations have tried to minimise energy consumption but with a larger energy buffer. Next, using the ORPL implementation it is compared to RPL under the same intermittent scenario. Distinctively, the energy storage restricts the listening ability, where limited EH causes a reduced duty cycle, instead of existing works that control the duty cycle but without consideration of the energy consumption. Following this, the work from Chapter 3 on WuRx is incorporated to demonstrate how WuRx enable communication with very low power EH supplies. Altogether, these contributions demonstrate how opportunistic protocols can be applied to the challenging novel field of intermittently-powered WSN. The modification to the routing protocol allow the metric to be calculated and the extensive simulations quantify the performance for data collection and cross network routing. Each section is now elaborated on in turn.

To measure the performance as described above, Section 5.2 describes the steps taken to simulate the protocols in an EH scarce environment, including the WuRx implementation, routing protocol implementation and result collection methodology. First the simulation tool itself is described, along with the motivation for using it. Subsequently, the components that were missing in this simulator were created and are described in Section 5.2.1, highlighting the more layered approach enabling components to be interchanged more easily, and for other algorithms to be tested. Whilst an implementation of RPL already exists, some modifications were made for intermittency which are explained next. Additionally, the elements of the ORW/ORPL protocol reworked for intermittency are explained in Section 5.2.2, allowing the metric to be calculated without prior duty cycle knowledge. The final part explains the the methodology for measuring the protocol performance. This is using multiple randomized simulation runs over a long duration and also where the initial metric values are estimated to improve the routing convergence speed.

Although RPL is not designed for intermittency, it is important to see how it performs under intermittent conditions, and especially with scenarios which require multiple hops and assess how the distance affects the delivery rate. For the benchmark scenario in Section 5.3.1, a grid of 225 nodes generating packets at different fixed rates is used. This grid forms the basis of the future experiments and the radio hardware is also chosen to be comparable in further experiments. The RPL is directly compared with the implementation of opportunistic RPL (ORPL) using the same radio hardware in Section 5.3.2. This is to demonstrate the benefits of protocols that opportunistically route through the network using instantaneously available next-hop nodes. However, this comparison uses conventionally powered radios limiting its ability to operate under very low EH conditions.

Alternatively, in Chapter 3, the trade offs between higher power transmissions and WuRx capability were considered, as well as the advantage of reaching a higher number of nodes with higher power transmissions but lower power WuRx. However, in Chapter 4, you see that the transmission rate of a node affects its ability to act as a forwarder, since it does not spend so much time receiving. Exceeding the optimum rate means messages that are received will be dropped to reduce the transmission rate. Good routing will mean that nodes do not reach the limit, so fewer messages are dropped and the end-to-end delivery rate is higher. Moreover, when considering when the EH is limited, it is necessary to better utilize the network deployment, which is investigated in Section 5.4 by measuring the packet delivery rate as the EH is decreased and with four models of WuRx in a multihop network.

Additionally, the performance of both directions of routing, upwards to the routing hub or downwards from the routing hub should be assessed, since even in networks where a majority of communication is upwards, there remains downwards control and updating information as well as there being the potential for inter node communication. This is measured in Section 5.4.5 by sending to a select number of nodes, from across the network, requiring downwards routing to work fully.

Before describing how the proposed network are measured, first the network model itself is described.

5.1 Network Model

The experiments in this chapter are concerned with operating 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, methods that are lightweight in these respects are required. In a sensor network the data requirements are typically low, but using the available energy effectively is very important.

Taking this into account, the proposed network model is as follows: 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

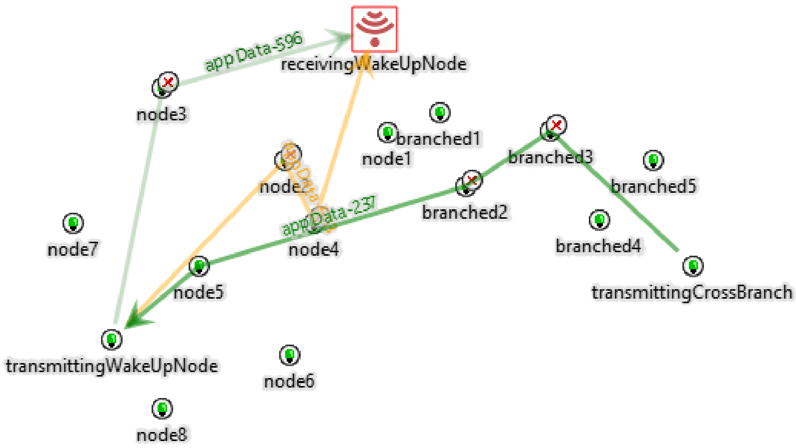


FIGURE 5.1: Network model of intermittently-powered scattered nodes using multiple hop communication to route to the hub “receivingWakeUpNode” from the “transmittingWakeUpNode” and cross network communication (appData-237) from “transmittingCrossBranch” routing upwards towards the hub and then downwards towards the destination. Nodes marked with a red x are off but may have taken part in the routes before running out of energy.

other nodes, but it is not assumed that it will be continuously powered either. Nodes in the network all have the same communication hardware and energy storage, which helps ensure the devices cost can be kept down. The hub device and potentially some other devices for redundancy should have a way of storing sensor readings and periodically communicating them outside the network for processing, however this is not modelled here.

Since the considered EH network is largely concerned with collecting data, most of the application data is from outer nodes upwards to the hub. However, it is not correct to assume that the network layer does not need to be capable of downwards routing. Instead effective downwards routing is necessary in IoT networks for several reasons. Primarily, transport and application level acknowledgements must be possible for connection oriented communication, congestion control and service status information. Also, there is also a need for routing to take place across the network or from the hub to the other nodes. For example, in a smart home network, where a temperature sensor reading needs to be received by a heating valve, or where a humidity sensor reading controls a fan. Such a network is demonstrated in Figure 5.1. Furthermore, in all networks, the nodes in the network need to be able to discover the network, be controlled and updated which necessitates routing in the opposite direction to the majority flow. Whilst the end nodes may be fully powered in these scenarios, the intermediate nodes are not, and the network model considers routing the data across the network when intermittently-powered.

Routing takes place by forwarding data through cooperative neighbouring nodes, but where the position and availability of the nodes determines which nodes takes on the task of forwarding. This is seen in Figure 5.1 where the two messages from "transmittingWakeUpNode" take different routes and where the nodes along the route have become unavailable since forwarding the message. The range of the communication hardware affects the number of neighbours available and therefore the routes taken. The availability of nodes is determined by whether they have sufficient EH or stored energy to operate where they shutdown to replenish the energy storage.

To fulfil the routing needs of this network model, two potential protocols are analysed in detail, RPL and ORW (which is extended to ORPL). ORW and ORPL have been previously proposed for duty-cycled networks [125] but have not been analysed where energy constrained nodes cause intermittency or compared to other protocols like RPL. An existing implementation of RPL is used and ORW, which is designed for asynchronous low duty cycle networks, is implemented in the same framework for comparison. The next section describes these routing protocols.

5.1.1 Protocol Description

To keep the routing protocol simple enough for low power memory constrained wireless sensor nodes, ORW and RPL rely on orienting their routing around a central hub node. RPL uses the rank metric to record the number of hops to the hub, whereas ORW uses a metric called EDC to record the expected number of duty cycles to the route. When the destination is the hub node, or closer to the hub than the sender, the protocols use upwards routing to send the data closer to the destination. If the destination is further from the hub then the data must be routed downwards, away from the hub node. Downwards routing is against the metric gradient, and requires extra information overheads to define specific nodes to forward or to specify the address of the destination node. If the destination is not immediately downwards of the current sending node, it must first be forwarded upwards until it reaches a node that has the destination downwards of it. The mechanisms for routing upwards RPL and ORW and downwards ORPL are now discussed in turn.

5.1.2 Upwards Routing Comparison

When routing upwards (towards the sink) both protocols route to a node with a lower metric value. RPL specifies what node this should be in advance, by querying its DODAG for the parent node, which specifies a single forwarder, as well as a back-up forwarder. ORW instead specifies a maximum qualifying EDC threshold for forwarding, this means the forwarder is chosen dynamically at the time of reception, according to what nodes are available. Specifying a single forwarder reduces the negotiation following a transmission, however it has less redundancy, so as the duty cycle of nodes is reduced, routes will become unstable, and potentially completely unusable. Whereas, opportunistic forwarder selection in ORPL, increases the number of paths available providing resilience against constantly changing forwarder nodes.

When the next hop is specified precisely in RPL, the MAC protocol can complete the communication hop in 2 transmissions, the first is the data and the second is an acknowledgement. If the data transmission is unsuccessful, the MAC layer can retransmit the data after a wait period. If the specified next hop is unavailable, the frame is dropped and the RPL protocol should be notified that a new parent should be chosen, from the set of candidate parents. This also may trigger a DODAG information object (DIO) to notify the child nodes of a change of rank, so they can choose a new preferred parent if appropriate. An additional problem is that this data may then be lost regardless of its progress to the destination, unless the routing layer is able to intercept the packet drop and reinject it.

For ORW, where the metric will include several candidate nodes, there must be a period of contention to ensure there is only a single forwarder [124]. The nodes that meet the criteria of a lower EDC are called the CRS, which reply to a data transmission if they are listening. Every node that receives the data transmits an acknowledgement, and if the sender receives only a single acknowledgement, it is considered a success and no more transmissions are made. Where multiple forwarders respond, a contention management process takes place, where by the data is retransmitted but the sending node can change the EDC condition. Some receiving nodes drop out of the contention process randomly until there is only one node remaining, and a single acknowledgement is received. When there is high node availability the contention period is longer, however in this situation there is already sufficient energy so the energy wastage is not too problematic. However, there is an increased probability of collision, so the sending node may think only one node has responded, when many nodes have actually responded. In this scenario there is a increased probability of duplication and therefore the maximum capacity is decreased.

5.1.3 Downward Routing Comparison

For transmitting information away from the sink (downwards) the RPL protocol uses a source routing set inserted into the IPv6 header which is then used to route through specified parents in the DODAG. Since RPL was designed purely for data collection networks routing to a sink, downwards routing is weak in RPL and consumes significant extra network resources. Each node is required to keep track of the next hop to each downward neighbour requiring additional microcontroller resources, and each packet must have longer headers to contain the source routing header, which might be out of date by the time energy is harvested to send the message.

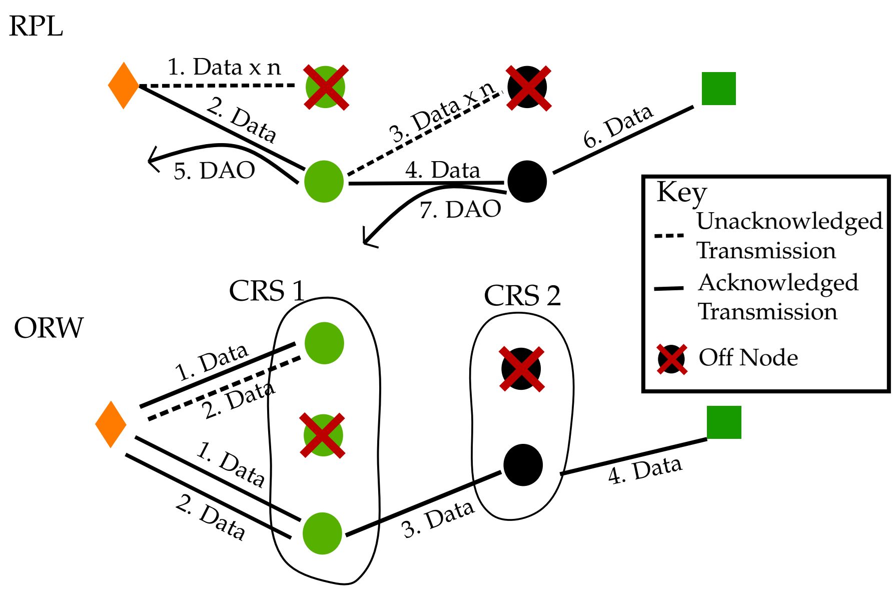


FIGURE 5.2: Example of multihop transmission with RPL and ORW routing upwards (left to right) to hub (green square) under intermittently-powered conditions. The preferred parent in RPL is unavailable for both hops, due to previous transmissions, causing several wasted transmissions before a new parent is chosen. In ORW the variety of available forwarders in the CRS means after only 2 transmissions it has been forwarded to CRS 1. This is a simplistic view, where in reality there would be more potential forwarders.

To enable downwards routing in intermittently-powered networks, ORPL extends ORW [125] to record and transmit the descendant nodes in routing sets. When a node transmits an advertisement or normal data packet, the routing layer attaches the downwards routing set, but this doesn't have to be as often as normal advertisements.

The downwards routing set is determined from the nodes in the immediate neighbour table with a higher value of EDC, merged with the downwards routing set of those nodes. The merging of the downward routing set removes the need to record the exact path through downward nodes over several hops. This means it is small enough to transmit the entire routing set piggybacked to a normal advertisement, but comes at the cost of not knowing the cost to reach nodes in the downward routing set, except for the first hop. The insertion of the routing set is discussed later and shown in Figure 5.3.

5.1.4 Reaction to Intermittency

Since ORW and RPL do not consider node intermittency in their design, this section analyses the expected response. There is a significant problem caused by the predetermined next hop approach in RPL. When the data transmission does not receive an acknowledgement, the MAC protocol will try resending up to n times. Since the node has run out of energy, there will still be no acknowledgement, and RPL can select a new preferred parent. As long as this parent is available, the packet can be resent. This is shown in Figure 5.2, for a two hop transmission to the sink where n transmissions are made to the sink before , additionally, when the new parent is selected RPL sends an additional transmission of a DODAG advertisement object (DAO) for the new route to the parent. This diagram shows how a relatively low proportion of off nodes can cause an avalanche of extra transmissions. This in turn causes a higher node energy consumption, more nodes turning off entering a downward spiral.

In the opportunistic approach of ORW, the flexibly chosen forwarders means that the system is resilient to lower duty cycles, as long as the candidate relay set has some node availability. When multiple acknowledgements are received, a retransmissions causes some nodes to back out of contention for forwarding, according to the contention algorithm. When all nodes back out simultaneously, this causes a retransmission where a backout probability of 0.5 and two nodes results in a retransmission probability of 0.25. Moreover, the number of wasted transmissions actually decreases as the proportion of active nodes decreases, so long as the CRS is large enough to still provide some forwarders, since the number of nodes contending to forward the message is reduced.

The opportunistic approach in ORW is based around duty cycled nodes, where nodes set their own duty cycle, and this is used in the calculation of the EDC metric. Whilst EH nodes can control their own duty cycle, it requires them to run an additional clock consuming power when all other peripherals are turned off. Additionally, as the EH rate varies, the node duty cycle must change, but updating the neighbouring nodes with this availability requires additional transmissions, which in turn reduce the availability. Instead, the precision of nodes setting their own duty cycle must be replaced with observation based duty cycle estimation. This is discussed further in Section 5.2.2.

5.2 Simulation Approach

The performance of the proposed networks is variable depending on multiple hardware parameters and different routing methodologies. To evaluate these effectively, the scenarios must be comparable and reproducible and must be evaluated across a large range of parameters. Therefore I use network simulation which provides a highly reconfigurable and reproducible platform.

OMNeT is used for the comparison of these protocols. It is a discrete event simulator designed for simulating computer networks that uses C++ implementations of modules linked together with message channels. From the OMNeT simulation base the INET framework has been built, containing network components such as link error models and implementations of communication protocols, it also provides generic node infrastructure for energy generation, consumption and lifecycle management. Other simulators such as ns-2 are available but do not offer the cross-platform capability, nor the graphical user interface that OMNeT provides. The selection of protocols that implement lifecycle operations of shutdown and start up is small and the only ad-hoc protocols that implement this are AODV and AODVv2 (DYMO). RPL is modified to enable this behaviour, and Opportunistic RPL has been written from scratch to enable opportunistic next hop selection which does not yet exist in the INET framework.

The main factors leading to choosing OMNeT over ns-2 or Cooja are as follows. The INET library for OMNeT provides a state based energy consumer model for radios this is also provided in ns-2 and is not available in Cooja. The ability to set power consumption dependant on transmit power is essential to wake-up radio experiments. The breadth of radio models available in OMNeT allows for implementation of the preferred two-slope path loss model, however in ns-2 the physical models are not easily interchangeable and the two-slope model is not available. Finally, the availability of other models to compare against leads to using OMNeT, even though the ORPL model is developed in Cooja, because it does not implement energy modelling and the ORPL implementation did not follow a component based design that would allow easy modification.

5.2.1 Components/Layers Design

Several new components have been added to model the desired network in OMNeT. These are WuRx models, OR modules, neighbour discovery protocols and neighbour overhearing MAC layer interfaces. The modules are designed to implement common interfaces to make future comparison with other protocols simpler. Furthermore, the implementation of upwards opportunistic routing, ORW forms the basis of the downwards routing, ORPL. The structure of the routing stack can be seen in Figure 5.3. New interfaces between layers enable cross-layer communication such as overhearing acknowledgements to improve a per-node model of neighbours, routing set piggyback and sharing to update the wider network model.

Following a packet reception, first the MAC protocol that will check the acceptance criteria using a hook or message, implemented as `IOpportunisticLinkLayer` and `IForwardingJudge` before contending to become the forwarder of a received packet. Any response from the routing layer is timing dependent and must therefore occur before the receive window elapses and is shown in Figure 5.3 by the direct connection between the Routing Table and MAC. The routing layer must build up a model of the network for direct addressing, a preferred forwarder list and calculating a progress metric. The acknowledgement sent back acts both to improved the neighbour table

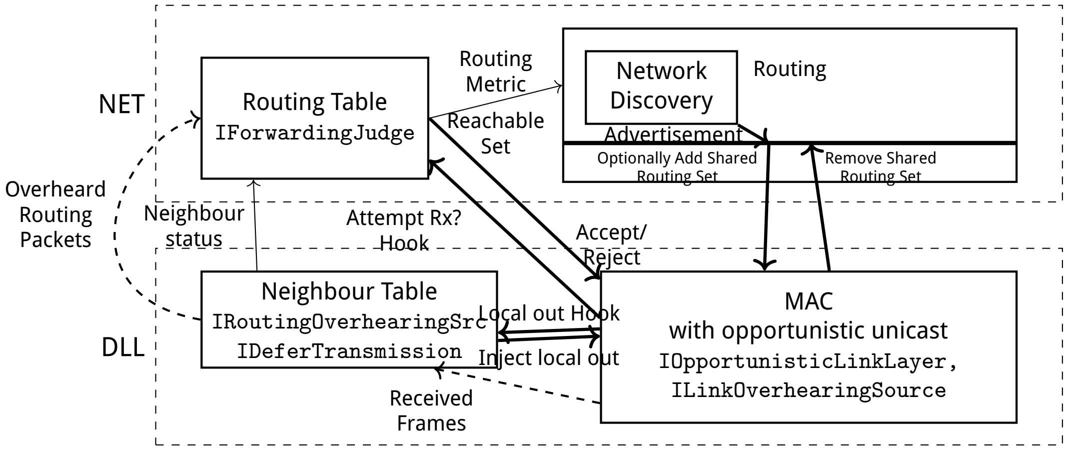


FIGURE 5.3: Layers Diagram of Opportunistic Routing

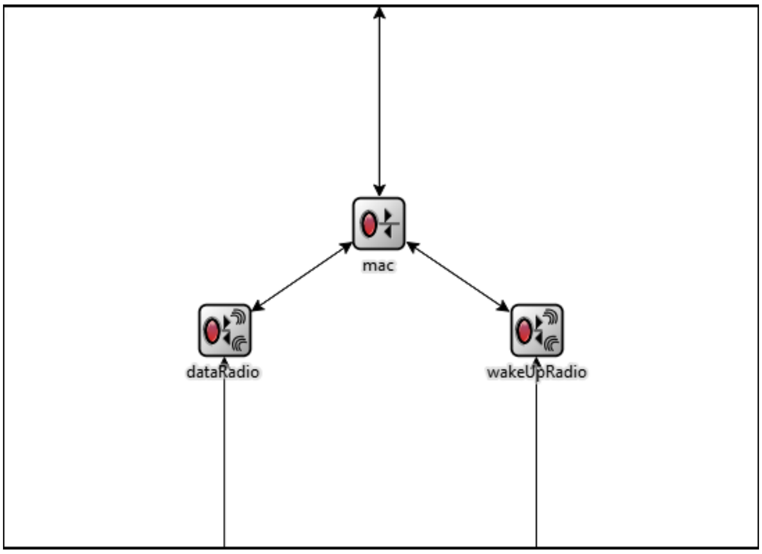


FIGURE 5.4: Implementation of two radio MAC interface in OMNeT++, showing gates for data from two radios to the MAC layer.

of the sender as well as being overhead by the other awake nodes nearby. This is implemented by the `ILinkOverhearingSource`.

If a packet is received, it is passed up to the routing layer. If the message requires forwarding, the routing module updates the upwards routing metric from the routing table and can also share the downwards reachable set using the `TlvOption` specification. This reachable set can be overheard with `IRoutingOverhearingSource` in neighbouring nodes and is an important way to disseminate information about the reachable set of neighbours, and hence reduces the need for extra advertisement packets.

To implement a wake-up radio and main radio the Narrowband Scalar Radio model has been reused in a MAC interface, as shown in Figure 5.4, the wake-up transmissions come from the wake-up transmitter. This abstracts the wake-up radio transmission into a separate logical module, where an real device would use the main radio at a higher transmission power, but still have the wake-up receiver radio. The main difference in this behaviour is the reduced carrier sense capability in the model, and the extra delay that would be present in a real device while the main radio started.

5.2.2 Modifications of Opportunistic Routing for WSN (ORW) and ORPL for Intermittent Devices

The ORW routing mechanism relies on estimating the number of transmissions required to reach the routing hub. Using this metric it requires selective multicasting to address the downwards set and listening nodes can contend to be the selected forwarder. The ORW metric calculation mechanism relies on nodes keeping track of time to calculate the probability of a neighbour being available. Intermittent devices do not have this capability, so instead I have implemented a modified metric called EqDC, which weights each encounter and takes the *relative* probability of each neighbour being encountered.

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

$$\mathrm{p}(n) = \frac{\sum^{enc_n} w}{enc} \tag{5.1}$$

$$w = \begin{cases} 2, & \text{Coincidental} \\ \frac{0.8}{2^{round-1}}, & \text{Expected} \end{cases} \tag{5.2}$$

The weighting of encounters takes into account whether any encounters were expected, i.e. in response to a "Hello" message or forwarding request. If an encounter is received "coincidentally" 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. Encounter recording beyond the first round is included because it was observed that encounters were missed when collisions occurred, but a second round is very likely if collisions occur. The numerator of 0.8 was chosen because if each collision misses one of the two encounters, and 1 more round occurs then the average encounter weighting recorded is 1. The series is such that this is also true if the collision occurs in subsequent rounds.

In original ORW the contention probability is set to 0.5, which means when just 2 nodes are left contending for the packet, there is a 25 % chance of needing to repeat the original message. A value of 0.5 was shown to be beneficial by the earlier work so that value is maintained with the simulations.

The other addition in the implementation is to define protocol behaviour on shutdown and startup. A standard approach is to remove all routes on shutdown or startup, however when these events are high frequency the loss of information means the network cannot be formed. Additionally, the behaviour of the advertisement module should be taken into account. For example, when the time between advertisements exceeds the on time of the device, without another mechanism to send advertisements, they would never be sent.

In ORPL, the "Hello advertisement" module has both a conventional timer, to send broadcasts as well as a minimum proportion of cycles to transmit in. For example, if the minimum proportion of cycles is 0.2, then in *at least* 20% of duty cycles, a broadcast advertisement will be sent. I also modify the RPL implementation and IPv4 module to not delete the routes, preferred parents and backup parent sets upon shutdown or start-up.

5.2.3 Modifications of RPL for Intermittent Devices

An implementation of RPL for OMNeT++ is used that works with the IEEE 802.15.4 Radio model also implemented in OMNeT++ [136]. Only upwards routing has been compared for this protocol since the downwards routing is not yet implemented. The implementation is slightly adjusted to use the IPv4 protocol instead of IPv6 so that it is compatible with shutdown and restart. Upwards RPL does not require any of the additional features of IPv6 and the addressing agnostic because it is abstracted behind the INET L3Address interface.

The RPL implementation that is used is for OMNeT version 5.7 however the models are still comparable to the results from the ORPL simulations in OMNeT 6. To enable intermittent operation several adaptations were required. First, the trickle timer will begin with a very short period when the node starts to help quickly notify nodes about its presence. However, this behaviour has to be replaced with a restore operation which reduces the interval upon restart, but does not reset it to the minimum. Additionally, all pending DAOs have timers waiting for acknowledgements, when nodes shutdown these have to be cancelled, since the node cannot receive the acknowledgements when off.

Some generic INET routing components are also modified to be more sympathetic to intermittent conditions. First, in the routing table, the routes stored must not be cleared when the node shuts down because in a static network, the routes will still be valid when the node restarts, where flushing the routes is particularly detrimental to the intermittent scenario. Second, the ARP implementation is modified to not flush the cache except for pending cache entries which are still flushed. Third, the UDP packet generation source is modified to match the operation of the packet generator for the ORPL network. Where nodes only retransmit on startup, if the interval since the previous transmission is larger than specified interval. This is to prevent the packet transmission rate going up dramatically when nodes are intermittent with a intermittency charging time less than the packet interval. Finally, I modify the INET IEEE 802.15.4 Radio model to correctly report the link broken signal which the RPL module harnesses for transmissions.

5.2.4 Simulation Methodology

To compare the suitability of network protocols for Intermittently-powered networks large networks are used where nodes have a significant number of neighbours so when intermittency occurs it is likely that at least one other neighbour will be active. This is necessary in intermittent scenarios because the probability of any one node being active is small.

The network simulations are run for a large simulation time over 10 000 s to allow for good statistical certainty. At the start of the simulation, the nodes have a significant energy buffer so that the DODAG automated construction (in RPL) and EqDC metric (in ORPL) can propagate through the whole network before intermittency occurs. This would still work even if nodes were intermittent from the beginning, but since would take longer so providing an initial energy storage reduces the computation time required. The data from the initial 2000 s of the network simulation will be discounted while the network self organisation takes place and to allow the effects of intermittency to stabilize. In a real deployment, the starting conditions could be preprogramed after estimating them in a simulation, or the nodes could be allowed to perform it automatically.

In order to speed up the settling time of the EqDC metric, a heuristic equation was established to preset the metric at the start. This empirically reduced the settling from 4000 s to under 1000 s in the worst cases of the most intermittent networks. When the steady state is reached quicker, it increases the amount of usable simulation data, and therefore decreases the relative error.

Each simulation instance is run with its own random number generation which can be seeded with different values. The different seeds result in different initialization values of randomized parameters in the simulation. Many different parameters are randomised but most significantly, the randomisation affects the initial energy storage and first packets generation time.

Each set of simulation parameters is repeated several times with different random seeds to obtain a estimate for the spread in the simulation results. Either three or five repeats are done, more repeats would improve the accuracy of the results and the error interval but requires more simulation time. For three repeats, the error interval (where shown) represents the maximum and minimum of the measured results.
For five repeats, unless otherwise specified, the results spread represents the 90 % confidence interval for the results collected.

5.3 Benchmark Scenarios

In order to analyse the performance of wake-up radios in very low-power scenarios, suitable benchmark scenarios should be analysed. Firstly, since some wake-up radios have reduced sensitivity it may be advantageous to use a star topology with a single hop, but higher power wake-up radio. Secondly, when harvested power is higher, routing mechanisms like RPL may work effectively, so long as intermittency doesn't cause advertisement storms or an overload of retransmissions due to broken links.

A grid network is tested to allow for simpler comparisons of multi-hop performance because the expected number of hops is easier to predict. The network is set up so there is more than one node in range in either direction, to enable a potential for other routes when intermittency occurs. The network is setup as a 15×15 grid spaced at 150 m as in Figure 5.5 using the Martinez Open area model, which results in range of approximately $2.5\times$ the inter-node spacing and a downwards set of up to 7 nodes. Each configuration is repeated 3 times with different random seeds, and where error bars are shown these shown the largest and smallest of the results.

5.3.1 Benchmark Results

To determine the performance of the routing protocols, the measure of packet delivery ratio (PDR) is calculated as a ratio of packets received to packets sent at the destination for various groupings. The nodes are grouped depending on their distance from the packet destination in approximate number of hops as demonstrated in Figure 5.5. Each group transmits to a different unacknowledged datagram protocol (UDP) port and the resulting number of packets delivered can be measured. Since the groups have different numbers of nodes in, first the packets received is divided by the number of nodes, before being divided by the expected number of packets sent. Each node transmits UDP packets at an average interval of 70 s and a second setup with an interval of 40 s. In the 70 s load interval RPL scenario 114 packets are expected per node, in the 40 s load interval scenario 200 packets are expected to be sent per node. The measurements of the sending nodes shows that all scenarios

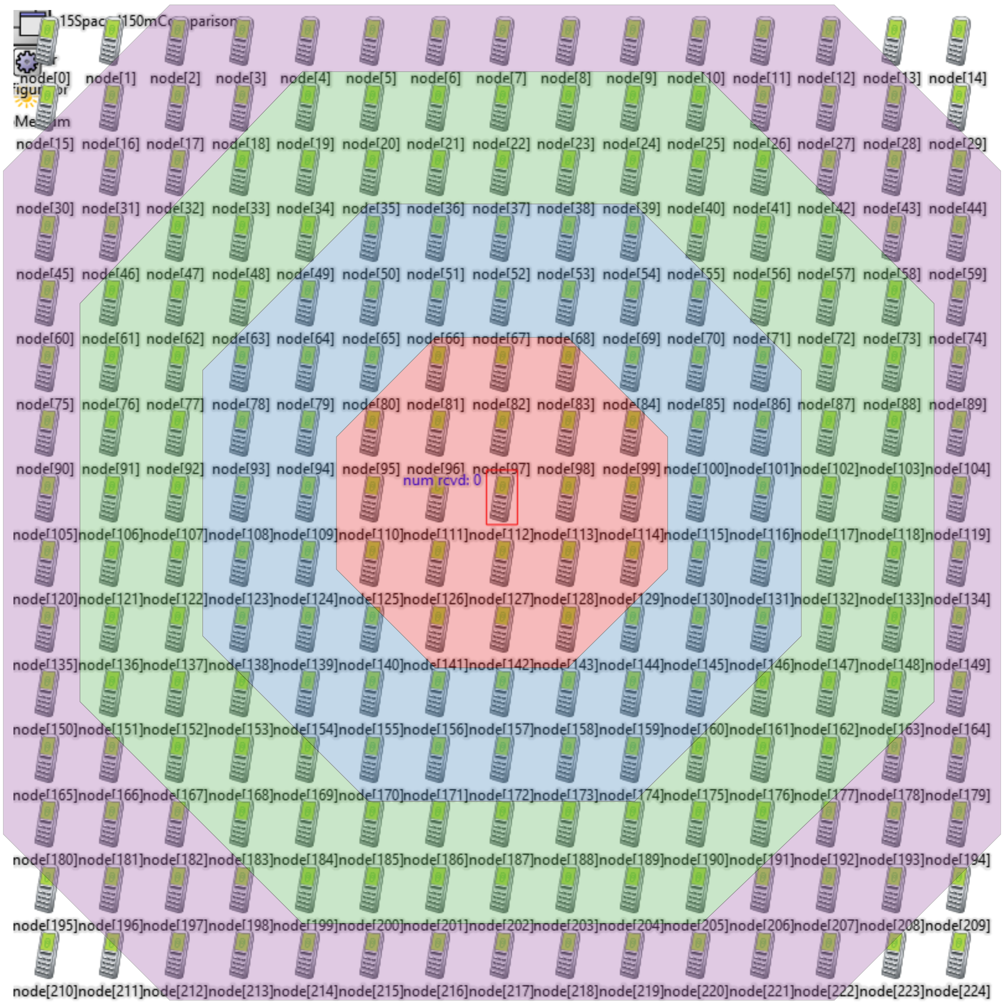


FIGURE 5.5: 15x15 Grid of EH nodes for benchmark scenario, hub node of node[112] at centre. Nodes in red zone are within 1 hop, within blue area 2 hops, green area 3 hops, purple area 4 hops and white area 5 hops.

are within 0.5 % except the 4 mW and load interval of 40 s scenario which is 2 % lower sending rate. Since the measured sending rate is so close to the set sending rate, and only a small dip is seen when the delivery rate is zero, the measured sending rate is not shown here.

By testing the RPL network in Figure 5.5 under gradually decreasing energy generation conditions, the effect of intermittency cause by limited energy supply can be seen in Figure 5.6. It shows that as soon as intermittency occurs, there is a sudden drop in performance, even while the nodes have 90 % of the listening power of the radio supplied. The RPL mechanism for switching to a backup parent does not increase the probability for the next packet, because the other parent is also intermittent. Upon switching to a new parent, the RPL protocol cannot update the MAC address of the existing packets in the MAC layer, so they are dropped. Subsequent packets are sent to the new parent, but that may then also not be available so a lot of energy is wasted just switching to parents which aren't available.

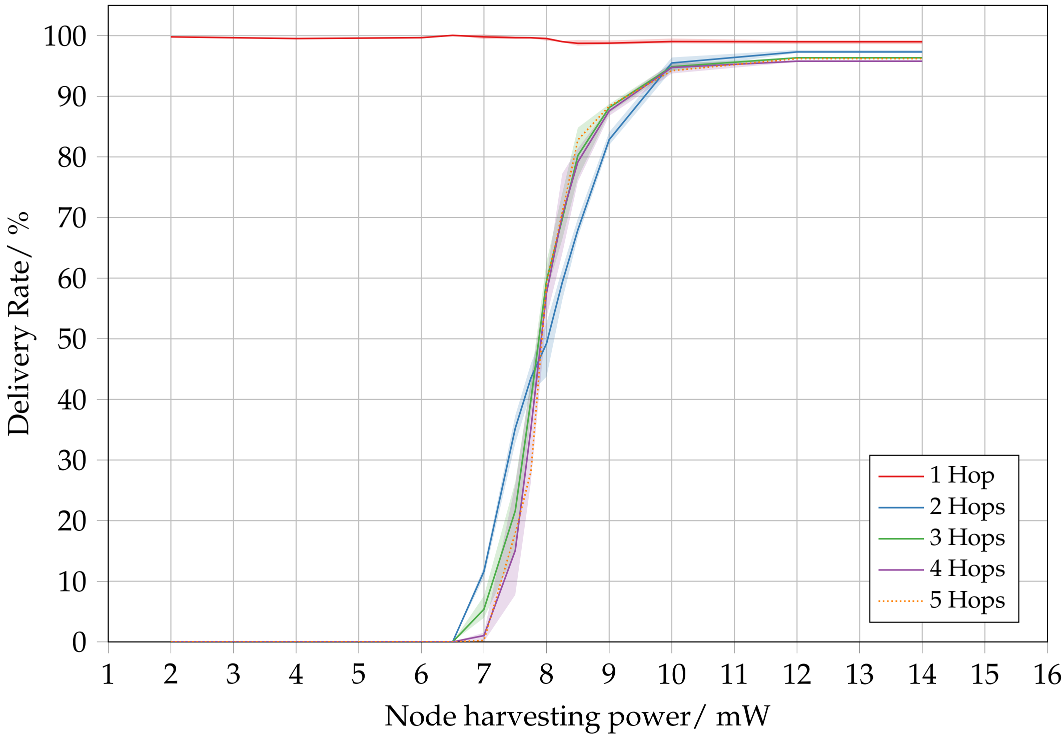
The nodes that are within 1 hop still successfully deliver their packets, but the effect of parent nodes becoming intermittent on anything beyond the first hop is catastrophic. This is compounded by the additional transmission of DIOs when the parent is changed and is demonstrated by the steeper gradient transitioning between fully powered at 12 mW to intermittently-powered at 8 mW in Figure 5.6, where the count of received packets at the hub corresponds to each of the coloured regions in Figure 5.5. It is clear that multihop RPL cannot even handle a very small amount of intermittency without there being a significant effect on the packets delivered.

When fully powered the packet delivery rate is over 99 % for one hop to the sink, dropping slightly for each extra hop resulting in 96 % at 5 hops. Given that the listening power is 6 mW the effect of intermittency is seen substantially higher, dropping below the 75 % delivery threshold at 8.5 mW. This is because the power consumption of transmitting and reception is higher when the full RF chain is active. The drop in the delivery rate to 0 is so sudden because at the lower energy levels, before sending a packet the rediscovery of the rank and available next hop takes place before an attempt to send the packet. In the process of the rank and next hop discovery, energy is exhausted and the packet is deferred, until the discovery is again restarted, thus the data itself is never sent.

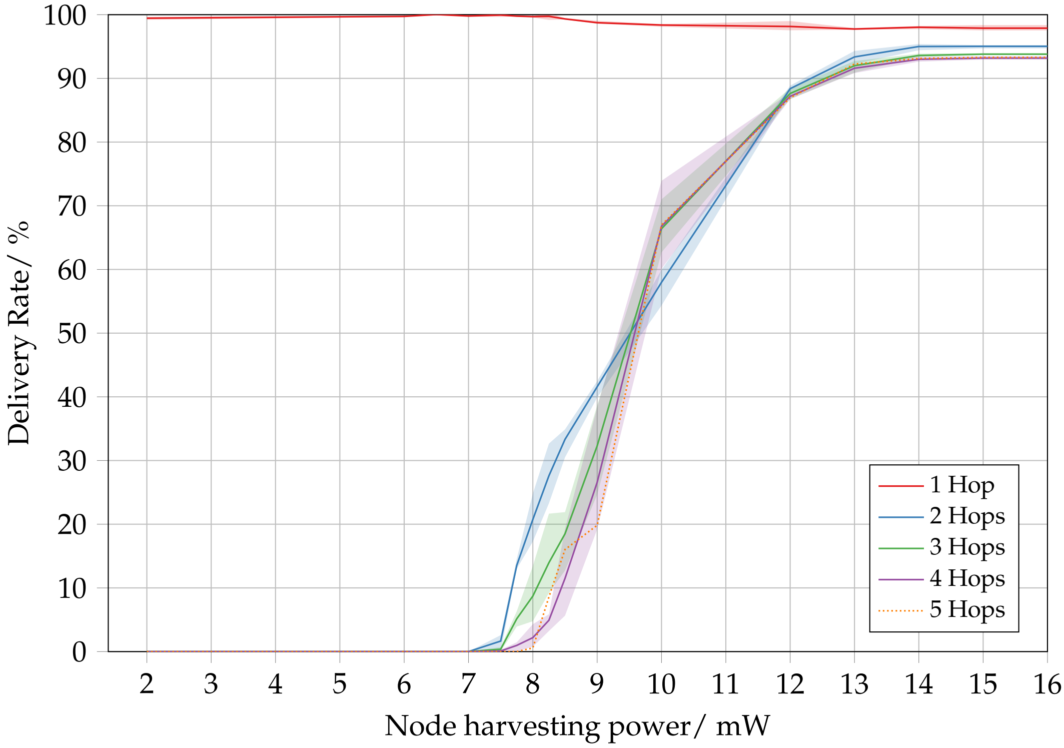
The shape of the results is very similar for the higher rate transmissions (average interval of 40 s). When fully powered, there is a slightly lower multi-hop packet delivery rate of 95 % due to the high medium usage around the sink dropping to 93 % at 5 hops. The drop off due to intermittency happens at a higher harvesting power, dropping below the 75 % delivery rate at 11 mW due to the increased amount of energy being spent on extra packet transmissions.

5.3.2 Direct Comparison with Opportunistic RPL (ORPL)

Taking the same node configuration in Figure 5.5, the routing can instead be done opportunistically, using ORPL. Again three experiments are done per configuration. The measured actual load sent over 8000 s is shown in Figure 5.7 for the different loads. This is shown because, contrary to the previous RPL scenario, the measured sending rate decreases signficiantly when intermittency occurs, due to how the timers are set to retransmit. By calculating the delivery rate shown in Figure 5.8 onwards, greater detail is visible at low EH values, when the number of packets sent is smaller, but where the delivery rate is still good. The nodes closest to the hub (1 hop) drop first as they are the first to become intermittent. This is because they expend more energy forwarding the information from other nodes. In the higher load interval configurations 70 s to 150 s this effect is less significant but still the nodes are unable to keep up the load rate when the harvested power is too low. This packet sending rate reduction is a significant sending limit of nodes due to their limited EH, which



(A) Load interval of 70 s



(B) Load interval of 40 s

FIGURE 5.6: Packet delivery rate to the central node of a 15x15 grid of RPL nodes, normalized for number of sent packets and 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. The packet delivery rate from nodes in immediate range of the hub is not impacted, nodes 2 hops away see an earlier drop due to the extra retransmissions for preferred parent updates but show a slightly slower drop off in delivery rate. All higher hop counts (3, 4 and 5) show a steeper drop when intermittency occurs.

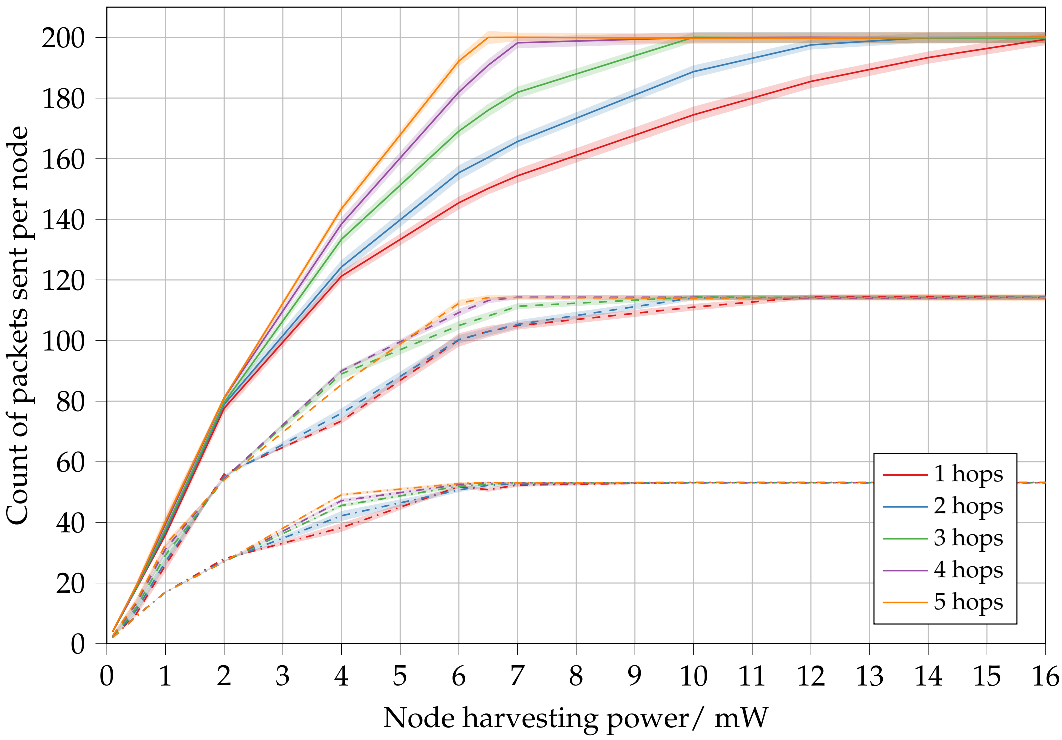
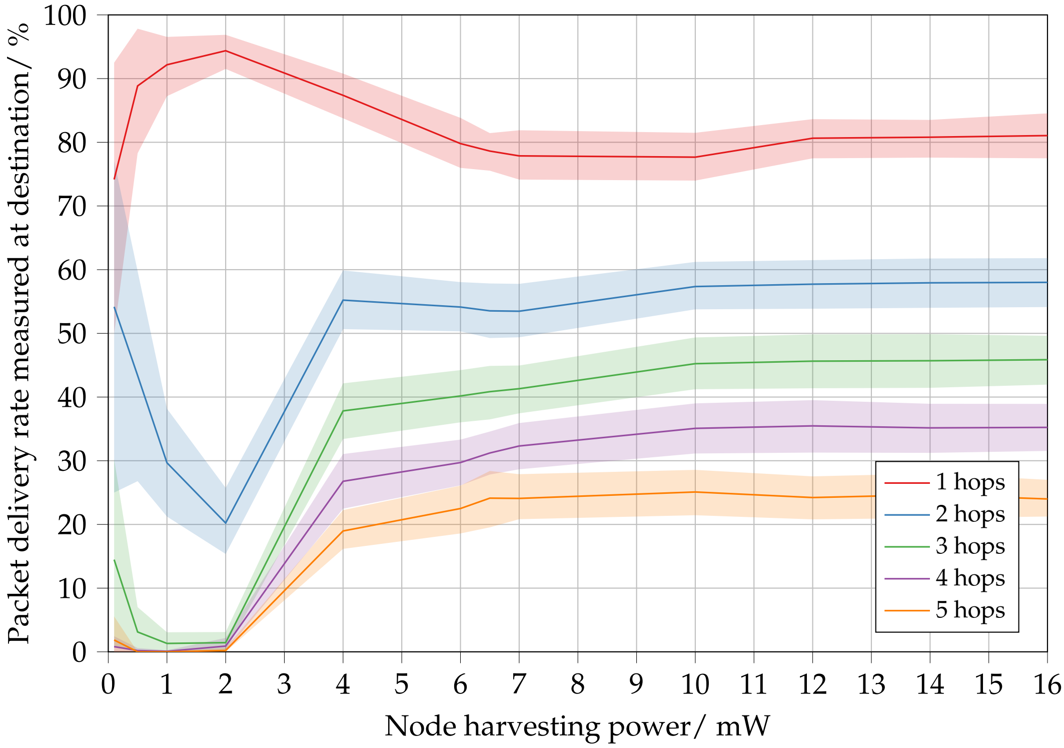


FIGURE 5.7: Measured packets sent by nodes in 15x15 grid running ORPL to send data at fixed intervals to the hub node. Grouped by estimated number of hops to hub and by sending interval as; 40 s interval with solid lines at the top, 70 s interval with dashed lines in the middle, 150 s interval with dash-dotted lines at the bottom.

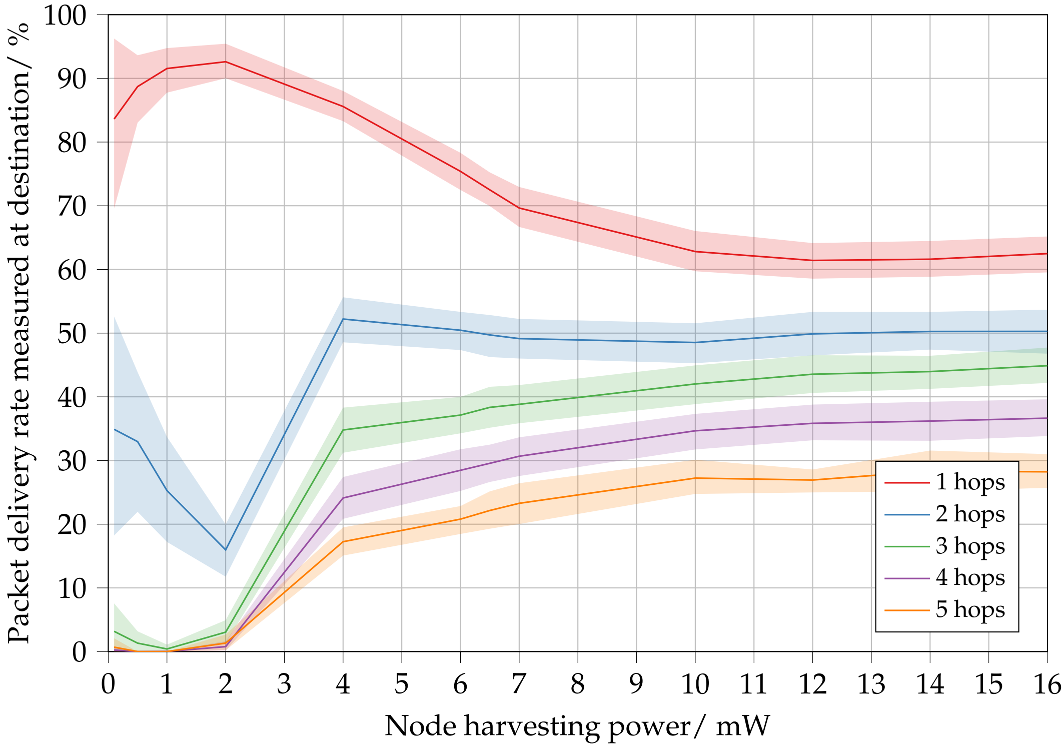
may reduce end to end reliability if not accounted for in a transport level protocol. However, whilst the sending rate at a node can be controlled internally, the network delivery rate is determined next, to see the delivery rate once a message leaves the node.

At the hub there is a clear difference in the packet delivery rate between different numbers of hops to the destination. The per node delivery rate is averaged across the nodes in each hop group and is shown in Figure 5.8. Unsurprisingly, the further away from the hub that nodes are, the lower the packet delivery rate is. When fully powered, ORPL delivers a lower proportion of packets than RPL. However, ORPL continues to be able to deliver 50 % of packets from 2 hops and 45 % of packets from 3 hops at the load interval of 40 s. Whilst far from the best packet delivery rate from RPL, it demonstrates the resilience to intermittency where RPL cannot deliver anything past 1 hop.

In the lower load scenario with a load interval of 70 s in Figure 5.8a, you see higher packet delivery rate particularly of 1, 2 and 3 hop nodes compared with the 40 s load interval. The 150 s is not shown as it is very similar to the 70 s load interval, and the only significant difference is that the 1 hop delivery rate does not decrease, staying above 88 %.



(A) Average per node packet delivery ratio with a load interval of 70 s



(B) Average per node packet delivery ratio with a load interval of 40 s

FIGURE 5.8: Packet delivery rate calculated per sending node at the hub. The nodes within 1 hop have the highest success rate which actually increases as the load from more distant nodes decreases, there is a progressive decrease in delivery ratio as the number of hops increases.

5.4 Wake-up Receiver Experiments

Looking to operate wireless networks in even more constrained EH conditions motivates this next section on ultra low power WuRx. The network is the same layout and number of nodes to demonstrates the suitability of the opportunistic approach to a large network, but where the simulation time required is still suitable to allow a large number of configurations to be tested. The WuRx in the study are selected to cover both the minimum distance between nodes, up to a being able to reach the whole network in two hops, but with a much larger power consumption. The intermediate WuRx balance these two factors, but it should be noted that the transmission cost is also considered if a long preamble is required or if there is a low data rate. This is important in a homogeneous EH network and because this is the first work to consider multi-hop uses of WuRx, it is the first to consider this issue of transmit cost.

5.4.1 Node Configuration

The network is setup to have both upwards (to the sink node) and downwards (to the leaf nodes) traffic. It is important that downwards routing is supported, at the minimum so that updates about data requirements, software upgrades etc. can be communicated to leaf nodes. Furthermore, effective cross-layer communication can enable new applications that perform multi-node data inference or distributed processing and decision making. The downward routing is measured by creating leaf node to leaf node traffic, where destinations not immediately upwards of the source can only be reached with some proportion of downwards routing.

For all the wake-up radio experiments, the same data radio is used, based on the CC1120 radio from Texas Instruments. The power consumption used are nominal values available in the datasheet at 200 $\text{kbit}\,\text{s}^{-1}$. The radio range is determined by the two-slope path loss model for an outdoor flat area [46].

5.4.2 Wake-up Receiver Configurations

Following the investigation of suitable WuRx in Chapter 2.3.4, a range of different capability wake-up radio devices are simulated to investigate the effect of range, data rate and available neighbouring nodes. To enable comparison between different wake-up radios, the power consumption parameters are adapted for all nodes using a 3 V battery supply, required by the data radio. Where WuRx provide parameters for other voltages, such as 1.8 V [81] or as low as 0.5 V [78], a very low quiescent current converter is needed. The power consumption is therefore calculated including the TPS62840 converter [137], except for the radio from Abe et al. [78] where the higher power consumption means the TPSM8282 [138] provides better efficiency.

Given there is not a single dominating parameter that allows simple abstraction of wake-up radios few of the state of the art (SoA) transceivers have been modelled. These achieve the best sensitivity to power consumption ratio in the 915 MHz band for their sensitivity level. However, there is a broad range of datarates, required preamble durations and addressing functionality, that all affects the overall network performance. Either with an increase in transmitter and receiver on time, or with an increase in false wake-ups. The radios chosen for implementation, with their source publication are listed in Table 5.1.

Whilst I modelled quite a broad range of radios, in the experiments, as indicated in Table 5.1, only a narrower range of radios have been selected. However, because the other radios parameters have been extracted and modelled, it allows for easy future comparison in novel application scenarios. Such as when there are other be particular reasons for choosing another type of radio, for example, taking the cost or physical size constraints into account. The parameters modelled are: sensitivity to wake-up messages, where a lower value indicated higher range; wake-up duration when there is an additional preamble or EH period; datarate for communicating the wake-up code to the device; and the power consumption when listening, P_{Li} and when receiving messages P_{Rx}.

5.4.3 Optimising Performance of Opportunistic RPL (ORPL)

There are many parameters within the Opportunistic routing stack that need to be optimised, other than the WuRx power and sensitivity. These include some link layer parameters such as timing parameters, acknowledgement window and contention probability. At the network layer examples of parameters that can be tuned are: the preferred next hop distance, the routing table refresh rate and advertisement broadcast rate.

The simulation of ORPL can allow for a broad range of parameters to be investigated, as well as a variety of traffic scenarios and network topologies. This has not previously been done for intermittent networks, and this evaluation will also be the first of with WuRx for other protocols. For the experiments, it is determined that an appropriate forwarding cost is 0.5EqDC, this ensures that the forwarding node must have an EqDC value at least 0.5 lower before responding to a forwarding request. This confirms what the original ORW work showed, where the number of transmissions was minimized at 0.5, and delay and node duty cycle is only slightly higher than a cost of 0.2 [124].

The other parameters that can be adjusted at the MAC layer include the data listening duration and acknowledgement wait duration which determine the maximum transmission unit and collision rate during forwarding contention respectively, they

Author	Year	Sensitivity (dBm)	Data Rate (kbps)	t_{WU} (ms)	Nominal P_{Li} (µW)	Nominal Supply (V)	3 V P_{Li} (µW)	P_{Rx} (µW)	Wake-up filtering	Model Name	Selected
Hambeck et al. [76]	2011	-64	200	1	2.4	1	3		Static	Hambeck1	
Hambeck et al. [76]	2011	-71	200	5	2.4	1	3		Static	Hambeck2	Y
Roberts and Wentzloff [82]	2012	-41	n/a	10	0.098	0.5	0.392		None	Wenzloff1	
Oh et al. [74]	2013	-43	12.5	5	0.116	0.5	0.8544	0.8544	Static	Wenzloff2	
Milosiu et al. [77]	2013	-82	8.1		216.75	2.5	240		Dynamic	Milosio1	
Milosiu et al. [77]	2013	-82	1		28.25	2.5	31.3		Dynamic	Milosiu2	
Abe et al. [78]	2014	-87	50	1	44.2	0.5	88.4	1576.8	Dynamic	Abe	Y
Moazzeni et al. [79]	2014	-75	200	0.9	16.4	0.5	32.8	45.8	Dynamic	Moazzeni	Y
Magno et al. [81]	2016	-32	8.3		0.192	1.8	0.48	63	Dynamic	Magno1	
Magno et al. [81]	2016	-42	8.3		0.405	1.8	0.81	63	Dynamic	Magno2	
Magno et al. [81]	2016	-55	8.3		1.24	1.8	1.77	63	Dynamic	Magno3	Y

TABLE 5.1: Selection of SoA Wake-up radios with varying sensitivity and capabilities. Wake-up duration information is only available for some radios as the others are only data rate dependant.

Category	Parameter	Value
Data Link	Radio Model	Ground plane model [46]
	Main radio turn-on delay	0.6 ms
	Data listening duration	20 ms
	Acknowledgement wait duration	1.4 ms
MAC	Relay Contention Probability	0.5
	Retransmission attempts	4
Network	Forwarding cost, w	0.5EqDC
	Advertisement send wait	150 s
	Per duty cycle minimum advertisement rate	0.2
Node	Turn on energy threshold	4 mJ
	Turn off energy threshold	2 mJ
Simulation	Duration	10 000 s
	Warm-up period	2000 s
	Node Count	15×15
	Node Spacing	20 m

TABLE 5.2: Static simulation parameters for simulation of Intermittently-powered ORPL network of WuRx equipped EH nodes.

are recorded in Table 5.2. The data listening duration is long enough to ensure that it does not affect the small test data sent over the 200 kbps data radio, activated by the wake-up radio. The acknowledgement wait duration allows at least 6 nodes to respond within the window, determined by the length of the acknowledgement in bits, and the data rate.

The focus of these experiments is on the effect of WuRx power consumption and the transmissions required to reach those nodes. I investigate the reliability of multihop packet transmissions with the different implemented radio models, and whether downwards routing is possible as well as upwards routing to a hub node.

5.4.4 WuRx Sensitivity Experiment

In this scenario, wake-up transmissions at 15 dBm are used, consuming 103 mW while transmitting. Four WuRx are selected from Abe [78], Moazzeni [79], Hambeck [76] and Magno [81] that give a range of approximately 28 m to 200 m. On a grid spacing of 20 m, almost all nodes with the Abe radio are immediately in range of the hub, whereas the Magno radio can only reach its closest and closest diagonal neighbour, and the other two are in between. The harvesting power determines the amount of power available to the nodes and experiments are run with a range of 0 µW to 500 µW, however, for all of the scenarios of medium sensitivity radios there is not a significant difference between 100 µW and 500 µW. Therefore, most of the results restrict the range to show greater detail.

Each node attempts to send a packet of 8 B to the hub at a specified load interval, with randomized start times to avoid bursty behaviour and an overload of the medium. If the EH power is low, nodes cannot send as many packets but the actual packet send rate is recorded and reflected in the results. Additionally, the packet load interval is varied to investigate how the increase load affects delivery rate. If the packet can reach the hub directly it is most likely to be delivered directly, however, due to the opportunistic nature of the protocol, another node may still compete in the contention period and forward the message instead, over an extra hop. The number of packets received at the destination is recorded per origin allowing for per node delivery rates to be calculated.

5.4.5 Results of Upward Routing to Hub

The first test is of three different load intervals 200 s, 600 s and 1000 s, where all the load is directed towards the hub. The EH power of the hub is specified to ensure it always has enough power, but the situation where the hub is intermittent is also tested.

First, the actual transmission rate is presented in Figure 5.9, with all nodes able to send the full number of packets at a high harvesting power, but as the harvested energy is decreased the nodes are off for longer than the load interval. The transmissions of data consume a substantial proportion of the energy compared with the listening. For example a single transmission of a wake-up and packet would consume around 1.5 mJ which would power a wake-up radio for 20 s to 300 s. This is demonstrated by the similarity in the transmission rate between the different types of radio at low harvesting power. Unsurprisingly, when the transmission rate is lower, the drop off in the number of packets sent occurs at a lower EH power.

From the same set of experiments, the delivery rate can be calculated on a per source basis. Each received packet is counted at the routing hub, and recorded for each source node. Consequently, the average delivery rate is calculated and compared across each different type of WuRx as shown in Figure 5.10. 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.

However it is important to distinguish what distance the data has travelled, and whether the wake-up radios are still perform well across multiple hops. For this the packet reception data is separated into groups according to the distance from the hub (in hops) like in Figure 5.5 but with a distance of 2.75 times the nodes spacing,

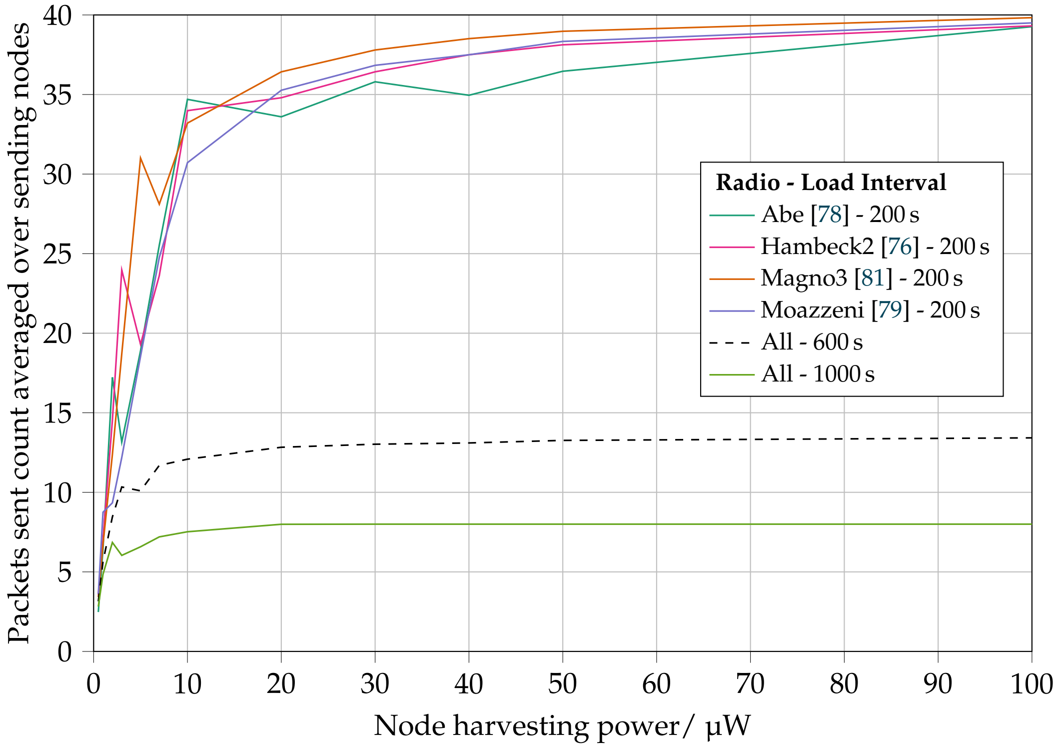


FIGURE 5.9: Packets sent per node during 8000 s simulation period averaged across all nodes in 15x15 grid. Only shown up to 100 µW to see the detail when the harvesting power cannot support the transmission rate. All the different radio types are grouped for load interval 600 s and 1000 s and they are very close in value anyway.

compared with 2.3 before. This is according to the hop distance for the Hambeck WuRx, where the range is approximately 55 m.

The increased range of the Abe radio has the effect of increasing the apparent density of nodes. This is because each node has a greater number of neighbours. Density is traded off for on-time, where in the downwards case because the end node is more available, the acceptable duty cycle is lower.

For the Abe WuRx the range is approximately 200 m, so all the nodes are directly within range of the hub, however nodes closer to the hub will still forward some messages from further out and also experience a higher false wake-up rate, depleting their own energy store so fewer of a nodes own packets are delivered. Interestingly you can see in Figure 5.11 that the packet delivery count is about 30 % greater for nodes further away when the load interval is 200 s. As the load interval increases to 1000 s, this difference in packet delivery count between nodes closest to the hub and far from the hub decreases to 15 % since the load on the closest nodes to the hub, and the load on the hub itself are no longer limiting. The Hambeck and Moazzeni WuRx exhibit similar characteristics for multihop behaviour. With an approximate range of 55 m and 80 m respectively, most data can only reach the hub in several hops. Even though the Hambeck WuRx has a much lower listening power consumption, the

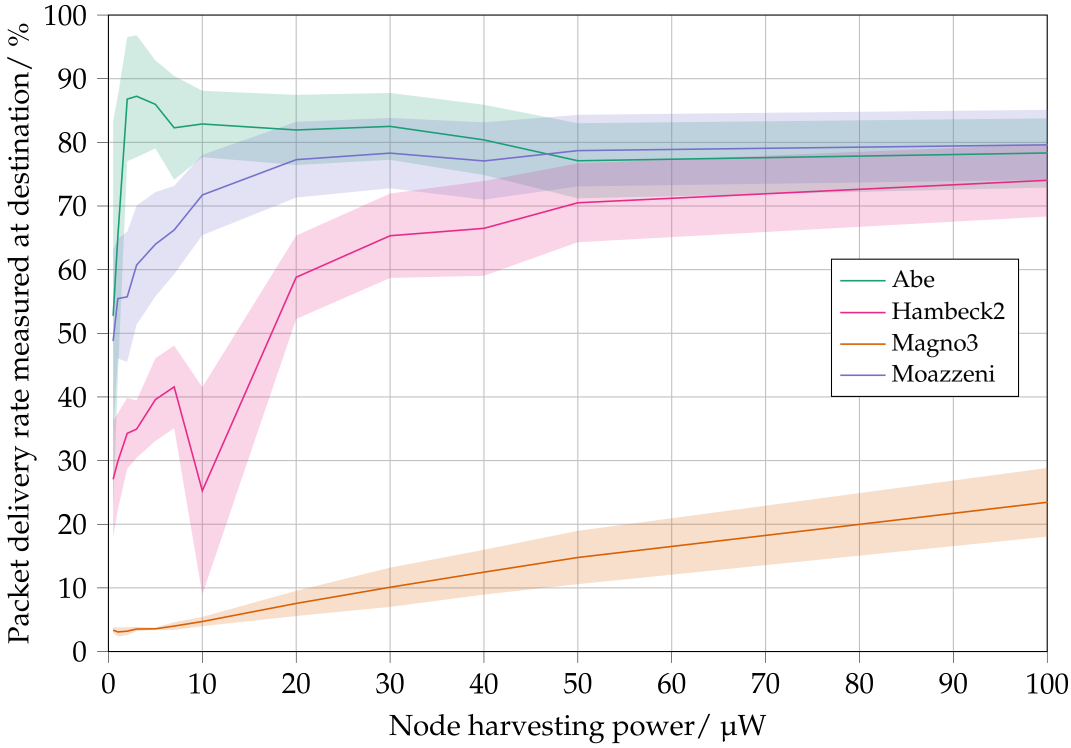


FIGURE 5.10: Packet delivery rate for various WuRx sending packets to always-on hub at an interval of 200 s, requiring multiple hops with all except the Abe radio configuration. Results averaged across 5 experiments and all nodes in 15x15 grid, uncertainty bounds showing 90 % confidence from 5 repeats.

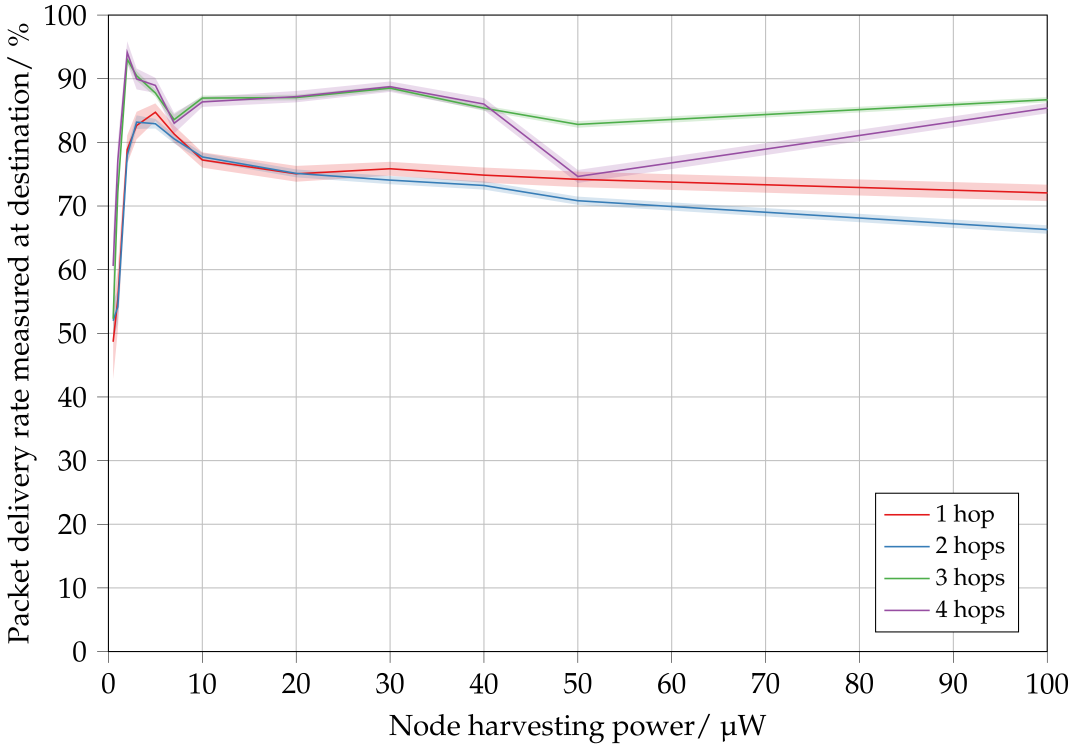


FIGURE 5.11: Packet delivery rate to hub from nodes with load interval of 200 s grouped by hops to hub. Using the Abe WuRx configuration with all nodes transmitting.

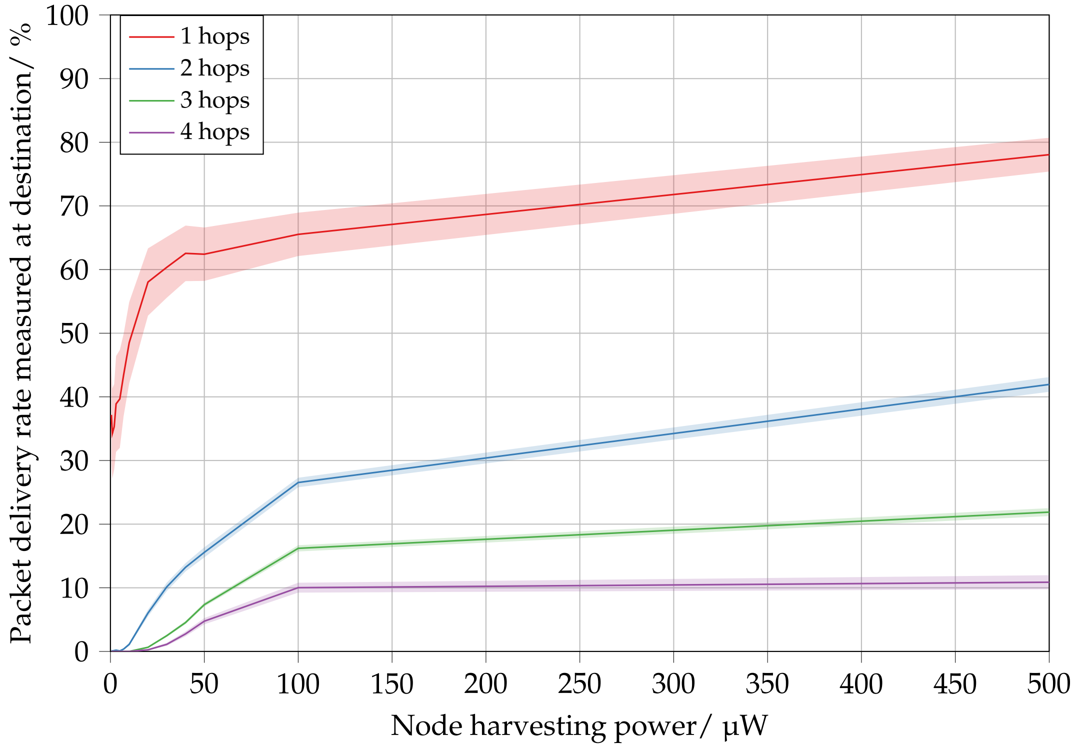


FIGURE 5.12: Packet delivery rate to hub from nodes with load interval of 200 s grouped by hops to hub. Using the Magno WuRx configuration with all nodes transmitting.

long wake-up preamble makes transmissions more expensive and therefore at lower power the Hambeck radio performs less well, but eventually reaches a very similar delivery rate.

For the Magno wake-up radio, the performance is considerably worse than the other three chosen radios. This is because even though the power consumption due to the listening is small, because there are only 8 nodes directly in range of the hub, they must act as the final forwarder for the other 216 nodes, meaning even at the larger per node load interval of 1000 s the actual transmission interval would need to be under 40 s to support this. Given the cost of transmitting a packet of around 1.5 mJ and the cost of receiving a packet at around 1 mJ, at 50 µW of harvesting power it takes at least 50 s of EH to send one packet. This shows that at the nodes closest to the sink there is not even enough energy to support the transmission and reception of the forwarding, regardless of energy consumed for other tasks, routing messages, overhearing and false wake-up.

An extended EH range is shown since there is a noticeable increase in performance at the additional configuration of 500 µW. However the delivery rate is still relatively low, because it is dominated by the overloading of the nodes close to the destination. Additionally, Figure 5.12 shows not only is the 1 hop group delivery rate worse, but there is a significant further drop off in the further groups. This is similar to the

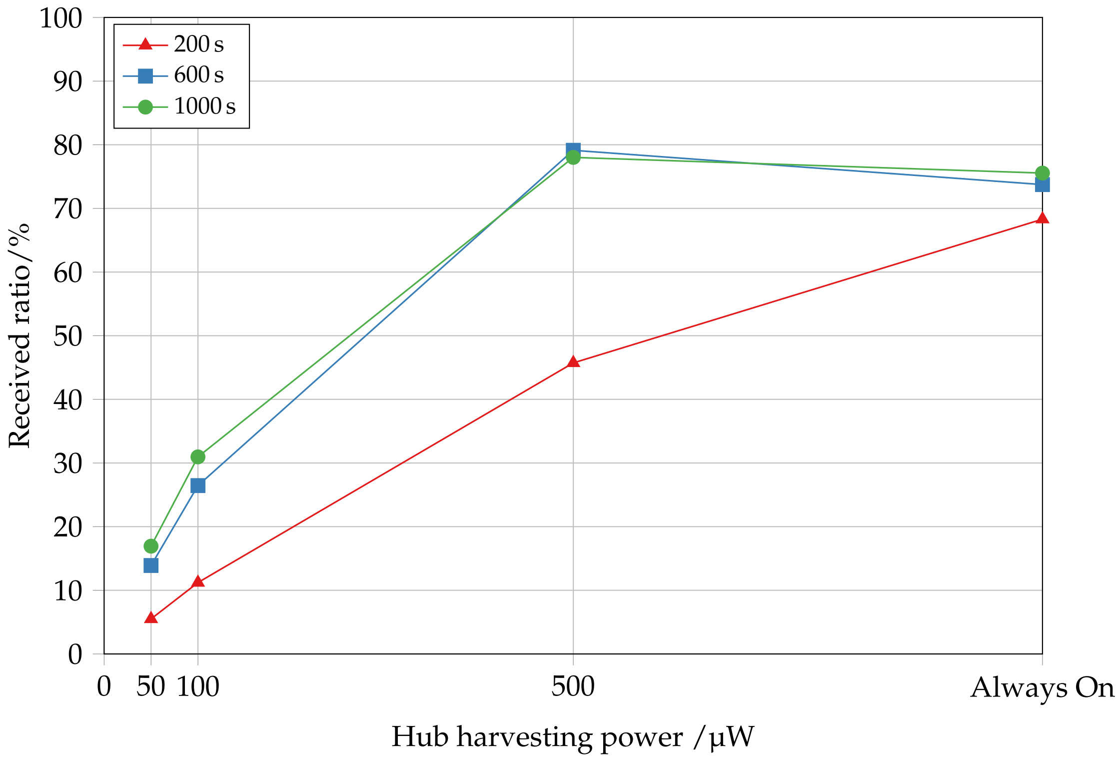


FIGURE 5.13: Packet delivery ratio to hub from sending nodes harvesting at 20 µW with Moazzeni WuRx, showing general trend for all WuRx. The received ratio is most affected for higher load settings, where the additional time spent with the main radio on reduces the duty cycle and increases packet loss.

configuration with conventional radios comparing RPL and ORPL in Figure 5.8, where both configurations have limited numbers of potential forwarders due to the distance between the nodes.

The packet delivery success is also dependant on the EH of the hub, as well as the general harvesting power of nodes. In Figure 5.13, comparing when the rest of nodes are harvesting at 20 µW, there is a reduction in delivery rate even at 500 µW, where other nodes would not be intermittent, but it is using more energy for receiving. When the load is lower, with a load interval of 1000 s the delivery rate is less affected. Additionally, there is a small reduction in when node are always-on, this is probably because the node is not correctly sending ORW update messages, and this performance could be improved by updating the “ORW Hello” parameters.

When comparing the different radio configurations in Table 5.3, the higher powered Abe and Moazzeni radios enable better performance for the lowest data rate interval of 1000 s. However, under higher load or with a lower hub harvesting power of 50 µW, the Hambeck radio performs better because the duty cycle of the hub node is improved. Also, the configurations with the Magno radios only experience a small

Hub harvesting power	Load interval 200 s	600 s	1000 s
50 µW			
Abe	5.2	12.2	13.4
Hambeck2	5.7	14.6	18.6
Magno3	4.8	12.9	18.1
Moazzeni	5.5	13.9	16.9
100 µW			
Abe	10.7	23.1	25.7
Hambeck2	9.3	26.8	33.0
Magno3	7.6	17.6	23.3
Moazzeni	11.2	26.4	31.0
500 µW			
Abe	45.3	81.1	77.2
Hambeck2	45.4	75.1	73.9
Magno3	7.6	17.6	23.3
Moazzeni	45.7	79.1	78.0
Always On			
Abe	78.4	80.3	79.1
Hambeck2	48.9	59.3	61.5
Magno3	9.7	15.5	17.1
Moazzeni	68.3	73.7	75.5

TABLE 5.3: Average delivery rate (%) for load interval and wake-up radio types when varying the EH power at the hub with other nodes harvesting at 20 µW

difference across the range of hub harvesting power because the quiescent consumption of the radio is less than 5 µW. Below 100 µW the performance of all WuRx configurations begins to be instead dominated by the cost of the individual transmissions and not the WuRx, so there is a narrowing of the difference between them.

5.4.6 Results using WuRxs for Cross Network Routing

Following this, the results of cross network routing are investigated, to determine whether choosing the best radio for upwards routing negatively impacts the downwards routing. This set of experiments follows the same EH profile, physical layout and wake-up radio selection as the previous experiment, however it has a different load. 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. The per node load interval is 5× smaller in the active nodes to keep the overall *network* load the same.

This scenario highlights the advantages of the lower power wake-up radios. Due to the higher power consumption with the Abe radio, end nodes have a short duty

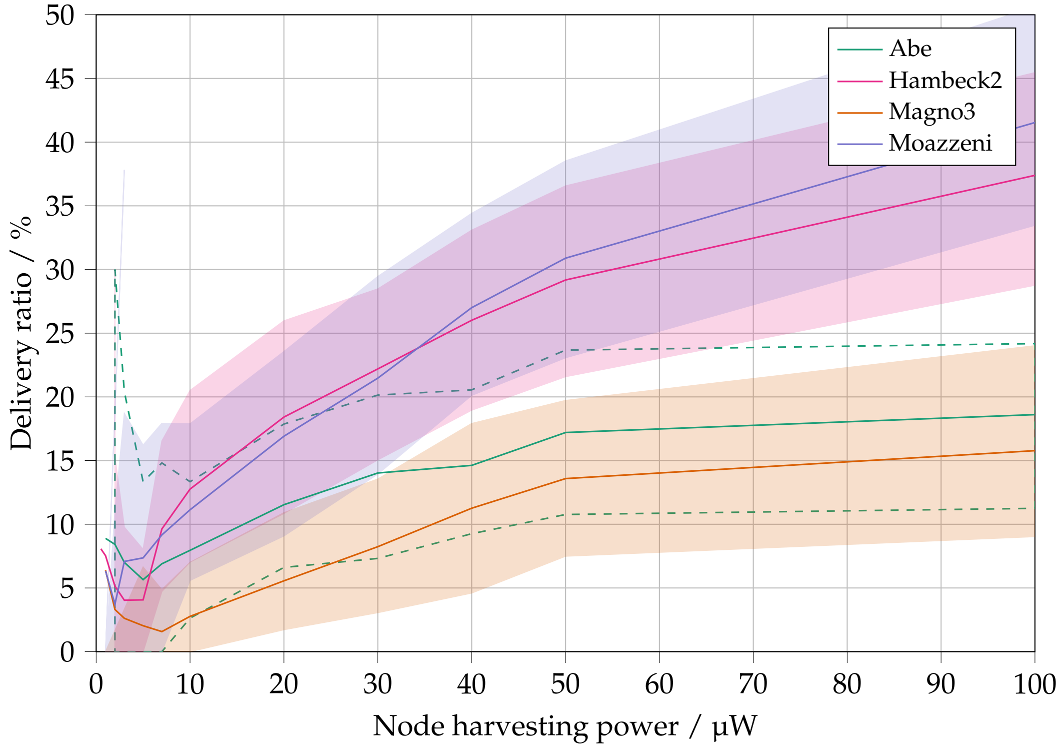


FIGURE 5.14: Packet delivery ratio in downward routing scenario for different WuRx for transmitting node load interval of 120 s and with intermittent hub. Showing mean of all receiving nodes across 5 repeats with areas around lines showing 10th to 90th percentile range to demonstrate the spread of results, the Abe radio uncertainty is bounded by dashed lines for clarity.

cycle so the downwards routing success is significantly lower than both the Hambeck and the Moazzeni devices. Returning to the analogy of density, in the Abe scenario, performing downwards routing, there is not enough redundant *active* nodes due to the higher power consumption. Similarly, with the Magno configuration, while the nodes have a high on-time, there is only a small number of neighbours so insufficient routing paths are provided. The downwards routing here relies on sufficient redunant paths being available, which is not the case for the Magno configuration. At the final hop, routing opportunistically only provides marginal improvement with the opportunity for multiple nodes to retry the transmission. For the Abe radio this is particularly apparent, where a harvesting power of 40 µW would limit the duty cycle to less than 50 %, before considering transmission cost. The advantage can be seen by looking at the average packet delivery ratio as the harvested energy is varied in Figure 5.14.

Unlike the upwards to the hub scenario, there are a range of destination nodes across many positions in the network, so you would expect there would be some variation in delivery rate depending on position. To visualize this variation, the delivery ratio is first calculated independently at each node and for each simulation run. For each EH

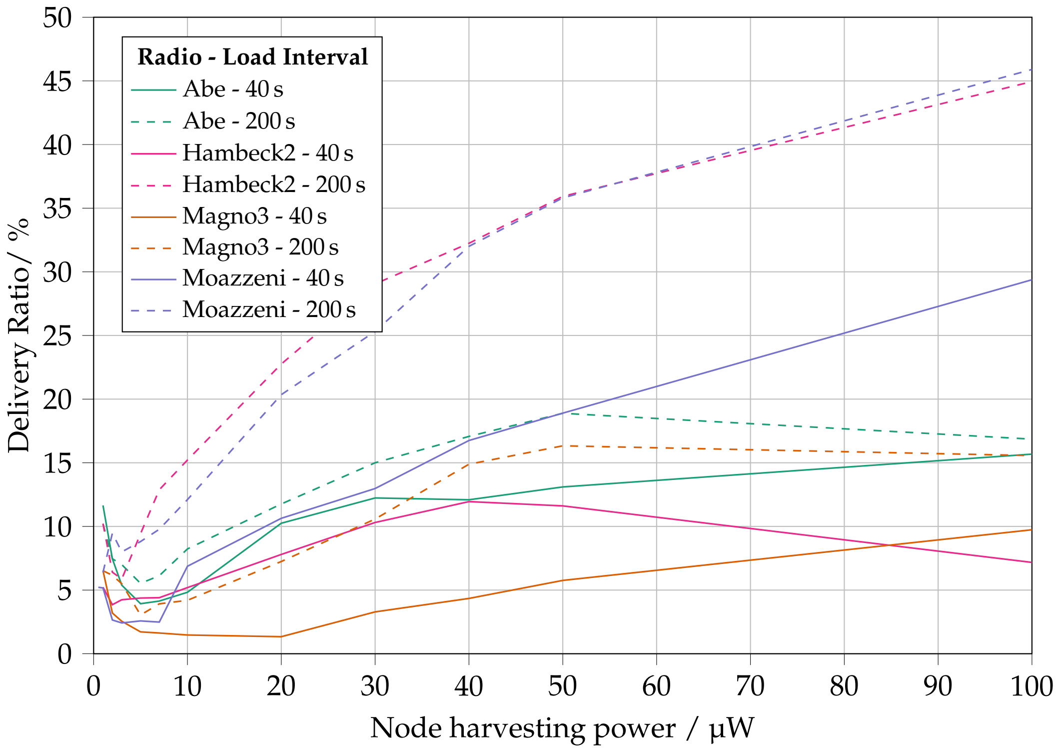


FIGURE 5.15: Packet delivery ratio with combinations of WuRx and load intervals (WuRx - Load Interval) with and intermittent hub harvesting at 50 µW. Showing mean delivery ratio of receiving nodes.

rate the results are grouped by the interface and in Figure 5.14 the area is bounded by the 10 % to 90 % and the line shows the average delivery rate.

The size across the central 80th percentile demonstrates that there is only a small variation between This delivery rate is for a load interval of 120 s and with an intermittent hub harvesting energy at 50 µW. The downwards performance is within 5 % at the higher hub harvesting power of 100 µW to fully powered. Unlike in the upwards to the hub scenario, this shows that the intermittent ORPL implementation does not rely on a fully powered hub, and can effectively route around an intermittent hub.

However, there is a big difference in performance when the load is increased, where the packet delivery rate is greatly reduced when the load interval is 40 s. In Figure 5.15, the effect of a high load is seen most on the Hambeck interface which goes from being the highest performing to the 3rd best, falling behind the Abe radio. The Abe radio experiences the smallest difference in performance at high loads but still does beat the Moazzeni WuRx configuration.

In all of the configurations with respect to the load, the Magno WuRx again has the lowest packet delivery ratio except for at nodes closest to the hub, 51, 111, 114 and 131 at a very low harvesting power, where it is better than the Abe radio. This also helps to confirm that the poor performance in the routing to the hub scenario is caused by

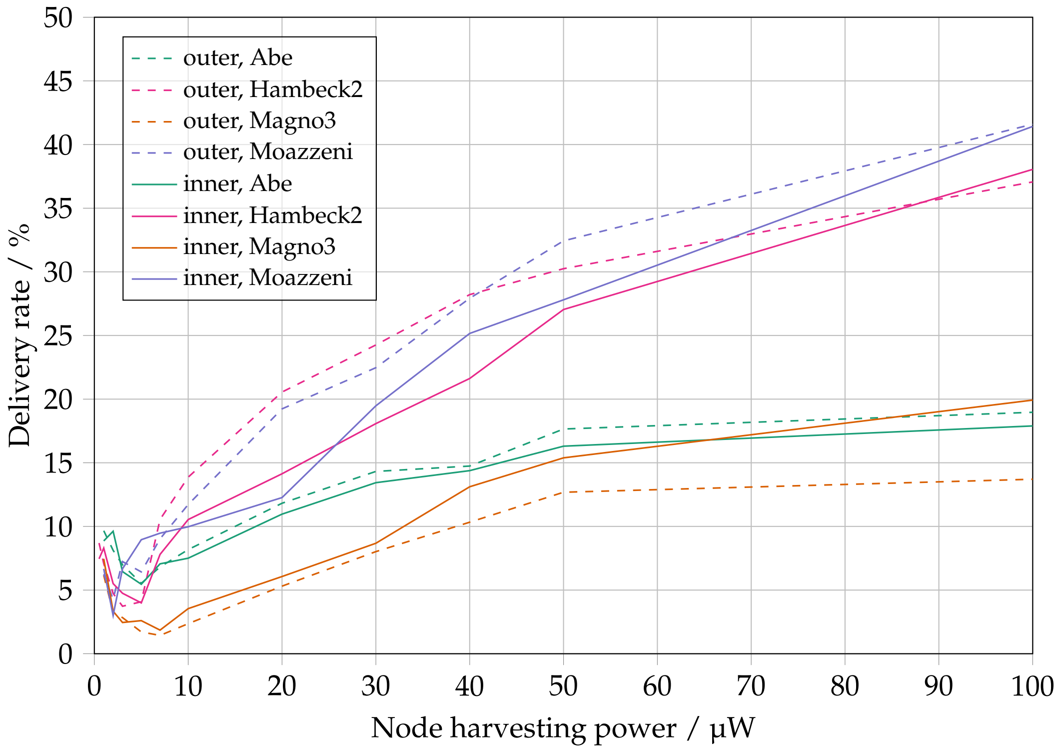


FIGURE 5.16: Positional variation in delivery ratio with intermittent hub harvesting at 100 µW and load interval of 120 s. Central nodes are 51, 111, 131 and 141, outer nodes are 21, 31, 41, 151, 161, 181, 191 and 201.

the overloaded central nodes, because here, while the network load is the same, it has distributed destinations and has higher delivery rates in the low power scenario. The Magno radio does not perform well at destinations further from the hub because it must be routed down the opportunistic gradient over more hops, compared with higher range devices.

The effect of the positions of the nodes on the delivery ratio has been assessed from two aspects. First the destination nodes can be separated into groups based on their distance from the centre of the network. The nodes 51, 111, 131, and 141 are categorised as central, and all the other nodes are categorised as outer as in Figure 5.16. There is a small but significant difference at a harvesting power under 40 µW, where the central nodes have a lower delivery rate at a lower harvesting power. This is because there is a tendency for central nodes in the network to have a higher forwarding load due to the gradient to hub metric usage, as well as the retransmissions required to reach the intermittent hub for upwards data.

Second, the sending nodes can be grouped by their distance from the destination nodes. This can verify that the packet delivery is not just from nodes that are a short distance from the destination, but that there is consistent delivery across a range of hops. However, due to the larger number of hops required with the Magno radio, there is a significant reduction in delivery rate over multiple hops. The destination

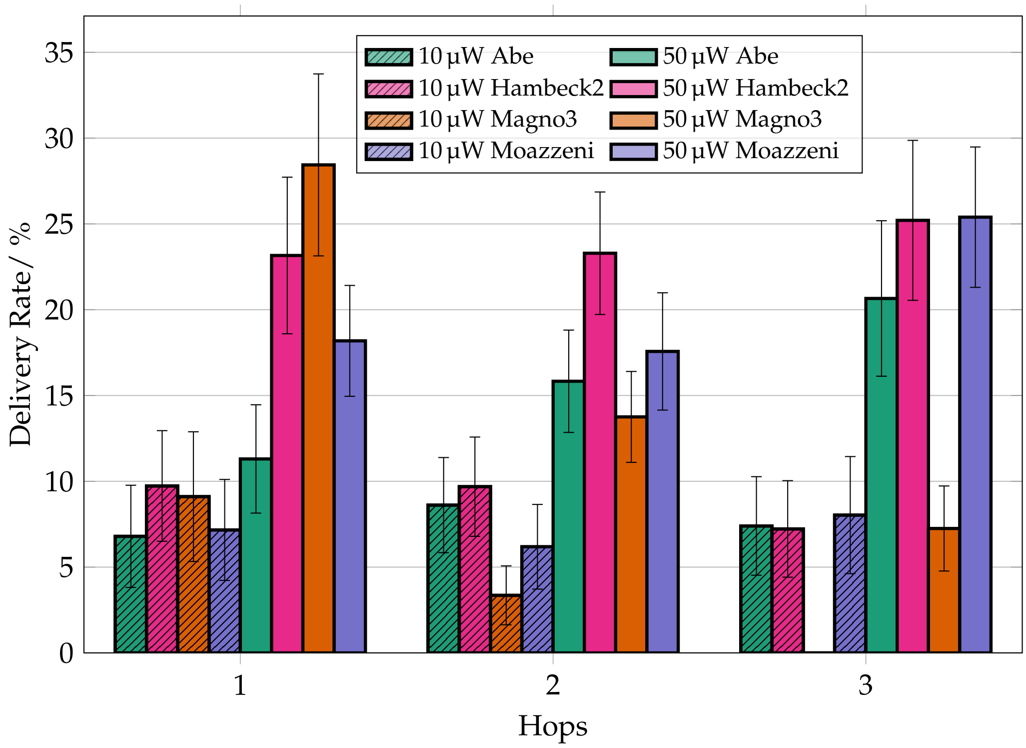


FIGURE 5.17: Delivery rate to nodes 111 and 141 over increasing hop distance based on Moazzeni range, uncertainty bounds show 90 % confidence interval around mean. Load interval of 120 s and hub EH of 100 µW. Two different harvesting power levels of 10 µW to 50 µW are used.

nodes appear in several vertical pairs, separated by 2× the node spacing, and combining the results from two destination nodes reduces the relative uncertainty in the result. The destination position is approximated to the position between the two nodes, and sending nodes are categorised by a measure of hops in reference to that position. The hop distance is defined by the range of a Moazzeni wake-up radio, which is 80 m or 4 node spacings.

The multi hop performance for two pairs is shown in Figure 5.17, first for destinations 111 and 141 which are close to the routing hub, second in Figure 5.18 for 161 and 191 which is over 1 hop from the hub. Again, the same hop distance definition is used.

Figure 5.17 shows that the Hambeck2 radio outperforms the Moazzeni radio, despite the range being shorter and fewer potential forwarders being available, however, as the range increases the Moazzeni delivery rate improves. Inspecting the delivery rate relative to hops also shows that the Magno3 delivery rate drops off significantly, whilst the Abe performance increases significantly at the 50 µW scenario. This is probably because the central nodes are wasting energy overhearing the outer nodes, due to their proximity to the hub.

Considering a pair of destination nodes further from the hub with 161 and 191 in Figure 5.18, whilst over 1 hop, the Hambeck radio performs the best, surprisingly the

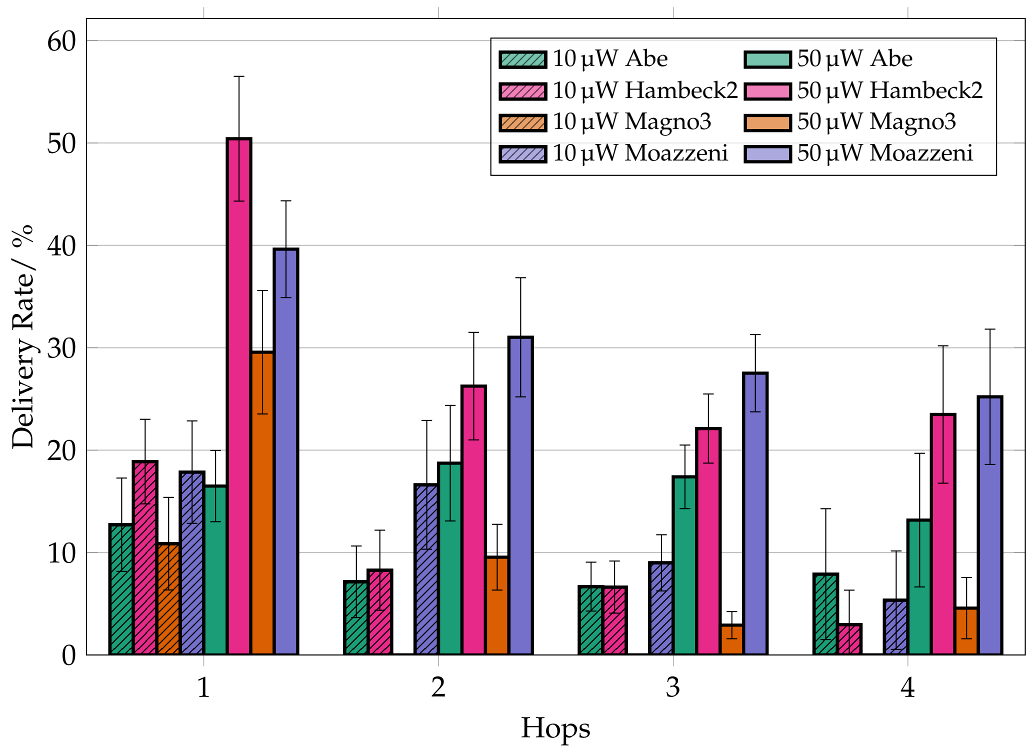


FIGURE 5.18: Delivery rate to nodes 161 and 191 over increasing hop distance based on Moazzeni range, uncertainty bounds show 90 % confidence interval around mean. Load interval of 120 s and hub EH of 100 µW. Two different harvesting power levels of 10 µW to 50 µW are used.

Moazzeni radio, with higher power consumption performs better over a larger number of hops. The Abe radio shows fairly uniform performance across the entire range, where there is no poor performance for close nodes because the destinations are further from the hub. In the case of the Magno radio it completely fails at 4 "Moazzeni" hops in the 10 µW scenario and shows a general large decrease in delivery rate for both harvesting power levels over each hop, like in the inner destination scenario.

The general delivery rate for the variation in load interval follows the similar trend for all hop distances as in Figure 5.15, where the delivery ratio decreases as the load interval decreases.

5.5 Conclusions

To address the need for multihop communication in Intermittently-powered networks, this chapter first addressed the problem caused by intermittency to existing multihop routing protocols. A consistent network layout was simulated in the OMNeT framework to provide a comparison between all the configurations, using a grid of 15x15 nodes. The initial comparison between RPL and ORPL investigated how intermittency affects the packet delivery rate in a multihop network with data routed to a central sink. Given the same radio output power, sensitivity and power consumption, the comparison demonstrates how the opportunistic approach can dramatically outperform conventional RPL in an intermittent scenario.

Incorporating the work in previous chapters, studying the capability and power consumption of WuRx, demonstrates the inter-operation with ORPL. Particularly, simulating the large network enables comparison of the benefits of the increased range in a multihop scenario and also considers the effect of interference and the delays and costs of medium access. When considering downwards routing to a powered hub the highest delivery rate is seen for the highest sensitivity radio. When the hub is fully powered, the longer the range of the radio, the higher delivery rate, where instead the performance is dominated by the cost to transmit messages from the EH powered edge nodes.

However, the consideration of downwards routing has demonstrated that when the end node duty-cycle is reduced by the increased energy required to listen, the resultant delivery ratio is substantially lower. Whilst the Abe radio performs marginally better for downwards routing, this comes at a cost of half the delivery rate of the Moazzeni radio and would be a preferred solution. The shorter range radios also result in a better performance in upward scenarios when there is a partially powered hub. Accommodating the need for downwards routing is important so that the network layer can provide full point to point routing to the transport layer above it.

Whilst the delivery ratio using ORPL shows a lower maximum success when fully powered, the implementation has demonstrated its suitability for Intermittently-powered networks. Furthermore, it achieves consistent performance across multiple hops, so long as sufficient forwarders are provided, and WuRx are able to effectively reduce the required consumption even further.

6
Conclusions

Central to very low power wireless sensor networks (WSNs) is the need to communicate with all nodes to exchange data, reconfigure nodes and adapt to the environment. With growing numbers of Internet of Things (IoT) networks, networking and communication methods are required to ensure nodes can still operate without battery sources, and only on small energy buffers recharged from energy harvesting (EH) causes challenges for conventional networking. The analysis and simulations from this thesis investigate whether useful multi-hop performance can be achieved and how opportunistic routing and wake-up receiver (WuRx) help to enable this.

In this thesis I have covered aspects of communication technologies for intermittently-powered devices. There are existing solutions that would benefit from removing the need for batteries, replacing them with purely EH devices. Additionally, without EH networked devices, many of the envisaged IoT applications will not be possible due to the environmental and financial impact of batteries, and the inability to deploy fully powered infrastructure in application settings.

Intermittently-powered devices using intermittent computing (IC) need some way to communicate with only very limited energy storage. For this, WuRx are a good solution to minimize the energy consumption of listening and increase the availability of a node to receive messages. Meanwhile, although it is possible to fully power nodes from the radio frequency (RF) energy of a neighbour, the dispersion of RF energy from the transmitter means this is wasteful. The case study on node types demonstrates that the cost of this would be too high and instead it is beneficial to use a very small amount of stored energy to hugely increase the sensitivity, and reduce the energy buffer size required at the transmitter. Whilst there may be future advances in low power reception, these would need to come a long way to be suitable in a homogeneous environment. Instead, they are possibilities when there is a fully powered coordinator node. In the homogeneous environment, nodes which utilize low power or completely passive RF EH to wake-up a device from its own small energy storage are most viable for a homogeneous environment. The wake-up remains relatively short, so does not consume a lot of the transmitters energy, whilst simultaneously, the power required from the listening node is acceptably small.

Harnessing the benefits of WuRx, I further investigated the real time allocation of harvested energy. Given the fixed hardware once a node is deployed, such as the EH source, small energy buffer and receiver radio is very important to maximize the communication capability. If there is no cost to the receiver's stored energy for each wake-up, I demonstrate that splitting the energy equally between transmitting and receiving, by limiting the number of transmissions, maximizes long term goodput. When the receiver must use a small amount of stored energy for each wake-up the optimum load is reduced to reserve some energy for wake-ups. If no adjustment is made for the false wake-ups then the achievable goodput drops by up to 20 % for the dense deployments modelled. From the analytical model I was able to easily test a wide variety of transmitter and receiver power consumptions, and the optimum combination significantly outperforms simplistic situations of shifting the burden to the transmitter or receiver. Hence, it is important to specify the hardware of the devices with respect to the energy harvested and expected node density to achieve the best performance as well as ensuring runtime energy allocation is correct.

Following this, I study the suitable range of transmitters by studying the available transceiver characteristics. This shows that the efficiency of the radio at low RF output power makes low power transmissions inefficient in transmission, and at very high power wasteful in radiative losses. The balance of these losses for the available transceivers, to reach the most neighbour nodes at the lowest per neighbour cost, is at around 10 dBm to 15 dBm output power. Beyond this output power, the efficiency gains at the transmitter are less significant than the dispersive losses of the RF signal. Incorporating this into the multiple neighbour scenario, with varying densities shows that maximum Goodput is consistently with a higher output power, where the WuRx must be chosen to achieve sufficient range, where to achieve highest Goodput, the WuRx should be appropriate for the density.

Given what this analysis showed about the potential performance differences between WuRx hardware and the benefit demonstrated from high power transmissions, further investigation was required to include network effects. For this, I have implemented an opportunistic routing protocol in order to compare the performance against conventional routing and multihop routing. The simulation allows for comparison of the protocols under the same energy conditions, and across much larger scales than practical implementations. The simulations compare a large network where nodes have radios that enable them to reach several neighbouring nodes as well as the potential for single hop transmission. The focus of these simulations was to determine if the opportunistic protocol, opportunistic RPL (ORPL), is suitable for intermittently-powered WSN.

First the problem with the conventional collection protocol routing protocol for low power and lossy networks (RPL) was demonstrated, where intermittency causes a complete collapse of multihop communication. Despite RPL having a mechanism to recover from a parent failure, it is ineffective when nodes have small energy storage and when the parent selection process causes a large amount of address resolution protocol (ARP) requests. Conversely, the results of a like for like network of ORPL nodes demonstrates that when nodes are intermittent, the delivery ratio is consistent up to half the EH level of the RPL scenario. This comes at a cost of overall delivery ratio which is lower when fully powered and which is more severely impacted by higher load, due to the longer acknowledgement period and potential for a higher numbers of retransmissions with multiple forwarders.

An additional benefit of the OMNeT network simulation is the ability to model the array of parameters that exist with WuRx. Whilst previous performance comparisons considered the sensitivity of WuRxs and the resultant cost of transmitting to them, it could not incorporate the datarate, preamble time and precise data radio consumption as well as node addressing differences. After selecting several wake-up radios (Abe, Hambeck2, Magno3 and Moazzeni) over a range of power consumption and sensitivities, a clear difference in performance was identified.

Firstly, when only considering upwards routing to a hub, the highest performance is achieved with longer range, lower power devices. However, when the routing hub has limited EH, instead it becomes beneficial to use a shorter range radio, and utilize multiple hops, especially when the data rate is lower. Secondly, to meet the need of future IoT networks, routing between nodes was investigated across the same 4 WuRx. In this scenario the longest range radio (Abe) performed worse than two lower range but also lower power alternatives (Hambeck2 and Moazzeni). These devices enabled a higher duty cycle of the intermittent end nodes, but also provided enough range to maintain consistent multhop delivery. At the extreme end of reducing power consumption was the Magno3 WuRx, which further reduced the energy consumption, however the small range meant that so many hops were required, each requiring higher power transmissions, that the overall performance was lower in the density of network that was analysed.

In this thesis I have demonstrated that intermittently-powered mesh networks can communicate effectively, without the need for a fully powered hub. By analysing, the energy consumption precisely within the context of an active network the benefits of using low power WuRx have been demonstrated, and ORPL has been shown to be able to communicate over multiple hops of intermittent devices. This proven capability of multihop routing in intermittent networks opens up future avenues for investigation with many WuRx combinations, a range of different densities and application specific performance evaluation.

6.1 Future Work

Since the investigation of communication in intermittently-powered networks was primarily concerned with proving multihop viability, there remain some performance considerations that could be analysed and presented. This could include packet duplication rate, false wake-up energy consumption, causes of packet loss and packet latency. To further improve the performance of the protocol different layered components can also be improved.

The investigation of the ORPL showed across multiple hops there was a certain amount of packet loss at each hop. Therefore the medium access control (MAC) protocol for opportunistic routing could be improved by improving the delivery and contention protocol. Initial experimentation would need to assess what the issues are that reduce the delivery ratio. Some theoretical causes are duplication causing unnecessary energy consumption, hidden nodes contention problems where two nodes interfere with each others acknowledgements and too conservative forwarding set selection that ignores closer nodes that make some progress in energy scarce scenarios.

Additionally, timing improvements could be made to the data transmission and contention periods, which are independent of the WuRx. This would require some redesign of the MAC protocol to adjust listening durations dynamically for long packets and also where retransmissions due to contention could be dramatically shortened to just the header information. These timing improvements would have a two fold effect, reducing the power consumption due to the data radio being active and also reducing the amount of time that the medium is occupied. These timing savings need to be made with sympathy to the range of forwarding contention nodes that there may be, according to the range and availability of radios.

Considering the implementation ORPL protocol itself, the main deviation from the initial publication is the adaptation of the metric calculation. Whilst this calculation allows intermittent routing to take place, the calculation has not been rigorously optimized. The space for optimization could include: metric update rate, weighting of encounters, and how the downward node EqDC values are combined. The metric calculation is stable, however its reactiveness could be improved by these optimizations.

Additionally, there may be potential for some performance improvements by more efficient routing and forwarder set selection.

Lastly, but importantly, other protocols to improve performance could be considered. This includes, using a different metric for the opportunistic routing for WSN (ORW), using multiple hubs, to reduce the number of hops or using an all together different routing method. Any protocol changes should keep in mind the limited memory resources of IoT devices and also should maintain the limited energy resources provided to EH nodes. This can also extend to the transport layer, where the possibility of transport level acknowledgements can be investigated. Current packet delivery rates are not high enough to support TCP, however there may be other alternatives that could provide a transport layer service.

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