Mesh Networking for Intermittently-powered Devices: Architecture and Challenges

Edward Longman, Oktay Cetinkaya, Mohammed El-Hajjar and Geoff V. Merrett

Abstract—**Recent advances in low power computing enable energy harvesting (EH) powered devices, even in energy scarce conditions. This reduces the reliance on batteries in Internet of Things (IoT) devices, reducing the cost and enabling new application domains. However, the energy scarcity requires devices to operate *intermittently*, with minimal stored energy and where the high-cost radio frequency (RF) communication dominates the power consumption, so transceivers are disabled most of the time. For deployment in challenging environments without high capability neighboring devices, a peer-to-peer topology for intermittently-powered devices is required. To remove the requirement for high capability devices, we categorize four receive types harnessing RF power transfer for a wake-up from other intermittently-powered devices. This mesh networking of homogeneous nodes could enable applications where high power coordinators are undesirable or impossible. In this article, we identify the cross-layer challenges of mesh networking with intermittently-powered devices and we describe the node receiver hardware required for peer-to-peer networking with intermittently-powered devices. We conclude with a case study of transceiver power consumption in this context.**

Index Terms—**Energy-harvesting networking, Harvest-then-consume, throughput maximization**

I. Introduction

Autonomous sensing and long term connectivity is a key requirement of many Internet of Things (IoT) applications, where device numbers are expected to grow considerably [1]. 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 structural health monitoring, low rate feedback control, and infrastructure management [2]. Ambient EH sources, such as mechanical, thermal, and radiant energy, can be exploited to create electricity, so energy storage is replenished without human intervention.

Most EH sources have high variability, such as a kinetic harvester on animals, and may produce orders of magnitude less energy than is consumed when active, like thermo-electric generators producing 100 µW for a low-power microprocessor consuming 5 mW [3]. 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 energy. Specifically, intermittently-powered devices do not have large battery storage like most EH systems, so spend a large proportion of time off with short operating bursts. Intermittent Computing is needed to ensure computation can make progress despite energy and storage scarcity. It does so by splitting large computation tasks across consecutive power cycles [4].

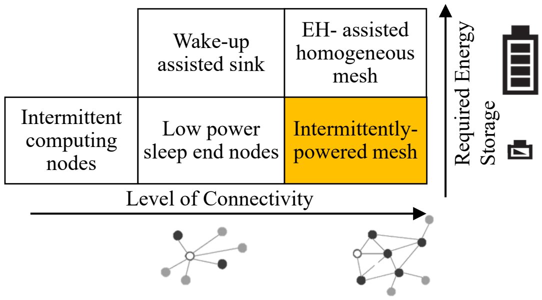

Fig. 1. Topics in EH computing and low power networking domains. Current networking is limited to star networks with low power end nodes, but high capability hubs. Otherwise, end nodes require increased storage for mesh networking or low power sleep hubs. This paper, highlighted in orange, proposes mesh techniques for EH devices without large energy storage.

However, in addition to computation, devices need to communicate their results and receive updates from other devices. This requires networking solutions that allow connectivity to be maintained with intermittent devices, in spite of the large proportion of time they spend off. Typically, to maintain connectivity, nodes use a large secondary energy storage source or increase the energy harvester size. However, the foreseen scale of IoT networks [1] motivates using the simplest devices with nearly zero energy storage and small harvesters, while still being resilient to power failures.

A particular communication problem is the point-to-point link between intermittently-powered devices, where existing solutions rely on a centralized entity/coordinator communicating with a low power receive node [5], [6]. However, this higher capability node contradicts the need for autonomy as it needs large energy storage and higher power energy source. In addition to power restrictions due to energy availability/storage, it is beneficial to reduce such reliance on infrastructure. Hence, in this paper, we focus on homogeneous mesh networks, which can enable the high degree of autonomy demanded by IoT applications for distributed computing and pervasive sensing [7].

Fig. 1 shows that intermittent techniques in the bottom row allows devices to operate with a tiny energy storage buffer. The higher capability networks in the top row require end nodes to have larger energy storage. For a wake-up

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assisted star network, nodes still require large energy storage to consistently send wake-ups, but require fewer retransmissions. For mesh networks, large energy storage ensures nodes are active and stay synchronized. Similarly, low-power sleep nodes still need a high capability device to synchronize them or provide a carrier in backscatter communications. This work, highlighted in Fig. 1, brings a mesh networking architecture to intermittently-powered devices without large energy storage.

In a homogeneous mesh topology, equal capability devices are connected to their immediate neighbors and when devices transmit messages, they are forwarded through the network by hopping between peer devices, termed nodes. Nodes in the network can operate without the need for higher capability coordinators used in star networks. Instead, depending on the location of the source and destination and the availability of intermediate nodes, the route taken by data varies widely.

Intermittency poses several cross-layer challenges to mesh networking, since timekeeping is impossible across power outages, consecutive transmissions are limited due to the small energy storage and the routes change dynamically, based on instantaneous forwarder availability. Such challenges have limited adoption in always-on networks [8] or intermittent nodes with star coordinators [5], [6].

The contributions of this paper are:

- We identify the cross-layer challenges that need to be overcome to realize intermittently-powered communication, exploring the shortcomings of existing approaches from other domains;
- We propose a device-to-device architecture for intermittently-powered nodes which can enable previously unachievable intermittently-powered mesh networks;
- We explore four potential receiver configurations for this architecture, and analyze the suitability of currently available hardware to realize them;
- We identify the technology barriers hindering the realization of the receiver types, and explore the future research required for fully intermittently-powered networks.

II. MESH NETWORKING CHALLENGES WITH INTERMITTENT NODES

To ensure routing is possible, the cost of transmitting and receiving must be less than the available energy for intermittently-powered nodes. Existing research for 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 [6]. From a whole network perspective, techniques are introduced to dynamically spread the load according to the EH and residual energy stored in nodes [9], where data is routed around or away from nodes with lower energy reserves, therefore reducing the EH power required. However, when nodes are intermittently-powered, there are challenges which these existing methods cannot handle, described in the following sections.

A. End-to-end Route Variation

When sending data over more than a single hop in a network, the best route to send data depends on the availability of nodes between the end points. Therefore, because the available intermittent nodes are constantly changing, predetermined routes between nodes are not feasible. In order to adaptively find the best route in the dynamic conditions, there are two main existing approaches, Proactive and Reactive routing.

Proactive protocols maintain a list of known forwarders to the destination node, and then upon receiving a request it chooses a forwarder, and then if unsuccessful it can try some other forwarders. The proactive approach requires more route maintenance to determine the best routes, which is not a good use of energy in low rate networks that we consider. Additionally, with intermittent nodes, when trying forwarders there is a low chance of success since the proportion of time nodes spend on is small, so there has to be many retransmissions.

Reactive protocols generate routes ad-hoc by flooding the network with route request packets. However, intermittent nodes mean routes have a very short lifetime. Therefore, in the process of finding a route, node energy buffers are exhausted thus breaking the route. When a route request occurs messages must be transmitted to try and reach the destination, but due to the energy consumed for each route request, the exhausted nodes then become unavailable when the data is transmitted.

This is the main challenge of routing with intermittent devices, where current proactive or reactive routing protocols do not meet the requirements of intermittent networks, and the difficulty is compounded by delays when nodes harvest energy before transmission. This results in sub-optimal routes being chosen because the first receiving node may not be available to transmit until later than other potential forwarding nodes.

B. Low-power Point-to-point Communication

Additionally, very low power link protocols are required to reduce the medium access control (MAC) power consumption for low data rate scenarios [8], 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.

One of the most significant effects of intermittency on networking is the inability to use scheduled MAC protocols [10] 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 use synchronization to only listen in scheduled slots. 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 neighbors. 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 [11].

Alternatively, unsynchronized methods must be used but recognizing this cannot be using conventional listening methods. Wake-up based communication is a promising candidate,

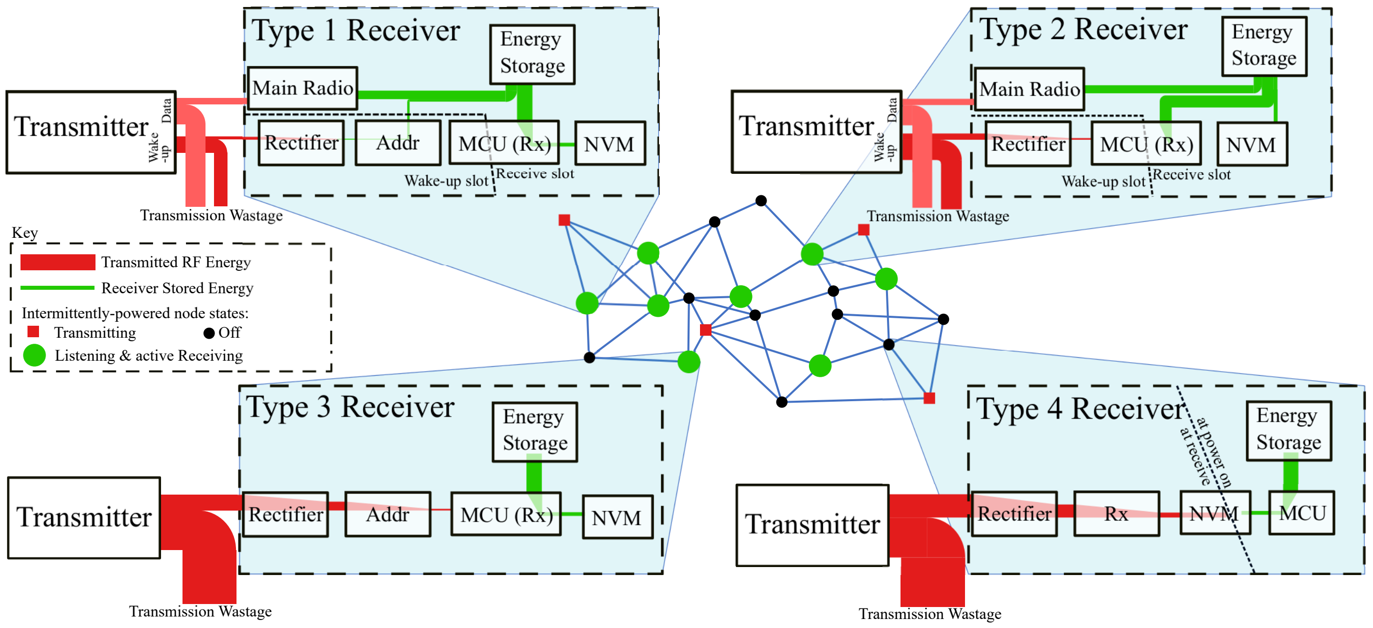


Fig. 2. Energy flow from transmitter radio and receiver energy storage in a network of intermittently-powered nodes, showing four types of receiver with different receive chain blocks. Energy consumed during the wake-up and receive in separate time slots are indicated by a dashed line within the node. The energy flows are not to scale and different receiver types would not coexist within the same network.

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) Does using higher range (and power consumption) receivers or transmitters outweigh the reduction in duty cycle for the mesh networking nodes, given they receive *and transmit* messages. All of these require optimization based on the density of the nodes, channel characteristics, hardware size limitations etc.

C. Intermittently Hidden Routes and Devices

A further challenge affects network layer message forwarding, dependant on the destination and network model it holds, where nodes may be unaware of other nodes that have already received the message. In order to propagate a message to a destination, the intermittent nodes must balance the delivery probability with the cost of transmitting too many duplicates.

With conventional 'always on' networks, the most naive 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 highly wasteful of resources since the message will be forwarded to completely irrelevant regions of the network. Nodes exchange control information to manage this by establishing accurate records of neighbors 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. This motivates cross-layer networking methods that *do not rely on predictable route availability* and can overhear messages.

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, since for other hops the data only has to make progress. At the final hop, 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 neighbors may be hidden when transmissions occur.

Additionally, where reception is successful, cross protocol communication is required to enable MAC overhearing. This allows intermittently hidden co-forwarders to neutralize queued forwarding messages with implicit acknowledgment.

In response to all these challenges, we propose four receiver types for intermittently-powered mesh networking nodes allowing for data reception in scarce EH conditions for effective network operation.

III. PROPOSED COMMUNICATION TYPES IN INTERMITTENTLY-POWERED NETWORKS

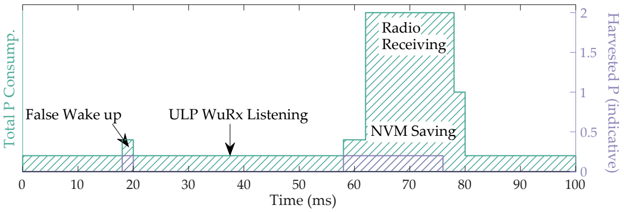
In order to enable communication when nodes have limited EH sources causing intermittency, we propose an architecture of passive reception to non-volatile memory (NVM) for processing or forwarding. We consider four candidate receive types for this architecture, where types are applicable to the same EH and traffic conditions. Currently unviable types may become viable with technology advances and depend on the operation of emerging cross layer routing protocols.

We first describe the generic topology of an intermittently-powered networked node, then for each type, using the illustrations in Fig. 2, we show how the energy burden of communication is shared between the transmitter and the receiver. The address decoder (Addr) block allows filtering of wake-ups, all receivers have NVM into which data is saved for later processing in the microcontroller unit (MCU). This compares using a small amount of the receivers stored energy in Type 1 with solely consuming received radio frequency (RF) energy in Type 4. The energy flow to each block is significant since it determines how long a node can listen from its small energy storage and how much energy must come from the transmitted RF energy.

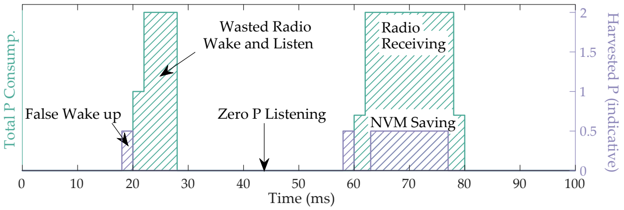
Nodes consist of a microcontroller powered from a small fixed capacity energy storage device, topped up by an energy harvester. The energy is used to listen and allow forwarding when there is enough energy stored. A node has a conventional radio, used for transmitting data packets and wake-up signals, and can be used as a high capability receiver, but at higher power consumption than alternatives. Nodes require different receiver hardware for each communication type, with active reception requiring stored energy, as in Fig. 3, or fully passive data reception with simultaneous wireless information and power transfer (SWIPT) possible with no stored energy. Optionally a passive or very low power radio wake-up source can aid active reception. We review the available hardware for wake-ups and SWIPT further in the next chapter.

We consider the operation, power consumption and receive sensitivity of these communication types below:

- **Type 1 - Selective Wake-up with Active Data Reception**: 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 time 18 ms in Fig. 3a. The WuRx is powered from a small energy reserve that the node has saved for listening. This small energy reserve also powers the node once it has received a wake-up signal for the receive event, as at time 58 ms in Fig. 3a. The receiver sensitivity to wake-ups is −40 dBm [12].
- **Type 2 - Passive Unselective Wake-up with Active Data Reception**: The entirely passive device, (consumes none of the receiver energy reserve), provides a wake-up from received RF energy. Therefore, 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 are powered by the energy reserve as shown by Fig. 2. This can currently be achieved using a rectifying antenna (rectenna) to detect activity in a certain frequency band and has a sensitivity of −15 dBm [13], but the node will still have to turn on the whole radio for false wake-ups like at time 18 ms in Fig. 3b.
- **Type 3 - Passive Reception with Active Storage**: The node wake-up is from an entirely 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 Fig. 2. The passive WuRx would be able to decode the address in case of a false wake-up wasting NVM energy consumption.



(a) Type 1



(b) Type 2

Fig. 3. Power consumption of receive types using separate wake-up and data transmissions to enable listening, using WuRxs or rectennas, in intermittently-powered nodes from minimal stored energy.

- **Type 4 - Passive Reception and Storage into NVM**: The node can passively receive data and then the data can be stored in the NVM, while only consuming the incident RF power as in Fig. 2. False wake-ups are negligible given a large enough NVM because the cost of computation to process the irrelevant messages is small compared to normal receive decoding. This is effectively SWIPT, and is discussed more in the next chapter.

We illustrate the configurations of these technologies to form different communication types in Fig. 2, to show how energy burden differs between the receiver in Type 1 to the transmitter in Type 4[1]. The energy for processing and saving to NVM in passive receive Type 3 and Type 4 comes from the transmitter. Due to the broadcast nature of radio transmissions, only a small proportion of the transmitted energy can be harnessed by the receiver, shown by the transmission wastage in Fig. 2. Alternatively, for Type 1 and Type 2, the receiver has very small power consumption for idle listening and wake-ups (including false wake-ups), shown in Fig. 3. This reduces the transmitter energy consumed for each transmission and the transmitter energy storage required, an important physical consideration.

IV. EXISTING TECHNOLOGY ENABLING INTERMITTENT COMMUNICATIONS

To implement the types described in Sec. III, we consider available physical, MAC and network layer techniques that enable the mesh communication architecture between intermittently-powered devices, by extending the listening time and utilizing the broadcast medium.

A. Physical layer wake-up techniques

The first approach to wake-up a node for Type 1 and 2 is with WPT from a more capable node, known as the

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[1] The SWIPT model and channel state estimation has been discussed previously by Bi et al. [13] and is out of scope for this article.

initiator [13]. By using the WPT from the initiator, a node with a passive rectenna can trigger an interrupt to wake-up and start listening. The rectenna converts the RF power into a DC signal combining power and data. After the power signal, the node is now active, i.e., *on*, and the main radio can communicate with a low power transmission. However, this requires a large enough energy buffer to wake-up a main radio at the receiver.

A solution to this issue is SWIPT, where the sink delivers energy and data at the same time, using the same signal [13], as in Type 3 and 4. SWIPT can reduce the power consumed at the initiator by limiting the number of transmissions to one while enabling the receiving node to match its active period without an idle listening cost. In so-called *backscattering* [14] the nodes with passive radios, can reflect their data such as an acknowledgment backed by changing their antenna impedance. Despite the promising advantages, SWIPT has several drawbacks, including the following, accurate channel state information is required so that the node can dynamically switch between information decoding and EH units. Also, whilst there is only a single transmission, it uses more energy to transmit since the bit rate is lower and the receiver is low sensitivity, thus again requiring increased energy storage.

Both wake-up methods and SWIPT consume the power of the incoming radio waves to generate a signal to wake-up the receiver or store data. Despite their simplicity, rectennas are prone to false wake-ups since any ambient signal propagating at the same frequency band may unintentionally wake the node up [4]. As an alternative to the fully passive methods, i.e., rectennas and SWIPT, WuRx adopt a preamble detection mechanism, used in Type 1 and 3, which also performs address checking. In general, it detects the signal sent by the initiator, and thus the node only wakes up when intended. Despite allowing ultra-low-power (but continuous) passive listening it increases the cost and complexity of the node. Furthermore, WuRxs still only offer low data rates and have low sensitivity compared to a main receive radio.

Depending on the specific requirements, applications can benefit from one or a combination of the above-mentioned solutions. Yet, these are not enough by themselves where novel MAC protocols should be developed for further reducing the power consumed by the wake-up methods.

B. Wake-up assisted MAC layer protocols

Existing MAC approaches can incorporate wake-ups, and optionally perform cross layer forwarding requests as in Fig. 4. They are either receiver initiated (RI) or sender initiated (SI) (also called transmitter initiated) denoting which end of the link initiates communication. Previous work presents both RI with On-Demand LoRa and SI with Wake-up MAC (W-MAC) methods [8]. However, the RI method is only used where an always-on transceiver can enable the entire network or address specific nodes, as in Sensor Network MAC (SNW-MAC) [6].

For the communication types described in Section III, RI based protocols are only viable for Type 1 and 2, where nodes have enough energy stored to transmit when a wake-up is received. With low data rate communications, RI methods have many unanswered initiation requests, so it is more wasteful than SI. Conversely, with SI methods many transmissions are ignored (from listening neighbors) if the forwarding neighbors are off. However, SWIPT nodes can receive even when off, but the required transmit power is high, so the transmission range and rate are limited by the transmission cost.

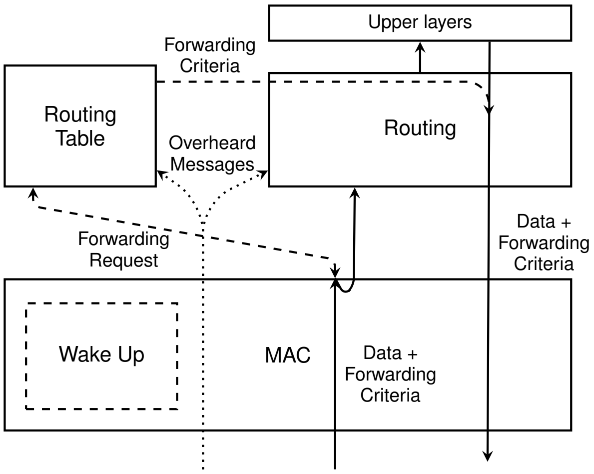

Fig. 4. High level cross layer protocol stack for intermittently-powered mesh networking. MAC protocols communicate with the routing table before accepting (flexible) forwarding requests, or selecting a forwarder and the routing layer is able to overhear messages as an implicit acknowledgment.

Another important consideration is the ability to overhear relevant messages for immediate neighbors, addressing the challenge of intermittently hidden devices. This requires co-operation with networking protocols, to enable acknowledgment of successful forwarding via unconventional means, like overhearing a subsequent broadcast of the same information, as shown in Fig. 4. Overhearing is improved by the receiving Type 2, 3 and 4, but is not possible when using generic address decoding WuRxs in Type 1. MAC overhearing of messages is particularly significant for Type 3 and 4 since the receiver cost is small, and it can reduce future transmissions.

C. Networking overview

To combat the challenge of varying route availability, opportunistic routing (OR) uses selective broadcasting, where a transmitting node sends data with a final destination marker and receivers decide whether the data will make sufficient progress if stored and forwarded. However, almost all OR protocols only consider time-slotted MAC protocols, designed to reduce overall listening by synchronizing the radio between nodes, instead asynchronous approaches must be considered. In previous work [10], [12] convergecast routing has been used but neither harnesses so-called “gossip”, the overhearing of forwarding or acknowledgments, to reduce retransmission and forwarding.

In addition to the MAC layer overhearing messages, it is important to overhear control messages for the routing table, shown by the dotted line in Fig. 4. Furthermore, the MAC protocol should interact with the routing layer to dynamically choose forwarders based on instantaneous information, as shown by the dashed line in Fig. 4. This is essential to enable the instantaneous flexible routing demanded by intermittency, where a transmitter cannot reliably know the next hop.

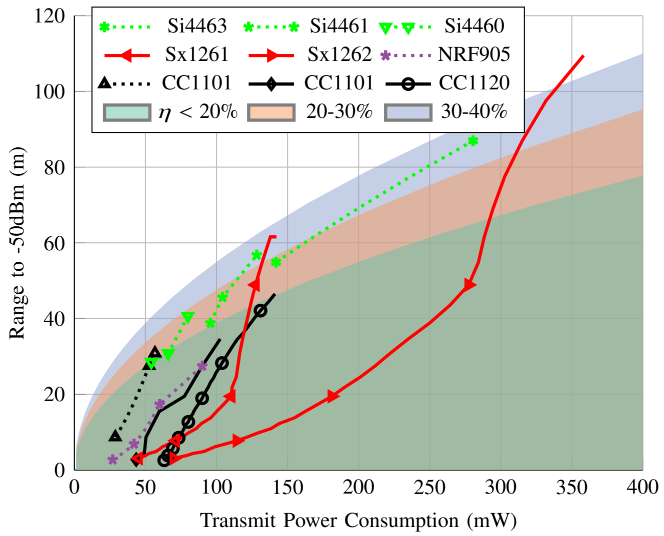

Fig. 5. Radio range of off-the-shelf transmitters to fixed receiver sensitivity of −50 dBm against a background of transmitter efficiency regions in % (η). Differing radio consumption values shown for Silicon Labs (Si), Semtech (Sx), Nordic Semi. (NRF) and Chipcon/Texas Ins. (CC) devices. As the power increases, the efficiency also increases, increasing the range growth rate.

V. HARDWARE IMPLEMENTATION CASE STUDY

Given the aforementioned hardware, in this section, we analyze the performance of the different receiver types. 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. As in Section III each transmission for management or forwarding messages subsequently reduces the time available for listening. Therefore, we analyze the power consumed for the high power transmissions required for wake-ups, where all mesh network nodes follow the same operation/transmission policy. Whilst all types are applicable to mesh networking, the power analysis helps determine which are realistic.

We have collated the power consumption of several low power 868/915MHz band radios for IoT applications in Fig. 5. This demonstrates how the range to a −50 dBm receiver 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 color in Fig. 5. This shows the advantage of higher power transmissions in spite of the increased radiative losses, allowing greater forward progress of data. For, 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. This is contrary to what happens with constant efficiency, like the colored bands in Fig. 5, or completely ideal radios. With constant efficiency, the power consumed is proportional to the forwarders reached, so lower power transmissions that reach fewer nodes but more selective forwarding would reduce wasted receiving energy consumption across the network.

Considering the node operation, it can turn on to transmit a wake-up signal and data packet or the node can perform other computing tasks then turn off everything but the WuRx, 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) remaining for listening, so a balance must be struck between more transmissions to attempt a higher success rate, and longer listening time for receiving data. In our earlier research [15], we show this is by equally splitting the harvested energy between receiving and transmitting.

Incorporating the mechanics of OR, the aim is to maximize the number of potential forwarding neighbor nodes. This increases the rate at which data makes forward progress towards the destination. However, increasing WuRx sensitivity to hear more neighbors decreases the listening time by the same amount [6]. For receive Type 1 and 2, this shrinks the effect of a passive WuRx. Instead, we see that optimal transmitter consumption is a more significant factor. With SWIPT in Type 4 there is a combined penalty of both 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 is larger without a significant increase in range, so there is a reduction in overall performance.

Receiver Type 1 and 2, therefore, currently show the highest potential since the initial transmission is very short and subsequent power consumption is $\approx \frac{1}{5}$ of what would be required for SWIPT, so more frequent transmissions outweigh the reduced listening. Receiver Type 3 may outperform Type 1 and 2 because it requires comparable transmission power comparable and does not have to wait for the main radio to start. 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. However, there are not yet any routing protocols that could adequately control the effect of not having instantaneous acknowledgments in Type 3.

VI. CONCLUSIONS AND FUTURE CHALLENGES

Anticipating the increase in IoT connected devices, and the need to power them from EH sources and without high power infrastructure devices, we have proposed four receive types for intermittently-powered nodes. Type 4 is the best solution for full intermittent communication, enabling forwarding to passive neighbors, but networks are impossible with present-day SWIPT technology, due to the large energy storage and resultant EH required to transmit. Receiver Types 1-3 are still sympathetic to the constraints of the homogeneous mesh architecture since they require less stored energy for transmission but still maintain very low power listening. The reduction in the energy storage required reduces time spent replenishing the energy, reduces leakage current and also reduces the device size. Based on our case study, Type 1 and Type 2 receivers are possible with existing technology. The best type to choose requires implementation and investigation of routing protocols that handle overhearing and flexible forwarding.

There remain several open research problems for implementing intermittently-powered mesh networking. First, adaptation of existing protocols is needed to enable flexible forwarding, handle delayed transmissions, and restart effectively after turning off. Forwarding is typically decided by the network layer as part of routing, however current protocols do not utilize indirect acknowledgment since the MAC layer will discard packets not addressed to it. This is a serious shortcoming in the envisaged mesh scenario where the intrinsic broadcast medium could be utilized. Additionally, the volatility of routing and neighbor information on shutdown should be carefully considered since retaining outdated information may lead to a false assurance of route availability. This motivates further investigation into cross-layer MAC and network solutions, and efficient use of NVM to hold messages until the transmission is available in consecutive power cycles.

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