Poster Abstract: Towards Robust and Scalable Battery-Free Group Communication

Jonas Kubicki
Technical University of Darmstadt, Germany
jonas.kubicki@tu-darmstadt.de

Marco Zimmerling
Technical University of Darmstadt, Germany
marco.zimmerling@tu-darmstadt.de

***Abstract*—Predictable and reliable communication in battery-free networks is an important milestone towards the adoption of battery-free systems. Previous work has mostly focused on neighbor discovery and two-node communication. Our ongoing work aims to push beyond the two-node case by enabling all-to-all communication within larger groups of neighboring battery-free devices. The goal is to facilitate synchronized, periodic radio rounds with all-to-all broadcasts between the nodes. Preliminary testbed experiments with our current protocol design demonstrate feasibility with 3 nodes. Further improving scalability and robustness of our approach is the focus of our ongoing work.**

***Index Terms*—Battery-free networks, energy harvesting, group communication, low-power wireless**

I. Motivation

Battery-free devices promise a series of advantages over traditional battery-powered solutions in terms of size, toxicity and maintenance requirements [1]. These advantages could even open up entirely new application scenarios that are otherwise limited by traditional batteries such as miniature mobile sensors or bio-absorbable medical implants.

Nevertheless, battery-free systems have yet to achieve widespread adoption. One of the major reasons is the highly variable energy availability caused by the combination of low-yield energy harvesting and small energy storage elements. This is a particular challenge for wireless networks of battery-free systems as it renders established communication methods ineffective. Some previous work in this area yielded *Find* [2], a protocol for neighbor discovery in battery-free networks and *Bonito* [3], a protocol for bidirectional communication between two battery-free nodes.

Our ongoing work extends the state of the art by enabling all-to-all communication among more than two neighboring battery-free nodes. Specifically, we report on the ongoing design, implementation and evaluation of a communication protocol that empowers neighboring battery-free devices to (i) form synchronized groups and (ii) exchange data in an all-to-all fashion in a completely decentralized way. Our approach, outlined in Section II extends upon *Find* and *Bonito*. Preliminary results from experiments on the *Shepherd Nova* [4] testbed, reported in Section III, demonstrate that our current prototype breaks through the limit of two nodes and achieves communication within a group of 3 battery-free devices.

II. Approach

We start with a brief overview of *Find* and *Bonito* before describing how we leverage and extend their core ideas.

Find and Bonito. Both protocols assume an intermittently operating system that tracks its own charge-time. *Find* enables neighbor discovery in battery-free networks. It delays the wake-up of the individual nodes according to a geometric distribution based on the current average charge-time. This significantly increases encounter probability, particularly in homogeneous energy environments. Like previous battery-powered protocols, *Find* uses a communication pattern that facilitates bidirectional discovery.

Bonito exploits the observation that the charge-times in different examined energy environments follow certain statistical distributions. The two participating nodes learn their distribution parameters independently at runtime. They can then exchange the learned parameters during neighbor discovery. Using both sets of parameters, they can independently schedule a rendezvous where both nodes will be fully recharged. During each rendezvous, the nodes exchange their updated distribution parameters along with application data.

Group communication protocol. To enable battery-free group communication, we address the following issues:

1) Orchestrating all-to-all communication in a group
2) Merging of multiple groups and individual nodes
3) Facilitating group discovery

We address the first issue by using a communication pattern where the radio phase is divided into a pre-configured number of slots. Nodes in a group are assigned a specific slot for transmission and receive in all other slots. Groups have synchronized radio phases and consistent slot assignments. By having each node include its distribution parameters in its transmission, all group members can calculate the next rendezvous time independently.

1	3	5	6	4	2

Fig. 1. Slot assignment order for 6 slots. The middle slots are filled last to enable bidirectional group discovery.

To address the second issue, we first facilitate bidirectional discovery between groups of nodes. We assign slots to nodes joining a group in a particular order as shown for 6 slots in

Figure 1. By starting from both ends, we keep the slots where the whole group receives clustered in the middle of the radio period. Thus, we can assume that if any group X discovers a group Y, group Y will also discover group X. In case of a single node, that node can dynamically decide to transmit again in the last slot to complete a bidirectional discovery. Merging the groups requires the latest distribution parameters P_i for each member N_i to schedule the shared rendezvous. By having each node transmit the parameters of its whole group, we ensure that receivers have sufficient information to perform the merge. Still, the first half of the later group can not yet know the updated parameters of its later slots, meaning half of that group can not be reliably merged. We use a heuristic to determine whether the merge operation will achieve progress towards the overall goal of unifying all nodes in one group. Figure 2 shows an exemplary merge of two groups with two members each. Since group 2 can not receive node 2's latest parameters, the latter will be dropped in favor of one group of 3 nodes. Node 2 can then be merged into the group during a future encounter.

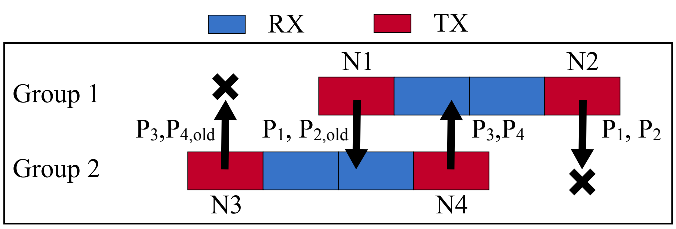

Fig. 2. Visualization of an encounter between two groups of 2 nodes each. Nodes 1, 3 and 4 exchange their latest parameters and form a new group. Since group 2 can not receive node 2's latest parameters, node 2 is dropped.

To facilitate the discovery between groups, we delay each rendezvous using *Find*'s geometric distribution. By synchronizing the pseudo-random number generator states of each node in a group, we ensure that the group agrees on a delay.

III. Preliminary Results

To demonstrate the feasibility of the protocol, we orchestrate a demonstration experiment on the *Shepherd Nova* testbed. We use the BLE radio of the nRF52-based testbed nodes for communication.

Experimental Setup. We use 3 nodes and configure a slot count of 4. The extra slot increases the probability of a single node's transmission falling into the receive-window of a group of two. We configure a static energy environment yielding a rather high harvesting power of $10\,\mathrm{mW}$ to keep the rendezvous interval manageable for the demonstration. We mark transmit and receive activity of the nodes using GPIO pins and use the testbed's GPIO tracing feature to record them.

Results. Figure 3 shows the results of the demonstration. In the beginning, nodes 1 and 2 are part of a group with node 1 transmitting in slot 1 and node 2 in slot 4. Node 3 starts off in a separate group. The highlighted part of the plot showcases the discovery and merge between the two groups. Node 3's transmission at $t = 29\,\mathrm{ms}$ falls into one of the empty slots

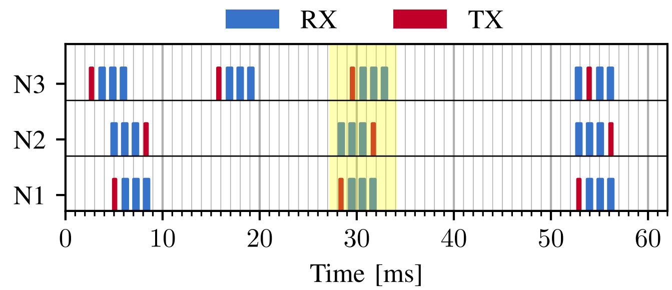

Fig. 3. Excerpt of an experiment with 3 nodes and slot count of 4. Nodes 1 and 2 start off in a group and encounter node 3 around $t = 30\,\mathrm{ms}$, forming a new group of all 3 nodes.

of the larger group. Subsequently, node 2's transmission at $t = 31\,\mathrm{ms}$ falls into a receive-slot of node 3, providing the parameters of both node 1 and 2. Thus, all nodes have the required information to schedule a rendezvous and the groups merge. We observe the first coordinated rendezvous of the new group at $t = 53\,\mathrm{ms}$ where node 3 occupies slot 2.

IV. Ongoing and Future Work

While our preliminary results demonstrate feasibility, several improvements are still needed before the protocol can be applied to larger, real-world single-hop networks. Our currently ongoing work focuses on two specific aspects:

Robustness. Currently, the loss of a single packet can disrupt previously synchronized groups. This is particularly relevant since distinct groups executing our protocol can experience collisions before having a successful encounter. These effects contribute significantly to the average time until all nodes in a network are unified in a single group.

Scaling. Currently, packet size scales with the slot count. Therefore, the maximum packet size of the radio limits the slot count and, by extension, the network size. Assuming $8\,\mathrm{B}$ of application data per packet, our protocol is currently limited to a maximum network size of 9 nodes.

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