Energy-Efficient Bootstrapping in Multi-hop Harvesting-Based Networks

Naomi Stricker
ETH Zurich
Switzerland
nstricker@ethz.ch

Jasmine Hora
ETH Zurich
Switzerland
jhora@student.ethz.ch

Andres Gomez
University of St.Gallen
Switzerland
andres.gomez@unisg.ch

Lothar Thiele
ETH Zurich
Switzerland
thiele@ethz.ch

***Abstract*—Short-range multi-hop communication is an energy-efficient way to collect, share, and distribute large amounts of data with Internet of Things (IoT) systems. Nevertheless, the resource demands of wireless communication impose a burden on battery-operated IoT nodes, limiting their lifetime. Energy harvesting can address the energy limitation but introduces significant power variability, which affects reliable operation causing nodes to disconnect and join the network repeatedly. To mitigate this, we present Dual-Range Bootstrapping (DRB), a new mechanism for bootstrapping harvesting-based IoT nodes in multi-hop networks. DRB has both a very low and predictable energy cost, key properties for efficient energy management of harvesting-based nodes. We demonstrate DRB's effectiveness in numerous scenarios using LoRa and FSK modulations, leveraging the former's long range and the latter's high data rate. We experimentally evaluate DRB with energy measurements performed on a communication testbed. Lastly, we use real-world energy harvesting traces to simulate the long-term behavior of a harvesting-based network.**

***Index Terms*—Indoor Energy Harvesting, Internet of Things, Multi-Hop Network, Synchronous Communication**

I. Introduction

The Internet of Things (IoT) envisions an ever-increasing number of devices exchanging data wirelessly. With multi-hop communication, nodes can leverage efficient short-range communication while relying on other nodes to re-transmit their data to bridge larger distances. Throughout the years, many multi-hop communication protocols have been proposed to support different traffic patterns (e.g. point-to-point, multi-cast, and broadcast) enabling numerous applications [1]. Such protocols include routing-based approaches where scheduling decisions depend on saved information about link qualities and network topologies, e.g. [2]. Other approaches build on synchronous transmissions that flood the network with data [3]. Many of these state-of-the-art protocols rely on central coordination to schedule the multi-hop network traffic, e.g [4].

Networks of battery-based IoT nodes have limited lifetimes which recent work extends with indoor photovoltaic energy. We consider scenarios where a network consists of harvesting-based IoT nodes and a central unit without relevant resource constraints. Indoor energy harvesting provides small amounts of energy with unpredictable temporal and spatial variability [5]. Harvesting-based nodes may therefore not be able to continuously support multi-hop communication and regularly need to re-join the network after recovering from power loss. When a node will have sufficient energy to re-join is difficult to predict, however, time synchronization is crucial in multi-hop communication [6]. Bootstrapping overheads to time synchronize and join a network need to be small, predictable, and exhibit little variability to enable nodes to efficiently manage their resources and operation.

One way to lower bootstrapping costs is to employ a wake-up receiver (WuR) to detect when relevant network traffic occurs. Despite WuRs' energy efficiency, this requires additional hardware components and is prone to trigger erroneous wake-ups which introduce variability in the bootstrapping overhead [7]. Another approach for time synchronization is to idle listen with the transceiver used for multi-hop communication until a network packet is received, e.g. [3], [8]. This can be inefficient since a node might need to idle listen for a full communication period, which could be in the order of minutes. It also results in highly variable energy costs as bootstrapping nodes can start listing at any point in time.

Recent transceivers support multiple modulation schemes thus enabling novel approaches where a single transceiver is utilized for different purposes with distinct communication requirements. In this work, we present Dual-Range Bootstrapping (DRB), a new mechanism for bootstrapping energy harvesting IoT nodes in a multi-hop network that leverages different communication ranges of a single transceiver. Bootstrapping with DRB has an extremely limited and predictable energy cost. An overview of DRB is depicted in Figure 1. A

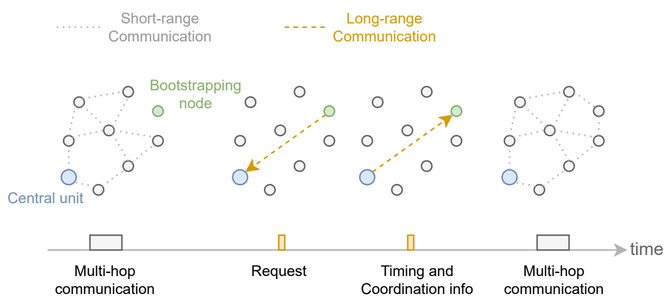

Fig. 1. Dual-Range Bootstrapping (DRB) overview. A bootstrapping node sends a request to the central unit. The latter sends network timing and coordination information, enabling the node to efficiently join the next multi-hop communication.

bootstrapping node first exchanges long-range packets with the central unit. Since the latter coordinates network traffic, it can provide information on when and how (e.g what channel) a node can join the network. With this information, a node turns off its radio, saving energy until the next relevant network activity for which it can wake up and thus efficiently join the multi-hop network.

Our contributions can be summarized as follows. We propose a new bootstrapping method, DRB, for energy harvesting IoT nodes. Compared to a single-hop and a multi-hop baseline, DRB increases the average data transmitted per node by leveraging a long-range packet exchange for time synchronization and short-range data transmissions. We furthermore experimentally measure the small and low-variability energy required for a successful bootstrapping with DRB. With long-term energy harvesting simulations, we demonstrate that a multi-hop network powered by indoor photovoltaics can bootstrap a few times per day and that DRB's energy cost characteristics are key properties for efficient utilization of a harvesting-based node's limited resources.

II. Related Work

Efficient bootstrapping to join a multi-hop network or coordinating when to communicate is essential for both battery-based and energy harvesting nodes. A number of different approaches have been proposed to address this.

Nodes can include additional hardware dedicated to continuously listening to network traffic, e.g. a wake-up receiver (WuR). Upon receiving a wake-up signal, a WuR enables the node's main transceiver with which it can then receive information about the network and join it. In a multi-hop network, nodes that have received the wake-up signal can retransmit it, allowing it to propagate through the network [9]. Since WuRs are not duty-cycled, WuRs have been proposed with ultra-low power dissipation, e.g. [7], [10]. Although these approaches can have low latency, WuRs are prone to erroneous wake-ups, e.g. [7] reports a false wake-up rate of $10^3/s$. The superfluous wake-ups of the main transceiver increase the bootstrapping energy cost. It also implies variability in energy requirement that depends on the number of false wake-ups. In addition, these approaches require each node to have additional hardware components such as microcontrollers and antennae.

Instead of relying on RF communication, methods have been proposed that utilize side channels and external events. In [11] wake-up signals are sent with visible light communication and an indoor solar panel acts as a wake-up receiver. The proposed method has a limited range and does not scale well to cover multi-hop networks. Temporal characteristics of external phenomena that nodes in the network are exposed to can also be leveraged for time coordination. In [12], nodes bootstrap to form a network based on correlated measurements of physical events. This method requires physical events to be sensed by multiple nodes and is thus only designed for event-based communication, which limits its applicability. In [13] solar-panel powered nodes bootstrap by exploiting temporal characteristics of imperceptible flickering in mains-powered artificial lighting. These changes in lighting conditions are observable with solar panels and provide the basis for efficient bootstrapping. However, nodes in indoor environments might be exposed to significant natural light [14] even when artificial lighting is off, thus limiting the applicability of this approach.

In a different approach, referred to as rendez-vous, nodes coordinate communication by periodically waking up to send, listen, receive, and acknowledge short communication packets with their main transceiver. Rendez-vous methods can be transmitter initiated, e.g. [15], [16], or receiver initiated, e.g. [16]. Both approaches require nodes to periodically wake up for communication coordination which introduces a variable energy overhead that is too costly for nodes with limited and varying energy availabilities. Furthermore, rendez-vous methods do not enable network-wide time synchronization which is important in efficient multi-hop communication.

Nodes can also bootstrap by listening with the main transceiver until receiving relevant network traffic [3], [8], [17]. Since the main transceiver is typically not as low-power as a WuR, this incurs a high and variable energy cost and is thus at odds with the efficient operation of energy harvesting IoT nodes. However, this approach does not require any additional communication dedicated to synchronization, and therefore the central unit and other energy harvesting nodes do not incur any significant overheads since they can keep their transceiver off when there is no traffic.

Bootstrapping is also necessary in time-synchronized single-hop networks for which more efficient approaches have been employed. LoRaWAN Class B [18] is a long-range synchronous communication protocol designed to increase downlink capacity by pre-allocating time slots according to GPS time. Gateways periodically broadcast beacons containing information about the network and/or gateway. An end-device can join the network by listening for one full period or by using the current GPS time to determine the next broadcast period. According to the LoRaWAN specification, gateways *may* assist end-devices by providing them with the GPS time via an asynchronous request [18]. This active join method for Class B networks is intuitively more energy-efficient than idle listening for a full period. However, due to the single-hop nature of LoRaWAN, all communication must use a long-range modulation scheme which results in a significant energy burden for time-synchronized communication.

In this work, we propose DRB, a novel method for energy harvesting nodes to efficiently join a multi-hop network. With long-range single-hop communication, energy harvesting nodes communicate with the central unit which provides them immediate access to the timing information of the (short-range) multi-hop network. With this timing information, nodes can join the short-range multi-hop network and transmit their data efficiently. DRB only requires a single transceiver and does not rely on external phenomena or a GPS signal for time reference. Nodes can nonetheless bootstrap requiring only a small and predictable energy.

III. SCENARIOS

Multi-hop communication protocols are found in various application domains. To efficiently support increased throughput or network sizes, multi-hop communication typically follows a schedule. We consider scenarios where the multi-hop network is centrally controlled. Thus the central unit, which schedules network traffic, knows when and how nodes can join the network. There are numerous communication protocols that satisfy these assumptions. Examples include TSCH [8] for which countless central schedulers such as MASTER [4] have been proposed. There are also protocols relying on synchronous transmissions that are centrally coordinated, e.g. LWB [3], [17]. In our considered scenario, a central unit is assumed not to have any relevant resource constraints, but the other IoT nodes are harvesting-based. This central unit can always maintain a (centrally) managed network, thus reducing the networking overhead for harvesting-based nodes. For most application scenarios, it is feasible to deploy a single energy-unconstrained unit managing an LPWAN.

A common architecture of energy harvesting IoT nodes follows the harvest-store-use scheme. A transducer converts primary energy into electrical energy which gets stored in an energy storage element, such as a supercapacitor, powering the application. These nodes can be modeled with a simple discrete-time model that has been experimentally validated [19]. Time is discretized into time intervals $t \in \mathbb{Z}_{\geq 0}$. The evolution of the energy storage's state of charge $b(t)$ is modeled according to

$$b(t+1) = \big(b(t) + E_{\text{harv}}(t) - E_{\text{used}}(t)\big)\Big]_0^B$$

where B is its capacity, $E_{\text{harv}}(t)$ the energy the node harvests and $E_{\text{used}}(t)$ the energy it uses during $[t, t+1)$. Nodes typically harvest limited and variable energy. In comparison to outdoor environments, indoor environments are energy scarcer, and feature variability that is more challenging to predict [20]. An excerpt of a harvesting trace recorded indoors [14] is depicted in Fig. 2.

In energy harvesting multi-hop networks, the non-deterministic harvesting characteristics imply that nodes may frequently run out of energy and leave the network. Furthermore, it is unknown and challenging to predict when nodes bootstrap and for how long they are able to join a network. Fig. 2 visualizes these behaviors. The depicted harvesting trace is insufficient for a node to sustain communication continuously. When it has energy to communicate is dictated by its local environment. To nevertheless efficiently use the harvesting-based node's limited resources, the bootstrapping mechanism needs to be energy-efficient and have a predictable energy cost. The latter is important for a node's energy management. Moreover, in multi-hop networks nodes rely on other nodes for forwarding data, these nodes however are also harvesting-based and thus do not have superfluous resources to assist bootstrapping nodes. We propose a new bootstrapping mechanism that facilitates energy harvesting nodes joining time-synchronized multi-hop networks.

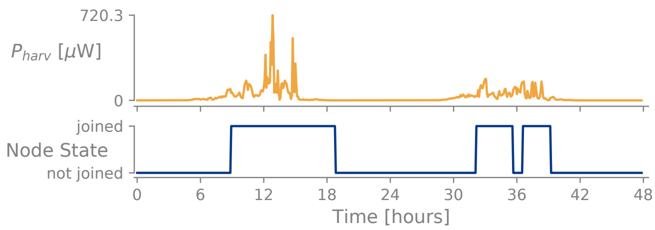

Fig. 2. The limited and non-deterministic available energy of a harvesting-based node is insufficient to continuously sustain synchronous communication with a central unit. The harvesting power dictates when the node can bootstrap to join the network and when it leaves again due to a power loss.

IV. DUAL-RANGE BOOTSTRAPPING

We present Dual-Range Bootstrapping (DRB), a bootstrapping mechanism for a network consisting of a central unit without relevant resource constraints and N energy harvesting IoT nodes. The central unit and energy harvesting nodes form a centrally coordinated short-range multi-hop network. In addition, all harvesting-based nodes have a direct link to the central unit, forming a single-hop network, when setting their radio to long-range. In the assumed network, the central unit knows how and when nodes can join the network.

DRB relies on both long- and short-range communication. With the former, a bootstrapping node directly communicates with the central unit to receive the time τ until the next relevant multi-hop communication. The node enters an energy-efficient state for length τ, subsequently wakes up, and joins the multi-hop network. Fig. 3 depicts an overview of DRB.

A. Long-Range Phase

A node can rely on one of numerous methods to manage its energy and determine when it can begin bootstrapping. The node will then begin bootstrapping by sending a long-range synchronization request packet. This packet may include information about the bootstrapping node such as a node identification number or its communication traffic demand. Between multi-hop communication rounds, the central unit listens for long-range packets. Upon receiving a valid request packet, it responds with the time τ until the next synchronous communication and any other information that is relevant for a node to join. Depending on the content of the request packet, the central unit can also update the coordination of the multi-hop communication. The energy harvesting node enters an energy-efficient deep-sleep state with its radio turned off for a length of time τ. A node may not receive the packet from the central unit for various reasons, the central unit could, for example, be unavailable because it is participating in short-range communication or due to simultaneous synchronization requests. There is a trade-off between the time dedicated to multi-hop communication and when the central unit is available for the long-range packet exchange. If the bootstrapping fails, the node makes another attempt at a later time depending on its energy availability and a random back-off interval.

This long-range phase relies on a symmetric use of long-range communication to exchange network information. It is nonetheless scalable since the packet size is very limited and nodes typically bootstrap only a few times per day. Furthermore, this phase has advantages that are essential for bootstrapping energy harvesting nodes in a multi-hop network. The bootstrapping energy increases linearly with the time τ but only at a very small rate. This is due to the very low and constant power dissipation in the deep sleep state. Although the power is not precisely constant in practice, it has relatively little variability and the bootstrapping energy maintains its linear trend. Moreover, the long-range packet exchange does not rely on other nodes since joined nodes are in sleep mode between multi-hop communication rounds. Employing different communication characteristics for this packet exchange also ensures that this network traffic is isolated from and does not interfere with the multi-hop communication. The latter is therefore not impacted in its performance and reliability by bootstrapping nodes sending synchronization requests.

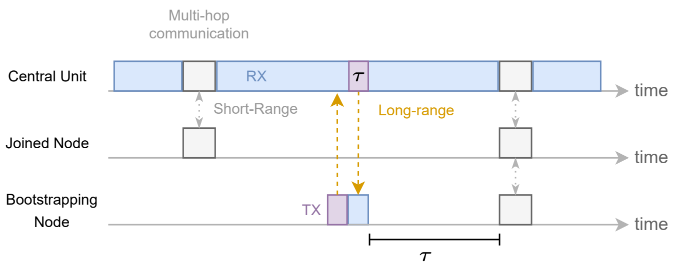

Fig. 3. Between multi-hop communication rounds, the central unit listens for long-range communication. A bootstrapping node sends a synchronization request and receives the time τ until the next relevant multi-hop communication. After waiting for τ in deep sleep, the bootstrapping node joins the short-range multi-hop communication.

B. Short-Range Phase

With the long-range packet exchange, the bootstrapping node learns when the subsequent relevant multi-hop communication will occur and is able to spend the time until then in an energy-efficient sleep state as no relevant network traffic will happen until then. To conclude joining the network, the bootstrapping node exits its sleep state prior to the known occurrence of the relevant communication. The node listens to short-range communication, and thus begins to scan the network for the relevant traffic shortly before it is scheduled to begin. Most nodes in a multi-hop network depend on other nodes to be communicating to successfully receive multi-hop communication. Yet, due to harvesting-based nodes' energy constraints in indoor environments, not all nodes participate in the short-range multi-hop communication at all times. Bootstrapping nodes can only receive the multi-hop communication and successfully join if nodes that they depend on participate in the multi-hop communication. If those nodes are currently not joined in the network, then a node is unable to join and needs to bootstrap again. The underlying multi-hop communication protocol suffers from the same limitation as it arises due to the fundamental energy constraints of harvesting-based nodes. Yet, we show in Section V that DRB's energy requirements are very limited, such that nodes can efficiently probe and attempt to join the network until their multi-hop communication dependency requirement is met.

C. Implementation

Our DRB mechanism has been implemented on top of the open-source Flora library [17] of the LWB protocol [3]. The software is compatible with the DPP2 LoRa platform [21], which consists of an STM32L433 microcontroller and a Semtech SX1262 transceiver.

The central unit, in LWB called the host, is, by definition, always joined and executes the short-range multi-hop communication rounds. With DRB, the host listens to network traffic with the long-range settings after each communication round. The host remains in receiving mode until a valid synchronization request is received or the next round begins. When a node wants to bootstrap, it sends a synchronization request packet with the long-range radio settings. The packet includes its node identification number and traffic demand. Upon receiving this request packet, the host replies with a long-range packet specifying the time τ until the next communication round, and updates the global schedule according to the communicated traffic demand, ensuring the bootstrapping node's traffic can be included in the next round. The host continues to listen until just before the next round when it changes its radio configuration to the short-range settings. After a bootstrapping node receives the time τ, it enters an energy-efficient sleep state for this time. Subsequently, it configures its radio for short-range communication and listens. With the reception of the first schedule that already considers the newly joining node, its time is synchronized to the global time.

In LWB, communication is time-triggered and follows a global schedule determined by the host with no relevant resource constraints. The protocol operates in communication rounds at the beginning of which the global schedule is communicated. Subsequently, nodes are assigned slots in which they transmit their data. Between rounds, nodes are in an energy-efficient sleep state. As long as nodes have energy, they are able to maintain the periodic rounds. When a node runs out of energy it drops out of the network and needs to bootstrap again once it has sufficient energy.

V. Experimental Evaluation

In this section, we evaluate the proposed DRB scheme and compare it to a single-hop and a multi-hop baseline. To this end, we first perform extensive experiments on Flocklab [22], using the DPP2 Lora platform, to verify functional correctness and characterize the energy consumption of the DRB scheme. We then use these experimental values to simulate the long-term temporal behavior of an energy-harvesting multi-hop network using an extensive indoor harvesting dataset [14].

A. Long-Range Phase Characterization

The applicability of DRB is tied to the achievable range for the long-range phase since it requires direct communication between the central unit and each node in the network. This long-range communication has different resource requirements than short-range multi-hop communication, as discussed in Section IV. We, therefore, characterize the long-range phase in terms of its energy requirement and demonstrate a trade-off with the receiver sensitivity.

The DPP2 Lora platform uses the Semtech SX1262 transceiver, which supports FSK and LoRa modulation schemes with a transmit power of up to 14 dBm. We summarize the transceiver's sensitivity for three radio settings as an indication of the communication range. The average energy required for a node to successfully execute the long-range packet exchange is experimentally measured with Flocklab. The energy spent during radio communication is averaged across 100 successful long-range packet exchanges. We evaluate the long-range phase for three radio settings representing short-, middle- and long-range scenarios: R_0) FSK modulation with a data rate of DR=250 kbit/s, bandwidth of BW=500 kHz and transmit power of P_{tx}=14 dBm, R_1) LoRa modulation with spreading factor SF=5, BW=125 kHz, and P_{tx}= 7 dBm, and R_2) LoRa modulation with SF=7, BW=125 kHz, and P_{tx}=14 dBm. For all settings, the central frequency is F_C=866.8125 MHz.

Fig. 4 depicts the average experimentally measured energy and the transceiver's sensitivity. Intuitively, radio settings that have a lower sensitivity and thus a longer communication range, require more energy for a successful long-range packet exchange. FSK communication ranges are on the order of covering a small floor in a building while LoRa packets with spreading factor 7 are able to reach across multiple buildings [23]. Since the long-range phase is based on direct communication between each node in the network and the host, the various achievable communication ranges for the long-range phase support numerous networks and scenarios with the single evaluated transceiver. In topologies with a large network radius, more energy-expensive long-range settings are necessary, but, as will be shown in the following sections, the energy cost for the long-range phase can nonetheless be temporarily supported by indoor energy harvesting.

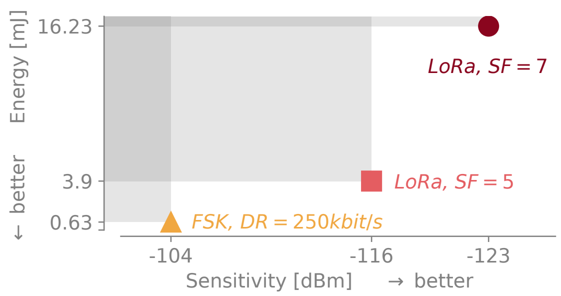

Fig. 4. A single transceiver can efficiently cover various scenarios. It supports a wide range of communication ranges while only requiring limited energy of nodes for the long-range packet exchange.

B. Testbed comparison of bootstrapping mechanisms

In this subsection, we experimentally compare DRB to a joining mechanism for multi-hop networks, denoted as *multi-hop* baseline, and a long-range active joining mechanism of a single-hop network referred to as *single-hop* baseline. The former is the idle listening bootstrapping approach found in standardized protocols like TSCH [8] and community-supported protocols like LWB [3], [17], where nodes listen to short-range multi-hop network traffic until receiving a valid schedule. The latter is analogous to the active joining mechanism in LoRaWAN Class B networks [18], where nodes send a long-range single-hop request to the host and receive network timing information.

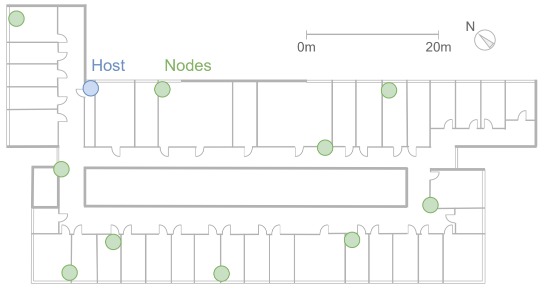

Fig. 5. Topology and layout of the Flocklab network. Ten nodes can communicate with the host either through a long-range single-hop or through a short-range three-hop network.

Flocklab Experimental Set-Up. We evaluate a FlockLab network consisting of 11 DPP2 LoRa nodes; 10 nodes and one host. They are distributed throughout the floor of a building according to the layout shown in Fig. 5. In all three approaches, nodes send 20 byte data packets in communication rounds with a period of 5 min. This period is the longest supported by the hardware without losing synchronization between rounds [24]. The multi-hop communication in DRB and the *multi-hop* baseline follows the LWB protocol [3]. Each packet is transmitted, respectively retransmitted, twice by all nodes in the network. To enable a fair comparison with the all-to-all communication in LWB, the *single-hop* baseline uses a modified long-range single-hop protocol: the host broadcasts the schedule and all data it receives while nodes are only active when transmitting their data or receiving data from the network (nodes do not re-transmit data). We assume successful bootstrapping attempts are equally likely to start at any time relative to communication rounds. Thus, for DRB and the *single-hop* baseline, a successful bootstrapping begins, on average, halfway between the end of a communication round and the beginning of the next round. Nodes are set up to start bootstrapping at specified times to align on average with this average successful bootstrapping time. Furthermore, one node begins shortly after and one shortly before a round to provide insights into the bootstrapping energy variability. For the short-range multi-hop communication, the transceiver uses FSK modulation with DR=250 kbit/s, BW=312 kHz, and P_{tx}=14 dBm. This results in a three-hop short-range network for the layout in Fig. 5. The *single-hop* baseline and long-range phase of DRB use radio settings R_2 from Section V-A to ensure reliable communication between each node and the host.

Bootstrapping Energy and its Variability. The energy for bootstrapping, E_{join} is measured from when a node begins bootstrapping until it has successfully received and, in the case of multi-hop communication re-transmitted, the schedule of a communication round.

Fig. 6 shows sample power traces of a node bootstrapping and the first communication round it participates in with the three approaches. For visibility, we have chosen a trace where the node starts bootstrapping 2.2 seconds before a communication round. With the *multi-hop* baseline, the node idle listens for network traffic from the time it starts bootstrapping until the communication round occurs. Since the multi-hop communication round uses high-data-rate short-range communication, its airtime is significantly shorter than the low-data-rate long-range round of the *single-hop* baseline. In the *single-hop* baseline, the node enters a sleep state after receiving the next round's start time, thus spending significantly less energy than the idle listening in the *multi-hop* baseline. DRB enables nodes to benefit from the advantages of each baseline.

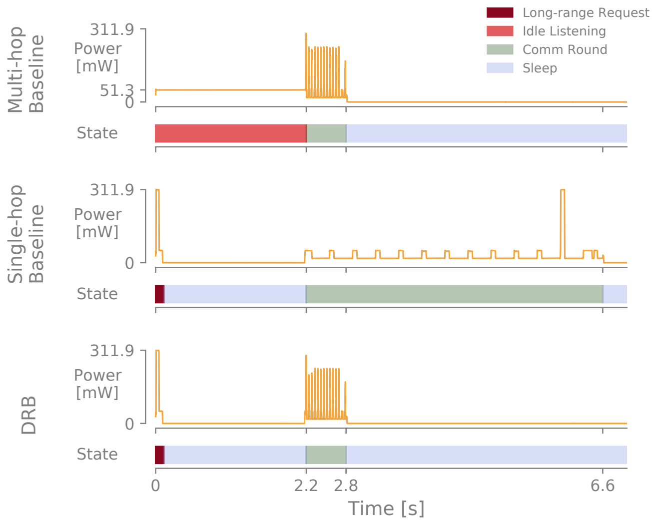

Fig. 6. Three sample traces of nodes bootstrapping 2.2 seconds before a communication round. DRB combines the efficient synchronization of the *single-hop* baseline with the high-data-rate communication of the *multi-hop* baseline.

Table I summarizes the average bootstrapping energy $E_{\text{join, avg}}$, the bootstrapping energy variability from the nodes with short and long bootstrapping times, and the energy, E_{com}, required for nodes to participate and communicate in a communication round. The results are an average across twenty test runs in which the nodes bootstrap at the beginning of the test. The average bootstrapping energy $E_{\text{join, avg}}$ with the *multi-hop* baseline is multiple orders of magnitude higher than that of the *single-hop* baseline. Furthermore, energy variability of the *multi-hop* baseline spans several orders of magnitude, while the *single-hop* baseline has a very narrow range. Conversely, the energy required per communication round, E_{com}, is significantly higher for the *single-hop* baseline than the *multi-hop* due to the long-range modulation scheme. The

TABLE I
MEASURED ENERGY REQUIRED FOR FLOCKLAB NODES (SEE FIG. 5) TO BOOTSTRAP (E_{JOIN}), AND COMMUNICATE (E_{COM}).

Approach	$E_{\text{join, avg}}$	E_{join} **variability**	E_{com}
multi-hop baseline	7.653 J	[9.6 mJ, 15.28 J]	22.64 mJ
single-hop baseline	23.9 mJ	[22.4 mJ, 26.6 mJ]	122.10 mJ
DRB	20.6 mJ	[19.1 mJ, 23.3 mJ]	22.63 mJ

communication energy dictates how long an energy-harvesting node is able to sustain communication and how frequently nodes bootstrap due to power outages. DRB combines the best of both by having a very small average bootstrapping energy with small variability while operating in a multi-hop network that can rely on energy-efficient short-range communication.

The small bootstrapping energy with little variability of the *single-hop* baseline and DRB is a result of a bootstrapping node being in an energy-efficient state for most of the time it takes to bootstrap, see Fig. 6. Thus, the time it takes to bootstrap mainly affects how long a node stays in its energy-efficient state. In contrast, for the *multi-hop* baseline a node spends most of the bootstrapping time with the radio on, listening for a schedule, which has a non-negligible power demand in comparison to the energy-efficient state.

Host Availability The advantages of the *single-hop* baseline and DRB build on shifting the resources required for idle listening for extended periods of time to the host. For the *single-hop* baseline, the host consumes 13.2 J, and for DRB 13.3 J from the end of a communication round until it has transmitted the schedule of the next round. The minor differences between the two arise from the shorter communication round in DRB; thus, the host idle listens for longer. In comparison, in the *multi-hop* baseline the host only requires 4.0 mJ since it is in an energy-efficient state between rounds. Yet, for the assumed network the host has no relevant resource constraints and this does not impact its behavior or performance. For the *single-hop* baseline and DRB, the host needs to be idle listening when a bootstrapping node sends a request for network timing and coordination information. For the *single-hop* baseline this is the case 98.63 % of the time and for DRB 99.81 %. The difference also arises from the longer communication round of the *single-hop* baseline. Nonetheless, for both, the host is available for request packets most of the time.

C. Long-term Energy Harvesting Simulations

We combine the results from Section V-B with an indoor harvesting dataset [14] to simulate the long-term behavior of an energy harvesting network. We demonstrate that the energy harvested with a photovoltaic cell of limited size may be insufficient to continuously maintain multi-hop communication and thus nodes have to bootstrap multiple times a day. We also evaluate the benefits of DRB's energy optimizations for harvesting nodes.

Simulation Parameters We simulate the resources of three energy harvesting nodes and a simplified communication state indicating whether a node is bootstrapping, joined and communicating, or disconnected from the network. The simulations are time-discrete with a time interval length equal to the communication period, i.e. $T_{com} = 5\,\mathrm{min}$. Each node's energy resources are simulated according to the simple model summarized in Section III. The energy storage capacity, $B = 16\,\mathrm{J}$, is sufficiently large so that it does not limit the node's behavior and is initially depleted. For the energy consumption, we only take into account communication and sleep between rounds since many ambient sensors, e.g. temperature and humidity sensors [25], consume significantly less energy. Thus, when a node has joined the network, it uses $E_{\text{used}}(t) = E_{\text{com}} + E_{\text{sleep}}$ and when it bootstraps $E_{\text{used}}(t) = E_{\text{join, avg}}$. Otherwise, we assume the node is not powered and consumes zero energy. For the nodes' harvested power, we use a single power trace from the dataset presented in [14], which was measured using a $50\,\mathrm{mm} \times 33\,\mathrm{mm}$ solar cell. These ideal conditions reveal important insights into the time and energy dynamics of an energy harvesting multi-hop network.

The host and energy harvesting nodes can form a three-hop short-range network and a long-range single-hop network. Nodes bootstrap when their state of charge surpasses a threshold. The threshold is such that the stored energy suffices to bootstrap and sustain communication for the next ten rounds. Since the bootstrapping energy can vary, the threshold accounts for the largest value in the variability range from Table I. In the *single-hop* baseline and DRB, nodes successfully complete the request packet exchange with probability equal to the host availability measured in Section V-B. The probability is independent between attempts and nodes and does not consider collisions since the exchange is very short. Long-range communication rounds of the *single-hop* baseline are assumed to always be successful. The short-range multi-hop communication is only successful if the nearest neighbor in the direction to the host is joined. If this condition is satisfied, short-range communication is also assumed to be successful. Otherwise, the node either stays in or enters the disconnected state. While connected to the network, nodes communicate until they run out of energy. The simulations provide performance statistics of the energy harvesting network over a six-month period for each bootstrapping mechanism.

Temporal Behavior. We now illustrate the effect the limited and variable harvested energy has on the temporal behavior of harvesting-based nodes in a centrally coordinated time-synchronized network. Fig. 7 depicts a six-day excerpt of the harvesting trace and the state of one of the three nodes for the *multi-hop* baseline, the *single-hop* baseline, and DRB. With the *multi-hop* baseline, the threshold to join the network is very high since not only the average bootstrapping energy is significantly larger than for the other two approaches but also the large variability has to be taken into account. Thus, with this approach the node waits multiple days, harvesting energy during the day until the threshold is surpassed. Since the average bootstrapping energy is notably lower than the threshold, it will have "excess" energy to continuously sustain communication for almost 29 hours once it has joined. Contrary, the *single-hop* baseline's activation threshold is

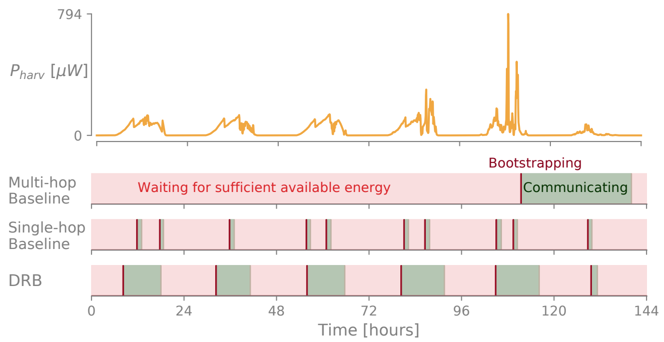

Fig. 7. The limited and varying harvested energy is insufficient to support communication continuously. The bootstrapping energy and its variability affect how long a node needs to wait until it has sufficient energy to join the network. The energy required to communicate dictates how soon the node runs out of energy again.

significantly lower and the node is able to bootstrap during each day of the excerpt. However, since the long-range single-hop communication is energy-intensive, it runs out of energy quickly and leaves the network. Lastly, DRB enables the node to bootstrap most efficiently since the threshold accounts for the low bootstrapping energy and ten energy-efficient multi-hop communication rounds. It also sustains communication longer than the *single-hop* baseline because it can leverage the more efficient short-range multi-hop communication.

Performance Metrics We now compare the long-term performance of the network when employing the *multi-hop* and *single-hop* baseline, and DRB over the six-month simulation horizon. We determine the number of communication rounds the nodes participate in on average per day and the average number of Bytes sent per day. These two numbers are proportional and indicate the amount of data received from the nodes. The energy costs are summarized in the energy spent on communication per day and the energy required to communicate one Byte. The former depends on the amount of data transmitted, while the latter depends on the used modulation scheme. Lastly, the temporal coverage encapsulates the percentage of time a node is joined to the network.

TABLE II

AVERAGE PERFORMANCE METRICS OF THE SIX-MONTH SIMULATION OF THE NETWORK WITH THREE HARVESTING-BASED NODES.

Metric	***multi-hop* baseline**	***single-hop* baseline**	**DRB**
Num rounds / day	53.3	17.5	82.7
Bytes / day	1066.8	349.2	1653.0
Energy / Byte [mJ]	1.13	6.11	1.13
Energy com / day [J]	1.21	2.13	1.87
Temporal coverage [%]	18.5	6.1	28.7

Table II summarizes the performance metrics averaged across the three nodes. The *multi-hop* baseline transmits on average large amounts of data per day because its short-range modulation is very efficient. Since the energy cost per Byte is low, it spends almost half as much energy to transmit over $3\times$

more data than the *single-hop* baseline. Because the *single-hop* baseline spends so much energy on long-range transmissions, the harvested energy results in a reduced temporal coverage. DRB enables an energy-efficient bootstrapping for multi-hop communication and thus benefits from the same low energy per Byte as the *multi-hop* baseline. Yet, it is able to employ more energy per day to communicate since less energy is spent on bootstrapping.

Effects of Scaling Harvesting Energy. The performance of an energy harvesting network greatly depends on the input energy, i.e. the amount of energy it harvests. We explore this relationship by simulating the energy harvesting network for nodes with various solar panel sizes. We scale the area of the simulated solar panel in relation to the original size in [14] of $50\,\mathrm{mm} \times 33\,\mathrm{mm}$ by multiplying the input power trace by a factor and adjusting the capacity B accordingly. For the simulated range, the temporal coverage increases linearly with the input energy, as depicted in Fig. 8, with DRB consistently outperforming the two baselines. Furthermore, even with a large 66 cm^2 solar panel, the indoor energy harvesting is unable to continuously power the network, highlighting the need for energy-efficient bootstrapping.

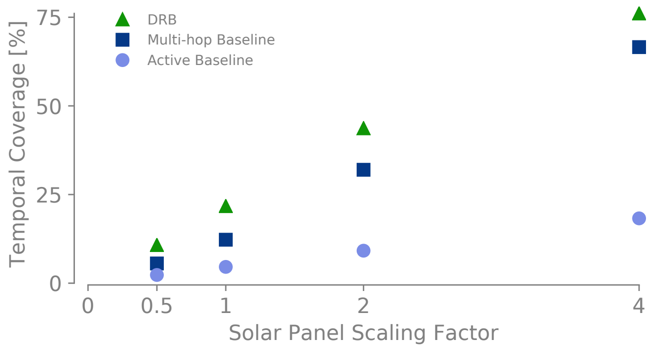

Fig. 8. The temporal coverage increases with larger solar panels as nodes harvest more energy and are able to sustain communication longer. Nonetheless, even for a large solar panel nodes communicate only part of the time.

VI. Conclusion

In this work, we present Dual-Range Bootstrapping (DRB), a method that facilitates the energy-efficient joining of energy harvesting nodes to a centrally controlled multi-hop network. Its low energy cost portrays little variability which allows harvesting-based nodes to efficiently manage their limited resources. With DRB, nodes bootstrap by exchanging long-range packets with a central unit to get information about network coordination and timing. They are then able to enter an energy-efficient sleep state until the relevant multi-hop network traffic occurs. DRB is experimentally shown to be suitable for numerous scenarios while only requiring limited and predictable energy for nodes to bootstrap. Furthermore, extensive testbed measurements show how DRB enables joining a short-range multi-hop network as efficiently as a long-range single-hop network. The long-term simulations demonstrate that energy harvesting nodes can run out of energy multiple times per day, highlighting the need for efficient bootstrapping mechanisms. DRB's increased energy efficiency results in nodes communicating larger amounts of data than single-hop and multi-hop baselines.

Acknowledgements. The authors wish to thank Roman Trüb and Reto Da Forno for their insightful discussions. This work was supported by the Swiss National Science Foundation under the NCCR Automation project, grant agreement 51NF40_180545, and the GFF-IPF Grant of the University of St.Gallen's Basic Research Fund.

References

[1] I. Demirkol *et al.*, "Mac protocols for wireless sensor networks: a survey," *IEEE Communications magazine*, 2006.
[2] T. Winter *et al.*, "Rpl: Ipv6 routing protocol for low-power and lossy networks," Tech. Rep., 2012.
[3] F. Ferrari *et al.*, "Low-power wireless bus," in *Procs of SenSys'12*, 2012.
[4] O. Harms *et al.*, "Master: Long-term stable routing and scheduling in low-power wireless networks," in *Procs of DCOSS'2020*. IEEE, 2020.
[5] A. Gomez *et al.*, "Dynamic energy burst scaling for transiently powered systems," in *Proc. DATE Conf.*, 2016.
[6] F. Sivrikaya *et al.*, "Time synchronization in sensor networks: a survey," *IEEE network*, 2004.
[7] C. Hambeck *et al.*, "A 2.4 μw wake-up receiver for wireless sensor nodes with- 71dbm sensitivity," in *ISCAS*. IEEE, 2011.
[8] S. Duquennoy *et al.*, "Tsch and 6tisch for contiki: Challenges, design and evaluation," in *Procs of DCOSS'2017*. IEEE, 2017.
[9] F. Sutton *et al.*, "Zippy: On-demand network flooding," in *Procs of SenSys'15*, 2015.
[10] N. M. Pletcher *et al.*, "A 52μw wake-up receiver with -72 dbm sensitivity using an uncertain-if architecture," *IEEE Journal of solid-state circuits*, 2008.
[11] C. Carrascal *et al.*, "A novel wake-up communication system using solar panel and visible light communication," in *2014 IEEE Global Communications Conference*. IEEE, 2014.
[12] A. Biri *et al.*, "Stec: Exploiting spatial and temporal correlation for event-based communication in wsns," in *Procs of SenSys'21*, 2021.
[13] K. Geissdoerfer *et al.*, "Bootstrapping battery-free wireless networks: Efficient neighbor discovery and synchronization in the face of intermittency," in *In Proc. NSDI Symp.*, 2021.
[14] L. Sigrist *et al.*, "Dataset: Tracing indoor solar harvesting," in *Proceedings of the 2nd Workshop on Data Acquisition To Analysis*, 2019.
[15] M. Buettner *et al.*, "X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks," in *Procs of SenSys'06*, 2006.
[16] E.-Y. Lin *et al.*, "Power-efficient rendez-vous schemes for dense wireless sensor networks," in *2004 IEEE international conference on communications*. IEEE, 2004.
[17] R. Trüb *et al.*, "Flora Software," https://eth.swisscovery.slsp.ch/permalink/41SLSP_ETH/lshl64/alma99117766552205503, 2021.
[18] LoRa Alliance., "LoRaWAN L2 1.0.4 Specification," https://lora-alliance.org/wp-content/uploads/2021/11/LoRaWAN-Link-Layer-Specification-v1.0.4.pdf#page=52, 2020.
[19] N. Stricker *et al.*, "Robustness of predictive energy harvesting systems: Analysis and adaptive prediction scaling," *IET Computers & Digital Techniques*.
[20] J. Singh *et al.*, "Energy harvesting in wireless sensor networks: A taxonomic survey," *International Journal of Energy Research*, 2021.
[21] J. Beutel *et al.*, "The dual processor platform architecture: Demo abstract," in *Procs of IPSN'19*, 2019.
[22] R. Trüb *et al.*, "Flocklab 2: Multi-modal testing and validation for wireless iot," in *CPS-IoTBench 2020*. OpenReview. net, 2020.
[23] R. Trüb, "Design and testing of mixed-range low-power wireless networks," Ph.D. dissertation, ETH Zurich, 2022.
[24] N. Stricker *et al.*, "Selective flooding-based communication for energy harvesting networks," in *Proc. IPSN Conf.* IEEE, 2022.
[25] N. Stricker *et al.*, "Secure communication with batteryless sensors," in *MECO*. IEEE, 2022.