Integrating Low-Power Wide-Area Networks in White Spaces

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Abstract—**Low-Power Wide-Area Networks (LPWANs) are evolving as an enabling technology for Internet-of-Things (IoT) that offer long communication range at low power. Despite their promise, existing LPWANs still face limitations in meeting scalability and covering much wider area which make their adoption challenging for future IoT applications, specially in infrastructure-limited rural areas. To address this, we consider achieving scalability by integrating multiple LPWANs that need to coordinate for extended coverage. Recently proposed *SNOW (Sensor Network Over White Spaces)* has demonstrated advantages over existing LPWANs in its performance. In this paper, we propose to scale up LPWANs through a seamless integration of multiple SNOWs that enables concurrent inter-SNOW and intra-SNOW communications. We then formulate the tradeoff between scalability and inter-SNOW interference as a constrained optimization problem whose objective is to maximize scalability by managing white space spectrum sharing across multiple SNOWs. We also prove the NP-hardness of this problem. We then propose an intuitive polynomial time heuristic algorithm for solving the scalability optimization problem. Hardware experiments through deployment in an area of (15x10)km^2 demonstrate the effectiveness of our algorithm and feasibility of achieving scalability through seamless integration of SNOWs with high reliability, low latency, and energy efficiency.**

I. INTRODUCTION

Low-Power Wide-Area Networks (LPWANs) are emerging as an enabling technology for Internet-of-Things (IoT) to overcome the range limit and scalability challenges in traditional wireless sensor networks (WSNs). Due to their escalating demand, LPWANs are gaining momentum, with multiple competing technologies being developed including LoRa, SigFox, IQRF, DASH7, NB-IoT, 5G (see survey [1]), etc. In parallel, we developed **SNOW (Sensor Network Over White Spaces)**, an LPWAN architecture to support wide-area WSN by exploiting the TV white spaces [2], [3]. *White spaces* refer to the allocated but locally unused TV channels, and can be used by unlicensed devices as secondary users [4]. Our design and experimentation demonstrated the potential of SNOW to enable asynchronous, low power, bi-directional, and massively concurrent communications between numerous sensors and a base station (BS) over long distances [2], [3].

Despite their promise, LPWANs still face limitations in meeting scalability and covering much wider area which make their adoption challenging for future IoT applications, specially in **infrastructure-limited rural areas**. The performance of LoRa, widely considered as an LPWAN leader [5], drops exponentially as the number of end-devices grows [6]. A typical smart city deployment can support only 120 LoRa nodes per 3.8 hectares [7] which is not sufficient to meet the future IoT demand. Without line of sight its communication range is quite low [8], specially in indoor (<100m [9]).

Most LPWANs are limited to star topology (except IQRF and DASH7) while the cellular based ones (NB-IoT, 5G, etc.) rely on wired infrastructure for integrating multiple networks to cover larger areas. Lack of proper infrastructure and connectivity hinders their rural applications such as agricultural IoT [10], oil-field monitoring [11], smart and connected rural communities [12], etc. Companies like Microsoft [10], Climate Corp [13], AT&T [14], and Monsanto [15] are promoting agricultural IoT which has now become a global need and also a recommendation by the United Nations to increase food production [16]. For oil-filed monitoring, process management companies such as Emerson are in need of deploying tens of thousands of nodes in oil-fields that can be very wide [11]. For example, the East Texas Oil Field is spread over 74x8km^2 [17]. Such wide area deployments also would need an integration of multiple LPWANs. Similar integration may also be needed in a smart city deployment for extended coverage or for running different applications on different LPWANs.

We address the above scalability challenge through integration of multiple SNOWs that are under the same management/control. Such integration raises several concerns. First, it needs a protocol to enable inter-SNOW communication, specially peer-to-peer communication (when a node in one SNOW wants to communicate with a node in a different SNOW). Second, since multiple coexisting SNOWs can interfere each other, thus affecting the scalability, it is critical to handle the tradeoffs between scalability and inter-SNOW interference. Specifically, we make the following novel contributions.

- We propose to scale up LPWAN through seamless integration of multiple SNOWs that enables concurrent intra- and inter-SNOW communications. This is done by exploiting the characteristics of the SNOW physical layer.
- We then formulate the tradeoff between scalability and inter-SNOW interference as a constrained optimization problem whose objective is to maximize scalability by managing white space spectrum sharing across multiple SNOWs, and prove its NP-hardness.
- We propose an intuitive polynomial time heuristic algorithm for solving the scalability optimization problem which is highly efficient in practice.

- We implement the proposed SNOW technologies in GNU radio [18] using USRP [19]. We perform experiments by deploying 9 USRP devices in an area of $(15x10)km^2$ in Detroit, Michigan. Testbed experiments demonstrate the feasibility of achieving scalability through seamless integration of SNOWs, allowing concurrent intra- and inter-SNOW communications with high reliability, low latency and energy while using our heuristic algorithm.

II. SNOW Overview

SNOW is an asynchronous, long range, low power WSN platform to operate over TV white spaces. A SNOW node has a single half-duplex narrowband radio. Due to long transmission (Tx) range, the nodes are directly connected to the BS and vice versa. SNOW thus forms a star topology. The BS
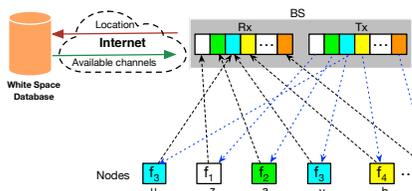
Fig. 1. SNOW dual radio BS and subcarriers.

determines white spaces in its area by accessing a cloud-hosted database through the Internet. The nodes are power constrained and not directly connected to the Internet. They do not do spectrum sensing or cloud access. The BS uses a wide channel split into orthogonal subcarriers. As shown in Figure 1, the BS uses two radios, both operating on the same spectrum – one for only transmission (called ***Tx radio***), and the other for only reception (called ***Rx radio***). Such a dual-radio of the BS allows concurrent bi-directional communication in SNOW.

A. SNOW Physical (PHY) Layer

PHY layer of SNOW uses a **D**istributed implementation of **OFDM** (Orthogonal Frequency Division Multiplexing) for multi-user access, called **D-OFDM**. The narrowband orthogonal subcarriers of the BS's wide spectrum carry parallel data streams to/from the distributed nodes from/to the BS as D-OFDM. Each node transmits/receives on its assigned subcarrier. Each subcarrier is modulated using Binary Phase Shift Keying (BPSK). A subcarrier bandwidth can be chosen as low as 100kHz, 200kHz, or 400kHz depending on the packet size and expected bit rate. Unlike OFDM for multiple access in WiMAX and LTE using multiple antennas [20], [21], D-OFDM enables multiple packet receptions using a single antenna which are transmitted asynchronously from different nodes. It also enables different data transmissions to different nodes through a single transmission using a single antenna. Experiments show a Tx range of 8km at 20dBm for a SNOW node [2], [3]. If the BS spectrum is split into n subcarriers, it can receive from n nodes simultaneously. Similarly, it can transmit n different data for n different users at a time. The BS can also exploit fragmented white space.

B. SNOW Media Access Control (MAC) Layer

This BS spectrum is split into n overlapping orthogonal subcarriers – $f_1, f_2, \cdots, f_n$ – each of equal width. Each node is assigned one subcarrier. When the number of nodes is no greater than the number of subcarriers, every node is assigned a unique subcarrier. Otherwise, a subcarrier might be shared by multiple nodes. The subcarrier allocation is done by the BS. The nodes in SNOW use a lightweight CSMA/CA protocol for transmission that uses a static interval for random back-off like the one used in TinyOS [22] . The nodes can autonomously transmit, remain in receive (Rx) mode, or sleep. Since D-OFDM allows handling asynchronous Tx and Rx, the link layer can send acknowledgment (ACK) for any transmission in either direction. As shown in Figure 1, both radios of the BS use the same spectrum and subcarriers - the subcarriers in the Rx radio are for receiving while those in the Tx radio are for transmitting. Both experiments and large-scale simulations show high efficiency of SNOW in latency and energy with a linear increase in throughput with the number of nodes, demonstrating its superiority over existing designs [2], [3].

III. System Model

We consider many coexisting SNOWs are under the same management/control and need to coordinate themselves for wider area coverage or hosting different applications. As such,
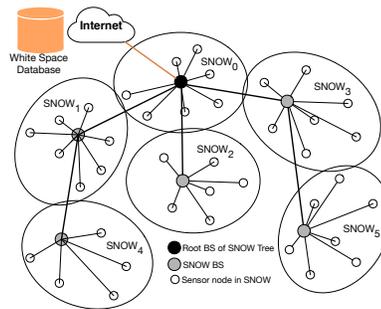
Fig. 2. A SNOW-tree.

we consider an inter-SNOW network as a SNOW-tree in the spirit of the new IEEE 802.15.4m [23] that considers a cluster tree, each cluster representing a personal area network under a coordinator, and **root** of the tree is connected to the white space database. Similarly, our inter-SNOW network of the coordinated SNOWs is shown in Figure 2 as a SNOW-tree. Each cluster is a star topology SNOW. All BSs form a tree that are connected through white space. Let there be a total of N BSs (and hence N SNOWs) in the SNOW-tree, denoted by BS_0, BS_1, $\cdots$, BS_{N-1}, where BS_i is the base station of $SNOW_i$. BS_0 is the **root BS** and is connected to the white space database via Internet. The remaining BSs are in remote places where Internet connection many not be available. Those BSs thus depend on BS_0 for white space information.

Every BS is assumed to know the location of its operating area (its location and the locations of its nodes). Localization is not the focus of our work and can be achieved through manual configuration or some existing WSN localization technique such as those based on ultrasonic sensors or other sensing

modalities [24]. BS_0 gets the location information of all BSs and finds the white spaces for all SNOWs. It also knows the topology of the tree and allocates the spectrum among all SNOWs. Each BS splits its assigned spectrum and assigns subcarriers to its nodes. In an agricultural IoT, Internet connection is not available everywhere in the wide agricultural field. Usually, the farmer's home can have Internet connection and the root BS can be there. Microsoft's Farmbeats [10] for agricultural IoT also exhibits such a scenario. Our work thus provides an enabling technology for such applications.

IV. ENABLING CONCURRENT INTER-SNOW AND intra-SNOW COMMUNICATIONS

Here we describe our inter-SNOW communication technique to enable seamless integration of the SNOWs for scalability. Specifically, we explain how we can enable concurrent intra- and inter-SNOW communications by exploiting the PHY design of SNOW. To explain this we consider *peer-to-peer* (P2P) inter-cluster communication in the SNOW-tree.
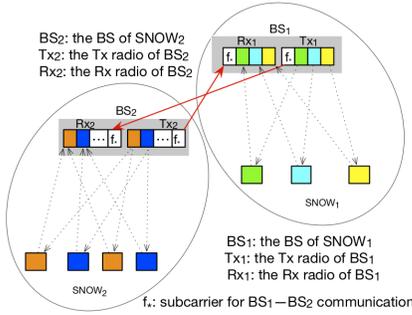
Fig. 3. Inter-SNOW communication.

For P2P communication across SNOWs, a node first sends its packet to its BS. The BS will then route to the destination SNOW's BS along the path given by the tree which in turn will forward to the destination node. Hence, the first **question** is *"How do two neighboring BSs exchange packets without interrupting their communication with their own nodes?"* Let us consider $SNOW_1$ and $SNOW_2$ as two neighboring SNOWs in Figure 3 which will communicate with each other. We allocate a special subcarrier from both of their spectrum (i.e., a common subcarrier among the two BSs) that will be used for communication between these two BSs. This subcarrier will not be used for any other purpose. In the figure, f_* is shown as that special subcarrier. D-OFDM allows us to encode any data on any subcarrier while the radio is transmitting. Thus the SNOW PHY will allow us to encode any time on any number of subcarriers and transmit. Exploiting this important feature of the SNOW PHY, Tx_1 radio will encode the packet on the subcarrier f_* which is used for BS_1–BS_2 communication in Figure 3. If there are pending ACKs for its own nodes, they can also be encoded in their respective subcarriers. Then Tx_1 radio makes a single transmission. Rx_2 will receive it on subcarrier f_* while the nodes of $SNOW_1$ will receive on their designated subcarriers. BS_1 can receive from BS_2 in the same way. They can similarly forward to next neighboring SNOWs. Thus both intra- and inter-SNOW communications can happen in parallel.

V. HANDLING TRADEOFFS BETWEEN SCALABILITY AND INTER-SNOW INTERFERENCE

Our objective of integrating multiple SNOWs is scalability which can be achieved if every SNOW can support a large number of nodes. The number of nodes supported by a SNOW increases if the number of subcarriers used in that SNOW increases. However, if each SNOW uses the entire spectrum available at its location, there will be much spectrum overlap with the neighboring SNOWs. This will ultimately increase inter-SNOW interference and huge packet loss. On the other end, if all neighboring SNOWs use non-overlapping spectrum, inter-SNOW interference will be minimized, but each SNOW in this way can support only a handful of nodes, thus degrading the scalability. This tradeoff between scalability and inter-SNOW interference due to integration raises a spectrum allocation which cannot be solved using traditional spectrum allocation approach in wireless networks. We propose to accomplish such an allocation by formulating a **Scalability Optimization Problem (SOP)** where our objective is to optimize scalability while limiting the interference. To our knowledge, this problem is unique and never arose in other wireless domains. We now formulate SOP, prove its NP-hardness, and provide polynomial-time near-optimal solutions.

A. SOP Formulation

The root BS knows the topology of the BS connections, accesses the white space database for each BS, and allocates the spectrum among the BSs. The spectrum allocation has to balance between scalability and inter-SNOW interference as described above. For SOP, we consider a uniform bandwidth ω of a subcarrier across all SNOWs. Let Z_i be the set of orthogonal subcarriers available at BS_i considering α as the *fraction of overlap* between two neighboring subcarriers, where $0 \leq \alpha \leq 0.5$ (as we found in our experiments [2], [3] that two orthogonal subcarriers can overlap at most up to half). Thus, if W_i is the total available bandwidth at BS_i, then its total number of orthogonal subcarriers is given by $|Z_i| = \frac{W_i}{\omega \alpha} - 1$.

We consider that the values of ω and α are uniform across all BSs. Let the set of subcarriers to be assigned to BS_i be $X_i \subseteq Z_i$, with $|X_i|$ being the number of subcarriers in X_i. We can consider the *total number of subcarriers*, $\sum_{i=0}^{N-1} |X_i|$, assigned to all SNOWs as the *scalability* metric. We will maximize this metric. Every BS_i (i.e., $SNOW_i$) requires a *minimum number of subcarriers* σ_i to support its nodes. Hence, we define **Constraint** (1) to indicate the minimum and maximum number of subcarriers for each BS. If some communication in $SNOW_i$ is interfered by another communication in $SNOW_j$, then $SNOW_j$ is its **interferer.** Since the root BS knows the locations of all BSs (all SNOWs) in the SNOW-tree, it can determine all interference relationships (identifying which SNOW is an interferer of which SNOWs) among the SNOWs based on the communication range of the nodes.

Let $I_i \subset \{0, 1, \cdots, N-1\}$ be such that each $SNOW_j$ with $j \in I_i$ is an interferer of $SNOW_i$ (i.e., BS_i). In the SNOW-tree, let $p(i) \in \{0, 1, \cdots, N-1\}$ be such that $BS_{p(i)}$ is the parent of BS_i and $Ch_j \subset \{1, 2, \cdots, N-1\}$ be such that each

BS$_j$ with $j \in Ch_i$ is a child of BS$_i$. The SNOWs associated with a BS's parent and children are its interferer already, i.e., $(\{p(i)\} \cup Ch_i) \subseteq I_i$. To limit inter-SNOW interference, let $\phi_{i,j}$ be the *maximum allowable number of subcarriers* that can overlap between two interfering SNOWS, SNOW$_i$ and SNOW$_j$. As explained in Section IV, there must be at least one subcarrier common between a BS and its parent which is defined in **Constraint** (2). **Constraint** (3) indicates the minimum and maximum number of overlapping subcarriers between other interfering pairs. Thus, SOP is formulated as follows where the root BS allocates the spectrum among all BSs (i.e., assigns subcarriers $X_i \subseteq Z_i$ to SNOW$_i$) in order to

$$\text{Maximize} \quad \sum_{i=0}^{N-1} |X_i|$$

$$\text{subject to} \quad \sigma_i \leq |X_i| \leq |Z_i|,\ X_i \subseteq Z_i \tag{1}$$

$$1 \leq |X_i \cap X_{p(i)}| \leq \phi_{i,p(i)}, 1 \leq i < N \tag{2}$$

$$0 \leq |X_i \cap X_j| \leq \phi_{i,j}, 0 \leq i < N$$
$$\forall j \in I_i - (\{p(i)\} \cup Ch_i) \tag{3}$$

SOP is a unique problem that we have observed first in integrating SNOWs. Traditional channel allocation techniques for wireless networks (see survey [25]), WSN (see survey [26]), or cognitive radio networks (see survey [27]) are not applicable as SOP involves assigning a large number of subcarriers to each BS allowing some degree of overlaps among interfering BSs for enhanced scalability. We have also proved that SOP is NP-hard. Due to page limits the proof of NP-hardness is provided in an extended version [28].

B. Efficient Greedy Heuristic for SOP

Since an optimal solution of SOP cannot be achieved in polynomial time unless P=NP, we propose an intuitive, highly efficient, polynomial time greedy heuristic. In the beginning, the greedy heuristic will assign to every BS the entire spectrum available in its location. It will then keep removing subcarriers from their assignments until the constraints are satisfied. The target is to remove as less number of subcarriers as possible.

Algorithm 1: Greedy Heuristic Algorithm

Data: Z_i for BS$_i$, $0 \leq i < N$ in a SOP Instance.
Result: Subcarriers X_i for BS$_i$, $0 \leq i < N$.

1 **for** *each BS$_i$ in the SNOW-tree* **do**
2     $X_i = Z_i$.

3 **for** *each BS$_i$ in inter-SNOW Tree* **do**
4   **for** *each BS$_j$ $\in I_i$* **do**
5   Let, $Z_{i,j} = Z_i \cap Z_j$.
6   **for** *each subcarrier $x_l \in Z_{i,j}$* **do**
7   **if** $|X_i \cap X_j| > \phi_{i,j}$ **then**
8   **if** $|X_i| \geq |X_j|\ and\ |X_i| > \sigma_i$ **then**
9   Delete x_l from X_i.
10   **else if** $|X_j| > \sigma_j$ **then**
11   Delete x_l from X_j.
12   **else**   /* Infeasible solution */
13   Don't delete x_l from X_i or X_j.

14   **else**
15   Break.

The greedy heuristic is described as follows. In the beginning, the root BS greedily assigns to every BS$_i$ all the subcarriers that are available at the location of BS$_i$ (i.e., the entire spectrum available in BS$_i$'s location). Note that such an assignment maximizes the *scalability* metric $\sum_{i=0}^{N-1} |X_i|$, but violates the constrains of SOP. Specifically, it satisfies Constraint (1), but may violate Constraints (2) and (3) that are defined to keep the BSs connected as a tree and to limit interference between neighboring or interfering BSs by limiting their common usable subcarriers. Now, with a view to satisfying those two constrains, the heuristic greedily removes some subcarriers that are common between interfering BSs. Such removal of subcarriers is done to make the least decrease in the scalability and to ensure that Constraint (1) is not violated. In other words, it tries to keep the subcarrier assignment balanced between BSs. Specifically, for every interfering BS pair, BS$_i$ and BS$_j$, we do the following until they satisfy Constraints (2) and (3): Find the next common subcarrier between them and remove it from BS$_i$ if $|X_i| > |X_j|$ and $|X_i| > \sigma_i$; otherwise remove it from BS$_j$ if $|X_j| > \sigma_i$.

The pseudocode of our greedy heuristic is shown as Algorithm 1. As shown in the pseudo code, the heuristic may not find feasible solution in some rare cases where some BS pairs, BS$_i$ and BS$_j$, cannot satisfy the condition $|X_i \cap X_j| \leq \phi_{i,j}$. In such cases, we can either use the infeasible solution and use the found subcarrier allocation or relax the constraints for those BSs (violating the constraints) by changing their values of σ_i or $\phi_{i,j}$ in Constraints (1), (2), and (3) of the SOP. Here, the time complexity of Algorithm 1 is $O(N^2 M \lg M)$.

VI. EXPERIMENTS

Implementation. We have implemented the SNOW technologies in GNU Radio [18] using USRP [19]. We have 9 USRP devices. We used 2x3 devices in 3 different SNOW BSs (each having 1 Tx-Radio and 1 Rx-Radio). Also, each BS is assigned 1 USRP device as node. We evaluate the performance of our design by experimenting at 9 different candidate locations covering approximately (15x10)km^2 of a large metropolitan area in the city of Detroit, Michigan (Figure 4).

Due to our limited number of USRP devices in real experiments, we create 3 different SNOW-trees at different candidate locations and do experiments separately. Also in a SNOW-tree, we choose to create 3 SNOWs to demonstrate the integration of as many SNOWs as we can with our limited number of devices, and most importantly, to cover more areas. In [2], [3], we have already performed a lot of experiments considering multiple nodes in a single SNOW. We perform experiments on white space availability at different locations and determine the value of $\phi_{i,j}$ in Constraints (2) and (3). We compare the performances of our greedy heuristic algorithm for SOP with a direct allocation scheme. A *direct allocation scheme* is unaware of scalability and inter-SNOW interference. It assigns each BS all the subcarriers that are available at its location.

A. Experimental Setup

Our testbed location has white spaces ranging between 518 - 686MHz (TV channel 21-51). We set each subcarrier bandwidth to 400kHz which was the default subcarrier bandwidth
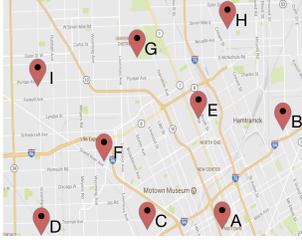
Fig. 4. SNOW BS positions in experiments.

in single SNOW [2], [3]. We use 40-byte (including header, random payload, and CRC) packets with a spreading factor of 8, modulated or demodulated as BPSK (Binary Phase-Shift Keying). We set the Tx power to 0dBm in SNOW nodes for energy efficiency. Receive sensitivity is set to -94dBm in both BSs and nodes. Meanwhile, BSs transmit with a Tx power of 15dBm ($\approx$40mW) to their nodes and neighboring BSs that is maximum allowable Tx-power in most of the white space channels at our testbed location. For energy calculations at the nodes, we use energy profile of CC1070 RF unit by Texas Instruments [29] that can operate in white spaces. Unless stated otherwise, those are our default parameter settings.

B. Finding Allowable Overlap of Spectrum

We first determine how many subcarriers can overlap between two interfering SNOWs without degrading their performances. We determine white spaces at 9 different locations from a cloud-hosted database [30]. Figure 5(a) shows the available white spaces at different locations confirmed by the database[1]. We conduct experiments in 3 different SNOW-trees to determine the maximum allowable subcarrier overlaps between interfering BSs. Locations of BSs in 3 trees are (1) B, A, E; (2) D, C, F; (3) I, G, H; respectively, where the BS in the middle location in each SNOW-tree is the root BS. In each tree, we allow BSs to operate with different magnitudes of white space overlaps between them. To determine the maximum allowable number of common subcarriers between interfering BSs in a tree, each node hops randomly to all the subcarriers that are available in its BS and sends consecutive 100 packets to its BS. Each node repeats this procedure 1000 times. Figure 5(b) shows in each tree, BSs can overlap 60% of their white spaces to yield an average *Packet Reception Rate (PRR)* of at least 85%. We consider that 85% PRR is an acceptable rate in wireless settings [31]. Thus, we set the value of $\phi_{i,j}$ in Constraints (2) and (3) based on this experiment.

C. Experiments on SOP Algorithms

To demonstrate the performances of our greedy heuristic, we set the value of σ_i in Constraint (1) to 100 for all the BSs. We choose the same value for each BS since most (8 out of 9) BS locations have same set of white spaces. Figures 6(a) - 6(c) show the number of subcarriers assigned to different BSs in 3 different SNOW-trees by corresponding root BS using greedy heuristic and the direct allocation, respectively. Figures show

[1]As of Oct. 13, 2017. In this paper, all experiments were run by that date.
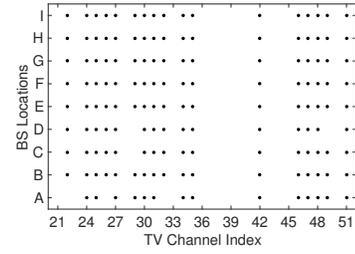
(a) Available white spaces (denoted by dots) at different BS locations.
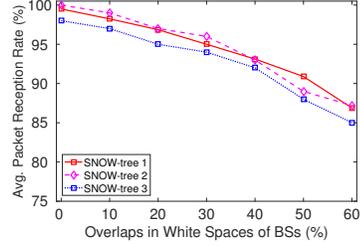
(b) Reliability in communication with different magnitude of white space overlaps between BSs.

Fig. 5. White spaces availability and reliability in different SNOW-trees.

that direct allocation scheme is assigning more subcarriers to all BSs, however, in later experiments we show that such assignments suffer in terms of reliability, latency, and energy consumptions compared to our greedy heuristic algorithm due to its violation of Constraints (2) and (3) of SOP.

D. Experiments on Intra- and Inter-SNOW Communications

To demonstrate both intra- and inter-SNOW communication performances, we perform parallel P2P communications between two nodes under two sibling BSs in each SNOW-tree, using the subcarriers assigned to BSs by different SOP algorithms in Section VI-C. Since, each BS in a tree has 1 node, we allow those nodes to use all the subcarriers of its corresponding BSs. Considering SNOW-tree 1, the node in BS at B (and E) will send P2P packets to the node in BS at E (and B) via root BS at A. Thus, this is level three P2P communication. In experiments, the node in BS at B (and E) randomly hops into different subcarriers of its BS and sends consecutive 100 packets destined for the node in BS at E (and B). BS at B (and E) first receives the packets (intra-SNOW) and then relays to its parent BS at A (inter-SNOW). Root BS at A then relays (inter-SNOW) the packets to BS at E (and B). Finally, E (and B) sends (intra-SNOW) the packets to its node. Considering the reception of a single P2P packet, since the receiving node is randomly hopping to different subcarriers (to transmit), the BS sends (intra-SNOW) the same packet via all subcarriers, thus the node may receive instantly. The whole P2P process is repeated 1000 times in every SNOW-tree.

Figure 6(d) shows that average higher PRR happens in all SNOW-trees when subcarriers assigned by greedy heuristic algorithm is used. For example, PRR is as high as 99.6% in SNOW-tree 3 compared to 78.1% while using subcarriers assigned by and direct allocation scheme. Figure 6(e) shows

(a) SNOW-tree 1.

(b) SNOW-tree 2.

(c) SNOW-tree 3.

(d) Reliability in 3rd-level P2P comm.

(e) Latency in 3rd-level P2P comm.

(f) Energy consumption.
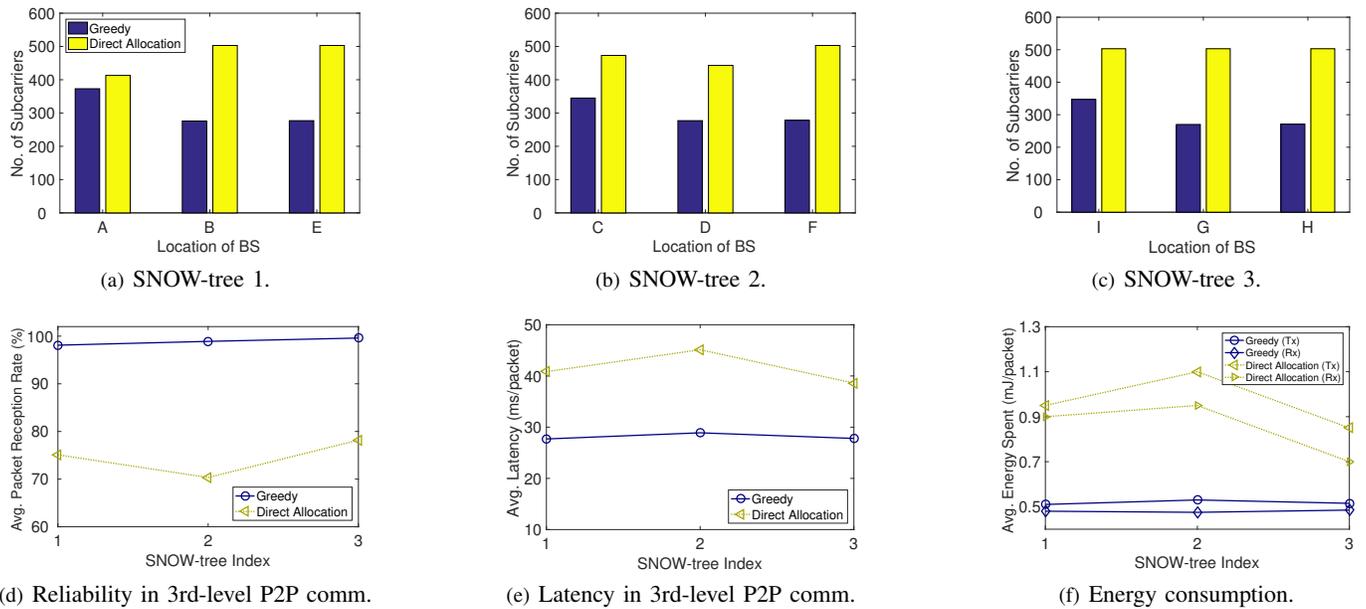
Fig. 6. Subcarrier assignments and observed latency of SOP algorithms by different root BSs at different SNOW-trees.

per P2P packet latency is also lower in all SNOW-trees in case of greedy subcarrier assignments. In SNOW-tree 3, it's on average 27.8ms compared to 39ms in case of direct allocation scheme assignment. Figure 6(f) shows average energy consumed per P2P packet at Tx and Rx nodes are lower in all SNOW-trees for greedy assignments. In SNOW-tree 3, Tx and Rx nodes consumes on average 0.52mJ and 0.49mJ energy, respectively. For direct allocation scheme, these values are 0.9mJ and 0.7mJ. Thus, all the experiments confirm that greedy heuristic is a practical choices for SOP.

VII. CONCLUSIONS

In this paper, we have proposed to scale up LPWANs through a seamless integration of multiple SNOWs that enables concurrent inter-SNOW and intra-SNOW communications. We have then formulated the tradeoff between scalability and inter-SNOW interference as a scalability optimization problem, and have proved its NP-hardness. We have also proposed a polynomial time heuristic that is highly effective in experiments. Testbed experiments demonstrate the feasibility of achieving scalability through integration of SNOWs with high reliability, low latency, and energy efficiency.

ACKNOWLEDGEMENTS

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