Low-Power Wide-Area Network over White Spaces
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Abstract—As a key technology driving the Internet-of-Things, Low-Power Wide-Area Networks (LPWANs) are evolving to overcome the range limits and scalability challenges in traditional wireless sensor networks. This paper proposes a new LPWAN architecture called Sensor Network Over White Spaces (SNOW) by exploiting the TV white spaces. SNOW is the first highly scalable LPWAN over TV white spaces that enables asynchronous, bi-directional, and massively concurrent communication between numerous sensors and a base station. This is achieved through a set of novel techniques. SNOW has a new OFDM based physical layer that allows the base station using a single antenna-radio (1) to send different data to different nodes concurrently and (2) to receive concurrent transmissions made by the sensor nodes asynchronously. It has a lightweight MAC protocol that (1) efficiently implements per-transmission acknowledgments of the asynchronous transmissions by exploiting the adopted OFDM design; (2) combines CSMA/CA and location-aware spectrum allocation for mitigating hidden terminal effects, thus enhancing the flexibility of the nodes in transmitting asynchronously. We implement SNOW in GNU radio using USRP devices. Experiments through deployments in three radio environments - a large metropolitan city, a rural area, and an indoor environment - as well as large-scale simulations demonstrated that SNOW drastically enhances the scalability of sensor network and outperforms existing techniques in terms of scalability, energy, and latency.

Index Terms—White space, Sensor Network, LPWAN, OFDM.

I. INTRODUCTION

Today, wireless sensor networks (WSNs) are emerging in large-scale and wide-area applications (e.g., urban sensing [1], oil field management [2], and precision agriculture [3]) that often need to connect thousands of sensors over long distances. Existing WSN technologies operating in the ISM bands such as IEEE 802.15.4 [4], IEEE 802.11 [5], and Bluetooth [6] have short range (e.g., 30-40m for IEEE 802.15.4 in 2.4GHz) that poses a significant challenge in meeting this impending demand. To cover a large area with numerous devices, they form multi-hop mesh networks at the expense of energy, cost, and complexity, limiting scalability. Low-Power Wide-Area Network (LPWAN) is becoming a promising Internet of Things (IoT) technology to overcome these range limits and scalability challenges [7], [8]. In this paper, we propose a highly scalable LPWAN architecture called Sensor Network Over White Spaces (SNOW) by designing sensor networks to operate over TV white spaces. White spaces refer to the allocated but locally unused TV channels, and can be used by unlicensed devices [9]. Compared to existing LPWAN technologies, SNOW offers higher scalability and energy-efficiency and takes the advantages of free TV white spaces.

Compared to the ISM bands, white spaces offer a large number of, less crowded channels, each 6MHz, in both rural and urban areas [10], [11]. The Federal Communications Commission (FCC) in the US mandates that a device needs to either sense the channel before transmitting, or consult with a cloud-hosted geo-location database [9] to determine the white spaces at a location. Similar regulations are adopted in many countries. Thanks to their lower frequencies (54 – 862MHz in the US), white spaces have excellent propagation characteristics over long distance and through obstacles, and hence hold enormous potential for WSN applications that need long communication range. To date, this potential has been exploited mostly for broadband access by industry leaders such as Microsoft [12] and Google [13] as well as by various standards bodies such as IEEE 802.11af [14], IEEE 802.22 [15], and IEEE 802.19 [16]. In contrast, our objective is to exploit them for wide-area, large-scale WSNs. Long transmission range will reduce many WSNs to single-hop that has potential to avoid the complexity, overhead, and latency associated with multi-hop. Such a paradigm shift faces the challenges that stem from long range such as increased chances of packet collision. It must also satisfy the typical requirements of WSNs such as low cost nodes, scalability, reliability, and energy efficiency.

We address the above challenges and requirements of WSN in the SNOW design. SNOW is the first design of a highly scalable low power and long range WSN over the TV white spaces initially presented in [17], [18]. At the heart of its design is a Distributed implementation of Orthogonal Frequency Division Multiplexing (OFDM), called D-OFDM. The base station (BS) splits the wide white space spectrum into narrowband orthogonal subcarriers allowing D-OFDM to carry parallel data streams to/from the distributed nodes from/to the BS. Each sensor uses only one narrow-band radio. The BS uses two wide-band radios, one for transmission and the other for reception, allowing transmission and reception in parallel. Each radio of the BS and a sensor is half-duplex and equipped with a single antenna. SNOW supports reliable, concurrent, and asynchronous receptions with one single-antenna radio and multiple concurrent data transmissions with the other single-antenna radio. This is achieved through a new physical layer (PHY) design by adopting D-OFDM for multiple access in both directions and through a lightweight Media Access Control (MAC) protocol. While OFDM has been embraced for multiple access in various wireless broadband and cellular technologies recently, its adoption in low power, low data rate, narrowband, and WSN design is novel. Taking the advantage of low data rate and short payloads, we adopt OFDM in WSN through a much simpler and energy-efficient design.

The key contributions of this paper are as follows.

- We design a D-OFDM based PHY for SNOW with the following features for scalability, low power, and long
range. (1) Using a single-antenna radio, the BS can receive concurrent transmissions made by the sensor nodes asynchronously. (2) Using a single-antenna radio, the BS can send different data to different nodes concurrently. (3) The BS can exploit fragmented white space spectrum. Note that the above design is different from MIMO radio adopted in various wireless domains such as LTE, WiMAX, and IEEE 802.11n [19] as they rely on multiple antennas to enable multiple transmissions and receptions. Setting up multiple antennas is expensive and difficult for lower frequencies due to large form factor and required space (half of wavelength) between antennas.

- We develop a lightweight MAC protocol that handles subcarrier allocation and operates the nodes with flexibility, low power, and reliability. It has the following features. (1) Considering a single half-duplex radio at each node and two half-duplex radios at the BS, we efficiently implement per-transmission ACK of the asynchronous transmissions by taking the advantage of D-OFDM design. (2) It combines CSMA/CA and location-aware subcarrier assignment for mitigating hidden terminals effects, thus enhancing the flexibility of the nodes that need to transmit asynchronously. (3) The other features include the capability of handling peer-to-peer communication, load balancing, and spectrum and network dynamics.

- We implement SNOW in GNU Radio [20] using Universal Software Radio Peripheral (USRP) [21] devices. In our experiments, a single radio of the SNOW BS can encode/decode 29 packets on/from 29 subcarriers within 0.1 ms to transmit/receive simultaneously, which is similar to standard encoding/decoding time for one packet.

- We perform experiments through SNOW deployments in three different radio environments - a city, a rural area, an indoor testbed. Both experiments and large-scale simulations show its high efficiency in terms of latency and energy with a linear increase in throughput with the number of nodes, demonstrating its superiority in scalability over existing designs.

**Organization.** Sections II, III, and IV describe the network architecture, PHY, and MAC protocol of SNOW, respectively. Sections V and VI present implementation and experiments, respectively. Sections VII and VIII compare SNOW with other LPWANs and related work. Section IX is the conclusion.

### II. SNOW Architecture

A WSN is characterized by small packets, low data rate, and low power [4], [22]. The nodes are typically battery-powered. Thus, scalability and energy efficiency are the key concerns in WSN design. We consider a lot of sensor nodes associated with a BS. Each sensor node (called ‘node’ throughout the paper) is equipped with a single half-duplex narrow-band radio operating in white space. Due to long transmission (Tx) range even at low power (e.g., several kilometers at 0dBm in our experiment in Section VI) of this radio, we consider that the nodes are directly connected (with a single hop) to the BS and vice versa as shown in Figure 1. However, the nodes may or may not be in communication ranges of the other nodes.

That is, some nodes can remain as hidden terminal to some other nodes. The BS and its associated nodes thus form a star topology. The nodes are power constrained and not directly connected to the Internet.

The BS uses a wide spectrum as a single channel that is split into subcarriers, each of equal spectrum width (bandwidth). Each node is assigned one subcarrier on which it transmits to and receives. For integrity check, the senders add cyclic redundancy check (CRC) at the end of each packet. We leave most complexities at the BS and keep the nodes simple and energy-efficient. The nodes do not do spectrum sensing or cloud access. The BS retrieves white space channels by inputting the locations of its own and all other nodes into a cloud-hosted database through the Internet as shown in Figure 1. We assume that it knows the locations of the nodes through manual configuration or some existing WSN localization technique such as those based on ultrasonic sensors or other sensing modalities [23]. Localization is out of the scope of this paper. We use two radios at the BS to support concurrent transmission and reception which will be described in Section IV.

### III. SNOW PHY Layer Design

The PHY layer of SNOW is designed to achieve scalable and robust bidirectional communication between the BS and numerous nodes. Specifically, it has three key design goals: (1) to allow the BS to receive concurrent and asynchronous transmissions from multiple nodes using a single antenna-radio; (2) to allow the BS to send different packets to multiple nodes concurrently using a single antenna-radio; and (3) to allow the BS to exploit fragmented spectrum.

#### A. Design Rationale

To achieve scalability and energy efficiency, the PHY layer of SNOW is designed using a Distributed implementation of OFDM for multi-user access, called D-OFDM in this paper. OFDM is a frequency-division multiplexing scheme to carry data on multiple parallel streams between a sender and a receiver using many orthogonal subcarrier signals. It has been adopted for multi-access in the forms of OFDMA (Orthogonal Frequency Division Multiple Access) and SC-FDMA (Single Carrier Frequency Division Multiple Access) in some broadband and cellular technologies recently [24] both of which require strong time synchronization among nodes. As a major difference from those, D-OFDM enables multiple receptions using a single antenna and also enables different
data transmissions to different nodes using a single antenna, and does not need time synchronization.

In SNOW, the BS’s wide white space spectrum is split into narrowband orthogonal subcarriers which carry parallel data streams to/from the distributed nodes from/to the BS as D-OFDM. Narrower bands have lower bit rate but longer range, and consume less power [25]. We adopt D-OFDM by assigning the orthogonal subcarriers to different nodes. Each node transmits and receives on the assigned subcarrier. Each subcarrier is modulated using Binary Phase Shift Keying (BPSK) which is highly robust due to a difference of 180° between two constellation points.

The key feature in OFDM is to maintain subcarrier orthogonality. If the integral of the product of two signals is zero over a time period $T$, they are orthogonal to each other. Two sinusoids with frequencies that are integer multiples of a common one satisfy this criterion [26], i.e., two subcarriers at center frequencies $f_1$ and $f_2$ are orthogonal when over $T$:

$$\int_0^T \cos(2\pi f_1 t) \cos(2\pi f_2 t) dt = 0.$$  

The orthogonal subcarriers can be overlapping, thus increasing spectral efficiency. As long as orthogonality is maintained, it is possible to recover the individual subcarriers’ signals.

In the downward communication in SNOW (when a single radio of the BS transmits different data to different nodes using a single transmission), OFDM encoding happens at a single radio at the BS while the distributed nodes decode their respective data from their respective subcarriers. In the upward communication (when many nodes transmit on different subcarriers to the BS), OFDM encoding happens in a distributed fashion on the nodes while a single radio at the BS decodes their data from the respective subcarriers.

Let the BS spectrum is split into $n$ orthogonal subcarriers: $f_1, f_2, f_3, \ldots, f_n$. Then, it can receive from at most $n$ nodes simultaneously. Similarly, it can carry $n$ different data at a time. When the number of nodes is larger than $n$, a subcarrier is shared by multiple nodes and their communication is governed by the MAC protocol (Section IV). To explain the PHY design we ignore subcarrier allocation and consider only the $n$ nodes that have occupied the subcarriers for transmission.

B. Upward Communication

Here we describe how we enable parallel receptions at a single radio at the BS. In D-OFDM, we adopt Fast Fourier Transformation (FFT) to extract information from all subcarriers. We allow the nodes to transmit on their respective subcarriers whenever they want without coordinating among themselves. Figure 2 shows a workflow of the steps for decoding packets from multiple subcarriers at the BS.

Every node independently encodes based on BPSK the data on its subcarrier. To decode a composite OFDM signal generated from orthogonal subcarriers from the distributed nodes, we adopt FFT as a Global FFT Algorithm (G-FFT) which runs a single FFT algorithm on the entire BS spectrum, instead of running a separate FFT to decode each of the concurrently received packets. Specifically, G-FFT runs a single FFT algorithm even if the BS spectrum is not continuous (i.e. some parts of the spectrum is unavailable or unused). Such an approach will help us decode asynchronous transmissions and also exploit fragmented white space spectrum using a single radio with a single FFT module. To receive asynchronous transmissions, the BS keeps running the G-FFT algorithm. Every incoming packet on any subcarrier follows preamble bits for packet detection. Once a preamble is detected on a subcarrier, the receiver immediately gets ready to receive subsequent bits of the packet. A vector $v$ of size equal to the number of FFT bins stores the received time domain samples. G-FFT is performed on $v$ at every cycle of the baseband signal.

For $n$ subcarriers, we apply an $m$ point G-FFT, where $m \geq n$ ($m$ is a multiple of $n$). Each subcarrier corresponds to $\frac{m}{n}$ bins with one middle bin representing its center frequency. The frequency bins are ordered from left to right with the left most $\frac{n}{2}$ bins representing the first subcarrier ($f_1$). Each FFT output gives a set of $m$ values. Each index in that set represents a single energy level and phase of the transmitted sample at the corresponding frequency at a time instant.

In BPSK, bit 0 and 1 are represented by keeping the phase of the carrier signal at 180° and 0° degree, respectively. We use a phase threshold that represents maximum allowable phase deviation in the received samples. One symbol is mapped into one bit. Since any node can transmit any time without any synchronization, the decoding of all packets is handled by maintaining a 2D matrix where each column represents a subcarrier or its center frequency bin that stores the bits decoded at that subcarrier. The last step in Figure 2 shows the 2D matrix where entry $b_{i,j}$ represents the $i$-th bit (for BPSK) of subcarrier $f_j$. The same process thus repeats.

Handling Spectrum Leakage. The G-FFT algorithm works on a finite set of time domain samples that represent one period of the signal. The captured signal may not be an integer multiple of periods, resulting in a truncated waveform. Thus, FFT outputs some spectral components that are not in the original signal, letting the energy at one spectral component leak into the neighboring ones. To mitigate the effects of such
Handling Carrier Frequency Offset:

In OFDM communication, the orthogonal subcarriers are subject to carrier frequency offset (CFO), thereby loosing orthogonality and introducing inter-carrier interference (ICI). CFO stems from a frequency mismatch between the local oscillators at the transmitter and receiver due to hardware non-ideality and also from the Doppler shift, which is a result of the relative motion between the transmitter and receiver in mobile environments. ICI caused by CFO attenuates the ideality and also from the Doppler shift, which is a result of the relative motion between the transmitter and receiver in mobile environments. For node joining, SNOW uses one (or more) subcarrier, called join subcarrier, that does not overlap with any other subcarrier. Each node joins the network by first communicating with the BS on a join subcarrier. Each way communication follows preamble that is used to estimate CFO on join subcarrier. Specifically, preamble from a node to BS allows to estimate CFO at the BS, and that from BS to a node allows to estimate CFO at the node on the join subcarrier. Later, based on the CFO on a join subcarrier, we determine the CFO on a node’s assigned subcarrier as described below. CFO estimation technique for both upward and downward communication is similar. However, we adopt different approach for CFO compensation in upward and downward communication. We first describe the CFO estimation technique.

First we explain how we estimate CFO on a join subcarrier \( f_i \). Since it does not overlap with other subcarriers, it is ICI-free. If \( f_{Tx} \) and \( f_{Rx} \) are the frequencies at the transmitter and at the receiver, respectively, then their frequency offset \( \Delta f = f_{Tx} - f_{Rx} \). For transmitted signal \( x(t) \), the received signal \( y(t) \) that experiences a CFO of \( \Delta f \) is given by

\[
y(t) = x(t) e^{j2\pi \Delta f t}
\]

We estimate \( \Delta f \) based on short and long preamble approach, similar to IEEE 802.11a [28], using time-domain samples. In our implementation, we divide a 32-bit preamble into two equal parts, each of 16 bits. First part is for coarse estimation and the second part is for finer estimation of CFO [28]. Considering \( \Delta t \) as the short preamble duration,

\[
y(t - \Delta t) = x(t) e^{j2\pi \Delta f (t - \Delta t)}.
\]

Since \( y(t) \) and \( y(t - \Delta t) \) are known at the receiver,

\[
y(t - \Delta t)y^*(t) = x(t) e^{j2\pi \Delta f (t - \Delta t)} x^*(t) e^{-j2\pi \Delta f t} = |x(t)|^2 e^{j2\pi \Delta f - j\Delta t}
\]

Taking angle of both sides,

\[
\angle y(t - \Delta t)y^*(t) = \angle |x(t)|^2 e^{j2\pi \Delta f - j\Delta t} = 2\pi \Delta f \Delta t.
\]

Thus,

\[
\Delta f = -\frac{\angle y(t - \Delta t)y^*(t)}{2\pi \Delta t}.
\]

A SNOW node calculates the CFO on join subcarrier \( f_i \) using the preambles from the BS to the node using the above approach. Note that, for upward communication, the BS keeps running G-FFT on the entire BS spectrum including the join subcarrier as other nodes may be transmitting to it. Therefore, the G-FFT outputs for the join subcarrier are converted to time-domain samples using Inverse FFT (IFFT). These time-domain samples are used for CFO estimation on the join subcarrier \( f_i \) at the BS based on the above approach. Then the ppm (parts per million) on the receiver’s (BS or SNOW node) crystal is given by \( ppm = 10^6 \frac{\Delta f}{f_i} \). Thus, the receiver (BS or a node) calculates \( \Delta f_i \) on subcarrier \( f_i \) as

\[
\Delta f_i = \frac{f_i \times ppm}{10^6}.
\]

Thus the BS and a SNOW node that is assigned subcarrier \( f_i \) calculates CFO on \( f_i \) on its respective side. To take into account Doppler shift, CFO has to be estimated using the above approach while a node moves. For simplicity, we do not consider mobility and ignore CFO due to Doppler shift.

As the nodes asynchronously transmit to the BS, doing the CFO compensation for each subcarrier at the BS is quite difficult. Hence we adopt a simple feedback approach for proactive CFO correction in upward communication. \( \Delta f_i \) estimated at the BS for subcarrier \( f_i \) is given to the node (through downward transmission) that is assigned \( f_i \) during its joining process. The node can then adjust its transmitted signal based on \( \Delta f_i \) (when transmitting on subcarrier \( f_i \)) which will align its signal so that the BS does not need to compensate for \( \Delta f_i \). Such feedback based proactive compensation scheme was studied before for multiple access OFDM [29] and is also used in global system for mobile communication (GSM).

C. Downward Communication

One of our key objectives is to enable transmission from the BS which will encode different data on different subcarriers. A node’s data will be encoded on the associated subcarrier. The BS then makes a single transmission and all nodes will decode data from their respective subcarriers. In the following, we describe our technique to achieve this.

Our goal in D-OFDM is to enable distributed demodulation at the nodes without any coordination among them. That is, from the received OFDM signal, every node will independently decode the data from the signal component on its subcarrier only. The main design technique lies in the encoding part at the BS. We enable this by adopting IFFT (Inverse FFT) at the transmitter side. IFFT is performed after encoding data on the subcarriers. We can encode data on any subset of the subcarriers. The transmission is made after IFFT. If the OFDM transmitter uses \( m \) point IFFT algorithm, consecutive \( m \) symbols of the original data are encoded in \( m \) different frequencies of the time domain signal with each...
run of IFFT. We encode different symbols for different nodes on different subcarriers, thus obviating any synchronization between symbols. We use a vector \( v \) of size equal to the number of IFFT bins. Each index of \( v \) is a frequency bin. If the BS has any data for node \( i \), it maps one unit of the data to a symbol and puts in the \( i \)-th index. If it has data for multiple nodes, it creates multiple symbols and puts in the respective indices of \( v \). Then the IFFT algorithm is performed on \( v \) and a composite time domain signal with data encoded in different frequencies is generated and transmitted. This repeats at every cycle of baseband signal. A node listens to its subcarrier center frequency and receives only the signal component in its subcarrier frequency. The node then decodes data from it.

**Handling CFO.** In Section III-B, we have already described how a node that is assigned subcarrier \( f_i \) estimates CFO \( \Delta f_i \). In downward communication, the node compensates for CFO in time-domain using Equation (1).

![Graph showing CDR under varying SF, packet sizes](image1)

(a) CDR under varying SF, packet sizes

![Graph showing BER over distances when SF=8](image2)

(b) BER over distances when SF=8

**Fig. 3.** Determining spreading factor

**D. Using Fragmented Spectrum**

An added advantage of our design is that it allows to use fragmented spectrum. When we cannot find consecutive white space channels while needing more, we may use non-consecutive channels. The G-FFT and IFFT algorithms will be run on the entire spectrum as a single wide channel that includes all fragments (and the occupied TV channels between them). The occupied spectrum will not be assigned to any node and the corresponding bins will be ignored in decoding and encoding in G-FFT and IFFT, respectively.

**E. Design Considerations**

1) **Link parameters:** Bit spreading is a technique to reduce bit errors by transmitting redundant bits for ease of decoding in noisy environments [4], [5]. By adopting a proper spreading factor, its effects can be made similar to extended Cyclic Prefix (CP), thereby significantly mitigating inter-symbol interference (ISI). Specifically, in D-OFDM, time synchronization is avoided by extending the symbol duration (repeating a symbol multiple times) and sacrificing bit rate. The effect is similar to extending CP beyond what is required to control ISI. CPs of adequate lengths have the effect of rendering asynchronous signals to appear orthogonal at the receiver, increasing the guard-interval. As it reduces data rate, D-OFDM is suitable for LPWANs. Using USRP devices in TV white spaces and using narrow bandwidth (400kHz) we tested with different packet sizes and bit spreading factors (SF). We define **Correctly Decoding Rate (CDR)** - as the ratio of the number of correctly decoded packets at the receiver to the total number of packets transmitted. A receiver can always decode over 90% of the packets when the sender is 1.1km away and transmits at 0 dBm (Figure 3(a)). Figure 3(b) shows that bit error rate (BER) remains negligible under varying distances (tested up to 1.1km). For wireless communications, a packet is usually dropped if its BER exceeds \( 10^{-3} \) [30]. Thus we will use SF=8 as our experiments found it to be sufficient for robust communication. We have tested the feasibility of different packet sizes (Figure 3(a)). WSN packet sizes are usually short. For example, TinyOS [31] (a platform/OS for WSN motes based on IEEE 802.15.4) has a default payload size of 28 bytes. We use 40-byte (28 bytes payload + 12 bytes header) as our default packet size in our experiment.

Note that, like many other LPWANs (e.g., LoRa, SigFox) and most WSN devices, we also do not do channel estimation to keep node design very simple. Choosing an effective bit spreading factor allows us to decode without estimating channel. It is understandable that channel state information can help us better mitigate the multipath effects, specially in indoor environments. In the future, we shall study the trade-offs between the overhead of channel estimation in low-power node design and the reliability gain through it.

2) **Subcarriers:** The maximum transmission bit rate \( R \) of an AWGN channel of bandwidth \( W \) based on Shannon-Hartley Theorem is given by \( R = W \log_2(1 + SNR) \), where SNR is the **Signal to Noise Ratio**. Based on Nyquist Theorem, \( R = 2W\log_2 2^k \) where \( k \) is the number of bits per symbol (\( 2^k \) being the number of signal levels) needed to support bit rate \( R \) for a noiseless channel. The 802.15.4 specification for lower frequency band, e.g., 430-434MHz band (IEEE 802.15.4e [32]), has a bit rate of 50kbps. We also aim to achieve this bit rate. We consider a minimum value of 3dB for SNR in decoding. Taking into account default \( SF = 8 \), we need to have 50 * 8kbps bit rate in the medium. Thus, a subcarrier of bandwidth 200kHz can have a bit rate up to 50 * 8kbps in the medium. Since BPSK has \( k = 1 \), it is theoretically sufficient for this bit rate and bandwidth under no noise. Using similar setup as the above, Figure 4(a) shows the feasibility of various bandwidths. In our experiments, 400kHz bandwidth provides our required bit rate under noise. Hence, we use 400kHz as our default subcarrier bandwidth. We have also experimentally found that our 400kHz subcarriers can safely overlap up to 50% with the neighboring ones (as shown in Figure 4(b)). In our low data rate communication, using a
IV. SNOW MAC PROTOCOL

We develop a lightweight MAC protocol for operating the nodes with flexibility, low power, and reliability. As the nodes transmit asynchronously to the BS, implementing ACK for every transmission is difficult. Considering a single half-duplex radio at each node and two half-duplex radios (both operating on the same spectrum) at the BS, we demonstrate that we can implement ACK immediately after a transmission. Under such a design decision in SNOW, we can exploit the characteristics of our D-OFDM system to enable concurrent transmissions and receptions at the BS.

A. Location-Aware Spectrum Allocation

This BS spectrum is split into $n$ overlapping orthogonal subcarriers: $f_1, f_2, \cdots, f_n$, each of equal width. Considering $w$ as the subcarrier bandwidth, $W$ as the total bandwidth at the BS, and $\alpha$ as the magnitude of overlap of the subcarriers (i.e., how much two neighboring subcarriers can overlap),

$$n = \frac{W}{w\alpha} - 1.$$ 

For example, when $\alpha = 50\%$, $W=6\text{MHz}$, $w=400\text{kHz}$, we can have $n = 29$ orthogonal subcarriers. The BS can use a vector to maintain the status of these subcarriers by keeping their noise level or airtime utilization (considering their usage by surrounding networks), and can dynamically occupy or leave some subcarrier. Since our PHY can use fragmented spectrum, such dynamism at the MAC layer is feasible.

Subcarrier allocation is done at the BS. Each node is assigned one subcarrier. Let $g(u)$ denote the subcarrier assigned to node $u$. When the number of nodes is no greater than the number of subcarriers, i.e. $N \leq n$, every node is assigned a unique subcarrier. Otherwise, a subcarrier is shared by more than one node. The nodes that share the same subcarrier will contend for and access it using a CSMA/CA policy that we will describe in Section IV-B. The subcarrier allocation aims to minimize interference and contention among the nodes. Hence, if two nodes $u$ and $v$ are hidden to each other, we aim to assign them different subcarriers (i.e., $g(u) \neq g(v)$), if possible. If two nodes that were hidden to each other are assigned different subcarriers, the hidden node problem is removed. We also should ensure that there is not excessive contention (among the nodes that are in communication range of each other) on some subcarrier. Let $H(u)$ denote the estimated set of nodes that are hidden terminal to $u$ (when using the same subcarrier). Note that the BS is assumed to know the node locations (see Section II). Hence, it can estimate $H(u)$ for any node $u$ based on the locations and estimated communication range of the nodes. Let $\Phi(f_i)$ be the set of nodes that are assigned subcarrier $f_i$. In the beginning, $\Phi(f_i) = \emptyset$, $\forall i$. For every node $u$ whose subcarrier is not yet assigned, we do the following. We assign it a subcarrier such that $|\Phi(g(u))\cap H(u)|$ is minimum. If there is more than one such subcarrier, then we assign the one with minimum $|\Phi(g(u))|$. After this assignment, hidden terminals of the associated nodes are updated. Thus, our approach reduces the impact of hidden terminal problem.

B. Transmission Policy

In SNOW, the nodes transmit to the BS using a CSMA/CA approach. It keeps the nodes more flexibility, decentralized, and energy efficient. We do not need to adopt time synchronization, time slot allocation, or to preschedule the nodes. The nodes will sleep (by turning off the radios), and will wake up if they have data to send. After sending the data, a node will go back to sleep again. This will provide high energy-efficiency to the power constrained nodes. We adopt a CSMA/CA policy similar to the one implemented in TinyOS [31] for low power sensor nodes which is very simple (with no RTS/CTS). It uses a static interval for random back-off. Specifically, when a node has data to send, it wakes up by turning its radio on. Then it performs a random back-off in a fixed initial back-off window. When the back-off timer expires, it runs CCA (Clear Channel Assessment) and if the subcarrier is clear, it transmits the data. If the subcarrier is occupied, then the node makes a random back-off in a fixed congestion back-off window. After this back-off expires, if the subcarrier is clean the node transmits immediately. This process is repeated until it makes the transmission. The node then can go to sleep again.

The BS station always remains awake to listen to nodes’ requests. The nodes can send whenever they want. There can
also be messages from the BS such as management message (e.g., network management, subcarrier reallocation, control message etc.). Hence, we adopt a periodic beacon approach for downward messages. Specifically, the BS periodically sends a beacon containing the needed information for each node through a single message. The nodes are informed of this period. Any node that wants/needs to listen to the BS message can wake up or remain awake (until the next message) accordingly to listen to the BS. The nodes can wake up and sleep autonomously. Note that the BS can encode different data on different subcarriers, carrying different information on different subcarriers if needed, and send all those as a single OFDM message. As explained in Section III-C, the message upon reception will be decoded at the nodes, each node decoding only the data carried in its subcarrier.

C. Handling ACK

Sending ACK after every transmission is crucial but poses a number of challenges. First, since the nodes asynchronously transmit, if the BS sends ACK after every reception, it may lose many packets from other nodes when it switches to Tx mode. Second, the BS uses a wide channel while the node needing ACK uses only a narrow subcarrier of the channel. The AP needs to switch to that particular subcarrier which is expensive as such switching is needed after every packet reception. Note that the BS can receive many packets in parallel and asynchronously. Thus when and how these packets can be acknowledged is a difficult question. We adopt a dual radio design at the BS of SNOW which is a practical choice as the BS is power-rich. Thus the BS will have two radios - one for only transmission, called Tx radio, and the other for only reception, called Rx radio. The Tx radio will make all transmissions whenever needed and can sleep when there is no Tx needed. The Rx radio will always remain in receive mode to receive packets. As shown in Figure 5, both radios use the same spectrum and have the same subcarriers - the subcarriers in the Rx radio are for receiving while the same in the Tx radio are for transmitting. Such a dual radio BS design will allow us to enable n concurrent transmissions and receptions. Since each node (non BS) has just a single half-duplex radio, it can be either receiving or transmitting, but not doing both at a time. Thus if k out of n subcarriers are transmitting, the remaining n - k subcarriers can be receiving, thereby making at most n concurrent transmissions/receptions.

Handling ACK and two-way communication using a dual-radio BS still poses the following challenges. First, while the two radios at the BS are connected in the same module and the Tx radio can send an ACK immediately after a packet is received on the Rx radio, it has to send ACK only to the nodes from which it received packet. Thus some subcarriers will need to have ACK frame while the remaining ones may carry nothing or some data packet. While our PHY design allows to handle this, the challenge is that some ACK/s can be due while the radio is already transmitting some ACK/s. The key question is: “How can we enable ACK immediately after a packet is received at the BS?” Second, another serious challenge is that the receptions at the Rx radio can be severely interfered by the ongoing transmissions at the Tx radio as both radios operate on the same spectrum and are close to each other. Third, ACK on a subcarrier can be interfered if a node sharing it starts transmitting before the said ACK is complete.

D-OFDM allows us to encode any data on any subcarrier while the radio is transmitting. Thus the design allows us to encode any time on any number of subcarriers and enable ACKs to asynchronous transmissions. If there is nothing to transmit, the Tx radio sleeps. Since a node has a single half-duplex radio, it will either transmit or receive. Let us first consider for a subcarrier which is assigned to only one node such as subcarrier f1 in Figure 5 assigned only to z. Node z will be in receive mode (waiting for ACK) when the Tx radio at the BS sends ACK on f1. Now consider for a subcarrier which is assigned to more than one node such as subcarrier f3 in Figure 5 which is assigned to u and v. When u is receiving ACK from the BS, if v needs to transmit it will sense the subcarrier busy and make random back-off. Thus any node sharing a subcarrier f1 will not interfere an ACK on f1. Hence, transmitting ACK on a subcarrier f1 from the Tx radio has nothing to interfere at f1 of the Rx radio at the BS. Subcarrier f1 at Rx will be receiving the ACK on it sent by the Tx radio and can be ignored by the decoder at the Rx radio. Thus the subcarriers which are encoded with ACKs at the Tx radio will have energy. The remaining ones that are not encoded with ACK/data have no energy. During this time, the nodes may be transmitting on those subcarriers. Thus when the Tx radio transmits, its un-encoded subcarriers cannot interfere the same subcarriers at the Rx radio. The subcarriers carrying ACKs are orthogonal to them and will not interfere either.

D. Other Features of The MAC Protocol

1) Further Mitigating Hidden Terminal Problem: We partially handle hidden terminal problem in subcarrier allocation and MAC protocol. Consider nodes u and v in Figure 5 both of which are assigned subcarrier f3. Now consider u and v are hidden to each other. When the TX radio of the BS sends ACK to node u that has just made a transmission to the BS, this ACK signal will have high energy on the subcarrier f3 at the Rx radio of the BS. At this time, if node v makes a transmission to the BS, it will be interfered. Since v will run CCA and sense the energy on f3 it will not transmit. This result is somewhat similar to that of the CTS frame used in WiFi networks to combat hidden terminal problem.

2) Peer-to-Peer Communication: Two nodes that want to communicate can be hidden to each other or may have different subcarriers. Hence, we adopt peer-to-peer communication through the BS. For example, in Figure 5, if node a wants to send a packet to node b, it cannot send directly as they use different subcarriers. First, a transmits to the BS on subcarrier f2, and then the BS transmits to b on subcarrier f1 (in its next beacon when b will wake up if it is sleeping).

3) Handling Various Dynamics: First, we handle spectrum dynamics as follows. When the BS’s spectrum availability changes due to primary user activity, the BS performs a new spectrum allocation. The nodes whose subcarriers may no more be available may have no way to know the new
subcarrier allocation. We handle this by allocating one or more backup subcarriers (similar to backup whitespace channels adopted in [10]). If a node does not receive any beacon for a certain interval, it will assume that its subcarrier is no more available and will switch to a backup subcarrier and wait for BS message. The BS will keep sending rescue information on that backup subcarrier which will be received by that node. For robustness, we maintain multiple backup subcarriers.

Second, we share the loads among the subcarriers by reallocating or swapping. That is, if a subcarrier becomes congested we can un-assign some node from it and assign it a less congested one. Third, we allocate some subcarrier for node joining and leaving. When a new node wants to join the network, it communicates with the BS on this subcarrier. It can transmit its identity and location to the BS. The BS then assigns it an available subcarrier. Similarly, any node from which the BS has not received any packet for a certain time window can be excluded from the network.

We implement the decoder at the BS using 64-OFDM. GNU Radio is software-defined radio [21]. USRP is a hardware platform to transmit and receive for software-defined radio [21]. We have used 9 USRP devices (2 as BS and 7 as SNOW nodes) in our experiment. Two of our devices were USRP B210 while the remaining are USRP B200, each operating on band 70 MHz - 6GHz. The packets are generated in IEEE 802.15.4 structure with random payloads. We implement the decoder at the BS using 64-point G-FFT which is sufficient due to our limited number of devices. In downward communication, multiple parallel packet lines are BPSK modulated on the fly and fed into a streams-to-vector block that is fed into IFFT that generates a composite time domain signal.

VI. EXPERIMENTS

We deployed SNOW in the Detroit metropolitan area (Michigan), in an indoor environment, and in a rural area of Rolla (Missouri) to observe its performance in various radio environments. In the following subsections, we describe our experimental results in these three deployments. We also compare its performance with existing technologies.

A. Deployment in A Metropolitan City Area

1) Setup: Figure 6 shows different nodes and the BS positions of our deployment in the Detroit metropolitan area. Due to varying distances (max. $\approx 1.1\text{km}$) and obstacles between the BS and these nodes, the SNR of received signals varies across these node positions. We keep all of the antenna heights at 5ft above the ground. Unless mentioned otherwise, Table I shows the default parameter settings for all experiments.

2) Reliability over Distances and Tx Power: To demonstrate the reliability at various distances, we place the nodes at 300m, 500m, 700m, 900m, and 1100m away from the BS, respectively. At each distance, each node transmits 10,000 packets asynchronously to the BS and vice versa. CDR (which indicates the correctly decoding rate as defined in Section III-E1) is used as a key metric in our evaluation. Figure 7(a) demonstrates uplink reliability under varying subcarrier bandwidths when the nodes are at different distances from the BS and all transmit at 0dBm. As all nodes transmit at the same Tx power from different distances, the uplink communication in this scenario is subject to near-far effect. Namely, the signals at the BS from the nearer transmitters are stronger than those from the farther transmitters, thereby causing packet loss from the formers. This happens because the side-lobes of the stronger signals from nearby nodes may overwhelm the weaker signals from the faraway nodes. In our setup, the maximum difference between the distances of any pair of transmitters from the BS is $\approx 1\text{km}$. Yet, we have observed at least 98% CDR from all transmitters (Figure 7(a)) which indicates that this distance difference is not enough to cause near-far effect. This is reasonable because near-far effect is relatively lesser in D-OFDM, compared to CDMA (Code Division Multiple Access) where it is quite high, due to orthogonality of the signals. It needs more extensive experiments and perhaps very large differences between the node distances to observe the effect of near-far problem, which we have not explored in this paper.

Figure 7(b) demonstrates high reliability in downlink under varying distances. As shown at five different nodes for a subcarrier bandwidth of 400kHz, all the nodes can decode more than 99.5% of the packets even though they are 1.1km away from the BS. To demonstrate the feasibility of adopting SNOW in LPWAN, we moved one node much farther away from the BS and vary the Tx power from 0 dBm up to 20 dBm. As shown in Figure 7(c), with 20dBm of Tx power, SNOW BS can decode from approximately 8km away, hence showing its competences as an LPWAN technology.

3) Maximum Achievable Throughput: In this experiment, we evaluate the maximum achievable throughput (i.e., maximum total bits that the BS can receive per second) in SNOW.

![Node positions in the Detroit metropolitan area.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<td>Frequency Band</td>
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</tr>
<tr>
<td>Orthogonal Frequencies</td>
<td>574.4, 574.6, 574.8, 575.0, 575.2, 575.4, 575.6, 575.8MHz</td>
</tr>
<tr>
<td>Subcarrier modulation</td>
<td>BPSK</td>
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<tr>
<td>Packet Size</td>
<td>40 bytes</td>
</tr>
<tr>
<td>BS Bandwidth</td>
<td>6MHz</td>
</tr>
<tr>
<td>Node Bandwidth</td>
<td>400kHz</td>
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<tr>
<td>Spreading Factor</td>
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</tr>
<tr>
<td>Transmit (Tx) Power</td>
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</tr>
<tr>
<td>Receive Sensitivity</td>
<td>-94dBm</td>
</tr>
<tr>
<td>SNR</td>
<td>6dB</td>
</tr>
<tr>
<td>Distance</td>
<td>1.1km</td>
</tr>
</tbody>
</table>

**TABLE I**

**DEFAULT PARAMETER SETTINGS**
Each node transmits 10,000 packets, each of 40 bytes. In SNOW, after each transmission a node waits for its ACK (hence it does not continuously transmit). Figure 8 shows that SNOW can achieve approximately 270kbps when 7 nodes transmit. We consider the maximum achievable throughput in a typical IEEE 802.15.4 based WSN of 250kbps bit rate as a baseline. Its maximum achievable throughput is shown considering ACK after each transmission. As expected, the number of nodes does not impact its maximum achievable throughput as its BS can receive at most one packet at a time. A channel in the IEEE 802.15.4 based network is much wider than a SNOW subcarrier and has a higher bit rate (250kbps vs 50kbps). Hence, SNOW surpasses the baseline when it has at least 6 nodes. But the SNOW throughput keeps increasing linearly with the number of nodes while that in the baseline remains unchanged. Thus, although we have results for up to 7 nodes, the linear increase in SNOW throughput gives a clear message that it is superior in throughput and scalability to any protocol used for traditional WSN.

<table>
<thead>
<tr>
<th>Device mode</th>
<th>Current Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx</td>
<td>17.3 mA</td>
</tr>
<tr>
<td>Rx</td>
<td>18.8 mA</td>
</tr>
<tr>
<td>Idle</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.2 μA</td>
</tr>
</tbody>
</table>

**TABLE II**

| Current consumption in CC1070 |

4) **Energy Consumption and Latency:** To demonstrate the efficiency in terms of energy and latency, we compare SNOW with a traditional WSN design. Specifically, we consider A-MAC [33] which is an energy efficient MAC protocol for IEEE 802.15.4 based WSN. To estimate the energy consumption and network latency in SNOW nodes, we place 7 nodes each 280m apart from the BS. For a fair comparison, for A-MAC, we place the nodes 40m apart from each other making a linear multi-hop network due to their shorter communication ranges.

In both of the networks, we start a convergecast after every 60 seconds. That is, each node except the BS generates a packet every 60 seconds that is ready to be transmitted. Our objective is to collect all the packets at the BS.

Since the USRP devices do not provide any energy consumption information, we use the energy model of CC1070 by Texas Instruments [34]. This off-the-shelf radio chip operates in low frequencies near TV white spaces and also uses BPSK modulation. Table II shows the energy model of CC1070. Since the BS is line-powered, we keep it out of the energy calculation. We run multiple rounds of convergecast for 2 hours in both of the networks. Figure 9(a) shows the average energy consumption in each node per convergecast. Regardless of the number of nodes, on average a SNOW node consumes nearly 0.46mJ energy. On the other hand in A-MAC, on average each node consumes nearly 1.2mJ when 7 nodes participate in convergecast. For a large number of nodes, this value will be very high. Figure 9(b) shows the convergecast latency in both SNOW and A-MAC. We calculate the total time to collect all the packets at the BS from all the nodes counting from the time the packets were generated at the
nodes. SNOW takes approximately 8.3ms while A-MAC takes nearly 77ms to collect packets from all 7 nodes. Theoretically, SNOW should take almost constant amount of time to collect all the packets as long as the number of nodes is no greater than that of available subcarriers. Again, due to a small network size, the differences between SNOW and A-MAC are not significant in this experiment.

**Energy and Latency over Distances.** Using the same setups as the above, Figure 10 compares energy and latency between SNOW and A-MAC over distances. Figure 10(a) shows that, a node in SNOW consumes on average 0.475mJ of energy to deliver a packet to the BS that is 280m away. On the other hand, an A-MAC node consumes nearly 1.3mJ of energy to deliver one packet to a sink that is 280m away. Also, Figure 10(b) shows that a SNOW and A-MAC node takes 8.33ms and 92.1ms of latency to deliver one packet to the BS, respectively. As the distance increases, the differences become higher, demonstrating SNOW’s superiority.

5) **Handling Hidden Terminal Problem:** To test the performance of SNOW under hidden terminal, we adjust the Tx powers of the nodes at the positions shown in Figure 6 so that (i) nodes A, B and C are hidden to nodes D and E; (ii) D and E are not hidden to each other; (iii) A, B and C are not hidden to each other. We conduct two experiments. In experiment 1 (Exp1), the hidden nodes are assigned the same subcarriers. For example, the BS assigns one subcarrier to node A and D (hidden to each other), another subcarrier to nodes B, D and E (B is hidden to D and E). In experiment 2 (Exp2), the BS assigns different subcarriers to the nodes hidden to each other. Exp2 reflects the SNOW MAC protocol. Each node sends 100 packets to the BS in both experimental setups. After getting the ACK for each packet (or, waiting until ACK reception time), each node sleeps for a random time interval between 0-50ms. After sending 100 packets, each node calculates its packet loss rate and averages it. We repeat this experiment for 2 hours. Figure 11 shows the CDF of average packet loss rate. In Exp1, average packet loss rate is 65% while in SNOW MAC protocol (Exp2) it is 0.9%, which demonstrates the benefits of incorporating location-aware subcarrier allocation.

6) **Using Fragmented Spectrum:** To test the performance of SNOW under fragmented spectrum, we choose different local TV channels such that there are white spaces available on both sides. For this experiment, the BS bandwidth is chosen to be 8 MHz, where the middle 6 MHz is occupied by a TV channel. We use two SNOW nodes that will transmit to the BS and do three experiments. In each experiment, the BS uses a different 8MHz bandwidth having a different TV channel (6MHz) in the middle. In each experiment, the SNOW nodes send 100 consecutive packets and then randomly sleep between 500 to 1000ms. We run each experiment for 2 hours. In all experiments, we run G-FFT over the entire 8MHz channel and collect data from the SNOW nodes only. Under different fragmented spectrum, the SINR (signal-to-interference-plus-noise ratio) is different as the TV channels change. Figure 12 shows three sets of experiments on fragmented spectrum, each having different ranges of SINR condition. In experiment 1, the SINR varies from 3 to 5dB and SNOW achieves at least 95% CDR in at least 96% cases. In experiment 2, the SINR varies from 6 to 8dB that results in at least 99% CDR in 90% cases. Experiment 3 with varying SINR from 9 to 11dB or more shows even better CDR. The results show that SNOW works well under fragmented spectrum.

7) **BS Encoding Time and Decoding Time:** Although we have seven devices to act as SNOW nodes, we can calculate the data encoding time or decoding time in all 29 subcarriers at the BS as it depends on the number of bins in the IFFT algorithm. Theoretically, the encoding/decoding time for any number of nodes at the BS should be constant as the IFFT/G-FFT algorithm runs with the same number of bins every time. However, we do separate experiments by encoding/decoding
data to/from 1 to 29 nodes. We run each experiment for 10 minutes and record the time needed in the worst case. Figure 13 shows that both encoding time and decoding time are within 0.1ms. This encoding/decoding time is very short as IFFT/G-FFT runs very fast, and is similar to standard encoding/decoding time in WSNs for one packet.

![Fig. 13. Encoding and decoding time](image)

B. Indoor Deployment

1) Setup: Figure 14(a) shows the positions of the SNOW nodes and BS (on floor plan) all on the same floor (293,000 sq ft) of the Computer Science Building at Wayne State University. We fixed the position of the BS (receiver) while changing the positions of the node. In this experiment a node transmits 10,000 consecutive packets at each position.

2) Results: Figure 14(b) shows the CDR over various SNR conditions under varying subcarrier bandwidths. At SNR of 3dB the CDR is around 98.5% for all bandwidths. We observe that increasing the SNR, the CDR increases accordingly for all bandwidths. This is due to the effect of noise, obstacles, and multipath over SNR. Figure 14(c) shows CDR under varying number of walls between sender and receiver. We achieve at least 98.5% CDR when the line of sight is obstructed by up to 7 walls (each 12” concrete). SNOW achieves reliable communication even in indoor environments due to low frequency and narrow bandwidth.

C. Deployment in A Rural Area

1) Setup: A rural deployment of SNOW is characterized by two key advantages - higher availability of TV white spaces and longer communication range due to lesser absence of obstacles such as buildings. We deployed SNOW in a rural area of Rolla, Missouri. In this deployment, we used five USRP devices that acted as SNOW nodes. We follow the similar antenna and default parameter setup as described in Section VI-A1 and Table I.

2) Distance, Reliability, and Throughput: The map embedded in Figure 15(a) shows the locations of the BS and a node 2km away from the BS. The node transmits 1000 40-byte packets consecutively. The same figure shows the reliability (in terms of CDR) of the link under varying Tx power. Specifically, SNOW achieves 2km+ communication range at only 0 dBm Tx power which is almost double that we observed in our urban deployment. This happens due to a cleaner light of sight in the former. Similarly, Figure 15(b) shows the BER at the SNOW BS while decoding packets from various distances. The results show the decodability of the packets transmitted (at 0dBm) from 2km away as BER remains \( \leq 10^{-3} \). Like our urban deployment, here also SNOW’s maximum achievable throughput linearly increases with the number of nodes (Figure 15(c)).

VII. COMPARISON WITH EXISTING LPWANs

A. SNOW vs LoRa/SIGFOX

LPWANs are emerging as a key technology driving the IoT, with multiple competing technologies being offered or under development. SIGFOX [7] and LoRa [8] are two very recent LPWAN technologies that operate in the unlicensed ISM band. Their devices require to adopt duty cycled transmission of only 1% or 0.1% making them less suitable for many WSNs that involve real-time applications or that need frequent sampling. SIGFOX supports a data rate of 10 to 1,000bps. A message is of 12 bytes, and a device can send at most 140 messages per day. Each message transmission typically takes 3s [35] while SNOW can transmit such a 12-byte message in less than 2ms.

Semtech LoRa modulation employs Orthogonal Variable Spreading Factor (OVSF) which enables multiple spread signals to be transmitted at the same time and on the same channel. OVSF is an implementation of traditional CDMA where, before transmission, each signal is spread over a wide spectrum range through a user’s code. Using 125KHz bandwidth and a LoRa spreading factor (LoRa-SF) of 10, a 10-byte payload packet in LoRa has an air time of 264.2ms typically [36], which is at least 100 times that in SNOW for the same-size message (according to our experiments). The higher the LoRa-SF, the slower the transmission and the lower the bit rate in LoRa. This problem is exacerbated by the fact that large LoRa-SFs are used more often than the smaller ones [37]. According to the LoRa specification [8], its range in urban area is 2–5 km and in rural area is 15–20 km. As Figure 7(c) shows, SNOW range is approximately 8km near urban areas (suburban), showing a similar communication ranges. Some recent studies have however shown that, without line of sight, LoRa communication range is quite small [38], specially indoors where it was found to be at most 100m [39].

1) Scalability Analysis: One important limitation of OVSF is that the users’ codes have to be mutually orthogonal to each other, limiting the scalability. LoRa uses 6 orthogonal LoRa-SFs (12 to 7), thus allowing up to 6 different transmissions on a LoRa channel of any bandwidth simultaneously. Using one TV channel (6MHz wide), we can get 29 OFDM subcarriers (each 400kHz) for SNOW which enables 29 simultaneous transmissions. Using a narrower bandwidth like SIGFOX/LoRa would yield even a higher number of subcarriers per channel in SNOW. Using \( n' \) white space channels, its number of simultaneous transmissions multiplies by \( n' \).

Scalability of SIGFOX/LoRa is achieved assuming extremely low traffic. For example, if a device sends one packet per hour, a LoRaWAN SX1301 gateway (that uses 8 separate radios) can handle about 62,500 devices [8]. With its 12-byte message and 140 messages per device per day, one SIGFOX gateway can support 1 million devices [7]. We now estimate the scalability of SNOW for this communication scenario. Using one TV channel (6MHz width), we can get 29 OFDM subcarriers.
subcarriers (each 400kHz). The total time for a 12-byte message transaction between a SNOW node and the BS is less than 2ms (including Tx-Rx turnaround time). A group of 29 nodes can transmit simultaneously, each on a distinct subcarrier. Note that SNOW uses an asynchronous MAC protocol for flexibility and scalability. We can reduce the MAC protocol to a simple polling scheme to roughly estimate the number of nodes that can be supported comfortably in a SNOW of a single BS. Specifically, every time we can schedule 29 nodes (n nodes) to transmit simultaneously. If every device sends 140 messages per day (like SIGFOX), every subcarrier can be shared by \( \frac{24 \times 3600 \times 1000}{4.45} > 308,571 \) devices. Thus 29 subcarriers can be shared by 308,571 * 29 > 8.9 million devices.

If we consider a downward message after every group of simultaneous transmissions by 29 nodes to schedule the next group of transmissions, SNOW with one white space channel can support at least 8.9/2 = 4.45 million devices. Using \( m' \) channels, it can support 4.45 * \( m' \) million devices. This back-of-envelope calculation indicates that SNOW can support a significantly larger number of devices than SIGFOX/LoRa. Next, we will compare their performance in simulations.

2) Energy and Latency in Simulation: For large-scale evaluation of SNOW, we perform simulations in QualNet [40]. Since there exists no publicly available specification for SIGFOX, we compare SNOW with LoRa to demonstrate higher efficiency and scalability of SNOW. The simulation setups and results are explained as follows.

Setup. We consider a LoRa gateway with 8 parallel demodulation paths, each of 500kHz wide (e.g., Semtech SX1301 [41]). For fair comparison, we choose a BS bandwidth of 500kHz * 8 = 4MHz from white spaces in SNOW and split into 19 overlapping (50%) orthogonal subcarriers, each of 400kHz wide. For each, we create a single-hop star network. All the nodes are within 2km radius of the BS/gateway. We generate various number of nodes in both of the networks. The nodes are distributed evenly in each demodulator path of LoRa gateway. In each demodulator path, LoRa uses the ALOHA protocol. In each network, we perform convergecast. Every node sends 100 40-byte packets with same spreading factor of 8 to the BS/gateway and sleeps for 100ms afterwards. For LoRa, we calculate the airtime of a 40-byte packet (34.94ms) using Lora-calculator [42] and use it in simulation. For its energy profiling, we consider the LoRa iM880B-L [43] radio chip with its minimum supported Tx power of 5dBm.

Results. Here we compare SNOW and LoRa in terms of energy consumption and network latency. As Figure 16(a) shows (in log scale), for a network of 2000 nodes, the packets are collected at the SNOW BS in 0.79 minutes consuming an average energy of 22.22mJ per node while the LoRa gateway collects those in 45.81 minutes consuming an average energy of 450.56mJ per node. Both energy consumption and latency in SNOW grow extremely slowly. The results indicate their linear (with number of nodes) growth with an extremely small slope as \( n \) nodes can transmit in parallel.

B. SNOW vs Other LPWAN Technologies

While OFDM has been adopted for multi-access in the forms of OFDMA and SC-FDMA in various broadband (e.g., WiMAX [44]) and cellular (e.g., LTE [24]) technologies, they...
relies on strong time synchronization which is very costly for low-power nodes. We adopted OFDM for the first time in WSN design and without requiring time synchronization. D-OFDM enables multiple packet receptions that are transmitted asynchronously from different nodes which was possible as WSN needs low data rate and short packets. To combat fading and to support high data rates, for uplink communication in both OFDMA and SC-FDMA adopted in WiMAX and LTE respectively, the BS depends on multiple antennas to receive from multiple nodes. Downlink transmissions in both OFDMA and SC-FDMA are made using single antenna. In contrast, D-OFDM enables multiple receptions using a single antenna and also enables different data transmissions to different nodes using a single antenna. Both WiMAX and LTE use OFDMA in downlink direction. WiMAX uses OFDMA in uplink direction also. Due to high peak-to-average power ratio (PAPR), OFDMA in uplink direction may cause high power dissipation of transmitter amplifiers of the low-power nodes, causing lower battery life. SNOW nodes use a single subcarrier and does not suffer from PAPR problem. While SC-FDMA has relatively lower PAPR, to meet the high data rate requirement in LTE (86 Mbps in uplink) and to allow concurrent transmitters its receiver is designed by using multiple antennas at the cost of high energy consumption [24]. Such issues are less severe for low data rate and small packet sizes and we realize D-OFDM with much simpler design.

5G [45] is envisioned to meet IoT use cases using the cellular infrastructure. Currently, the 5G standard is still under development. NB-IoT [46] is a narrowband LPWAN technology standard to operate on cellular infrastructure and bands. Its specification was frozen at Release 13 of the 3GPP specification (LTE-Advanced Pro [47]) in June 2016. These technologies would require devices to periodically wake up to synchronize with the network, giving a burden on battery life. Also, the receiver design to enable multiple packet receptions simultaneously using SC-FDMA requires multiple antennas. Note that setting up multiple antennas is difficult for lower frequencies as the antenna form factor becomes large. The antennas need to be spaced $\lambda/2$ apart, where $\lambda$ is the wavelength. Doing this is difficult as $\lambda$ is large for lower frequencies, and even more difficult and expensive to do this for every sector to be served by the base station. Having low data rate and small packets, SNOW PHY design remains much simpler and both the transmitters and the receiver can have a single antenna and the BS can receive multiple packets simultaneously using single antenna radio. Furthermore, the SNOW MAC has several novel features including a location-aware spectrum allocation for mitigating hidden terminal problems, per-transmission ACK for asynchronous transmissions, and the capability of handling peer-to-peer communication. Another important advantage of SNOW is that it exploits white spaces which have widely available free spectrum, while the above LPWANs operate in the licensed band or limited ISM band.

VIII. OTHER RELATED WORK

Prior work focused on accessing white spaces through spectrum sensing [48] or geo-location approach [49] for broadband service. A review of those work can be found in [11]. In contrast, the objective of the SNOW design is to exploit white spaces for designing highly scalable, low-power, wide-area WSN. The upcoming IEEE 802.15.4m [50] standard aims to exploit white spaces as an extension to IEEE 802.15.4. SNOW can therefore help shape and evolve such standards.

IX. CONCLUSIONS

In this paper, we have proposed the design of Sensor Network over White spaces (SNOW). SNOW represents the first low power and long range sensor network over TV white spaces to support reliable, asynchronous, bi-directional, and concurrent communication between numerous sensors and a base station. Hardware experiments through deployments in multiple geographical areas as well as simulations demonstrated that SNOW drastically enhances the scalability of WSN and is superior to existing technologies in the same line.

ACKNOWLEDGEMENT

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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, 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-field 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)km² 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 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 Distributed 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 \( f_1, f_2, \ldots, f_n \) – 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, 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\(_1\), \ldots, 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.

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_s 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_s 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_s 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 Scalloiability 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 \( \omega \) of a subcarrier across all SNOWs. Let \( Z_i \) be the set of orthogonal subcarriers available at BS_i considering \( \alpha \) 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 \( \omega \) and \( \alpha \) 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 \( \sigma_i \) 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 \( I_i \in \{0, 1, \ldots, N-1\} \) 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 \( p(i) \in \{0, 1, \ldots, N-1\} \) be such that BS_{p(i)} is the parent of BS_i and \( Ch_j \subseteq \{1, 2, \ldots, N-1\} \) be such that each
BS, with \( j \in Ch_i \) is a child of BS. 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 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 constraints 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 constraints, 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 \( |X_j| > \sigma_j \).

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 \( \sigma_i \) or \( \phi_{i,j} \) in Constraints (1), (2), and (3) of the SOP. Here, the time complexity of Algorithm 1 is \( O(N^2 M \log M) \).

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)km² 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 performance 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 - 686 MHz (TV channel 21-51). We set each subcarrier bandwidth to 400 kHz which was the default subcarrier bandwidth.

Algorithm 1: Greedy Heuristic Algorithm

```plaintext
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_j in inter-SNOW Tree do
   4. for each subcarrier \( x_i \in Z_{i,j} \) do
      5. if \( |X_i \cap X_j| > \phi_{i,j} \) then
         6. if \( |X_i| \geq |X_j| \) and \( |X_i| > \sigma_i \) then
            7. Delete \( x_i \) from \( X_i \).
         8. else if \( |X_j| > \sigma_j \) then
            9. Delete \( x_j \) from \( X_j \).
      10. else /* Infeasible solution */
         11. Don’t delete \( x_i \) from \( X_i \) or \( X_j \).
      12. else Break.
```

The greedy heuristic is described as follows. In the beginning, the root BS greedily assigns to every BS_i all the
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 (≈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. 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 \( \sigma_i \) 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 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 of 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 receipt 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
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 solving this problem, and have proved its NP-hardness. We have also shown 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.

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Demo Abstract: Implementing SNOW on Commercial Off-The-Shelf Devices

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Abstract—The recently proposed Sensor Network over White spaces (SNOW) has gained interest due to the availability and advantages of TV spectrum. SNOW is the first highly scalable Low-Power Wide-Area Network (LPWAN) over TV white spaces technology providing reliable, asynchronous, bi-directional, and concurrent communication between numerous sensors and a base station (BS). In this demonstration, we introduce our SNOW design and showcase the communication between multiple SNOW nodes and the BS.

I. INTRODUCTION

Recently, Low-Power Wide-Area Network (LPWAN) has gained interest. For many application, which require to connect thousands of sensors over long distances such as civil infrastructure monitoring [1] and oil field management [2] existing WSN technologies in the ISM band such as IEEE 802.15.4 [3] and 802.11 [4] cover a large area with numerous devices as multi-hop mesh networks at the expense of energy, cost, and complexity. One example is the applications in the agricultural domain (Figure 1). They require long-range communication due to the limited/lack of the availability of network infrastructure/coverage in such rural locations. In addition, using cellular-based technologies, in most cases, require recurring subscription fee to provide services, which introduces additional cost. These limitations can be overcome by deploying LPWAN.

Accordingly, we propose Sensor Network Over White Spaces (SNOW) [5], an LPWAN technology with potentials to overcome the scalability limitation of existing LPWAN technologies. SNOW operates over the unlicensed TV white spectrum. Thanks to their lower frequencies, white spaces have excellent propagation characteristics over long distance and obstacles. Compared to IEEE 802.15.4 or Wi-Fi, they offer a large number of and less crowded channels, each 6MHz wide. White spaces are available in both rural and urban areas, with rural (and suburban) areas tending to have more [6], [7]. SNOW presents a novel design eliminating the scalability limitation existing in LPWAN technologies. Hence, the number of supported nodes in SNOW increases with the spectrum availability. In this demonstration, we showcase the communication between several SNOW nodes and a BS. We show the capabilities of SNOW BS to decode packets from multiple asynchronous Commercial-Off-The-Shelf (COTS) transmitters (TI CC1310) simultaneously.

II. SNOW: MODEL AND DESIGN

SNOW is an asynchronous, long range, low-power platform operating over the TV white spaces [5], [8]. Each sensor node is equipped with a single half-duplex narrow-band white space radio. The white space spectrum provides excellent long transmission (Tx) range, hence, nodes are directly connected (with a single hop) to the BS and vice versa. The BS and its associated nodes thus form a star topology as shown in Figure 2. 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, each of equal spectrum width (bandwidth). It determines white spaces by accessing a cloud-hosted database through the Internet. In SNOW the assumption that the BS knows the locations of the nodes through manual configuration or some existing localization technique such as those based on ultrasonic sensors or other sensing modalities [9]. The BS selects white spaces available at its own location and at the locations of all other nodes. SNOW 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 bidirectional communication in SNOW.

The PHY layer of SNOW uses Distributed implementation of OFDM (Orthogonal Frequency Division Multiplexing) for multi-user access, called D-OFDM. In SNOW, the BS’s wide white space spectrum is split into narrowband orthogonal subcarriers which carry parallel data streams to/from the distributed nodes from/to the BS as D-OFDM. A subcarrier
bandwidth can be chosen as low as 100kHz, 200kHz, 400kHz depending on the packet and expected bit rate. Narrower bands have lower bit rate but provides longer range, while consuming less power [10]. Thus, SNOW adopted D-OFDM by assigning the orthogonal subcarriers to different nodes. Each node transmits and receives on the assigned subcarrier. Each subcarrier is modulated using Binary Phase Shift Keying (BPSK).

While OFDM has been adopted for multi-access in the forms of OFDMA and SC-FDMA in various broadband (e.g., WiMAX [11]) and cellular technologies (e.g., LTE [12]) recently, its adoption in SNOW was novel for LPWAN design. For uplink communication in both OFDMA and SC-FDMA adopted in WiMAX and LTE, the BS uses multiple antennas to receive from multiple nodes. Taking the advantages of low data rates and short packets, the transceiver design of SNOW was much simpler. D-OFDM enables multiple packet receptions using a single antenna which is transmitted asynchronously from different nodes. It also enables different data transmissions to different nodes through a single transmission using a single antenna. The BS can exploit fragmented spectrum. If the BS spectrum is split into \( n \) subcarriers, then it can receive from \( n \) different data at a time.

Currently, the sensor nodes in SNOW uses a very simple and lightweight CSMA CA approach for transmission like the one used in TinyOS [13]. The nodes can autonomously transmit, remain in receive mode, or sleep. When a node has data to send, it wakes up by turning its radio on. The BS periodically sends a beacon. The nodes are aware of this period. Any node that wants to listen to the beacon can choose to wake up for the beacon. Since D-OFDM allows handling asynchronous Tx and Rx, the link layer can send an acknowledgment (ACK) for any transmission in either direction. Both radios use the same spectrum and have the same subcarriers, the subcarriers in the Rx radio are for receiving while the same in the Tx radio is for transmitting. Since each node (non-BS) has just a single half-duplex radio, it can be either receiving or transmitting, but not doing both at the same time.

III. IMPLEMENTATION

We have implemented SNOW [5], [8] in GNU Radio [14] using Universal Software Radio Platform (USRP) [15] device for the BS [15] and Texas Instrument (TI) ultra-low power wireless micro-controller [16] as SNOW nodes. GNU radio is an open-source development toolkit provide signal processing blocks to develop software-define radio. USRP is a hardware platform designed for RF application. The BS USRP devices are B210, while the nodes are TI CC1310 [16] operating in operating on the Sub-GHz band. Packets generation, SNOW modulator, and decoder are implemented in GNU Radio. Figure 3 shows devices used for SNOW implementation.

IV. CONCLUSION

In this demonstration, we introduced the design of SNOW, the first highly scalable Low-Power Wide-Area Network (LPWAN) over TV white spaces technology supporting reliable, asynchronous, bi-directional, and concurrent communication between numerous sensors and a BS. We demonstrated the communication between SNOW nodes and BS COTS devices as a proof of concept. SNOW is a promising LPWAN technology that overcomes the scalability limitations in existing LPWAN technologies and provides support for different future applications.

REFERENCES