SNOW

Sensor Network over White Spaces

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CSE 521S

Slides courtesy of Abusayeed Saifullah @ Wayne State University
Wide Area IoT Applications

- Applications
  - Urban sensing, environmental/habitat monitoring
  - Precision agriculture, civil infrastructure monitoring
  - Large oil field monitoring
- Thousands of sensors connected over long distances.
LoWPAN
Low-power Wireless Personal Area Networks

- Traditional wireless sensor network (WSN) technologies
  - IEEE 802.15.4
  - WiFi
  - Bluetooth

- Multi-hop at the expense of energy, cost, complexity
  - Limits scalability
LPWAN
Low-Power Wide-Area Network

- NB-IoT, 5G
- *Operate over cellular infrastructure.*

- **SIGFOX**
  - 140 twelve-byte messages/day.
  - 0.1% or 1% duty cycle.

- **LoRaWAN**
  - Gateway uses 8 radios to support 8 concurrent Tx/Rx.
  - 0.1% or 1% duty cycle.
- *Achieve scalability for low traffic.*
Sensor network over TV white spaces.

**White Space**: unused TV channels between 54-698MHz.

**Advantage**
- Long transmission range
- Widely available

**Challenge**
- Need energy efficiency, scalability
- Long range → more interference

Prior work focused on exploiting white spaces for broadband service.

![Spectrum availability based on counties in USA](chart.png)
LoWPAN vs. LPWAN

- A-MAC is an energy efficient MAC protocol for traditional WSN.
- A multi-hop WSN for A-MAC becomes a single-hop SNOW.

<table>
<thead>
<tr>
<th># of nodes</th>
<th>Avg. Energy Consumption (mJoule in Log10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>1.5</td>
</tr>
<tr>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>1500</td>
<td>2.5</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th># of nodes</th>
<th>Convergecast Using QualNet Simulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
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<tr>
<td>1000</td>
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<tr>
<td>1500</td>
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<tr>
<td>2000</td>
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</tbody>
</table>

- Much lower energy consumption and latency than A-MAC.
SNOW Architecture

- Long range \(\rightarrow\) nodes directly Tx to the base station (BS).
- BS is line-powered and connected to white space database.
  - Has a single radio operating on wide white space spectrum.
  - Spectrum is split into narrow subcarriers \(\rightarrow\) assigned to nodes.

- Sensor nodes are power constrained.
  - No spectrum sensing or cloud access.
  - Operates on narrow subcarrier \(\rightarrow\) asymmetric bandwidth w.r.t. BS
SNOW Design Rationale

- Goal
  - Many parallel receptions at the BS using a single radio.
  - Asynchronous transmissions from the nodes.
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Goal
- Many parallel receptions at the BS using a single radio.
- Asynchronous transmissions from the nodes.

Design: physical layer using Distributed OFDM (D-OFDM)

- Tx on narrow OFDM subcarriers \(\rightarrow\) energy and spectrum efficiency
- Individual subcarrier modulation: ASK/BPSK/QPSK
- Nodes asynchronously Tx to BS \(\rightarrow\) simultaneous Rx \(\rightarrow\) scalability.
Adopting D-OFDM in SNOW

- Distributed orthogonal signals from the sensor nodes on orthogonal subcarriers.
Adopting D-OFDM in SNOW

- Distributed orthogonal signals from the sensor nodes on orthogonal subcarriers.

$$X(t) = \sum_{i=0}^{n-1} x(k) \sin\left(\frac{2\pi kt}{n}\right) - j \sum_{i=0}^{n-1} x(k) \cos\left(\frac{2\pi kt}{n}\right)$$
Adopting D-OFDM in SNOW

- Distributed orthogonal signals from the sensor nodes on orthogonal subcarriers.

- Decoding the composite signal at the BS
  - **Challenge:** Needs tight synchronization among senders.
  - **Approach:** leave complexities at BS; keep sensor nodes simple.
Demodulator Design

- Keep the BS always ON to receive.
  - Allow to receive asynchronous Tx.

- To extract spectral components from the composite OFDM signal, adopt FFT as global FFT (g-FFT)
  - Run FFT on entire spectrum of the BS.
  - Determine bits from each frequency bin from FFT outputs.
  - Allow to receive from the subcarriers that carry data.
A 2D matrix tracks data bits on all subcarriers: $b_{i,j}$ is the $i$-th bit of the $j$-th subcarrier.
Demodulator Design

A matrix tracks data bits on all subcarriers: $b_{i,j}$ is the $i$-th bit of the $j$-th subcarrier.

<table>
<thead>
<tr>
<th>Subcarrier 1</th>
<th>Subcarrier 2</th>
<th>⋯</th>
<th>Subcarrier $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>⋮</td>
<td>$b_{1,2}$</td>
<td>⋮</td>
<td>⋮</td>
</tr>
<tr>
<td>⋮</td>
<td>$b_{2,2}$</td>
<td>⋮</td>
<td>$b_{1,n}$</td>
</tr>
<tr>
<td>⋮</td>
<td>$b_{3,2}$</td>
<td>⋮</td>
<td>$b_{2,n}$</td>
</tr>
<tr>
<td>$b_{1,1}$</td>
<td>$b_{4,2}$</td>
<td>⋮</td>
<td>$b_{3,n}$</td>
</tr>
<tr>
<td>$b_{2,1}$</td>
<td>$b_{5,2}$</td>
<td>⋮</td>
<td>$b_{4,n}$</td>
</tr>
<tr>
<td>$b_{3,1}$</td>
<td>$b_{6,2}$</td>
<td>⋮</td>
<td>$b_{5,n}$</td>
</tr>
<tr>
<td>$b_{4,1}$</td>
<td>$b_{7,2}$</td>
<td>⋮</td>
<td>$b_{6,n}$</td>
</tr>
<tr>
<td>$b_{5,1}$</td>
<td>$b_{8,2}$</td>
<td>⋮</td>
<td>$b_{7,n}$</td>
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<tr>
<td>$b_{6,1}$</td>
<td>$b_{9,2}$</td>
<td>⋮</td>
<td>$b_{8,n}$</td>
</tr>
<tr>
<td>⋮</td>
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<td>⋮</td>
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</tr>
</tbody>
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Allows exploiting fragmented white space spectrum.
MAC Protocol

- The BS splits the (widest) white space spectrum into overlapping orthogonal subcarriers.
  - $n$ subcarriers are assigned to the sensor nodes.
  - One or more are reserved as management subcarriers.

- A Simple MAC protocol handles upper level functionality
  - Subcarrier allocation
  - Upward and downward communication
  - Spectrum dynamics
  - Network dynamics
  - Reliability
Implementation

- Implemented in GNU Radio
- Experiments with USRP device
  - Connected to laptop
  - Experiment with 6 nodes.
- Large-scale QualNet simulations

All the packets (up to # of subcarriers) are decoded within 0.1 ms → comparable to a single packet decoding time → scalability
Design Parameters

- **Key design parameters**
  - Bit rate: target bit rate at least 50kbps.
  - Packet size
  - Subcarrier bandwidth
  - Bit spreading factor

- **Default settings**
  - Frequency band: 547—553MHz
  - Tx power: 0dBm
  - Subcarrier bandwidth: 400kHz
  - BS bandwidth: 6MHz
  - Packet size: 40bytes
  - Bit spreading factor: 8
  - Indoor distance: 100m
  - Outdoor distance: 1.5km

Determined based on target bit rate, Shannon-Hartley Theorem, Shannon Theorem, and experiment.
Subcarrier Bandwidth

400kHz gives an effective bit rate of 50kbps
We tested only up to 1.5km distance. Tx range at 0dBm using 400kHz bandwidth should be even longer.
Two neighboring subcarriers (400kHz each) can safely overlap by up to 50%.
Indoor Testbed

Node positions on the CS building floor plan at Missouri S&T
Max. Achievable Throughput

Throughput increases linearly with the number of subcarriers due to parallel receptions at BS.
Conclusion

- **SNOW** is a sensor network design over TV white spaces.
  - For large and wide-area WSN applications.
  - Can be exploited by the future IoT and CPS.
  - Can help shape and evolve IEEE 802.15.4m standard.

- **SNOW** achieves scalability and energy efficiency
  - Multi-hop $\rightarrow$ single hop
  - Overlapping orthogonal subcarriers $\rightarrow$ many subcarriers.
  - Narrow subcarriers
  - Simultaneous receptions, asynchronous transmission
References
