Learning to Share: Narrowband-friendly Wideband Networks

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Emerging Multimedia Applications Challenge Wireless Networks

Users want:
- HD Video and Audio
- Gaming Content
- Virtual Reality

How can we scale wireless throughput to meet multi-Gbps demands?
Potential Solution:

Wideband Radios in the Unlicensed Spectrum

- Can span 100s of MHz to multiple GHz
- Scale to very high data rates

Emerging hardware achieves 100s of Mbps to a couple Gbps

Unlicensed spectrum is large, and it has low utilization

But…
Unlicensed Spectrum is Fragmented

Many narrowband technologies, and future ones could emerge

Cannot find long contiguous stretch of unoccupied frequencies
The Problem

Coexistence with dynamic and unknown narrowband devices in the unlicensed spectrum
Existing Solutions

1. Operate below noise-level

   - **Limits range**

   ![Diagram showing different solutions like Zigbee, 802.11a, and Others with a focus on Wideband and Unlicensed Spectrum]
Existing Solutions

1. Operate below noise-level
   - Limits range

2. Pick a contiguous unoccupied band
   - Limits throughput

Diagram:
- Zigbee
- 802.11a
- Others

Unlicensed Spectrum

Wideband
Existing Solutions

1. Operate below noise-level
   - Limits range

2. Pick a contiguous unoccupied band
   - Limits throughput

Sacrifice Throughput or Range!
Our Approach: Cognitive Aggregation

- **Cognition**: Detect unoccupied bands
- **Aggregation**: Weave all unoccupied bands into one link

Wideband

- Zigbee
- 802.11a
- Others
- Unlicensed Spectrum
Our Approach: Cognitive Aggregation

- **Cognition:** Detect unoccupied bands
- **Aggregation:** Weave all unoccupied bands into one link

**Provides Throughput, Range, and Coexistence!**

Diagram showing bands for Zigbee, 802.11a, Others, and Unlicensed Spectrum.
Research Issues

• How to detect available frequency bands?

• How to operate across chunks of non-contiguous frequencies?

• How do sender and receiver establish communication when their perceived available frequency bands differ?
SWIFT

- First wideband network to combine coexistence, throughput and range
- New approach to cognition that exploits network semantics
- Adapts OFDM algorithms to aggregate dynamic and non-contiguous bands
- Demonstrated in an actual FPGA implementation
Cognition: How do we detect occupied bands?

- Unlicensed $\rightarrow$ Can’t assume known narrowband devices
- Typical solution: Power threshold
Cognition: How do we detect occupied bands?

- Unlicensed → Can’t assume known narrowband devices
- Typical solution: Power threshold

![Graph showing baseband frequencies vs. narrowband power in dBm with an ideal threshold line and a peak labeled Faraway 802.11]
Cognition: How do we detect occupied bands?

- Unlicensed → Can’t assume known narrowband devices
- Typical solution: Power threshold

No Single Threshold Works Across All Locations
The Real Problem...

- The traditional approach only focuses on how wideband perceives narrowband transmissions.
- But the real question for coexistence is: Do wideband transmissions affect narrowband?
Unlicensed devices *typically react* to interference
Carrier sense in 802.11, TCP backoff, etc.

**Adaptive Sensing**

Intuitively:

- Poke the narrowband device, putting power in ambiguous bands
- If the narrowband device reacts, back away

Reasonable for unlicensed spectrum, which operates as best-effort
Detecting Narrowband Reaction

- Continuously sense the medium when not sending a packet
- Detect appearance of narrowband device when narrowband power exceeds noise level
- Detect reaction from changes in narrowband power profile
- What should be detection metrics?
<table>
<thead>
<tr>
<th><strong>Narrowband Reaction</strong></th>
<th><strong>Detection Metric</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier Sense (e.g., 802.11):</strong> Will not transmit when sensing a SWIFT packet</td>
<td>Probability of narrowband power immediately after a SWIFT packet</td>
</tr>
<tr>
<td><strong>Back-off (e.g., TCP, MAC):</strong> Will send less often</td>
<td>Inter-arrivals of narrowband power</td>
</tr>
<tr>
<td><strong>Autorate:</strong> Will use lower modulation, increasing packet size</td>
<td>Duration of narrowband power</td>
</tr>
</tbody>
</table>

**Look for statistically significant change in metric using standard tests (e.g. t-test)**
Adaptive Sensing in Action

- Start with a conservative choice of bands
- Keep tightening as long as narrowband is unaffected
Adaptive Sensing in Action

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Adaptive Sensing in Action

Wideband

Estimate Normal Behavior

Metric

Time
Adaptive Sensing in Action

Wideband

Metric

Time

Tighten

Sense

Test: Same as Normal
Adaptive Sensing in Action

Wideband

Tighten

Test: Different from Normal

Metric

Time
Adaptive Sensing in Action

Wideband

Loosen

Sense

Test: Same as Normal

Metric

Time
Aggregating Non-Contiguous Bands

- Leverage OFDM
  - Divides frequency band into multiple sub-bands that can be treated independently

- Transmitter: Puts power and data only in OFDM bands not occupied by narrowband devices
- Receiver: Extracts data only from OFDM bands used by transmitter
How does the receiver know which bands the transmitter uses?

When usable bands change, transmitter sends a short handshake.

But how do we send the handshake?
**Sending the Handshake**

Send in **Old Usable Bands?** → Interfere with narrowband device

Send in **New Usable Bands?** → Unknown insertions!

Transmitter: 1 0 1 1

Receiver: 1 X 0 1 1

Cannot fix the insertions with a standard error correcting code!
Transform Unknown Insertions into Errors

Stripe data in old usable bands

But transmit only in new usable bands

Can agree on usable bands in a completely distributed manner
Performance
Implementation

- Carrier Freq: 5.247 GHz
- Data Bandwidth: 100 MHz
- OFDM sub-band width: 1 MHz

Implemented in FPGA of custom wideband radio
Experimenting with Adaptive Sensing

- SWIFT is on
- At time = 5, turn 802.11 on
- SWIFT has no info about 802.11 bands
- Check that SWIFT finds the correct occupied bands
Adaptive Sensing

Bands Declared Occupied by Adaptive Sensing

Time (secs)

802.11 Starts

Tighten

Retreat

802.11 Starts

Tighten

Retreat

Time (secs)
Adaptive Sensing

- Bands Declared Occupied by Adaptive Sensing
- Time (secs)

802.11 Throughput (Mbps)

802.11 Starts
802.11 Reacts

Tighten
Retreat

802.11 Starts
802.11 Reacts
Does SWIFT Deliver on All Three Goals?

- Comparison of wideband designs
  - SWIFT
  - Baseline that operates below the noise of 802.11
SWIFT is as narrowband-friendly as a baseline that operates below noise level.
Wideband Throughput and Range

![Graph showing wideband throughput and range with distance on the x-axis and throughput on the y-axis. The graph includes a bar for baseline performance at different distances.]
Wideband Throughput and Range

Wideband Throughput (Mbps)

Baseline
SWIFT

SWIFT provides coexistence, high throughput, and good range
Wideband Network is Narrowband Friendly

4 802.11 Pairs
2 SWIFT Pairs
802.11 Throughput in a Network

Median Throughput (Mbps)

With SWIFT

A SWIFT network is narrowband-friendly
Related Work

- Cognitive Radios
  - 802.22, KNOWS, CORVUS, DIMSUMNet etc.

- Wideband systems
  - Intel, Chandrakasan et al., Mishra et al., Sodini et al.
Conclusion

- Wideband radios promise to satisfy the demands of rich media apps
- **SWIFT** is the first wideband system that combines coexistence, high throughput, and range
- Performs Cognitive Aggregation using Adaptive Sensing
- Demonstrated in an actual FPGA implementation