Frequency-aware protocols for wideband networks

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Wireless is moving to wider bands

- **UWB**
  - 100s of MHz to GHz

- **Whitespaces**
  - 100 to 250 MHz from analog-digital TV transition

- **802.11n channel bonding**
  - 40 MHz

- **Unchannelized 802.11 a/b/g**
  - Discard channels
  - Allow all nodes to use the entire 100 to 300 MHz
So, what changes?
So, what changes?
So, what changes?

In 20MHz Wi-Fi channels, different frequencies have similar SNRs
So, what changes?

In Wideband channels, different frequencies have very different SNRs. Cannot treat all frequencies the same!

Cannot treat all frequencies the same!
Need to Change Rate Adaptation
Need to Change Rate Adaptation

Using one bitrate for all frequencies is either unsafe or inefficient.

Wideband needs frequency-aware rate adaptation!
Is that all?
Need to Change MAC

Different clients prefer different frequencies
Need to Change MAC

Different clients prefer different frequencies

Wideband needs frequency-aware MAC!
FARA: Frequency-Aware Architecture

- Per-frequency SNR measurement with no overhead
- Frequency-aware rate adaptation
- Frequency-aware MAC
- FPGA implementation and testbed evaluation
FARA Architecture

Each Receiver Computes Per-Frequency SNR

- Frequency-Aware Rate Adaptation
- Frequency-Aware MAC
Leverage OFDM for Per-Frequency SNR

OFDM divides the bandwidth into subbands.
Leverage OFDM for Per-Frequency SNR

OFDM divides the bandwidth into subbands

Subband 2

Bandwidth
Leverage OFDM for Per-Frequency SNR

OFDM divides the bandwidth into subbands

Bandwidth

Subband N
Leverage OFDM for Per-Frequency SNR

OFDM divides the bandwidth into subbands

\[
\text{Bandwidth} = \begin{array}{cccccc}
0 & 1 & 1 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 \\
\end{array}
\]

Per-Frequency SNR = Per-OFDM Subband SNR
SNR in an OFDM Subband

\[ \text{SNR}_i = \frac{S_i}{N_i} \]

Signal Power in subband \( i \)
Noise Power in subband \( i \)

But receiver can measure only Received Power, \( R_i \)

\[ R_i = S_i + N_i \]

- **Challenge**: How do we find \( N_i \)?
- **Solution**: Exploit that channel noise, \( N_i \), is white, *i.e.*, the same across all subbands.
Exploit OFDM Pilots for Noise Computation

Pilots contain **known bit pattern**; used for synchronization

\[
\begin{array}{cccc}
0 & 1 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 \\
\end{array}
\]

Received Signal, \( y = H x + n \)

- **Noise**
- **Channel**
- **Transmitted Signal**
Exploit OFDM Pilots for Noise Computation

Pilots contain **known bit pattern**; used for synchronization

Received Signal, \( y = H x + n \)

Can Compute Noise Power, \( N \), using pilot subbands
Putting it all together

$$\text{SNR}_i = \frac{S_i}{N_i}$$
Putting it all together

$$\text{SNR}_i = \frac{R_i - N_i}{N_i}$$
Putting it all together

\[
\text{SNR}_i = \frac{R_i - N}{N}
\]

Per-frequency SNR Measurement with no Overhead!
FARA Architecture

Each Receiver Computes Per-Frequency SNR

- Frequency-Aware Rate Adaptation
- Frequency-Aware MAC
## From SNR to Bitrate

Bitrate is a choice of modulation and FEC code rate

<table>
<thead>
<tr>
<th>SNR (dB)</th>
<th>Optimal Bitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3.5</td>
<td>Suppress Subband</td>
</tr>
<tr>
<td>3.5 – 5.0</td>
<td>BPSK, 1/2</td>
</tr>
<tr>
<td>5.0 – 5.5</td>
<td>BPSK, 3/4</td>
</tr>
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<td>5.5 – 8.5</td>
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**How do we get this table?**

Easy to obtain from offline measurements
From SNR to Bitrate

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High Loss Rate

Low Loss Rate

Transition Region

SNR (dB)

Packet Loss Rate
### From SNR to Bitrate

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![Graph showing Packet Loss Rate vs SNR with a threshold for 16-QAM, 1/2 at 12.0 dB]
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12.0 – 16-QAM, 1/2

Packet Loss Rate vs. SNR (dB)

- Blue line: 16-QAM, 1/2
- Green line: 16-QAM, 3/4

Graph shows the relationship between Packet Loss Rate and SNR (dB) for different modulation schemes and coding rates.
SNR Thresh | Bitrate
---|---
< 3.5 | Suppress
3.5 – 5.0 | BPSK, 1/2
5.0 – 5.5 | BPSK, 3/4
5.5 – 8.5 | 4-QAM, 1/2
8.5 – 12.0 | 4-QAM, 3/4
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**Per-Frequency Rate Adaptation**

- Upon packet reception, receiver
  - Measures per-subband SNR
  - Maps it to optimal subband bitrate
  - Sends per-subband bitrates to transmitter in ACK

- Upon ACK reception, transmitter
  - Updates bitrates for next transmission

*Can directly map SNR to optimal bitrate*  
→ *Quickly converges to correct rate*
FARA Architecture

Each Receiver Computes Per-Frequency SNR

Frequency-Aware Rate Adaptation

Frequency-Aware MAC
Today, at any time, MAC assigns all subbands to one client
Frequency-Aware MAC

Today, at any time, MAC assigns all subbands to one client
Frequency-Aware MAC

But different clients prefer different subbands!
FARA MAC assigns subbands to clients based on performance
Frequency-Aware MAC

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Frequency-Aware MAC

FARA MAC assigns subbands to clients based on performance
FARA MAC assigns subbands to clients based on performance
How Does FARA Assign Subbands to Clients?

- Requirements
  - Efficiency: Assign each receiver its preferred subbands
  - Fairness: All receivers should get the same throughput

- Problem is **NP Hard**

- We need a heuristic
FARA MAC Allocation Algorithm

Iterate to maximize the minimum RateCounter

Throughput (Mbps/MHz)

Subband Assignment

RateCounter1=0

RateCounter2=0
FARA MAC Allocation Algorithm

Throughput (Mbps/MHz)

Subband Index

RateCounter1 = 0

RateCounter2 = 0
FARA MAC Allocation Algorithm

- For each subband, compute $\Delta$: change in total rate if subband is moved from maximum to minimum client
- Move subbands in decreasing order of $\Delta$s

Iterate:
FARA MAC Allocation Algorithm

For each subband, compute $\Delta$: change in total rate if subband is moved from maximum to minimum client

Move subbands in decreasing order of $\Delta$s
FARA MAC Allocation Algorithm

For each subband, compute $\Delta$: change in total rate if subband is moved from maximum to minimum client

Move subbands in decreasing order of $\Delta$s
Iterate:

• For each subband, compute $\Delta$: change in total rate if subband is moved from maximum to minimum client
• Move subbands in decreasing order of $\Delta$s
FARA MAC Allocation Algorithm

For each subband, compute Δ: change in total rate if subband is moved from maximum to minimum client

Move subbands in decreasing order of Δs

Iterate:
Performance
Implementation

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

Implemented in FPGA of custom wideband radio
Testbed
Testbed
How stable are SNRs?
How stable are SNRs?

SNRs are stable across time
What are the Gains of FARA Rate Adaptation?

Compared Schemes

• SampleRate: Existing Rate Adaptation
• FARA: Frequency-Aware Rate Adaptation

Metric

Throughput Gain =

\[
\frac{\text{Throughput of FARA Rate Adaptation}}{\text{Throughput of SampleRate}}
\]
What are the Gains of FARA Rate Adaptation?
What are the Gains of FARA Rate Adaptation?

2.1x Gains from FARA Rate Adaptation
What are the Gains of FARA MAC?

Compared Schemes

• SampleRate: Existing Rate Adaptation
• FARA: Frequency-Aware Rate Adaptation
• Full-fledged FARA: Frequency-Aware Rate Adaptation and MAC

Metric

Throughput Gain =

\[
\frac{\text{Throughput of Full-fledged FARA}}{\text{Throughput of SampleRate}}
\]
What are the Gains of FARA Rate Adaptation?

The graph shows the throughput gain for different fractions of clients using FARA Rate Adaptation and FARA Rate Adaptation and MAC. The graph indicates a throughput gain of 1.5x for the latter compared to the former.
What are the Gains of FARA Rate Adaptation?

Total Gain of 3.1x Gains for 100 MHz Channel!
Conclusions

• Wireless technologies are moving to wider bands
  – Cannot ignore frequency diversity

• FARA presents frequency-aware rate adaptation and MAC protocols

• Empirical results show 3.1x gains for 100 MHz bandwidth