Concurrent Channel Access and Estimation for Scalable Multiuser MIMO Networking

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MIMO Communication

- Multiple antennas create additional degree-of-freedom
- Limited by scattering environments
Multiuser MIMO

- Rich spatial diversity from geographically separated users
- $K$ antennas on the AP, expect $K$-times throughput improvement
Proposed **Concurrent Access** to Mitigate MAC Scalability Issue for MU-MIMO

- **No coordination**
- **Full coordination**

- **Staggered Access**

- **Scheduled Access**

- **Minimum control overhead**

- **Fully parallelized data frame**

- **Concurrent Access**

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Preamble | Data frame
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Proposed MU-MIMO Concurrent Access in Support of Random Access

• More aggressive senders, i.e., smaller backoff window size
  – Standard tricks applied (e.g., CSMA with exponential backoff)
  – *Automatically* adapt to additional degree-of-freedom

• No coordination
  – Senders choose to join concurrent transmissions *independently*
Challenges of Concurrent Access and Proposed Solutions

• Challenge: Precise synchronization is difficult
  – Proposed solution: Channel estimation from loosely synchronized preambles
  – Can be cast as a sparse recovery problem

• Challenge: Collision is expensive under MIMO
  – Proposed solution: Use delay packet decoding to exploit retransmissions to decode previously collided packets
Channel estimation with packet preambles measures channel distortion on data symbols.
# unknowns (h1, h2, etc.) in channel estimation proportional to delay spread

Multiuser case is analogous to multipath, but with much larger “delay spread”
Receive window

Synchronization offset

\[
\begin{bmatrix}
y_1 \\
y_2 \\
y_3 \\
\end{bmatrix}
= 
\begin{bmatrix}
d_{11} & d_{13} & d_{12} \\
d_{12} & d_{11} & d_{13} \\
d_{13} & d_{12} & d_{11} \\
\end{bmatrix}
\begin{bmatrix}
h_{11} \\
0 \\
0 \\
\end{bmatrix}
+ 
\begin{bmatrix}
d_{21} & d_{23} & d_{22} \\
d_{22} & d_{21} & d_{23} \\
d_{23} & d_{22} & d_{21} \\
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
h_{21} \\
\end{bmatrix}
\]
### Path delay (tap)

<table>
<thead>
<tr>
<th>Sender 1</th>
<th>t₁</th>
<th>t₂</th>
<th>t₃</th>
<th>t₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sender 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sender 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Scheduled and fully synchronized**

# unknowns = (# senders) x (# path delays)

### Random access and loosely synchronized

<table>
<thead>
<tr>
<th>t₁</th>
<th></th>
<th>t₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sender 1</td>
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</tr>
<tr>
<td>Sender 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sender 7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# unknowns =

(# potential senders) x (# potential timing misalignments)
The dimensionality of unknowns is enlarged, but the amount of channel coefficients per transmitting sender is the same, i.e., sparse in the new space... we just don’t know where they are.
Compressive Sensing

- A few random projections preserve all information of a sparse signal

\[ K \text{-sparse target signal} \]

\[ N \]

\[ K \]

\[ \text{Prophet} \]

\[ \text{Random linear combinations} \]

\[ O(K \log \frac{N}{K}) \sim 4K \]
Random Preamble Sequence

• Assign senders random preamble sequences \{1, -1\} to create random measurements

How long does the preamble need to be?

Ex: 4x4 MIMO, delay spread 60 ns, time sync offset 2 μs, 100 potential senders

Solve all vars  Our strategy
100 x 2 = 200 μs  4 x (4 x 0.06) ~ 0.96 μs
Furthermore, Exploit Receiver Diversity for Decoding

• *N*-antenna MIMO AP receives *N* copies of concurrent preambles
  – Channel coefficients to each antenna are different
  – Timing misalignment and senders are the same!
• Leads to **faster decoding** and **shorter preambles**
Not there yet, random access based concurrent transmission also means **collisions** are likely.
"Delay Packet Decoding":

Exploit Successful Retransmissions

Successful retransmission can be used to cancel out packets in previous collisions

Need to learn $h_1$, $h_2$, $h_3$ from collided packets
Enable Concurrent Channel Estimation for Collided Packets

• Most collisions are caused by only a few additional packets
• Slightly longer preamble allows concurrent channel estimation of these collided packets

Tolerate small fluctuation in channel booking
System Evaluation with a Software Defined Radio Testbed
USRP-N200 operates at 916MHz, 6.25MHz bandwidth. MIMO-OFDM

10MHz clock to synchronize USRPs

4 USRPs as four distributed users

4 synchronized USRPs as one AP
Concurrent Channel Estimation vs. Sequential Channel Estimation

Clean, sequential preamble

USRP-N200, 4x4 MIMO
6.25MHz Bandwidth
13 taps

Concurrent preamble

Sparsity constraint removes unwanted noise
4x4 MIMO Decoding Performance

Low SNR, sparsity assumption delivers more accurate channel estimation

High SNR, decoding performance is similar

Decoded SNR using Concurrent Preambles

Decoded SNR using Sequential Preambles
Number of Active Transmitters a Preamble Length Can Support

Best one can do: If senders and timing misalignments are known

<table>
<thead>
<tr>
<th>Antennas</th>
<th>FFT=128</th>
<th>FFT=256</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Successful recovery rate (%) vs Number of active transmitters

- FFT=128:
  - 4 antennas: 100%
- FFT=256:
  - 1 antenna: 0%

Graph shows the successful recovery rate for different numbers of active transmitters and FFT sizes.
Aggregated Throughput Improvement

- Staggered Access (avoids preamble collision)
- Concurrent Access w/o delay packet decoding
- Concurrent Access
- Optimal scheduler

Simulation: PHY 52Mbps
1500-byte packet
Aggregated Throughput Improvement

Simulation: PHY 52Mbps
1500-byte packet

210%

Concurrent Access

Optimal scheduler

Staggered Access (avoids preamble collision)
Throughput Scalability

Simulation: PHY 13Mbps
1500-byte packet

- Concurrent Access
- Optimal scheduler
- Concurrent Access w/o delay packet decoding
- Staggered Access
Conclusion

• Concurrent access allows efficient and scalable multiuser MIMO networking without strict synchronization and coordination

• Key enabling techniques
  – Compressive sensing to relax synchronization and coordination
  – Delay packet decoding to tolerate demand fluctuation in random access