Agenda

1. Exploiting overhearing
   – *ExOR*, Biswas et al.

2. The physical layer and the MIMO physical layer
   – Next time: *Interference alignment and cancellation*, and
     *Taking the sting out of carrier sense* (successive interference cancellation)
ExOR: Opportunistic Multi-hop Routing for Wireless Networks

- Dense 802.11-based mesh
- Goal is high-throughput and capacity

[Adapted from Biswas, SIGCOMM ‘05]
GZ06: The big wireless picture

<table>
<thead>
<tr>
<th>Adaptation</th>
<th>Opportunism</th>
<th>Diversity</th>
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<tbody>
<tr>
<td>SampleRate</td>
<td>ExOR</td>
<td>MRD</td>
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<tr>
<td>SampleWidth</td>
<td>ZigZag decoding</td>
<td>SOFT</td>
</tr>
<tr>
<td>RRAA, SoftRate</td>
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- **Today: ExOR**
  - Influence on later work
  - Real implementation
  - Evaluation methodology
Initial approach: Traditional routing

- Identify a route, forward over links
- Abstract radio to look like a wired link
Radios aren’t wires

• Every packet is broadcast
• Reception is probabilistic
ExOR: exploiting probabilistic broadcast

- Decide who forwards after reception
- Goal: only closest receiver should forward
- Challenge: agree efficiently and avoid duplicate xmits
Outline

• Introduction
• Why ExOR might increase throughput
• ExOR protocol
• Measurements
• Related Work
Why ExOR might increase throughput (1)

- Best traditional route over 50% hops: $3^{(1/0.5)} = 6$ tx
- Throughput $\cong \frac{1}{\#\text{transmissions}}$
- ExOR exploits lucky long receptions
- ExOR recovers unlucky short receptions
Why ExOR might increase throughput (2)

- Traditional routing: \( \frac{1}{0.25} + 1 = 5 \) tx
- ExOR: \( \frac{1}{(1 - (1 - 0.25)^4)} + 1 \approx 2.5 \) transmissions
- Assumes independent losses
Outline

• Introduction
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• Measurements
• Related Work
• Challenge: finding the closest node to have rx’d
• Send batches of packets for efficiency
• Node closest to the dst sends first
  – Other nodes listen, send remaining packets in turn
• Repeat schedule until dst has whole batch
Batch maps summarize receptions

\[\text{tx: \{2, 4\}}\]
\[
\text{batch map: \{1} \rightarrow \text{N3}, 2 \rightarrow \text{N2}, 4 \rightarrow \text{N2}\} 6 \rightarrow \text{N3}\}
\]


- Repeat summaries (batch maps) in every data packet
  - Cumulative: what all previous nodes rx’d
  - Allows src to receive acknowledgement
• Goal: nodes “closest” to the destination send first
• Sort by ETX metric to dst
  – Nodes periodically flood ETX “link state” measurements
  – Path ETX is weighted shortest path (Dijkstra’s algorithm)
• Source sorts, includes *forwarder list* in ExOR header
Scheduling transmissions

- **Goal**: Schedule transmissions such that only one node is sending at a time.

- **Can’t rely on receiving last transmission of node just before you in transmission order**

- **So can’t trigger your transmission on previous node’s final transmission**

- **ExOR’s approach**: Estimate when the previous fragment will finish
  - Overhear fragment number and fragment size of previous node’s transmissions
  - Estimate transmission rate and pass through EWMA filter
  - Set forwarding timer = current time + (estimated send rate × num. pkts. remaining)
Transmission timeline

Figure bars high
The measure comp
delivery
0.30
0.90
1.50
1.80
0.00
0.60
1.1
1.8
1.5
5.5
0.1
2
4
9
2
5
7
3
2
4
8
11
13
24
6
8
10
13
7
1
5
1
2
5
8
11
20
24
dest
N24
N20
N18
N11
N8
N17
N13
src
N5

Time (sec)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

src N5
high
low
dest N24
medium
low
high

Transmission timeline
Implementation

• Click userlevel, libpcap
  
  http://read.cs.ucla.edu/click/

• ExOR: unreliable delivery
• TCP/ExOR window size issue
• Prism 2.5 802.11b, Atheros AR5212
Using ExOR with TCP

- Batching requires more packets than typical TCP window
Outline

• Introduction
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• Measurements
• Related Work
ExOR Evaluation

Questions to answer experimentally:

1. Does ExOR increase throughput?
2. When/why does it work well?
65 Roofnet node pairs
Evaluation Details

- 65 Node pairs
- 1.0 Mbyte file transfer
- 1 Mbit/s 802.11 bit rate fixed
- 1 Kbyte packets

<table>
<thead>
<tr>
<th>Traditional Routing</th>
<th>ExOR</th>
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<td>802.11 unicast with link-level retransmissions, Hop-by-hop batching, UDP sending as MAC allows</td>
<td>802.11 broadcasts, 100-packet batch size</td>
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ExOR: 2x overall improvement

- Median throughputs: 240 Kbits/sec for ExOR,
  121 Kbits/sec for Traditional
25 Highest throughput pairs

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<tr>
<th>Node Pair</th>
<th>Throughput (Kbits/sec)</th>
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<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
</tr>
</tbody>
</table>

- **3 Traditional Hops**
  - 2.3x

- **2 Traditional Hops**
  - 1.7x

- **1 Traditional Hop**
  - 1.14x

Graph showing throughput comparison between ExOR and Traditional Routing for different hop counts.
25 Lowest throughput pairs

Throughput (Kbits/sec)

- ExOR
- Traditional Routing

4 Traditional Hops
3.3x

Longer Routes
Node Pair
ExOR uses links in parallel

Traditional Routing
3 forwarders
4 links

ExOR
7 forwarders
18 links
ExOR moves packets farther

- ExOR average: 422 meters/transmission
- Traditional Routing average: 205 meters/tx
Traditional approach constrains *who* routes

![Graph showing packet transmissions vs. Transmitter's ETX to Destination]

- ExOR
- Traditional

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Building further from ExOR

• Choosing the best 802.11 bit-rate
  – An important unsolved problem in ExOR
  – Mesh network bit rate adaptation problem
• Cooperation between simultaneous flows
• Coding and combining packets
Related work

• Network Coding (from information theory)
  [Ahlswede et al.][Katabi+Katti] [GZ06: Chachulski et al. paper]

• Relay channels
  [Van der Meulen][Laneman+Wornell]

• Flooding (dissemination) in meshes/sensor networks
  [Peng][Levis]

• Multi-path routing
  [Ganesan][Haas]

• Selection Diversity
  [Miu][Roy Chowdhury][Knightly][GZ06: Woo et al. paper]
Summary

• ExOR achieves 2x throughput improvement
• ExOR implemented on Roofnet
• Exploits radio properties, instead of hiding them

• Key open question: adapting bit rate in a mesh
Agenda

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   – ExOR, Biswas et al.

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   – Next time: *Interference alignment and cancellation*, and *Taking the sting out of carrier sense* (successive interference cancellation)
Multiple-input, Multiple-output (MIMO)

- MIMO: Term abused to stand for many different multi-antenna wireless systems
- Applications of MIMO:
  - Spatial division multiple access (SDMA; Tan et al.)
  - Build a faster link: Stripe data across multiple antennas
  - Mutually “align” many sources of interference, reducing their impact on transmissions of interest (Gollakota et al.)

- When do MIMO techniques improve capacity?
Introduction: the wireless channel

- Under certain conditions, can represent channel with a single complex number, $h$
- This is called a *single-input, single-output* (SISO) channel
- $w$: everything not accounted for in our model
  - Background noise
  - Noise introduced by the radio’s RF “front end”
  - Interference from transmissions not in the model

$$y = hx + w$$
A simplified model of the wireless channel

\[ y = hx + w \]

- Represent complex number \( h \) in magnitude-phase form:
  \[ h = a \cdot e^{j\theta} \quad (a, \theta \text{ real}) \]

- Channel impacts sent symbol in two ways:
  1. Rotates \( x \) by angle \( \theta \)
  2. Scales \( x \) by scalar quantity \( a \)
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   – The MIMO channel
   – The singular value decomposition (SVD)
   – Capacity of the MIMO channel
The MIMO channel

- Antennas could be co-located or not
- Simultaneously, transmit antenna $j$ sends $x_j$
- What will receive antenna $i$ receive? call it $y_i$
- $h_{ij} = $ complex number representing channel from transmit antenna $j$ to receive antenna $i$

Problem: Transmissions interfere with each other
Representing the channel as a matrix
Representing the data as vectors

\[
x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_j \\ \vdots \\ x_{n_t} \end{bmatrix}, \quad y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \\ \vdots \\ y_{n_r} \end{bmatrix}
\]

\[y_1 = h_{11} x_1 + h_{12} x_2 + \cdots + h_{1n_t} x_{n_t}\]
The vector MIMO channel: $y = Hx + w$

$$
\begin{bmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_i \\
  \vdots \\
  y_{n_r}
\end{bmatrix} =
\begin{bmatrix}
  h_{11} & h_{12} & \cdots & h_{1j} & \cdots & h_{1n_t} \\
  h_{21} & h_{22} & \cdots & h_{2j} & \cdots & h_{2n_t} \\
  \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
  h_{i1} & h_{i2} & \cdots & h_{ij} & \cdots & h_{in_t} \\
  \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
  h_{n_{r1}} & h_{n_{r2}} & \cdots & h_{n_{rj}} & \cdots & h_{n_{rn_t}}
\end{bmatrix} \cdot
\begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_i \\
  \vdots \\
  x_{n_t}
\end{bmatrix} +
\begin{bmatrix}
  w_1 \\
  w_2 \\
  \vdots \\
  w_i \\
  \vdots \\
  w_{n_r}
\end{bmatrix}
$$

Output

\[ y_1 = h_{11}x_1 + h_{12}x_2 + \cdots + h_{1n_t}x_{n_t} \]
\[ y_i = h_{i1}x_1 + h_{i2}x_2 + \cdots + h_{in_t}x_{n_t} \]

Input

Noise
The vector MIMO channel: \( y = Hx + w \)

- Problem: Each output is a mixture of all inputs; we say that the outputs are **coupled** together: \( y_i = h_{i1}x_1 + h_{i2}x_2 + \cdots + h_{in_i}x_{n_t} \)
- How can we **decouple** the inputs?
  - What we get out at each output only depends on one input: parallel, independent channels
  - The answer lies in a special way of “factoring” the channel matrix \( H \)
The singular value decomposition (SVD)

- **Fact:** Every matrix $H$ has a *singular value decomposition* $H = U\Lambda V^*$
  - $\Lambda (n_r \times n_t)$ contains *zeroes* off-diagonal
  - $U (n_r \times n_r)$ and $V (n_t \times n_t)$ are *unitary*: $UU^* = U^*U = VV^* = V^*V = I$
Singular value decomposition: Properties

- $\Lambda$ matrix contains the $m = \min(n_t, n_r)$ singular values of $H$: $\lambda_i$
- Number of non-zero singular values $= \text{rank}(H)$
- $V$ translates to a new coordinate system where the channels are decoupled ($U$ translates back)
  - Matrix multiplication by a diagonal matrix is simple!

\[
\Lambda \times \tilde{x} = \begin{bmatrix}
\lambda_1 & 0 & \cdots & 0 \\
0 & \lambda_2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \lambda_{n_t}
\end{bmatrix} \times \begin{bmatrix}
\tilde{x}_1 \\
\tilde{x}_2 \\
\vdots \\
\tilde{x}_{n_t}
\end{bmatrix} = \begin{bmatrix}
\lambda_1 \tilde{x}_1 \\
\lambda_2 \tilde{x}_2 \\
\vdots \\
\lambda_{n_t} \tilde{x}_{n_t}
\end{bmatrix}
\]
SVD: moving to a new coordinate system

- Singular value decomposition of $H$ represents:
  1. Translation to new coordinate system ($V^*$)
  2. **Decoupled** scaling ($\lambda_i$)
  3. Translation back to original coordinate system ($U$)
SVD of the channel matrix

1. Move noise addition into $H$
2. Define the following variables: $\tilde{x} = V^* x$ $\tilde{y} = U^* y$ $\tilde{w} = U^* w$

• Now we have **independent channels** from $\tilde{x}$ to $\tilde{y}$

*How do we use this for useful communication?*
Applying SVD to communication

- Pre-process with $V$, post-process with $U^*$; $V^*V = U^*U = I$
- Each **nonzero** singular value $\lambda_i$ supports a data stream
- Fact: The number of nonzero $\lambda_i$ is: $k = \text{rank}(H)$
Capacity of the MIMO channel

• Fact (Shannon): At high SNR (the common case in wireless LANs), with transmit power $P$:

$$C \approx \sum_{i=1}^{k} \log \left(1 + \frac{P \lambda_i^2}{kN_0}\right) \approx k \log(\text{SNR}) + o(\text{SNR})$$
Physical modeling of MIMO channels

• Key question: when is $k$ close to $\min(n_r, n_t)$?

• Next:
  – Gain intuition as to how the RF channel (ambient environment) impacts the SVD and thus capacity
  – We will restrict scope in GZ06 to linear antenna arrays
  – Details vary with more sophisticated antenna arrangements, but concepts do not
Line-of-sight SIMO channel

- Single input, multiple input (SIMO) channel
- **Free space**: no reflectors, scatterers; one path length $d_1$
- Receiver equipped with a linear antenna array
  - Array antenna separation $\Delta \ll d_1$
  - Line-of-sight transmitter at bearing $\theta_1$ with array
Line-of-sight SIMO channel: Detail

- Greater (or less) distance $\Delta \cos \theta_1$ to each antenna than to antenna 1

- Fact 1: There is a distance difference of $(n - 1) \Delta \cos \theta_1$ for the $n^{th}$ antenna
Distance rotates constellation

- Fact 2: Distance $d_1$ rotates received signal by $\frac{2\pi}{\lambda \cdot d_1}$
- Compared to first antenna, channel to $n^{th}$ antenna rotates received constellation point

\[
2\pi / \lambda \cdot (n - 1) \Delta \cos \theta_1
\]
Line-of-sight SIMO channel

\[ h_1 = a e^{j2\pi d_1 / \lambda} \begin{bmatrix} 1 \\ e^{j2\pi \cdot \Delta \cos \theta_1 / \lambda} \\ e^{j2\pi \cdot 2\Delta \cos \theta_1 / \lambda} \\ \vdots \\ e^{j2\pi \cdot n\Delta \cos \theta_1 / \lambda} \end{bmatrix} \]

- Facts 1 and 2 together:
- Distance difference of 
  \((n - 1) \Delta \cos \theta_1\) for the \(n^{th}\) antenna
- Distance rotates constellation

\(\theta_1\)

Antenna 1

Antenna 2

Antenna 3

Antenna 4

Transmitter

Receiver

\(\Delta\)
Capacity of line-of-sight SIMO channel

- Channel adds increasing phase shifts
- Receiver subtracts phase shifts
  - Signals combine constructively
  - This is called **maximal ratio combining** (MRC)

\[
\mathbf{h}_1 = a e^{j 2\pi d_1 / \lambda}, \quad e^{j 2\pi \cdot \Delta \cos \theta_1 / \lambda}, \quad e^{j 2\pi \cdot 2\Delta \cos \theta_1 / \lambda}, \quad \vdots \quad e^{j 2\pi \cdot n_r \Delta \cos \theta_1 / \lambda}
\]

- SIMO channel capacity:
\[
C = \log \left(1 + \frac{P \|\mathbf{h}\|^2}{N_0}\right) = \log \left(1 + \frac{P a^2 n_r}{N_0}\right) \text{ bits/s/Hz}
\]
- ↑ SNR, but no concurrency
- MIMO channel capacity:
\[
C \approx \sum_{i=1}^{k} \log \left(1 + \frac{P \lambda_i^2}{kN_0}\right) \approx k \log(\text{SNR}) + o(\text{SNR})
\]
The line-of-sight MIMO channel

- Only one direct line-of-sight path, no reflections
- Recall: $\mathbf{H} = [ h_{ij} ]$
- Recall the capacity formula for the MIMO channel:

$$C \approx \sum_{i=1}^{k} \log\left(1 + \frac{P\lambda_i^2}{kN_0}\right) \approx k \log(\text{SNR}) + o(\text{SNR})$$
The line-of-sight MIMO channel

- Distance between transmit antenna $i$ and receive antenna $k$:
  \[ d_{ik} = d_1 + (i - 1)\Delta \cos \phi_1 - (k - 1)\Delta \cos \theta_1 \]

\[
H = a_1 e^{-j2\pi d_1 / \lambda} \begin{bmatrix}
1 & e^{-j2\pi\Delta \cos \phi_1 / \lambda} \\
\ \ e^{-j2\pi\Delta \cos \theta_1 / \lambda} & e^{-j2\pi\Delta (\cos \theta_1 + \cos \phi_1) / \lambda}
\end{bmatrix}
\]
The line-of-sight MIMO channel

\[
H = a_1 e^{-j2\pi d_1/\lambda} \begin{bmatrix}
1 & e^{-j2\pi \cos \phi_1 / \lambda} \\
e^{-j2\pi \cos \theta_1 / \lambda} & e^{-j2\pi (\cos \theta_1 + \cos \phi_1) / \lambda}
\end{bmatrix}
\]

• Every column (row) in \( H \) is a multiple of the other columns (rows), so \( \text{rank}(H) = k = 1 \)

• One singular value \( \lambda_1 = a \sqrt{n_r n_t} \)

• Capacity: \( C \approx \sum_{i=1}^{k} \log \left( 1 + \frac{Pa^2 n_r n_t}{N_0} \right) \)

• Increased SNR, but no concurrent data streams
Spatially separated transmit antennas

If \( \cos \theta_1 \neq \cos \theta_2 \) then \( k = \text{rank}(H) = 2 \), concurrent streams possible.
Spatially separated receive antennas

\[ H = \begin{bmatrix}
  a_1 e^{-j2\pi d_1 / \lambda} & a_1 e^{-j2\pi (d_1 + \Delta \cos \phi_1) / \lambda} \\
  a_2 e^{-j2\pi d_2 / \lambda} & a_2 e^{-j2\pi (d_2 + \Delta \cos \phi_2) / \lambda}
\end{bmatrix} \]

If \( \cos \phi_1 \neq \cos \phi_2 \) then \( k = \text{rank}(H) = 2 \), concurrent streams possible.
The multipath MIMO channel

If $\cos \phi_1 \neq \cos \phi_2$ and $\cos \theta_1 \neq \cos \theta_2$ then $k = \text{rank}(H) = 2$, and concurrent streams are possible.
Vector representation

When multipath is present, vectors are independent.
“Poorly-conditioned” MIMO channels

When channel is poorly conditioned, vectors are ``closer.''

Only reflectors near receiver: $\phi_1 \approx \phi_2$

Only reflectors near transmitter: $\theta_1 \approx \theta_2$
# Next time

<table>
<thead>
<tr>
<th>21st Feb</th>
<th>23rd Feb</th>
<th>25th Feb</th>
</tr>
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<tbody>
<tr>
<td></td>
<td><strong>Exploiting Overhearing (KJ)</strong></td>
<td><strong>Overcoming Interference (KJ)</strong></td>
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<td><strong>Pre-Reading: ExOR</strong>&lt;br&gt;<strong>One-pager assignment (pdf)</strong></td>
<td><strong>Pre-Reading: Taking the Sting out of Carrier Sense</strong>&lt;br&gt;<strong>Pre-Reading: Interference Alignment and Cancellation</strong></td>
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<td><strong>Vehicle Tracking with the Viterbi Algorithm (KJ)</strong></td>
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<td><strong>Pre-Reading: The Viterbi Algorithm</strong>&lt;br&gt;<strong>Pre-Reading: VTrack</strong></td>
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