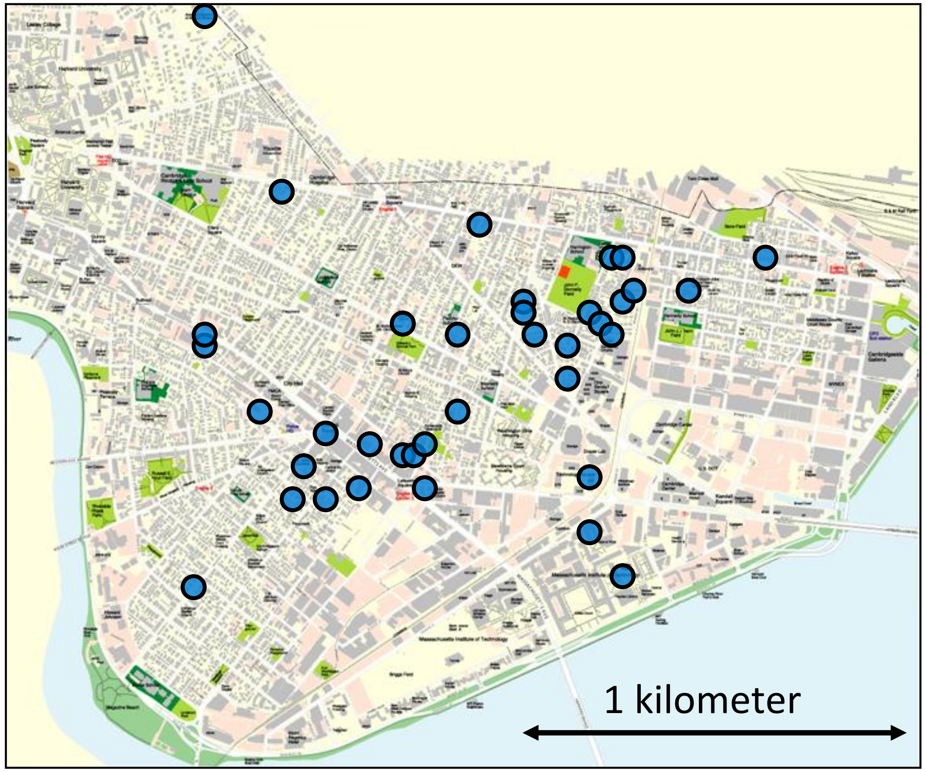
Agenda

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

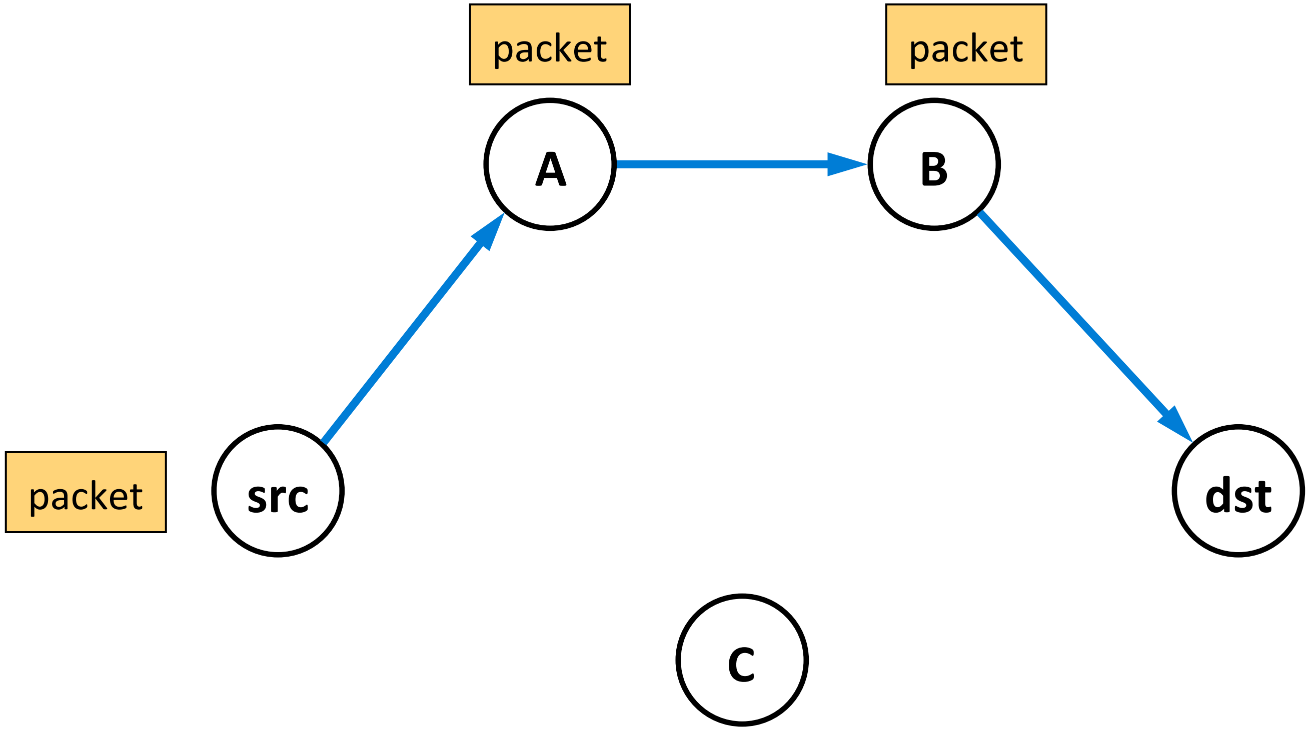
[Aadapted from Biswas, SIGCOMM ‘05]

GZ06: The big wireless picture

Adaptation	**Opportunism**	**Diversity**
SampleRate	ExOR	MRD
SampleWidth	ZigZag decoding	SOFT
RRAA, SoftRate		

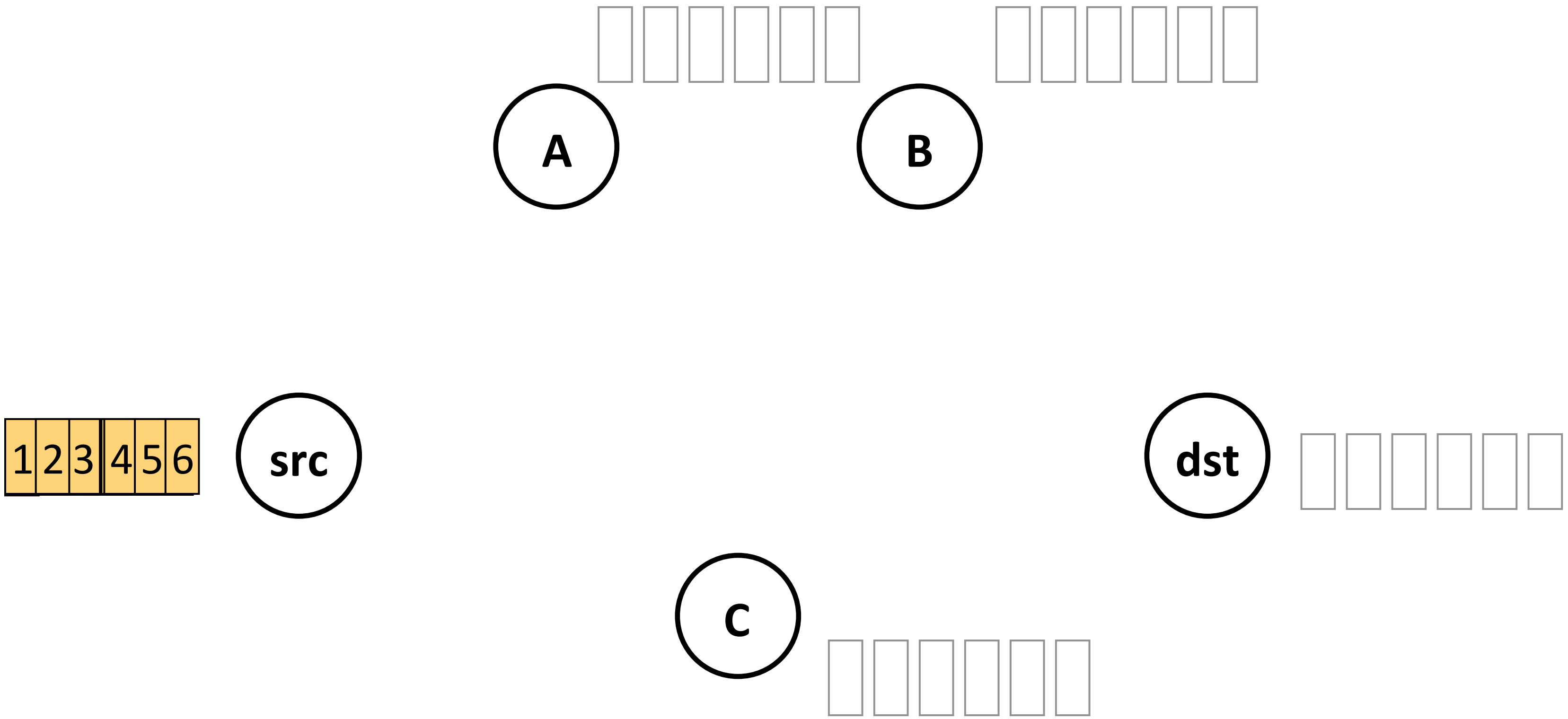
- Today: ExOR
  - Influence on later work
  - Real implementation
  - Evaluation methodology

Initial approach: Traditional routing



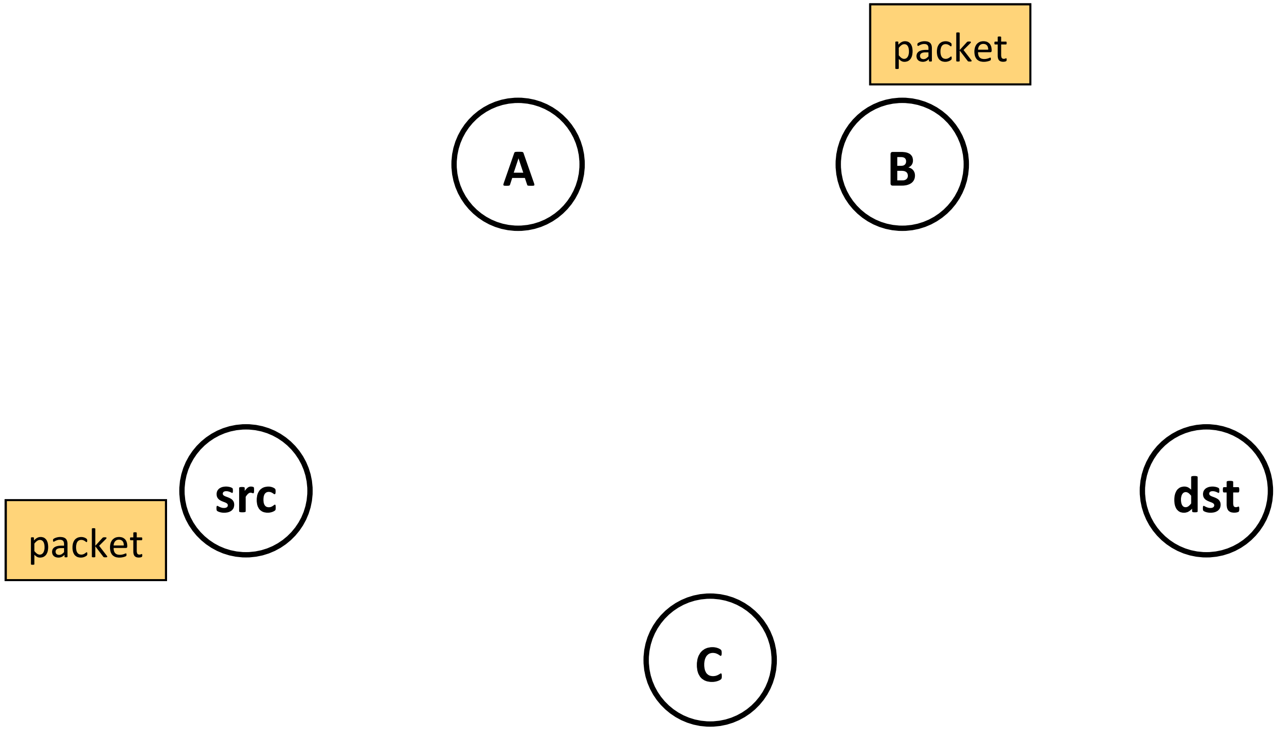
- Identify a route, forward over links
- Abstract radio to look like a wired link

Radios aren't wires



- Every packet is broadcast
- Reception is probabilistic

ExOR: exploiting probabilistic broadcast

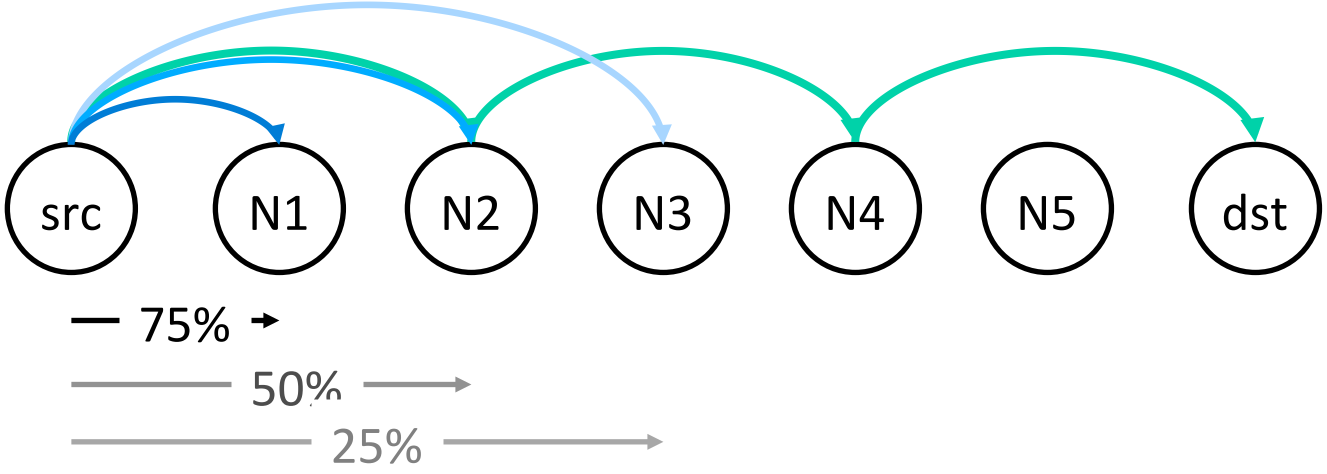


- Decide who forwards after reception
- Goal: only closest receiver should forward
- Challenge: agree efficiently and avoid duplicate xmits

Outline

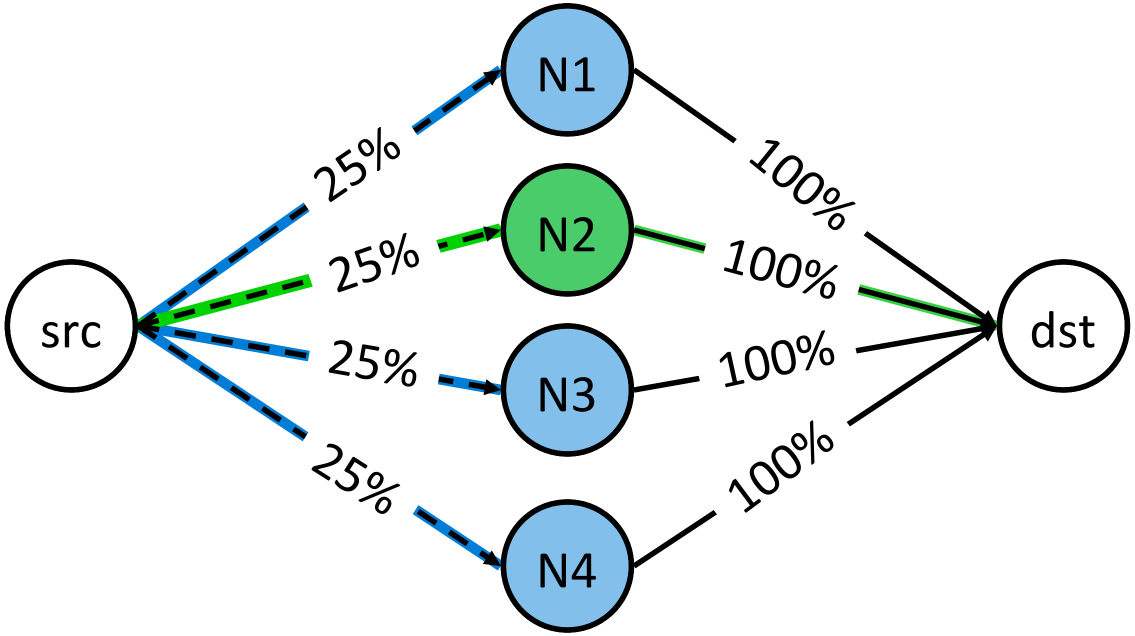
- Introduction
- Why ExOR might increase throughput
- ExOR protocol
- Measurements
- Related Work

Why ExOR might increase throughput (1)



- Best traditional route over 50% hops: $3(^1/_{0.5}) = 6$ tx
- Throughput ≅ $^1/_{\#\ \text{transmissions}}$
- ExOR exploits lucky long receptions
- ExOR recovers unlucky short receptions

Why ExOR might increase throughput (2)



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

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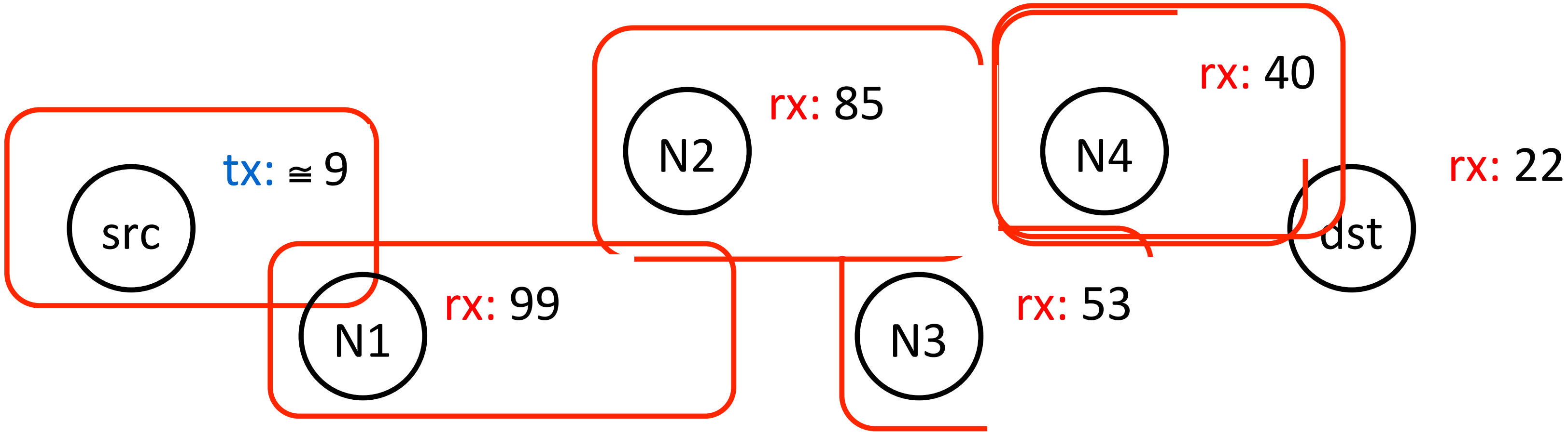
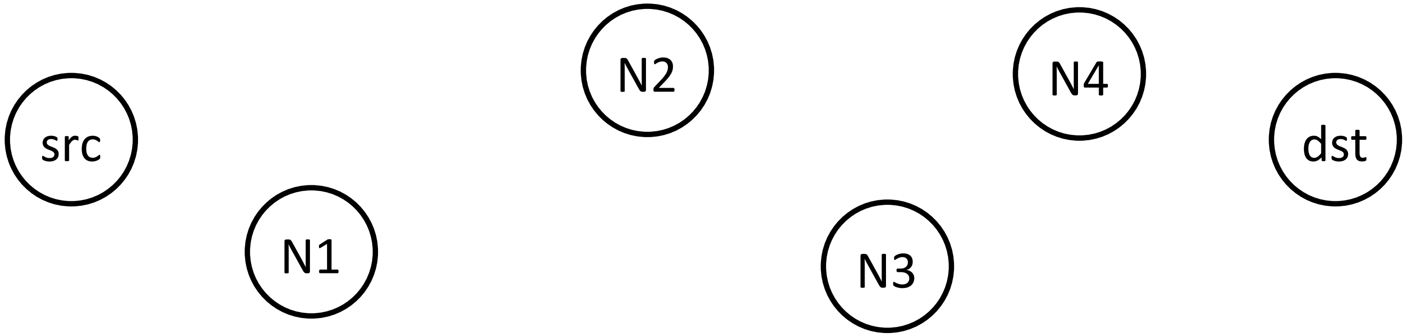
ExOR batching



- 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



tx: {2, 4}

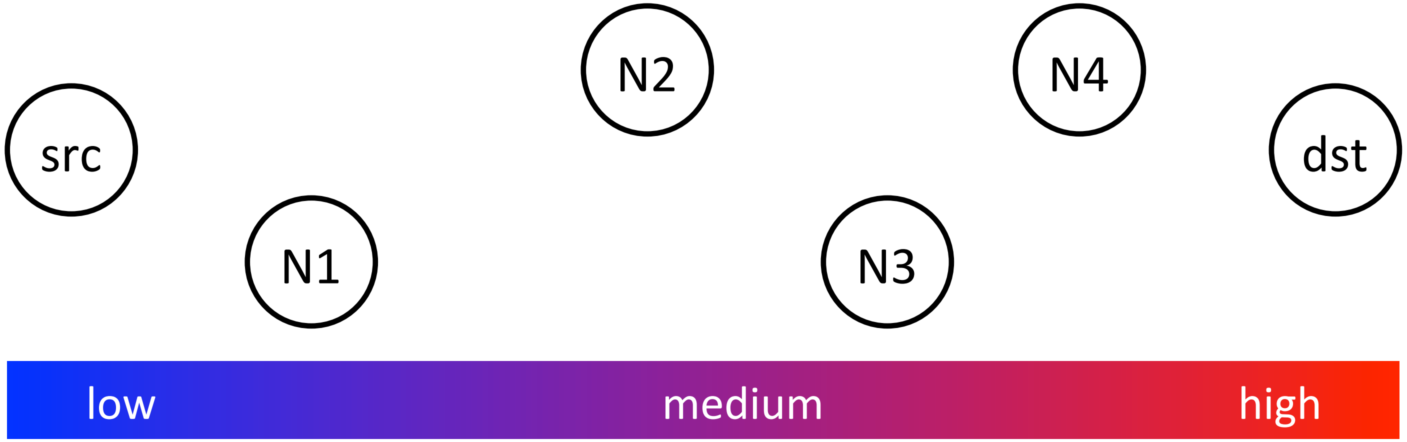
batch map: {1→**N3**, 2→N2, 4→N2} **6→N3**}

tx: {1, 6}

batch map: {1→N3, 6→N3}

- Repeat summaries (batch maps) in every data packet
  - Cumulative: what all previous nodes rx'd
  - Allows src to receive acknowledgement

Priority ordering



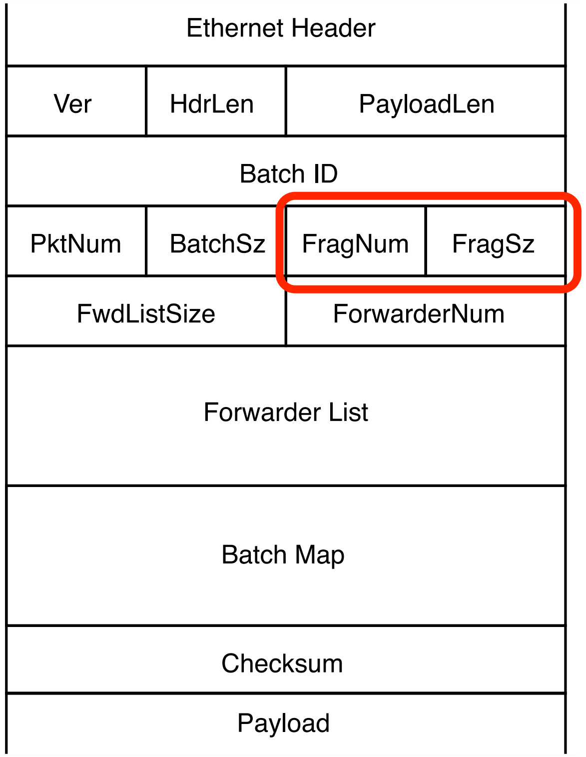
- Goal: nodes "closest" to the destination send first
- Sort by ETX metric to dst
  - Nodes periodically flood ETX "link state" measurements
  - Path ETX is weighted shortest path (Dijkstra's algorithm)
- Source sorts, includes *forwarder list* in ExOR header

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)



Ethernet Header

Ver | HdrLen | PayloadLen

Batch ID

PktNum | BatchSz | FragNum | FragSz

FwdListSize | ForwarderNum

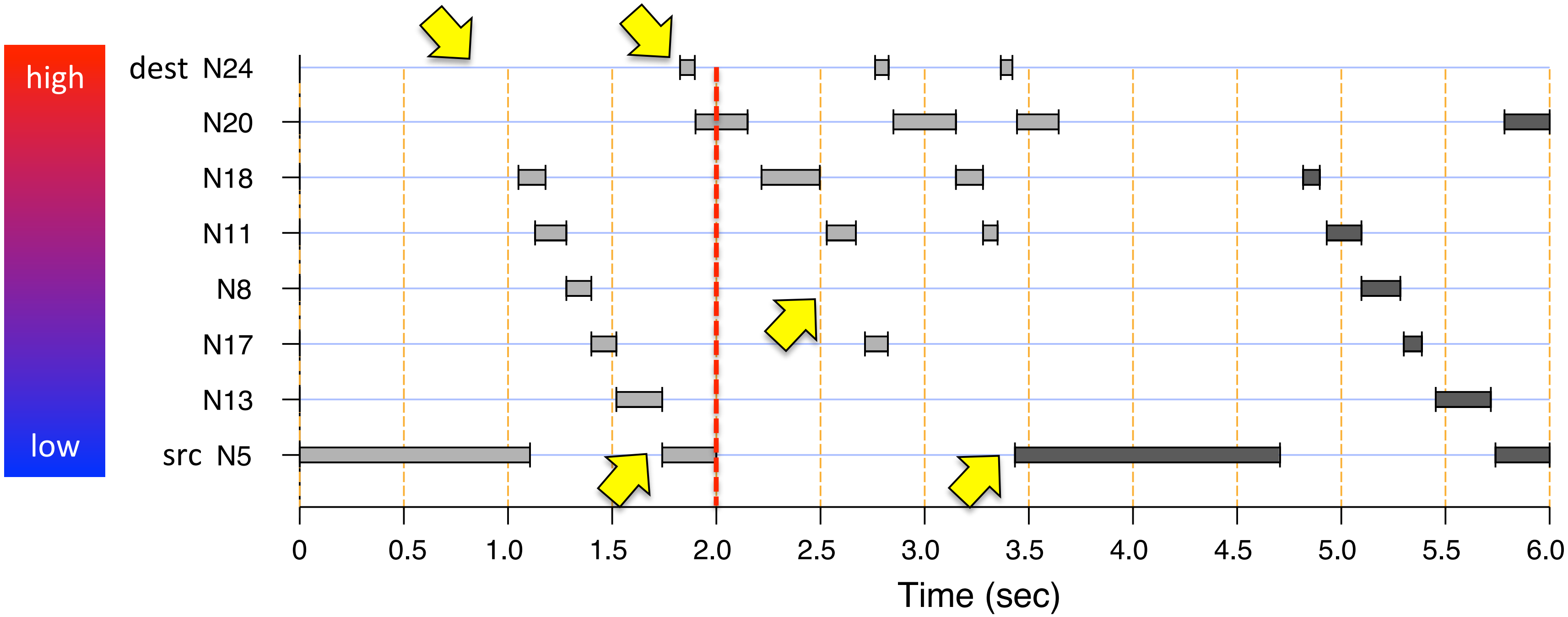
Forwarder List

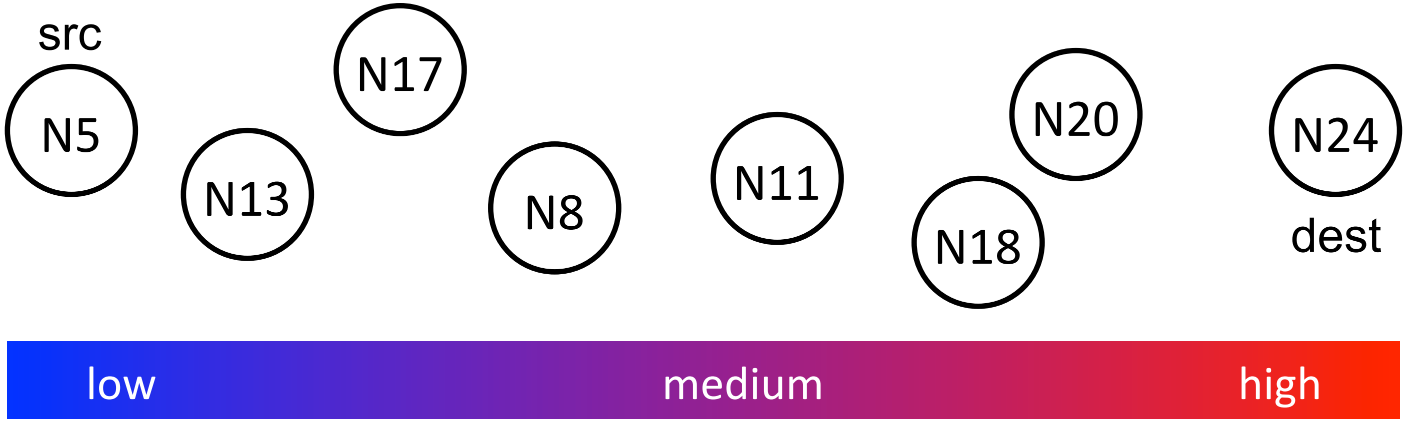
Batch Map

Checksum

Payload

Transmission timeline

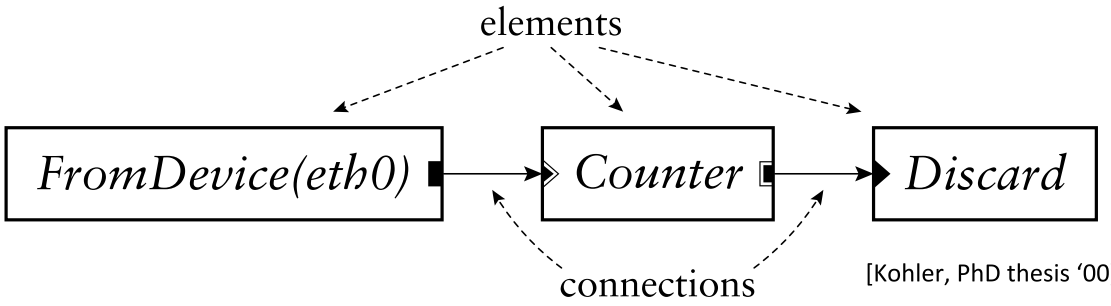




Implementation

- Click userlevel, libpcap

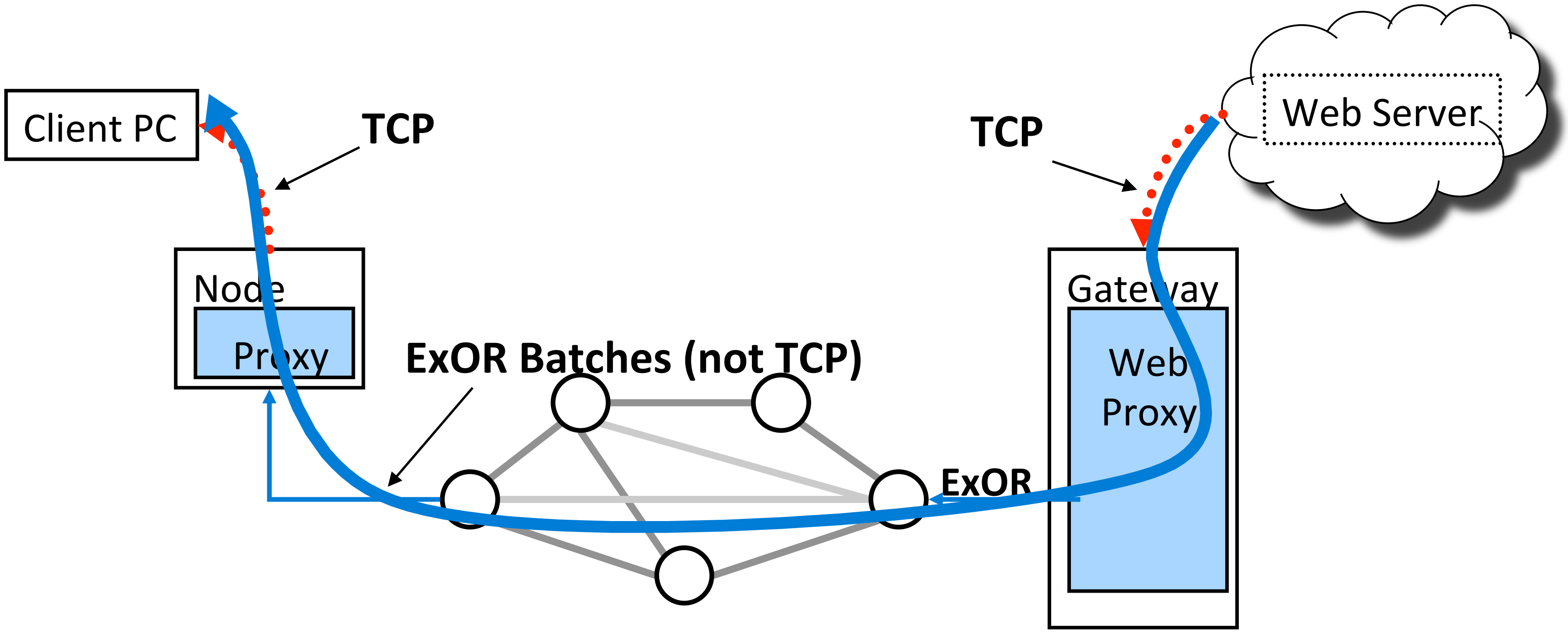
http://read.cs.ucla.edu/click/



[Kohler, PhD thesis ‘00]

- 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

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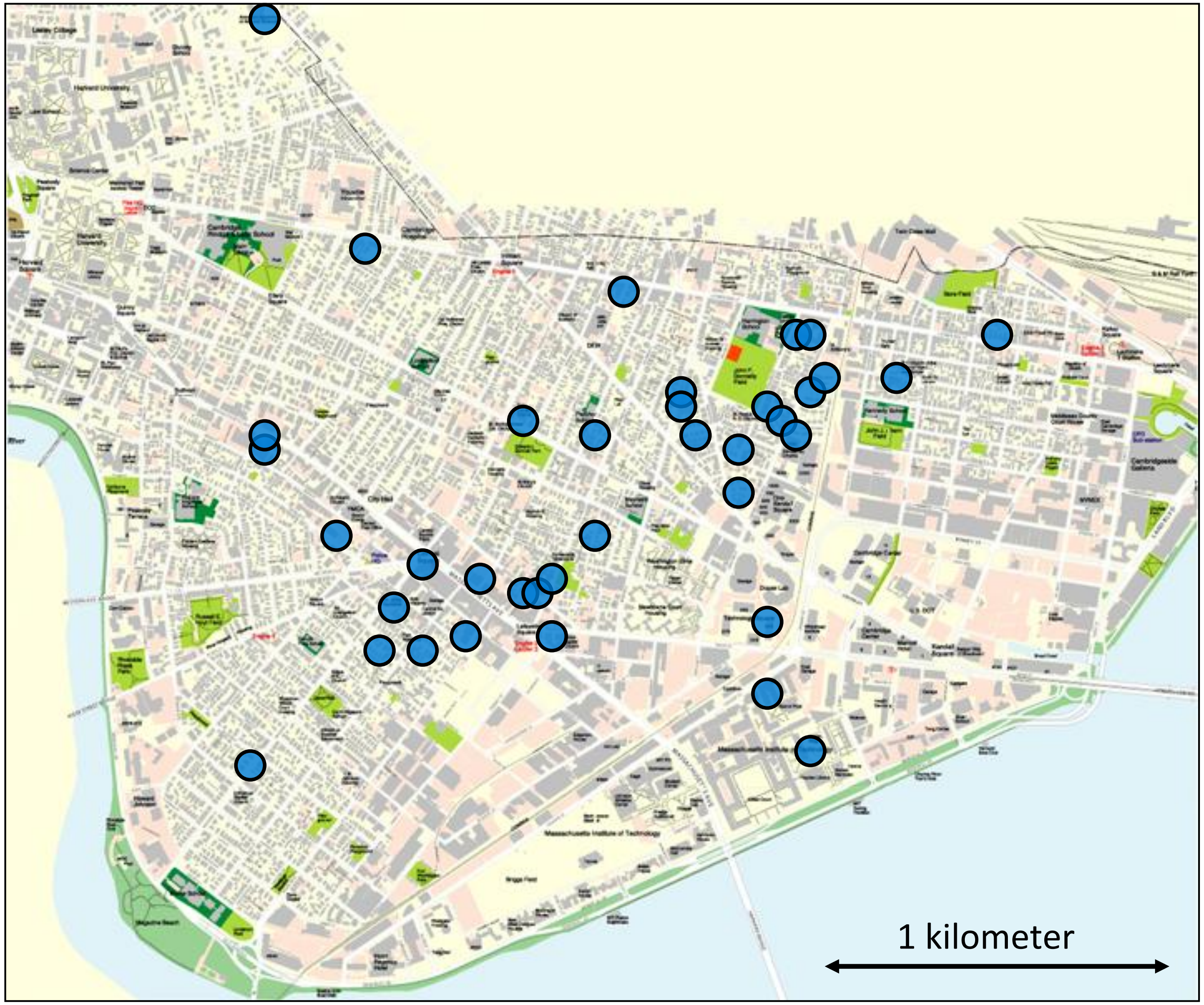
ExOR Evaluation

Questions to answer experimentally:

1. Does ExOR increase throughput?
2. When/why does it work well?

65 Roofnet node pairs

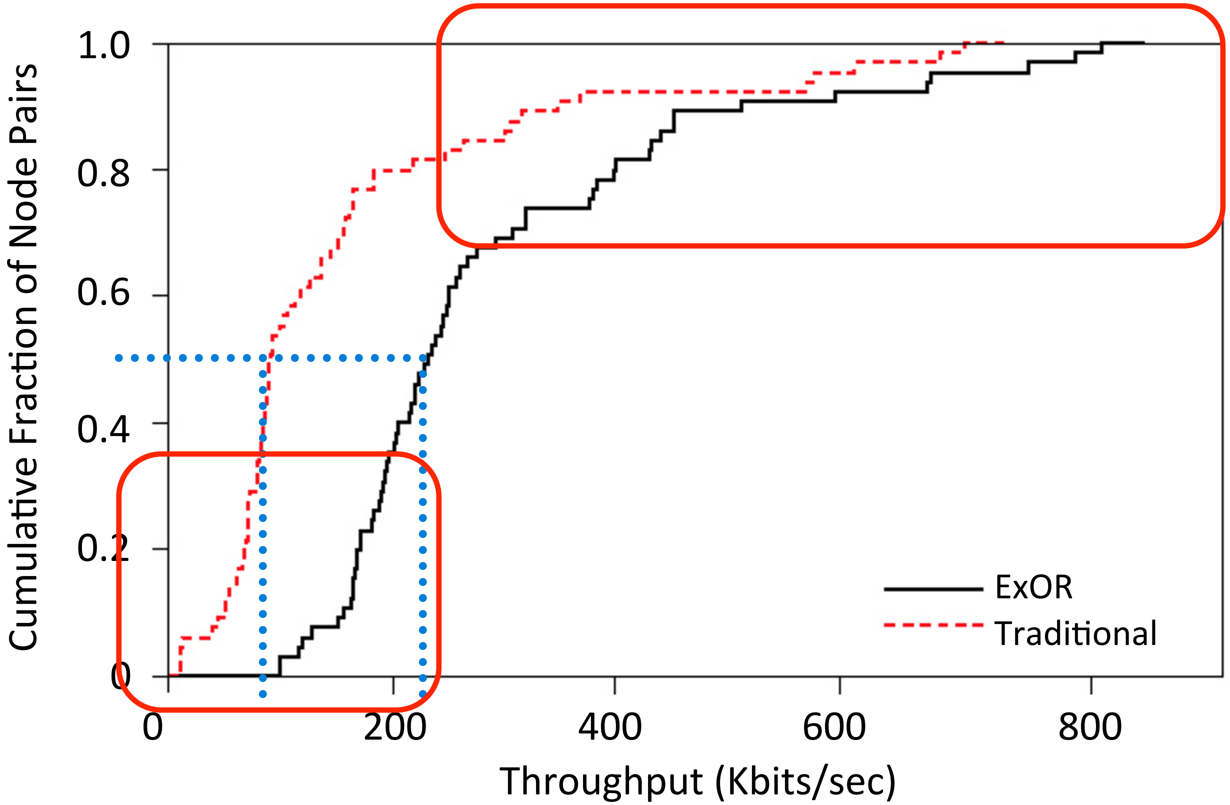


Evaluation Details

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

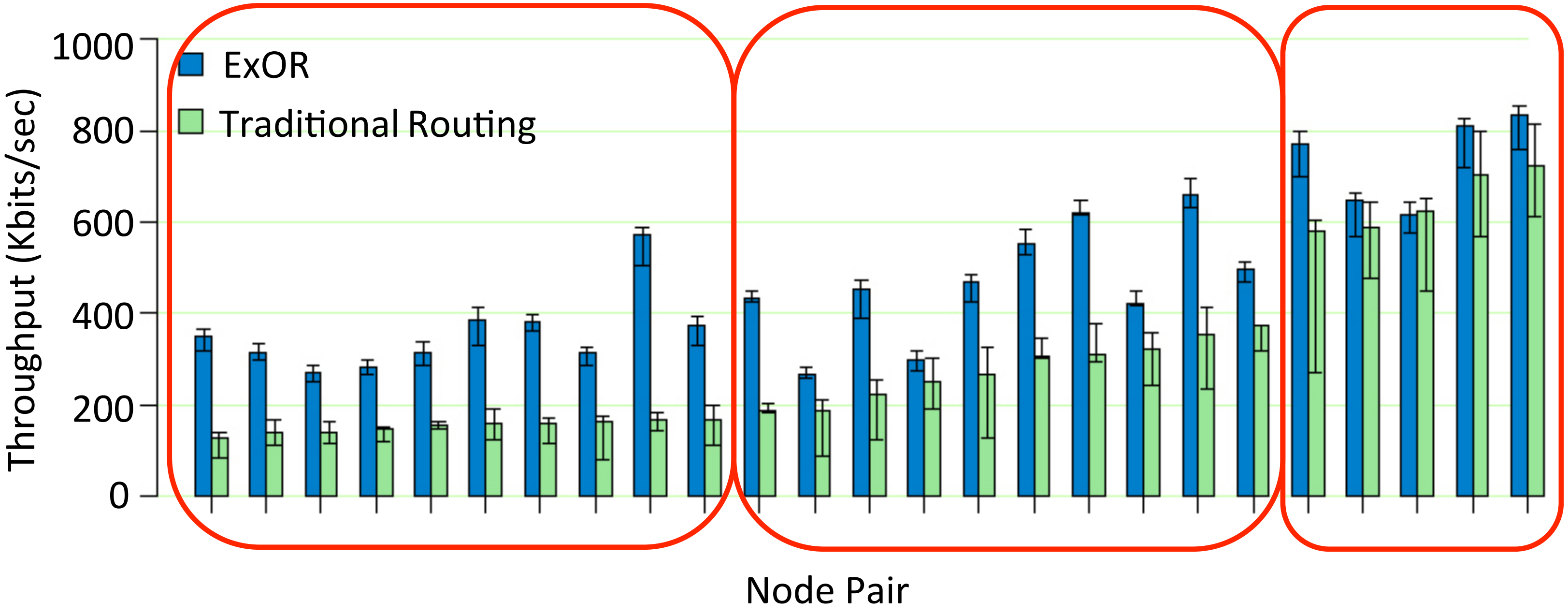
Traditional Routing	ExOR
802.11 unicast with link-level retransmissions, Hop-by-hop batching, UDP sending as MAC allows	802.11 broadcasts, 100-packet batch size

ExOR: 2x overall improvement



- Median throughputs: 240 Kbits/sec for ExOR,
  121 Kbits/sec for Traditional

25 Highest throughput pairs

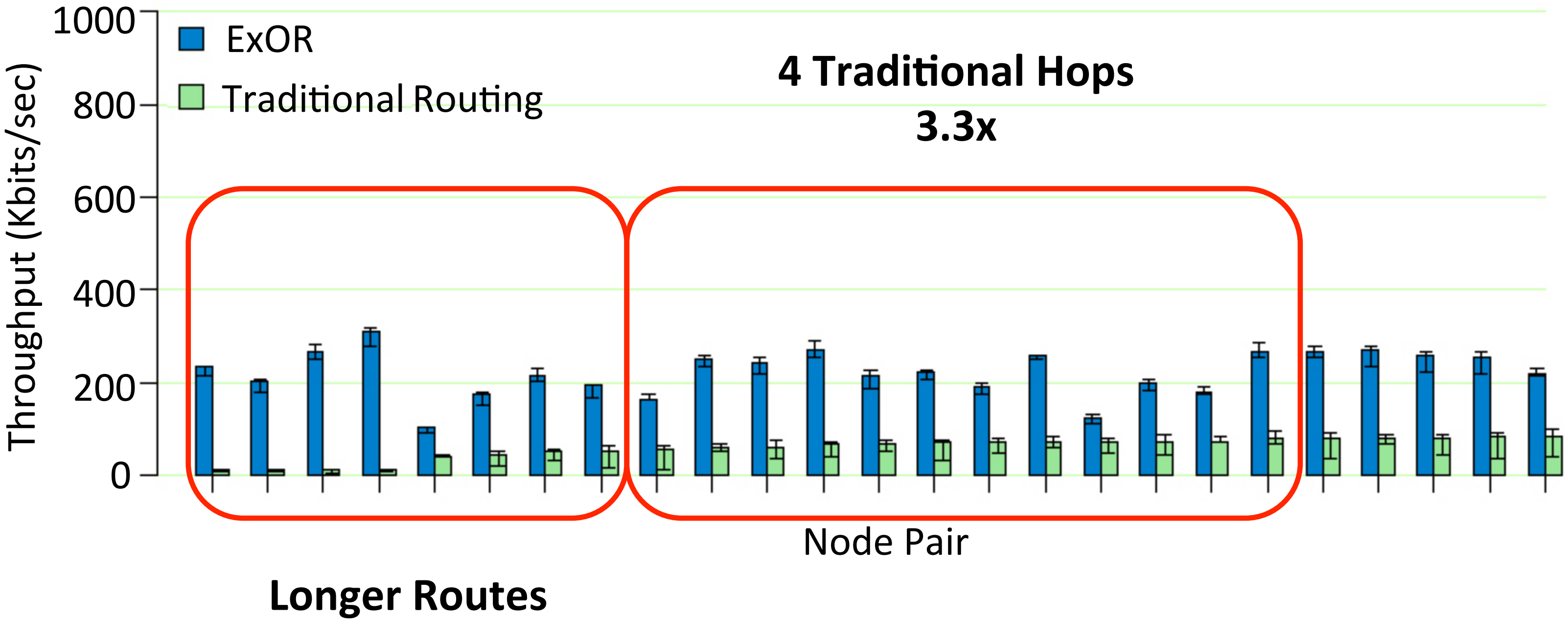


3 Traditional Hops
2.3x

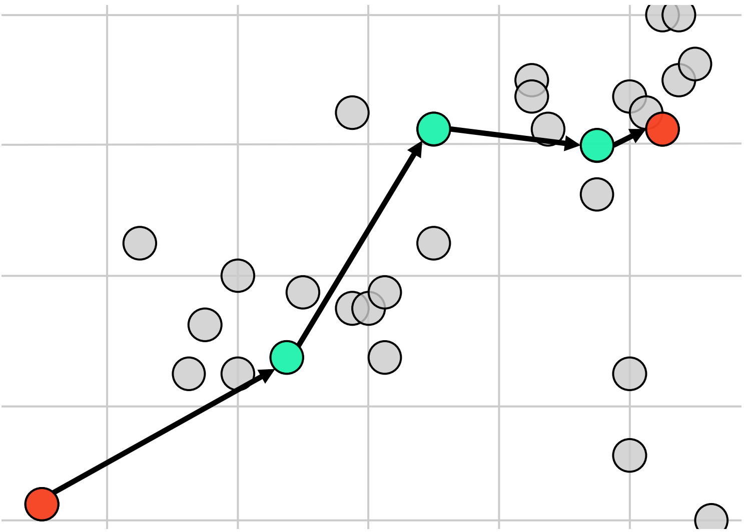
2 Traditional Hops
1.7x

1 Traditional Hop
1.14x

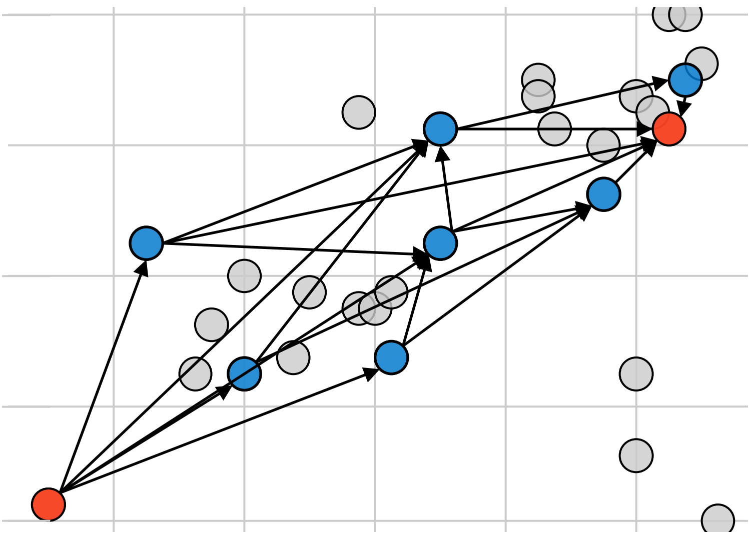
25 Lowest throughput pairs



ExOR uses links in parallel

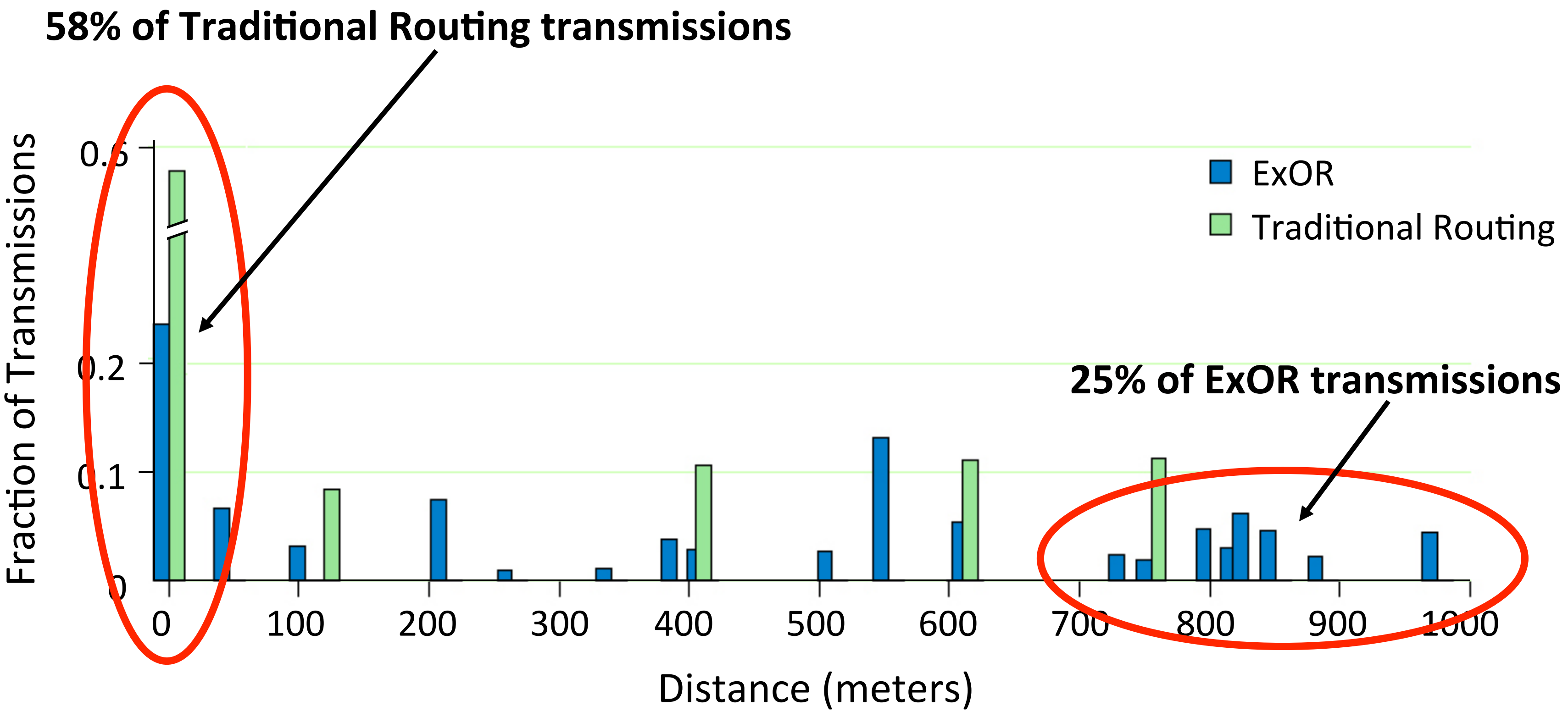


Traditional Routing
3 forwarders
4 links



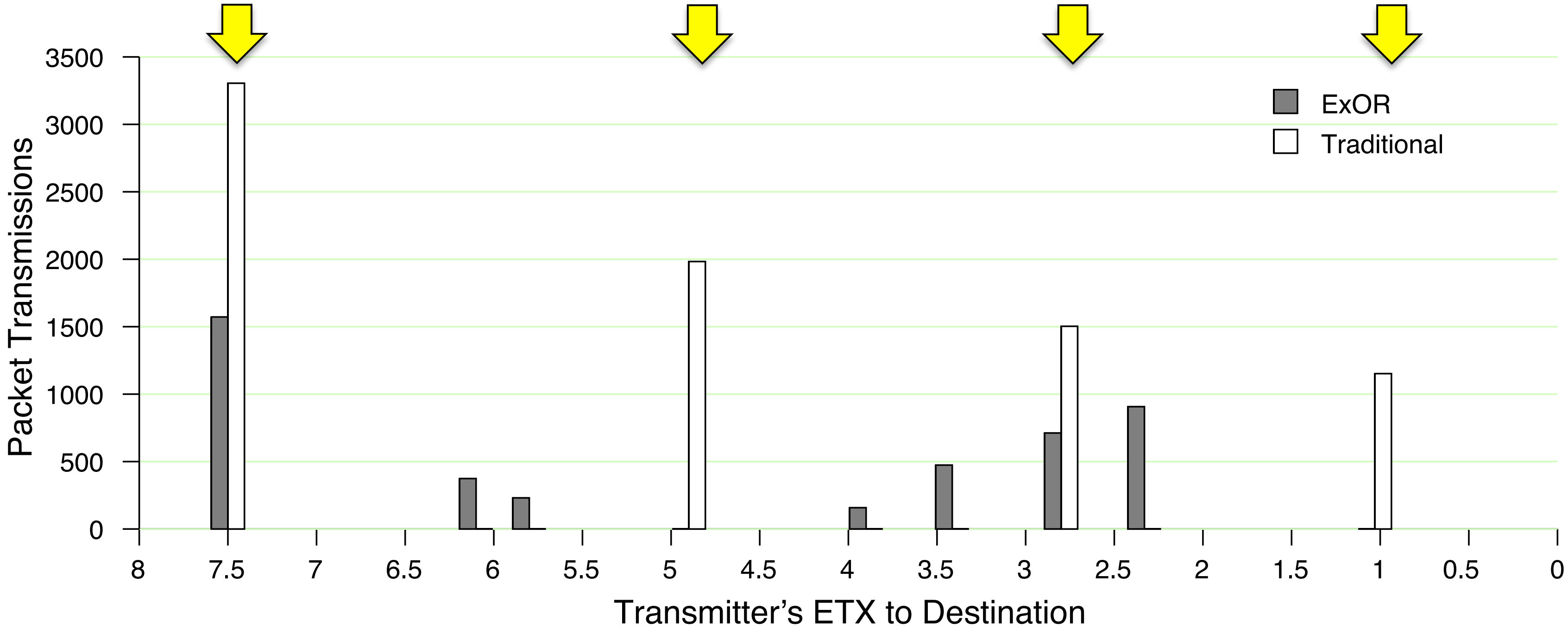
ExOR
7 forwarders
18 links

ExOR moves packets farther



- ExOR average: 422 meters/transmission
- Traditional Routing average: 205 meters/tx

Traditional approach constrains *who* routes



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

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

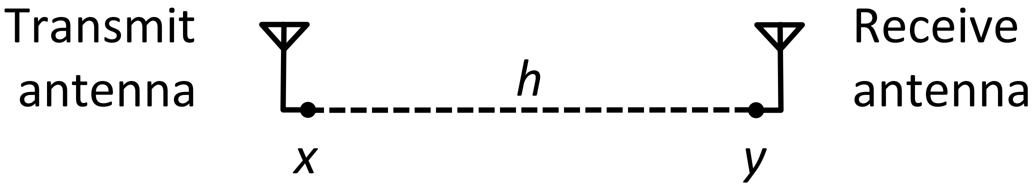
2. **The physical layer and the MIMO physical layer**
   - Next time: *Interference alignment and cancellation*, and *Taking the sting out of carrier sense* (successive interference cancellation)

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?*

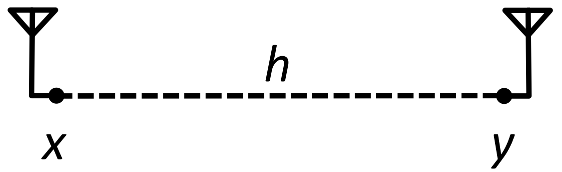
Introduction: the wireless channel



$$y = hx + w$$

- 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

A simplified model of the wireless channel

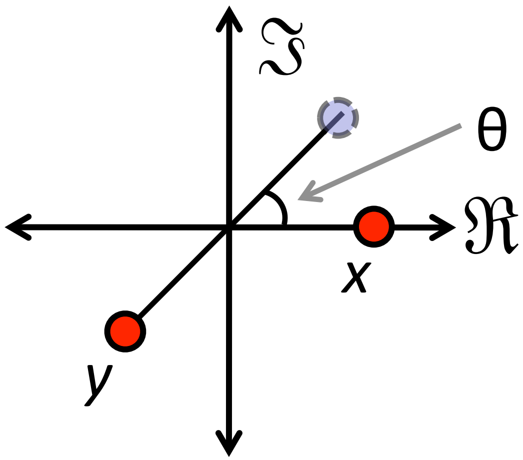


Transmit antenna

Receive antenna

$$y = hx + w$$

- Represent complex number *h* in magnitude-phase form:



$$h = a \cdot e^{j\theta}$$ (*a*, θ real)

- Channel impacts sent symbol in two ways:

1. Rotates *x* by angle θ
2. Scales *x* by scalar quantity *a*

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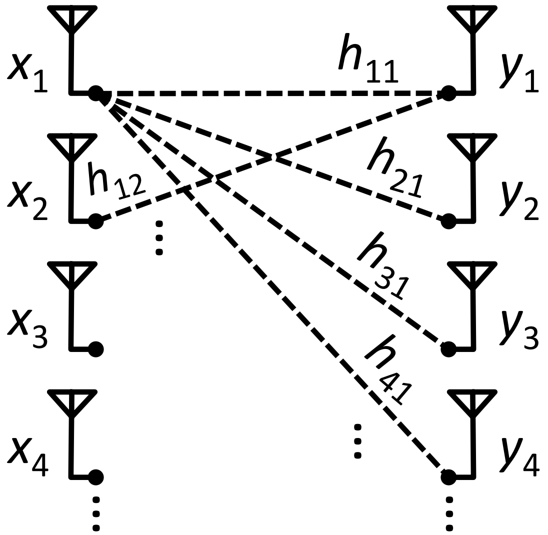
    - Next time: *Interference alignment and cancellation*, and *Taking the sting out of carrier sense* (successive interference cancellation)
    - **The MIMO channel**
    - The singular value decomposition (SVD)
    - Capacity of the MIMO channel

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*

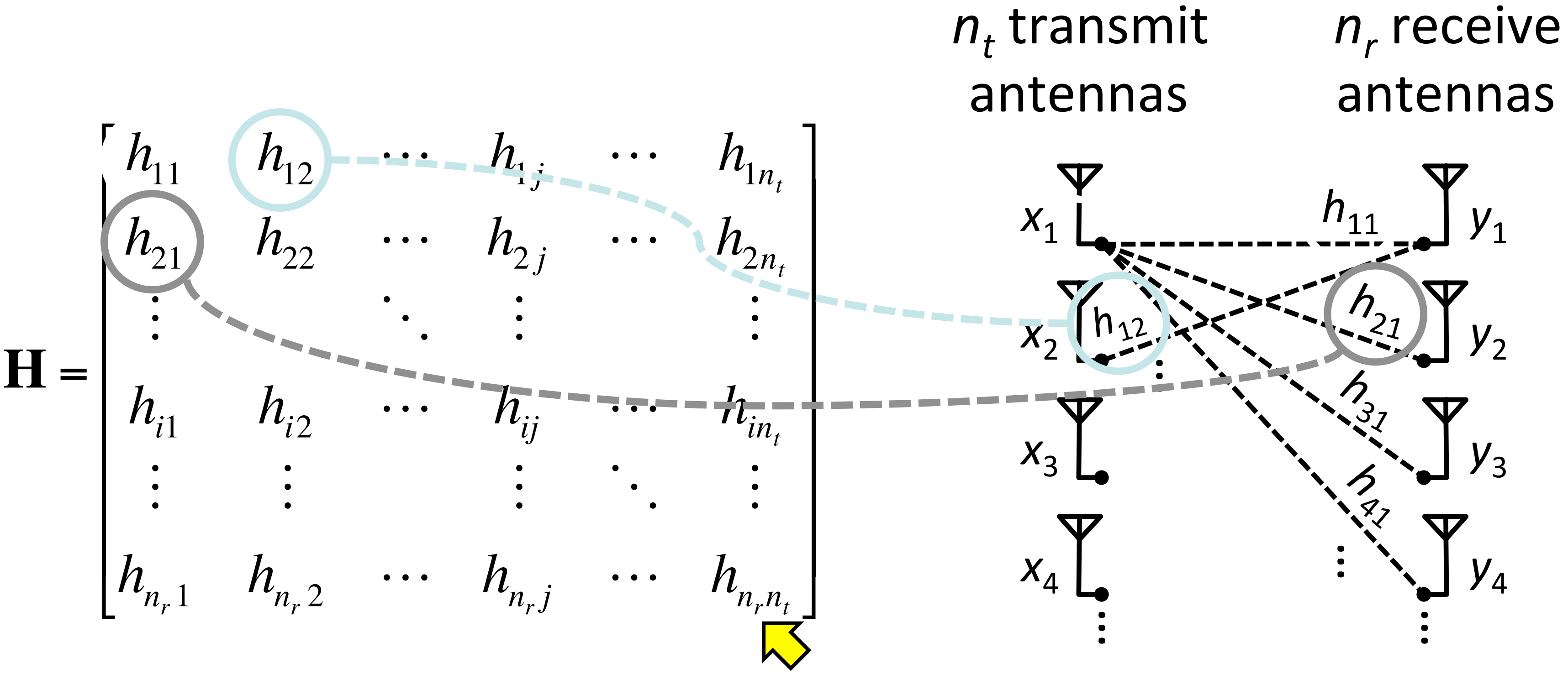
n_t transmit antennas

n_r receive antennas



Problem: Transmissions interfere with each other

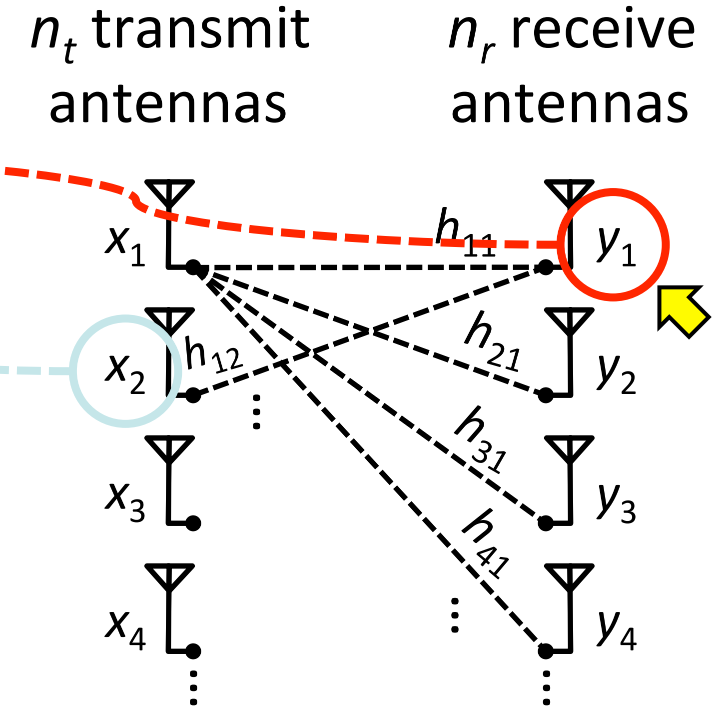
Representing the channel as a matrix



$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1j} & \cdots & h_{1n_t} \\ h_{21} & h_{22} & \cdots & h_{2j} & \cdots & h_{2n_t} \\ \vdots & & \ddots & \vdots & & \vdots \\ h_{i1} & h_{i2} & \cdots & h_{ij} & \cdots & h_{in_t} \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ h_{n_r 1} & h_{n_r 2} & \cdots & h_{n_r j} & \cdots & h_{n_r n_t} \end{bmatrix}$$

Representing the data as vectors

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_j \\ \vdots \\ x_{n_t} \end{bmatrix} \qquad \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \\ \vdots \\ y_{n_r} \end{bmatrix}$$



$$y_1 = h_{11}x_1 + h_{12}x_2 + \cdots + h_{1n_t}x_{n_t}$$

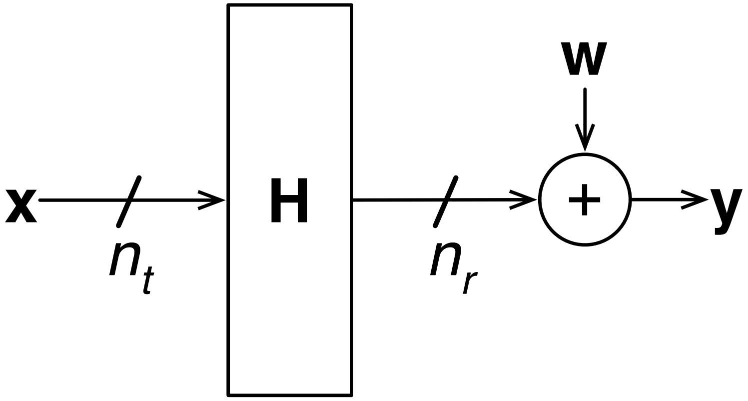
The vector MIMO channel: $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$

$$\underset{\substack{\uparrow\\ \text{Output}}}{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \\ \vdots \\ y_{n_r} \end{bmatrix}} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1j} & \cdots & h_{1n_t} \\ h_{21} & h_{22} & \cdots & h_{2j} & \cdots & h_{2n_t} \\ \vdots & & \ddots & \vdots & & \vdots \\ h_{i1} & h_{i2} & \cdots & h_{ij} & \cdots & h_{in_t} \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ h_{n_r1} & h_{n_r2} & \cdots & h_{n_rj} & \cdots & h_{n_rn_t} \end{bmatrix}}_{\text{Channel}} \cdot \underset{\substack{\uparrow\\ \text{Input}}}{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_j \\ \vdots \\ x_{n_t} \end{bmatrix}} + \underset{\substack{\uparrow\\ \text{Noise}}}{\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_i \\ \vdots \\ w_{n_r} \end{bmatrix}}$$

$$y_1 = h_{11}x_1 + h_{12}x_2 + \cdots + h_{1n_t}x_{n_t}$$

$$y_i = h_{i1}x_1 + h_{i2}x_2 + \cdots + h_{in_t}x_{n_t}$$

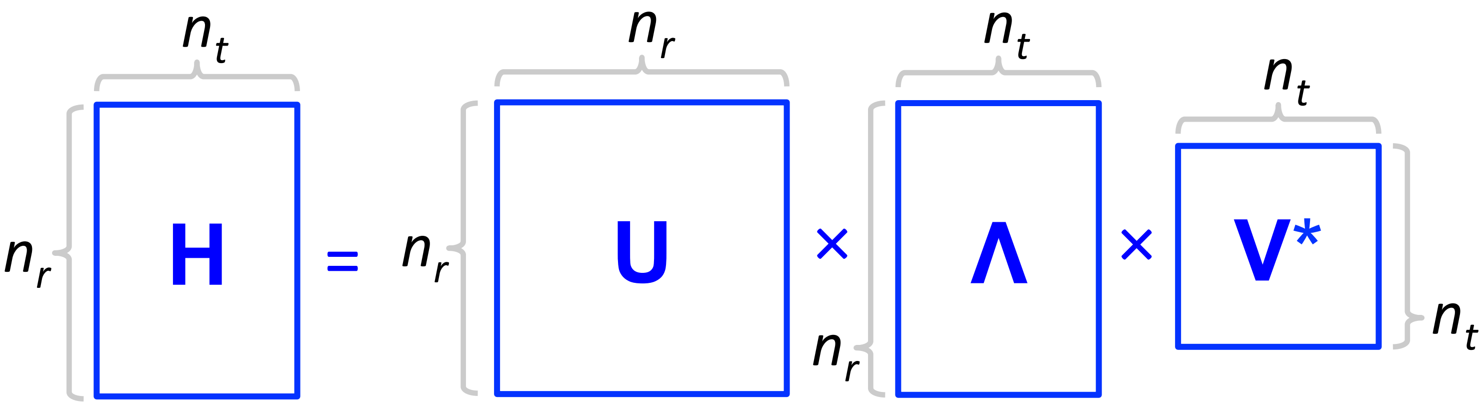
The vector MIMO channel: $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$



- Problem: Each output is a mixture of all inputs; we say that the outputs are **coupled** together: $y_i = h_{i1}x_1 + h_{i2}x_2 + \cdots + h_{in_t}x_{n_t}$
- 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**

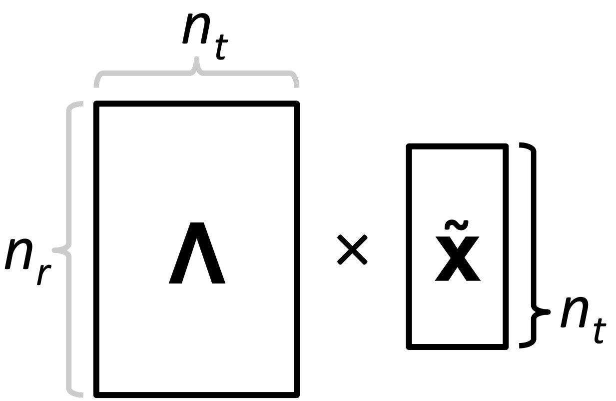
The singular value decomposition (SVD)

- *Fact:* Every matrix **H** has a *singular value decomposition* **H** = **UΛV***
  - **Λ** ($n_r \times n_t$) 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

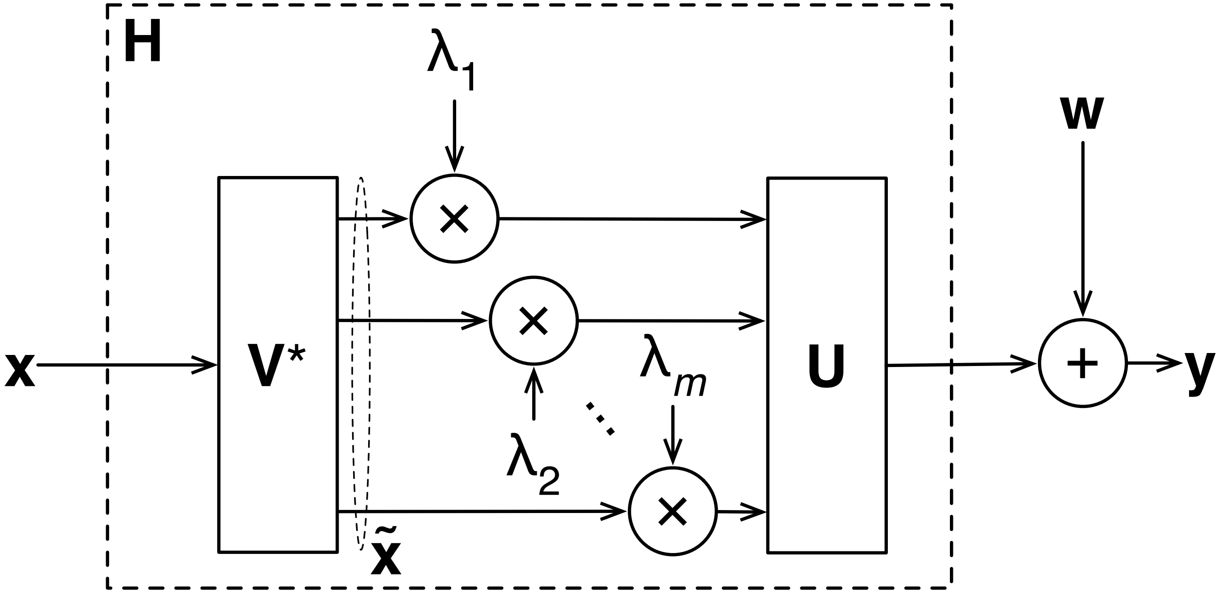
- **Λ** matrix contains the *m* = min(n_t, n_r) *singular values* of **H**: λ_i
- Number of non-zero singular values = rank(**H**)
- **V** translates to a new coordinate system where the channels are decoupled (**U** translates back)
  - Matrix multiplication by a diagonal matrix is simple!



$$= n_r\left\{\overbrace{\begin{bmatrix}\lambda_1 & & & 0\\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_{n_t}\\ 0 & & & \end{bmatrix}}^{n_t}\right. \times \begin{bmatrix}\tilde{x}_1\\ \tilde{x}_2\\ \vdots\\ \tilde{x}_{n_t}\end{bmatrix} = \left.\begin{bmatrix}\lambda_1\tilde{x}_1\\ \lambda_2\tilde{x}_2\\ \vdots\\ \lambda_{n_t}\tilde{x}_{n_t}\\ 0\\ \vdots\\ 0\end{bmatrix}\right\} n_r$$

SVD: moving to a new coordinate system

- Singular value decomposition of H represents:
  1. Translation to new coordinate system (V*)
  2. **Decoupled** scaling (λ_i)
  3. Translation back to original coordinate system (U)

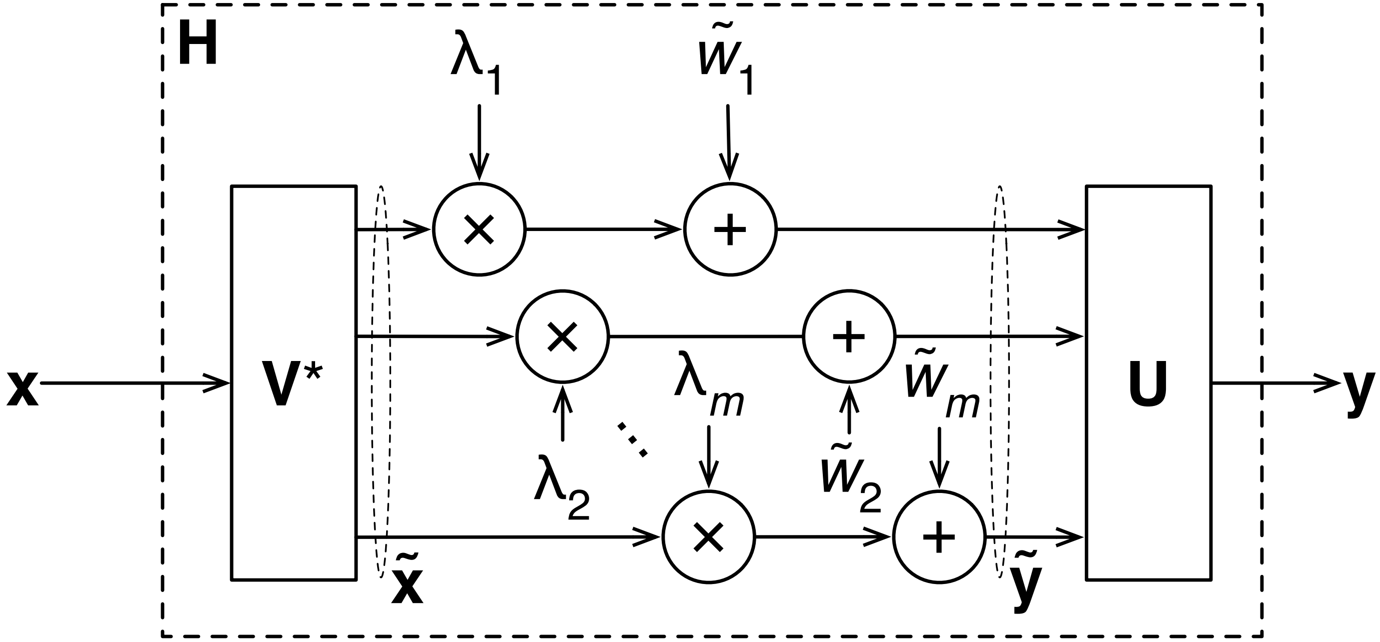


SVD of the channel matrix

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

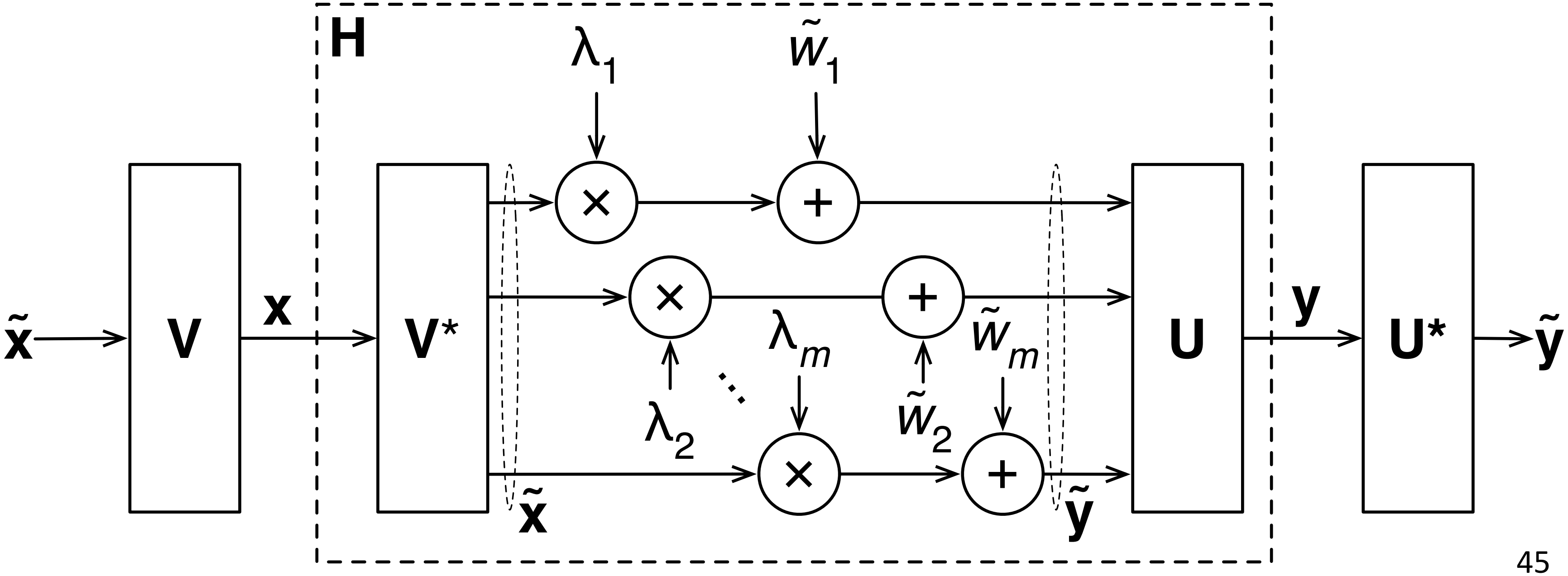
- Now we have **independent channels** from $\tilde{\mathbf{x}}$ to $\tilde{\mathbf{y}}$

How do we use this for useful communication?



Applying SVD to communication

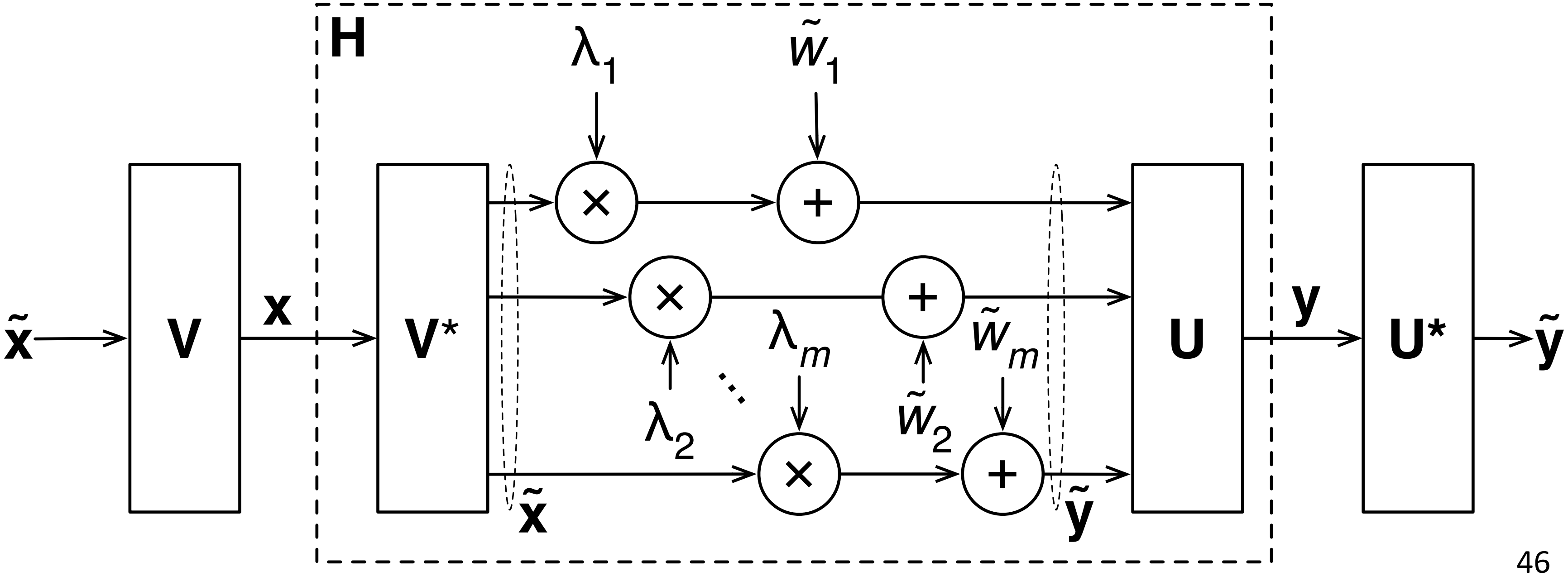
- Pre-process with **V**, post-process with **U***; **V*V** = **U*U** = **I**
- Each **nonzero** singular value λ_i supports **a** data stream
- Fact: The number of nonzero λ_i is: k = rank(**H**)



Capacity of the MIMO channel

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

$$C \approx \sum_{i=1}^{k} \log\left(1 + \frac{P\lambda_i^2}{kN_0}\right) \approx k\log(\mathrm{SNR}) + \mathrm{o}(\mathrm{SNR})$$



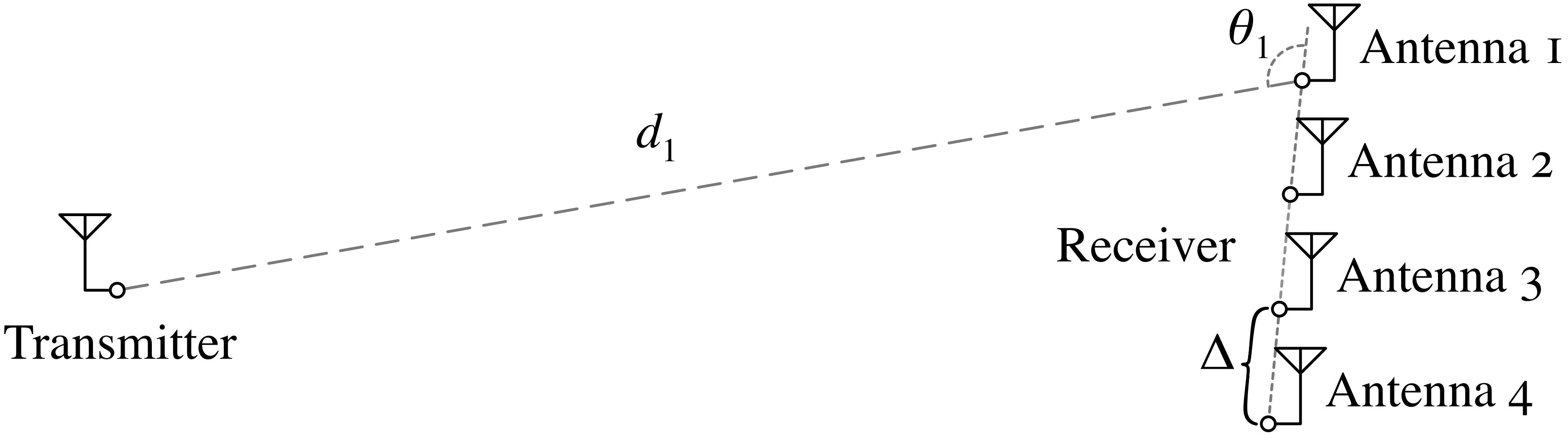
Physical modeling of MIMO channels

- 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

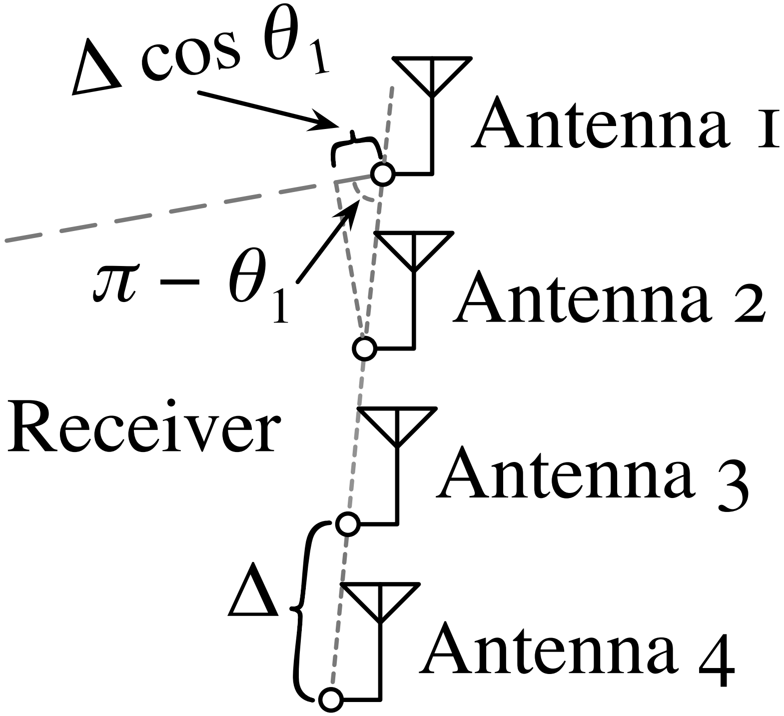
- Single input, multiple input (SIMO) channel
- **Free space:** no reflectors, scatterers; one path length d_1
- Receiver equipped with a linear antenna array
  - Array antenna separation $\Delta << d_1$
  - Line-of-sight transmitter at bearing θ_1 with array



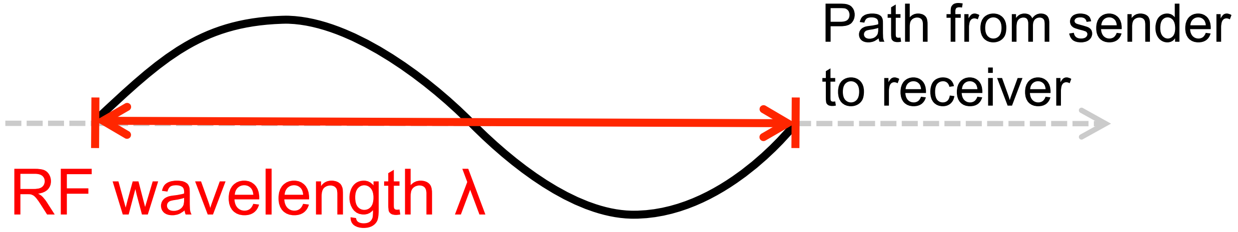
Line-of-sight SIMO channel: Detail

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

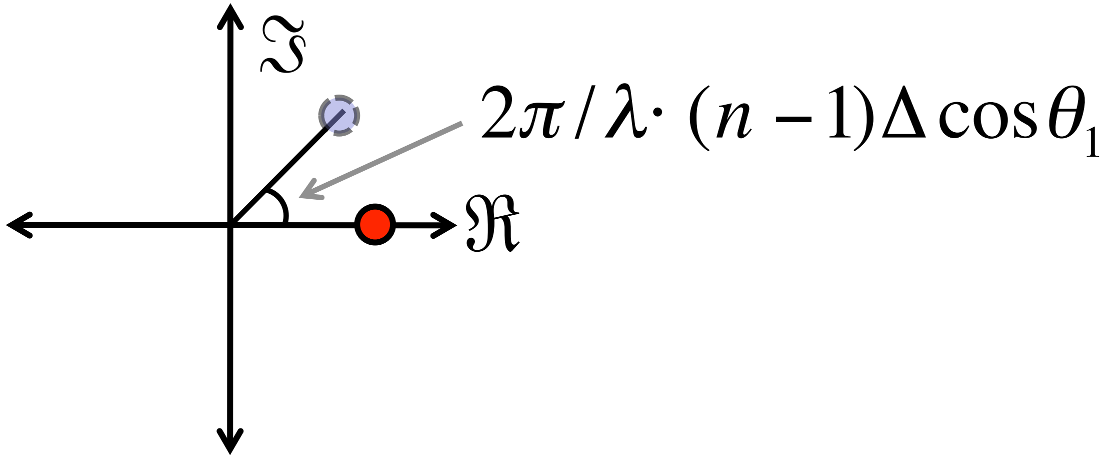
- Fact 1: There is a distance difference of $(n-1)\,\Delta \cos \theta_1$ for the n^{th} antenna



Distance rotates constellation



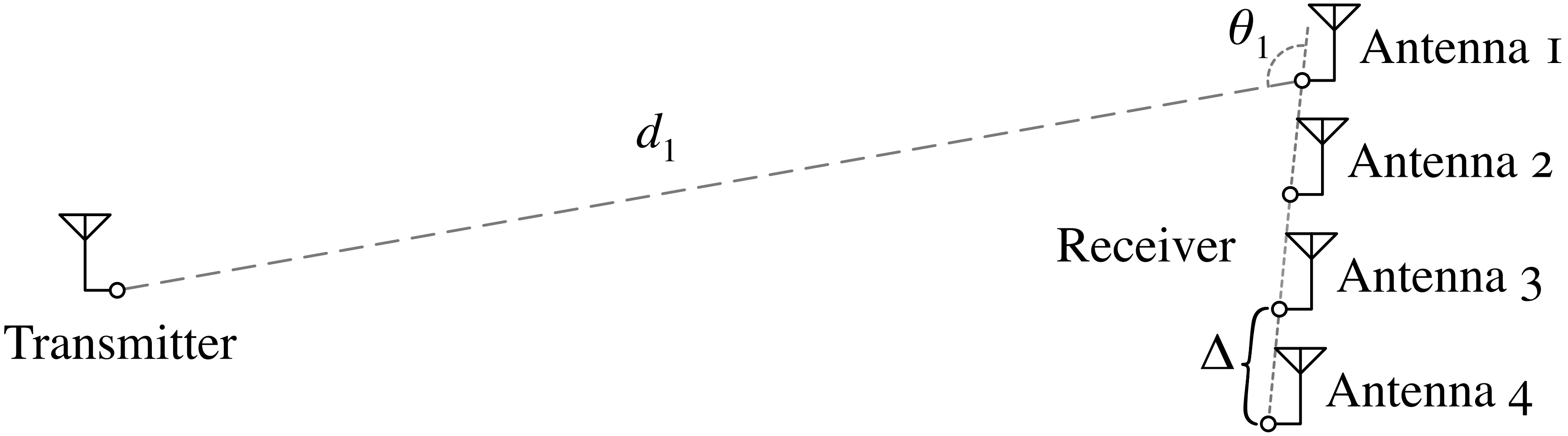
- Fact 2: Distance d_1 rotates received signal by $\measuredangle\ 2\pi/\lambda \cdot d_1$
- Compared to first antenna, channel to n^{th} antenna rotates received constellation point



Line-of-sight SIMO channel

$$\mathbf{h}_1 = a e^{j2\pi d_1/\lambda} \begin{bmatrix} 1 \\ e^{j2\pi \cdot \Delta \cos\theta_1/\lambda} \\ e^{j2\pi \cdot 2\Delta \cos\theta_1/\lambda} \\ \vdots \\ e^{j2\pi \cdot n_r \Delta \cos\theta_1/\lambda} \end{bmatrix}$$

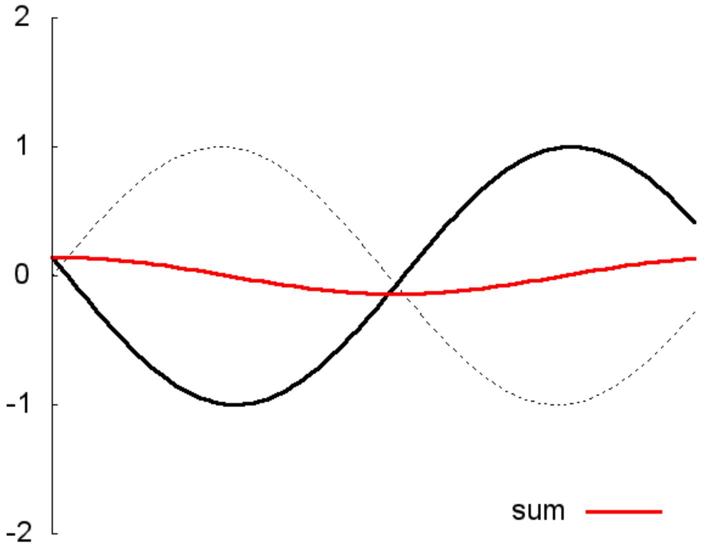
- Facts 1 and 2 together:
- Distance difference of $(n-1)\,\Delta\cos\theta_1$ for the nth antenna
- Distance rotates constellation



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)

$$\mathbf{h}_1 = ae^{j2\pi d_1/\lambda}\begin{bmatrix} 1 \\ e^{j2\pi\cdot\Delta\cos\theta_1/\lambda} \\ e^{j2\pi\cdot 2\Delta\cos\theta_1/\lambda} \\ \vdots \\ e^{j2\pi\cdot n_r\Delta\cos\theta_1/\lambda} \end{bmatrix}$$



MRC with n_r = 2

- SIMO channel capacity:

$$C = \log\left(1+\frac{P\|\mathbf{h}\|^2}{N_0}\right) = \log\left(1+\frac{Pa^2 n_r}{N_0}\right) \text{bits/s/Hz}$$

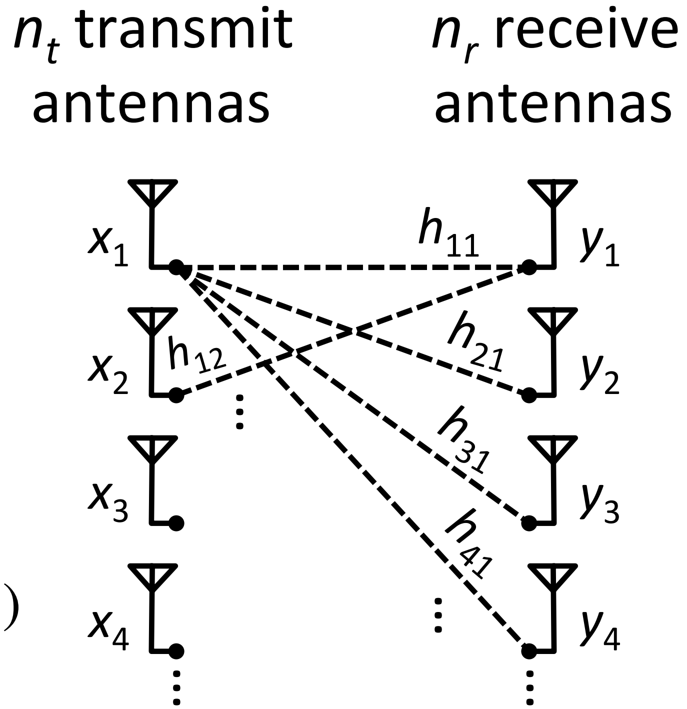
- ↑ SNR, but no concurrency
- MIMO channel capacity:

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

The line-of-sight MIMO channel

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

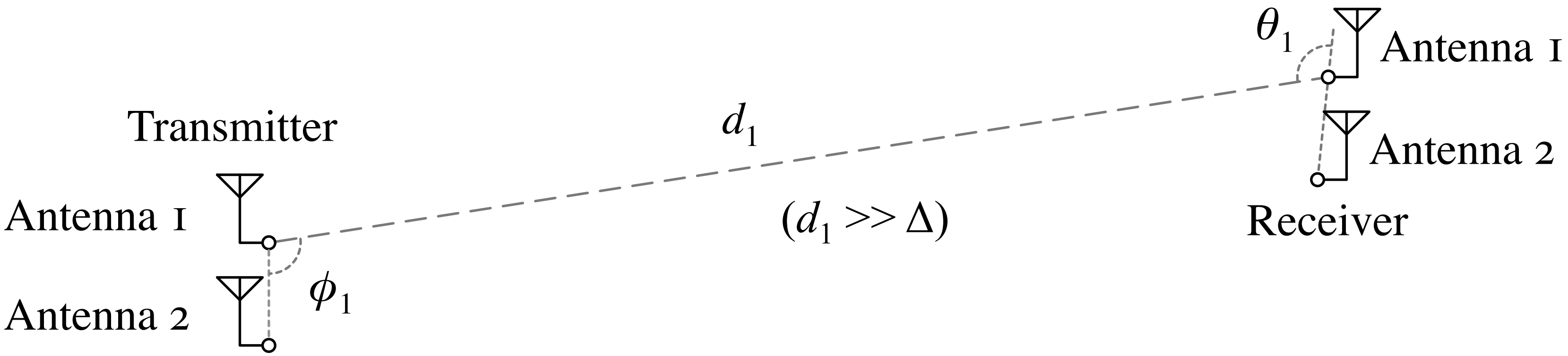
$$C \approx \sum_{i=1}^{k} \log\left(1 + \frac{P\lambda_i^2}{kN_0}\right) \approx k\log(\text{SNR}) + \text{o}(\text{SNR})$$



The line-of-sight MIMO channel

- Distance between transmit antenna *i* and receive antenna *k*:

$$d_{ik} = d_1 + (i-1)\Delta\cos\phi_1 - (k-1)\Delta\cos\theta_1$$



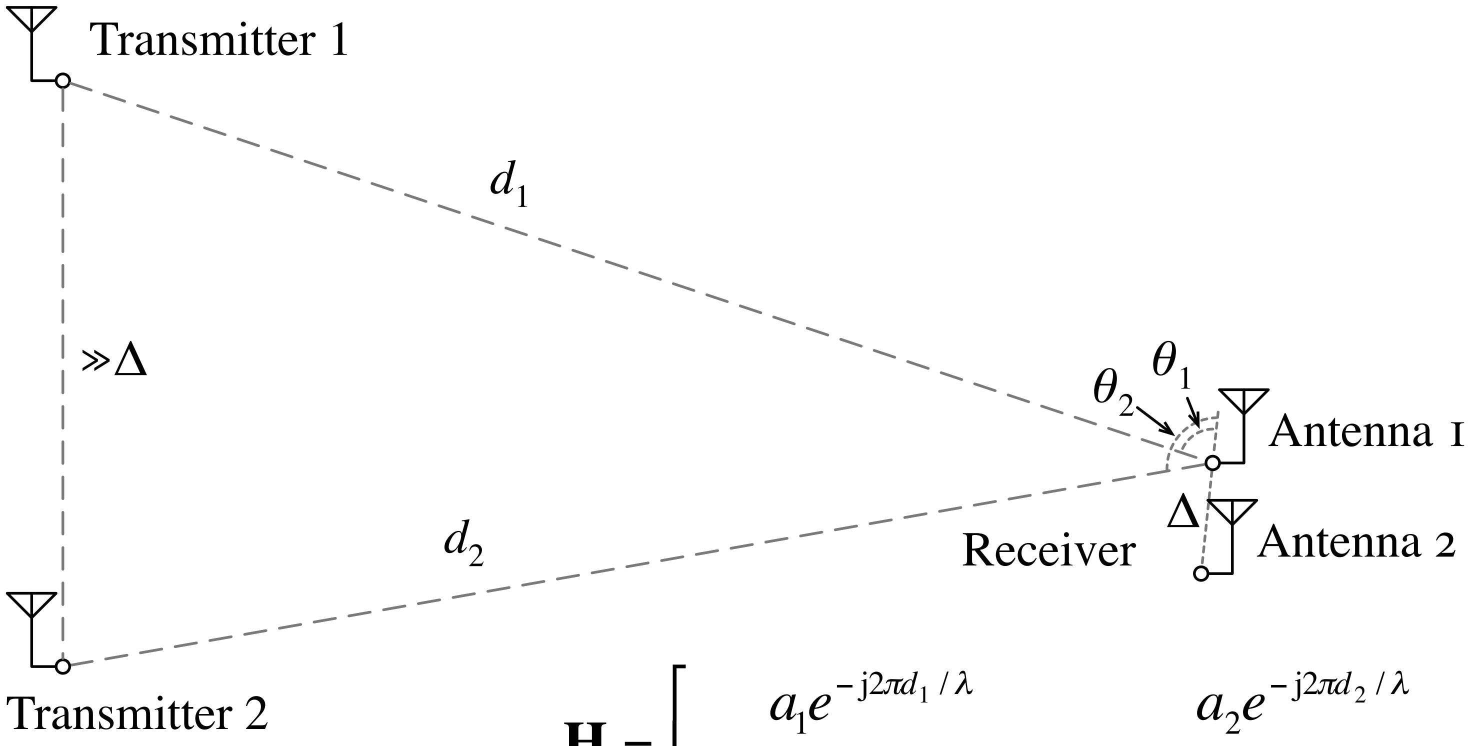
$$\mathbf{H} = a_1 e^{-j2\pi d_1/\lambda}\begin{bmatrix} 1 & e^{-j2\pi\Delta\cos\phi_1/\lambda} \\ e^{-j2\pi\Delta\cos\theta_1/\lambda} & e^{-j2\pi\Delta(\cos\theta_1+\cos\phi_1)/\lambda} \end{bmatrix}$$

The line-of-sight MIMO channel

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

- Every column (row) in **H** is a multiple of the other columns (rows), so 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**

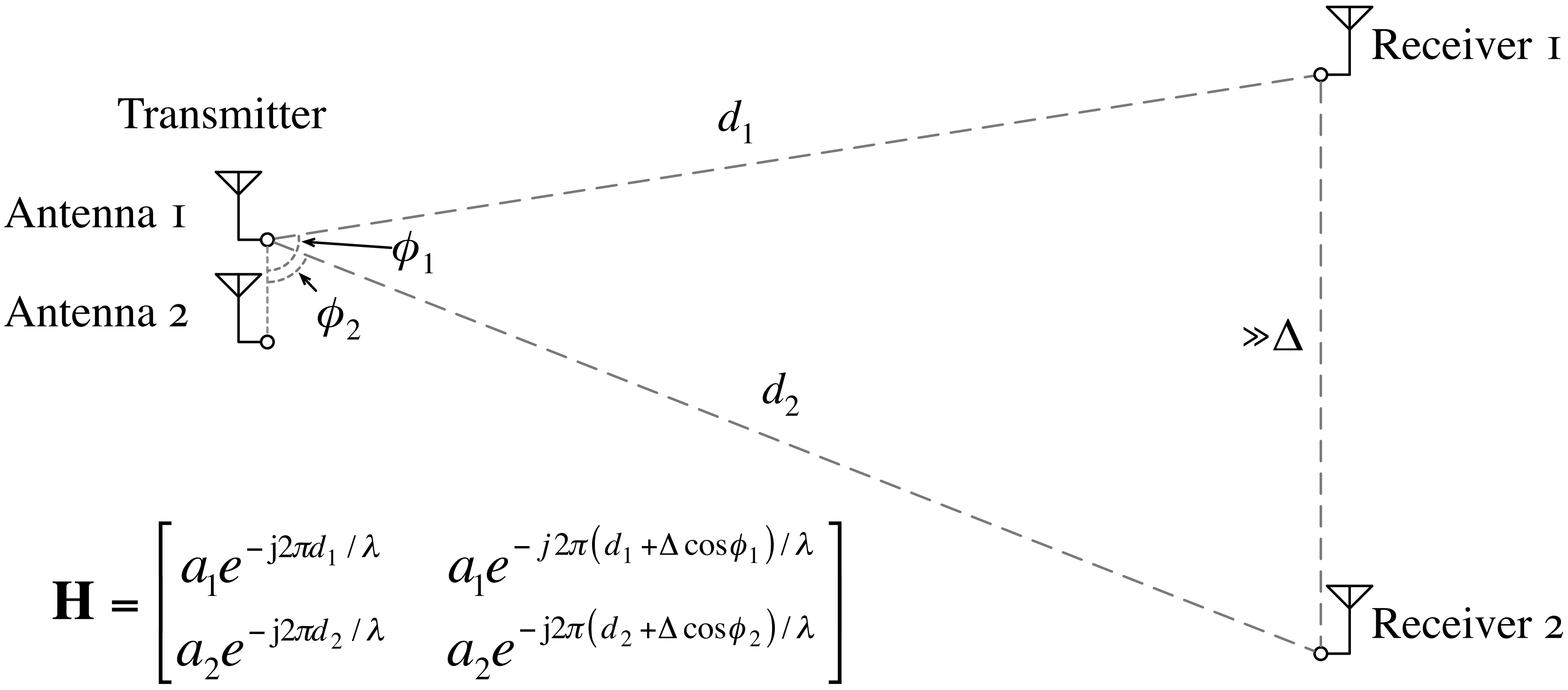
Spatially separated transmit antennas



$$\mathbf{H} = \begin{bmatrix} a_1 e^{-\mathrm{j}2\pi d_1/\lambda} & a_2 e^{-\mathrm{j}2\pi d_2/\lambda} \\ a_1 e^{-\mathrm{j}2\pi\left(d_1+\Delta\cos\theta_1\right)/\lambda} & a_2 e^{-\mathrm{j}2\pi\left(d_2+\Delta\cos\theta_2\right)/\lambda} \end{bmatrix}$$

If $\cos\theta_1 \neq \cos\theta_2$ then $k = \mathrm{rank}(\mathbf{H}) = 2$, concurrent streams possible.

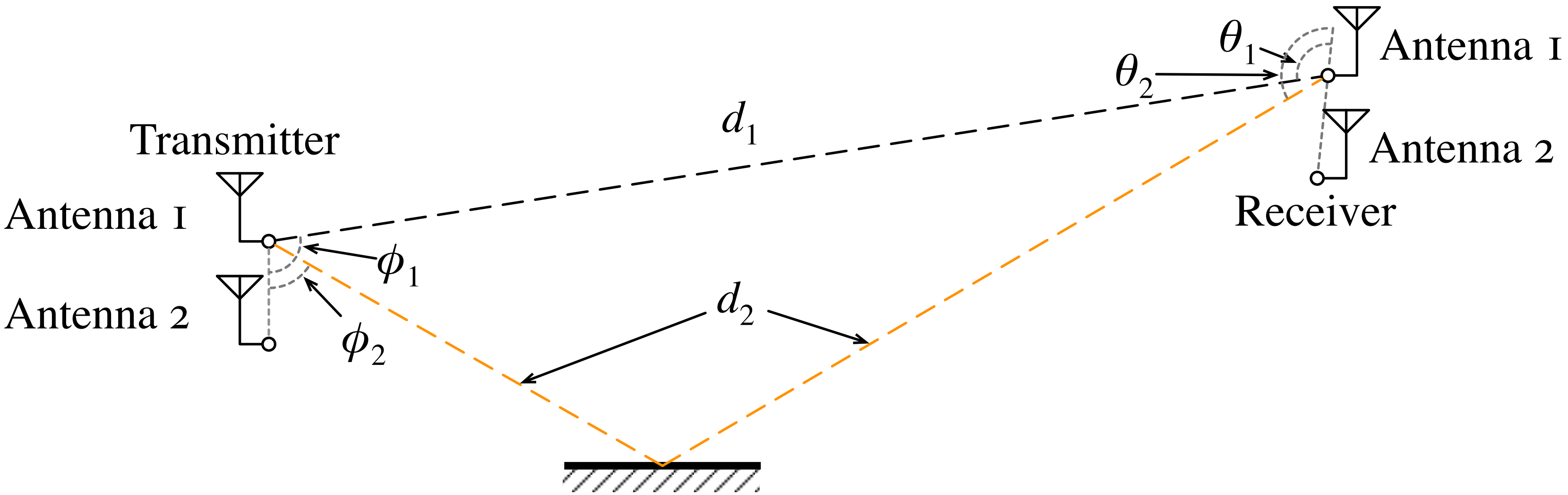
Spatially separated receive antennas



$$\mathbf{H} = \begin{bmatrix} a_1 e^{-\mathrm{j}2\pi d_1/\lambda} & a_1 e^{-j2\pi\left(d_1+\Delta\cos\phi_1\right)/\lambda} \\ a_2 e^{-\mathrm{j}2\pi d_2/\lambda} & a_2 e^{-\mathrm{j}2\pi\left(d_2+\Delta\cos\phi_2\right)/\lambda} \end{bmatrix}$$

If cos $\phi_1 \neq$ cos ϕ_2 then k = rank(**H**) = 2, concurrent streams possible.

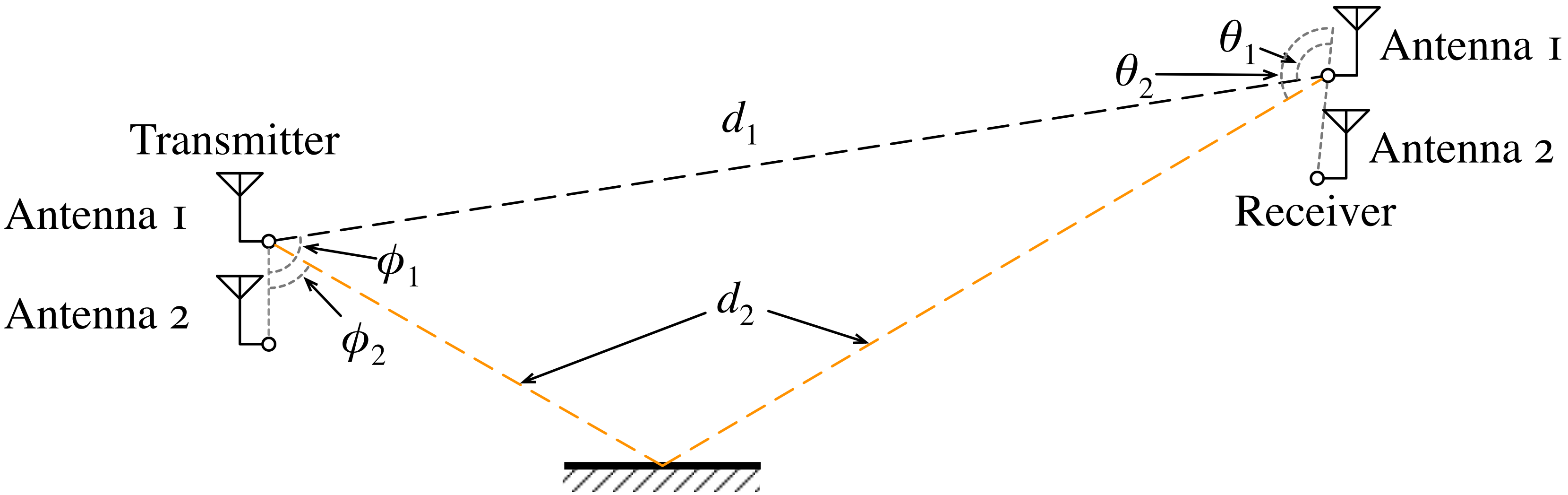
The multipath MIMO channel



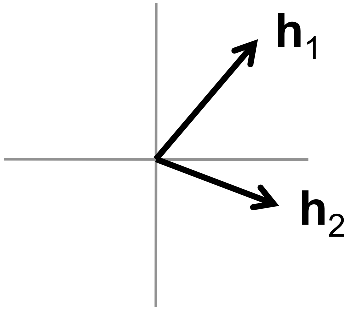
$$\mathbf{H} = \begin{bmatrix} a_1 e^{-j2\pi d_1/\lambda} + \underline{a_2 e^{-j2\pi d_2/\lambda}} & a_1 e^{-j2\pi(d_1+\Delta\cos\phi_1)/\lambda} + \underline{a_2 e^{-j2\pi(d_2+\Delta\cos\phi_2)/\lambda}} \\ a_1 e^{-j2\pi(d_1+\Delta\cos\theta_1)/\lambda} + \underline{a_2 e^{-j2\pi(d_2+\Delta\cos\theta_2)}} & a_1 e^{-j2\pi(d_1+\Delta\cos\phi_1+\Delta\cos\theta_1)} + \underline{a_2 e^{-j2\pi(d_2+\Delta\cos\phi_2+\Delta\cos\theta_2)/\lambda}} \end{bmatrix}$$

If cos $\phi_1 \neq$ cos ϕ_2 **and** cos $\theta_1 \neq$ cos θ_2 then k = rank(**H**) = 2, and concurrent streams are possible.

Vector representation

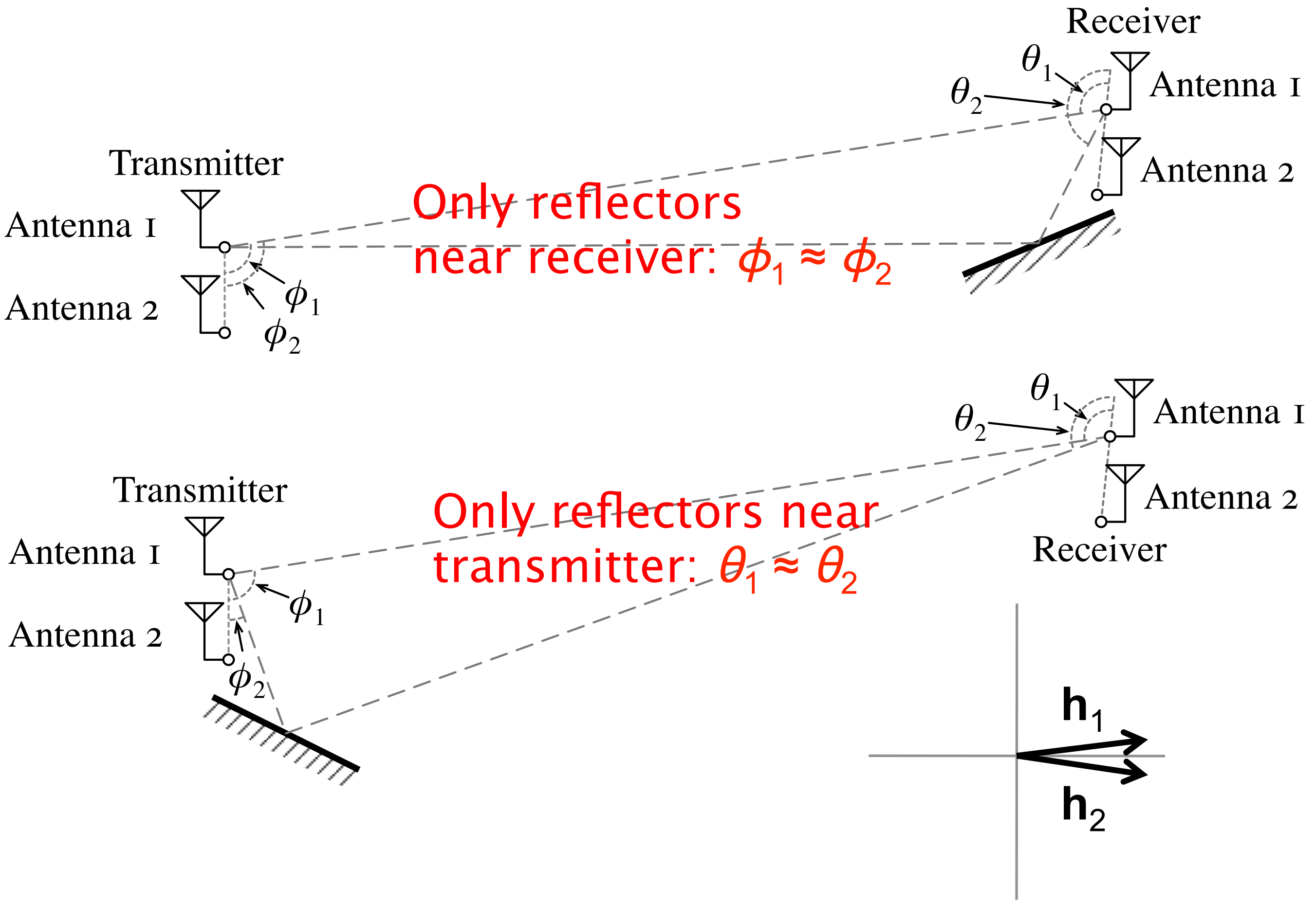


$$\mathbf{H} = \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 \end{bmatrix}$$



When multipath is present, vectors are independent.

“Poorly-conditioned” MIMO channels

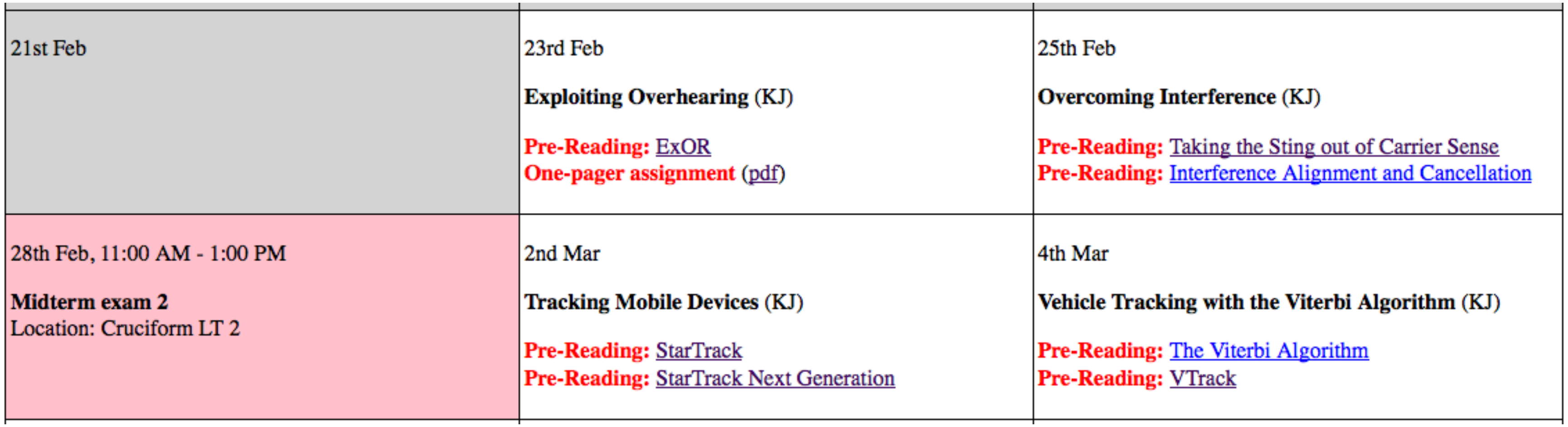


Only reflectors near receiver: $\phi_1 \approx \phi_2$

Only reflectors near transmitter: $\theta_1 \approx \theta_2$

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

Next time



21st Feb	23rd Feb **Exploiting Overhearing** (KJ) **Pre-Reading:** ExOR **One-pager assignment** (pdf)	25th Feb **Overcoming Interference** (KJ) **Pre-Reading:** Taking the Sting out of Carrier Sense **Pre-Reading:** Interference Alignment and Cancellation
28th Feb, 11:00 AM - 1:00 PM **Midterm exam 2** Location: Cruciform LT 2	2nd Mar **Tracking Mobile Devices** (KJ) **Pre-Reading:** StarTrack **Pre-Reading:** StarTrack Next Generation	4th Mar **Vehicle Tracking with the Viterbi Algorithm** (KJ) **Pre-Reading:** The Viterbi Algorithm **Pre-Reading:** VTrack