ECE 598HH: Special Topics in Wireless Networks and Mobile Systems

Lecture 22: Network Coding

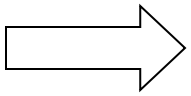
Haitham Hassanieh

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

CSL: COORDINATED SCIENCE LAB

*These slides are courtesy of Sachin Katti

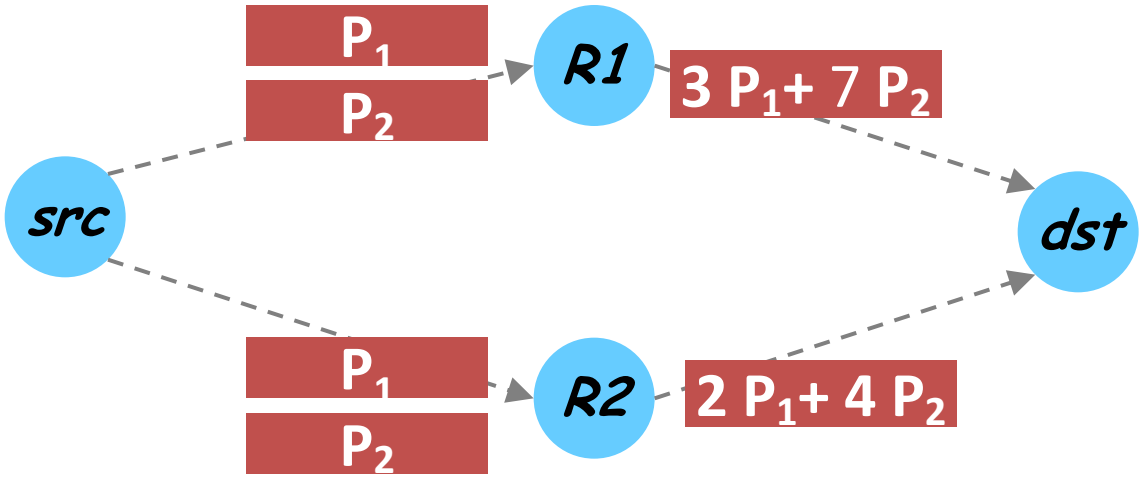
Lecture Outline



- Intra-Flow Network Coding with MORE
- Inter-Flow Network Coding with Cope
- Analog Networking Coding

Random Network Coding

Each router forwards random combinations of packets

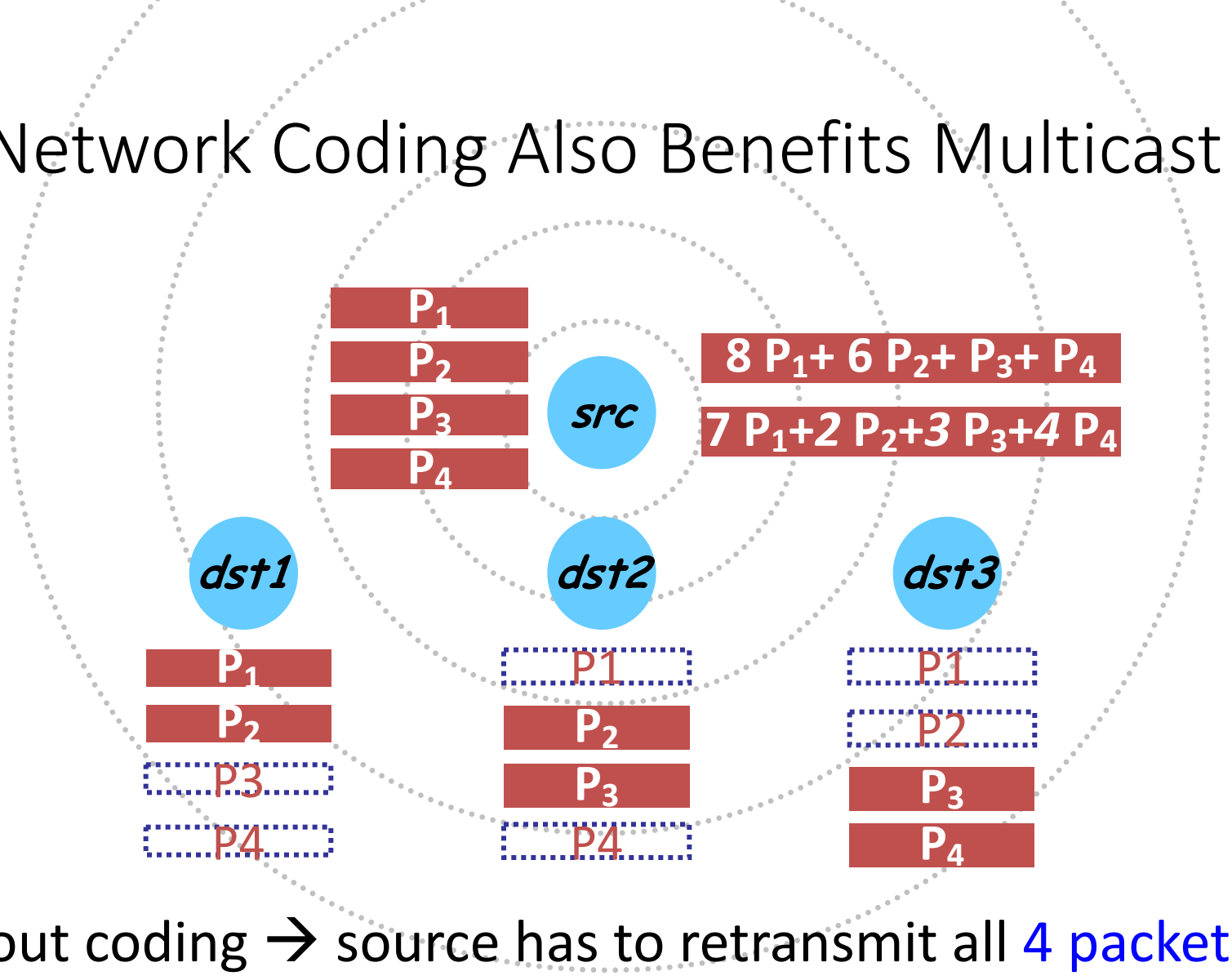


Randomness prevents duplicates

No need to know who received what

Can exploit spatial reuse

Network Coding Also Benefits Multicast

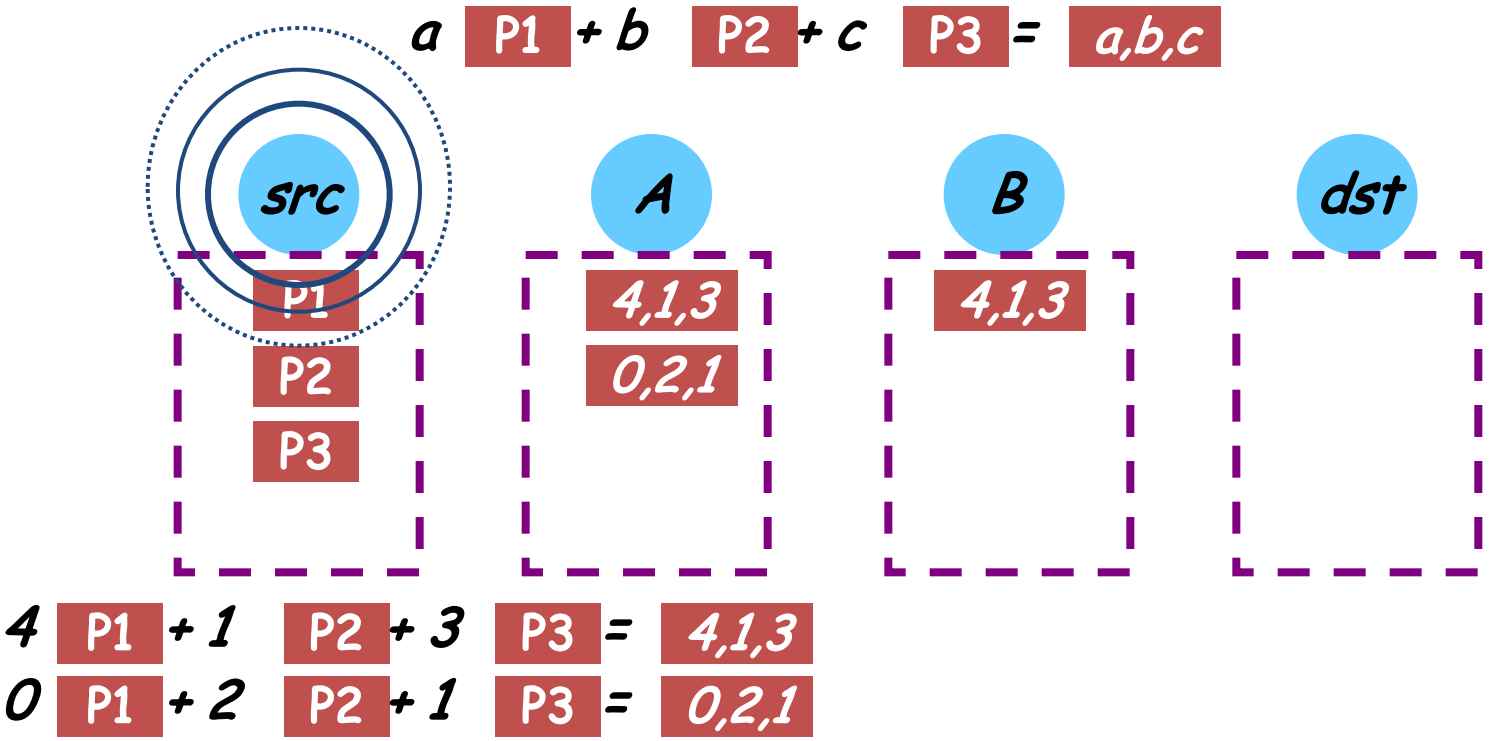


Without coding → source has to retransmit all 4 packets

With network coding → 2 packets are sufficient

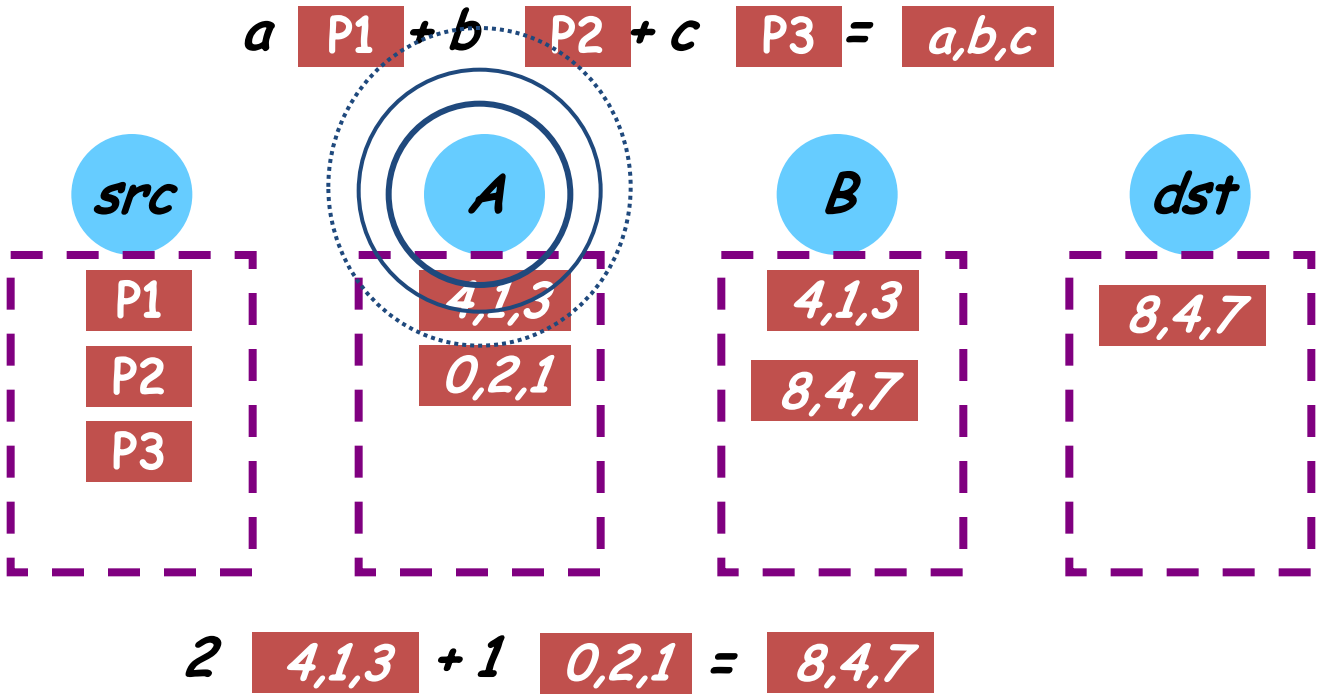
How Does MORE Work?

- Source sends packets in batches
- Forwarders keep all heard (innovative) packets in a buffer
- Nodes transmit linear combinations of buffered packets



How Does MORE Work?

- Source sends packets in batches
- Forwarders keep all heard (innovative) packets in a buffer
- Nodes transmit linear combinations of buffered packets



Network Coding

- Requires less coordination
  - No scheduler
- More flexibility
  - One framework for unicast and multicast
- More throughput
  - 22% more than ExOR and 95% more than current shortest path routing

Two Types of Network Coding

Intra-flow

- Codes packets within a connection
- Robustness to packet loss
- Unicast and Multicast
- E.g., MORE

Inter-flow

- Codes packets across connections
- Higher throughput
- Mainly Unicast
- E.g., COPE

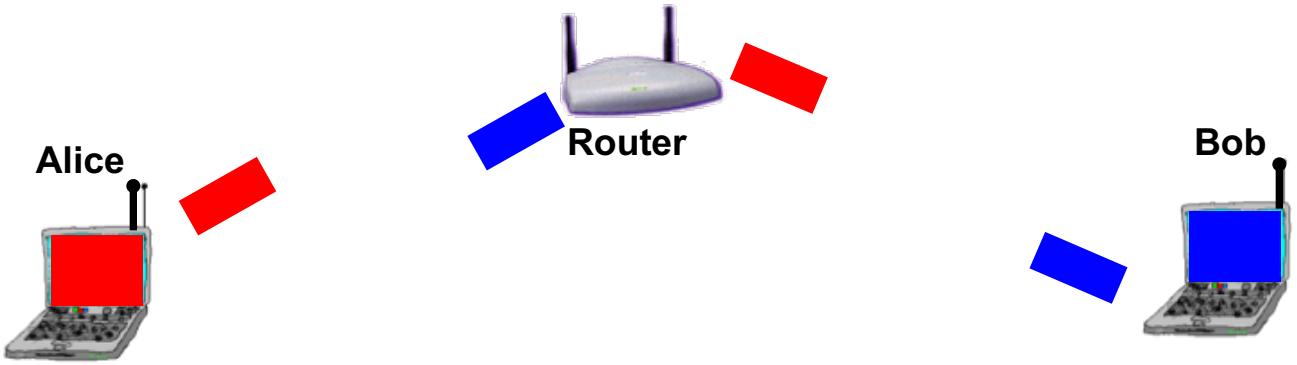
Lecture Outline

- Intra-Flow Network Coding with MORE
- Inter-Flow Network Coding with Cope
- Analog Networking Coding

COPE

An Example of Inter-flow Network Coding

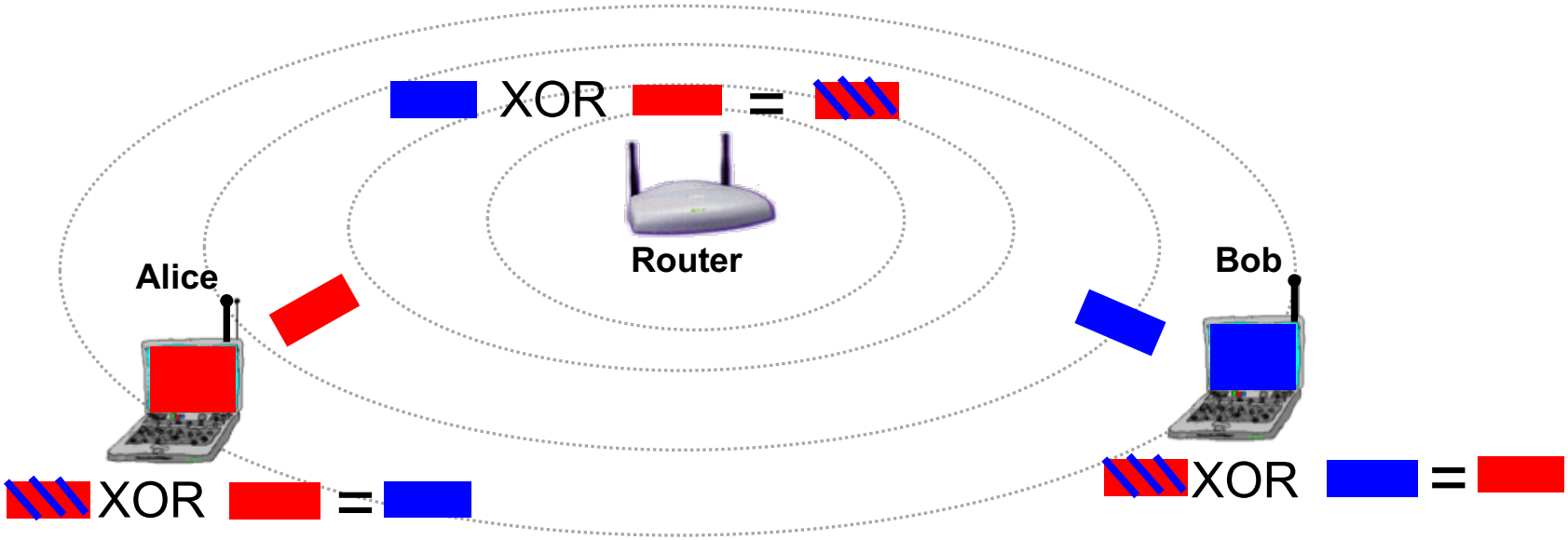
Traditional Approach



Requires 4 transmissions

- Alice to router; Router to Bob; Bob to router; Router to Alice
- Can we exploit broadcast to do better?

COPE

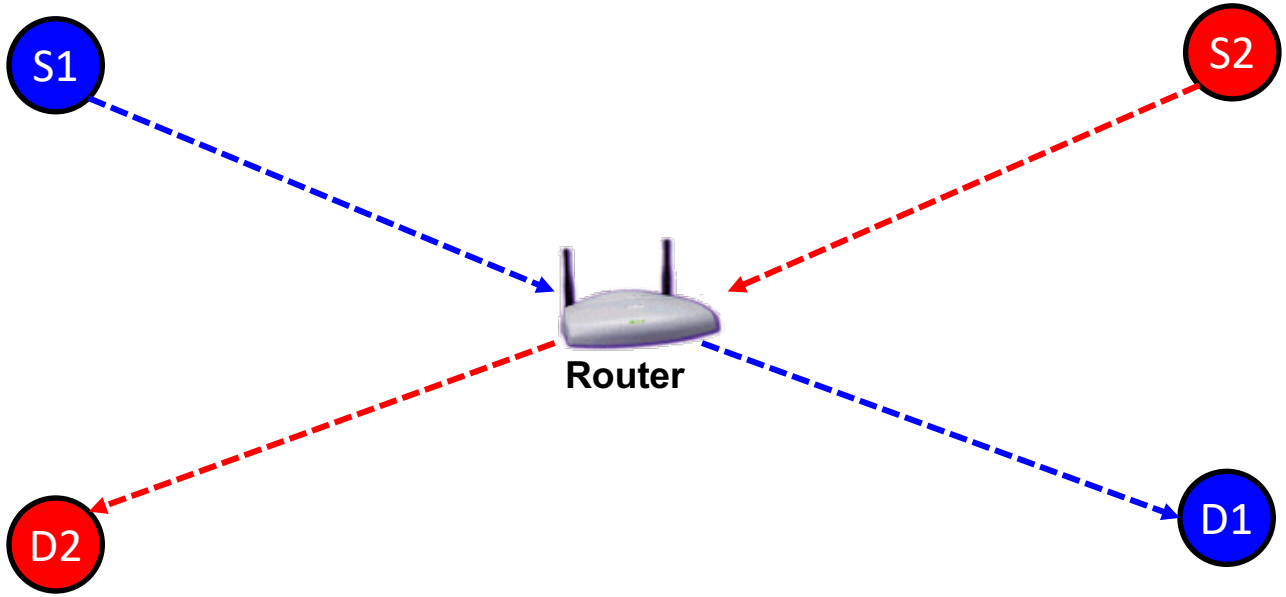


Requires 3 transmissions instead of 4

- Alice to router; Bob to router; and router to both Alice and Bob

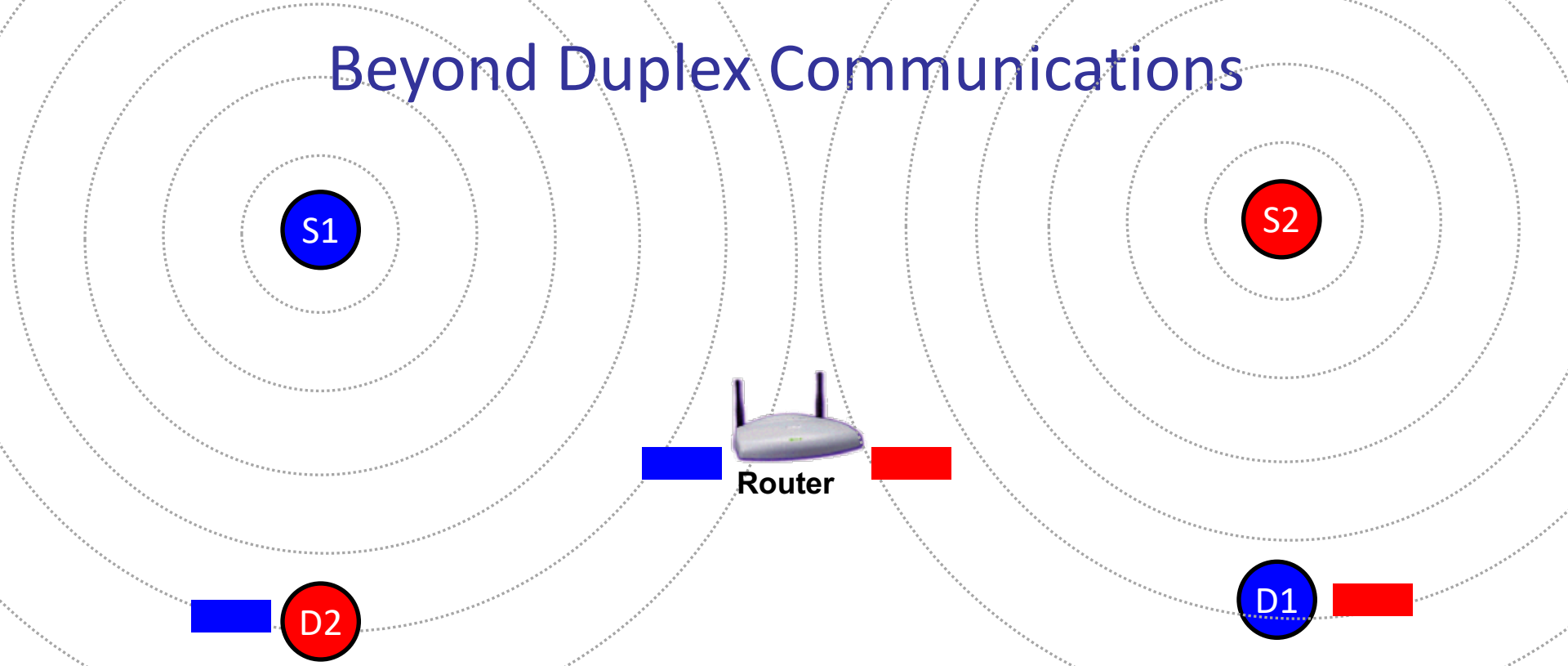
Network Coding → 3 Transmissions instead of 4
→ Increases Throughput

Beyond Duplex Communications



Two communication flows that intersect at a router

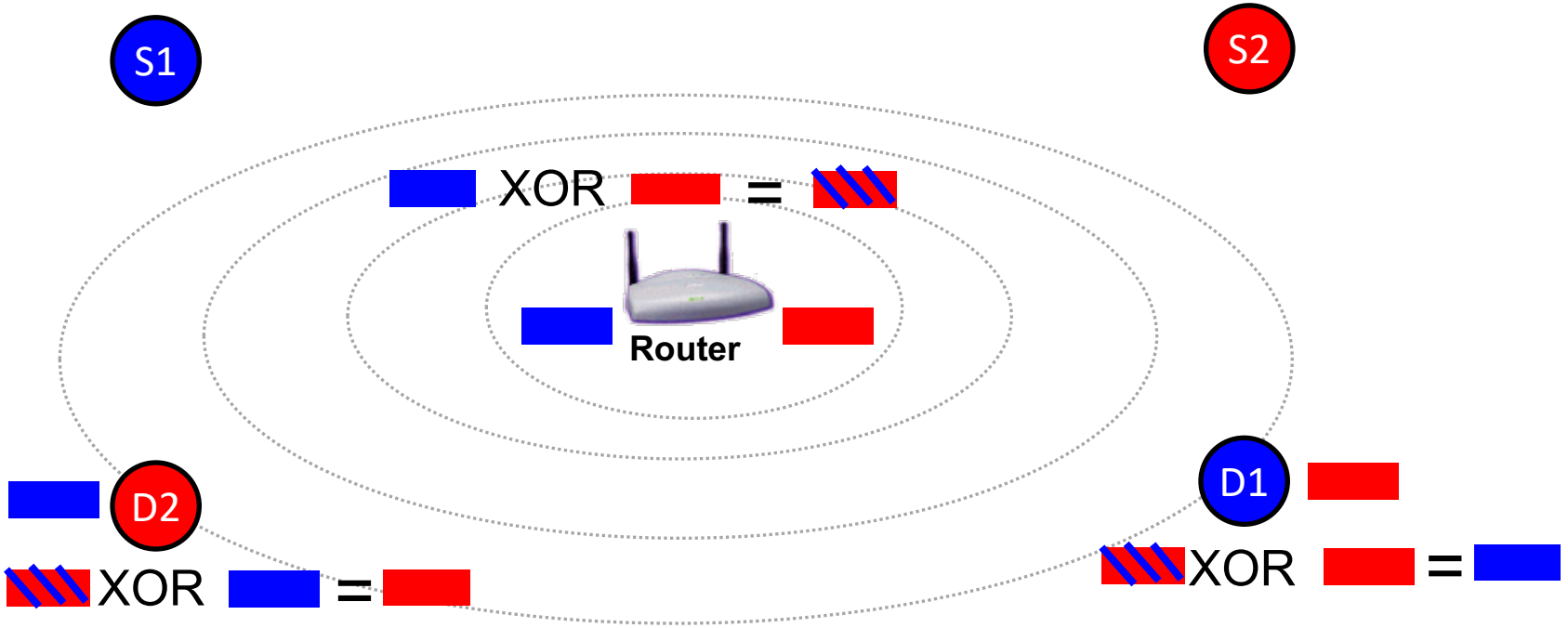
Beyond Duplex Communications



D2 overhears S1's packet

D1 overhears S2's packet

Beyond Duplex Communications



3 transmissions instead of 4 → Higher Throughput

COPE

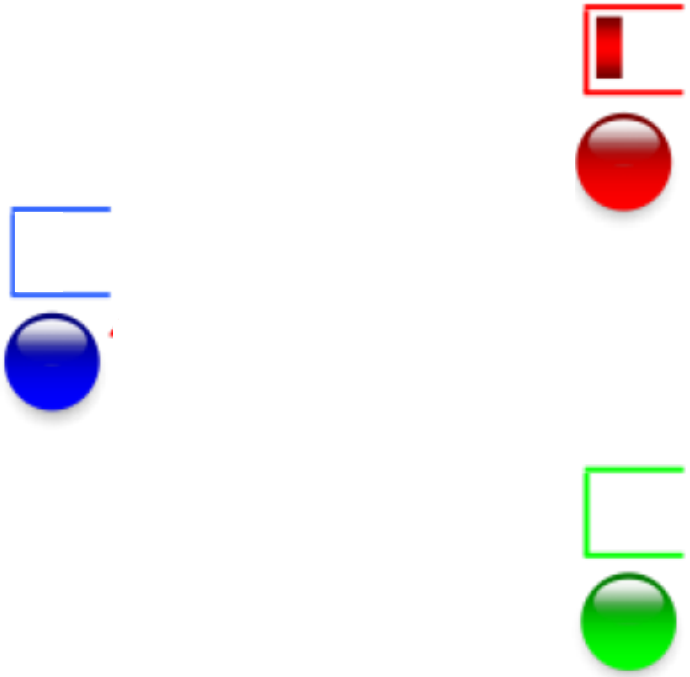
- Opportunistic Listening
- Opportunistic Coding

Opportunistic Listening

- Exploit wireless broadcast
- Every node snoops on all packets
- A node stores all heard packets for a limited time

Opportunistic Listening

- Exploit wireless broadcast
- Every node snoops on all packets
- A node stores all heard packets for a limited time



Opportunistic Listening

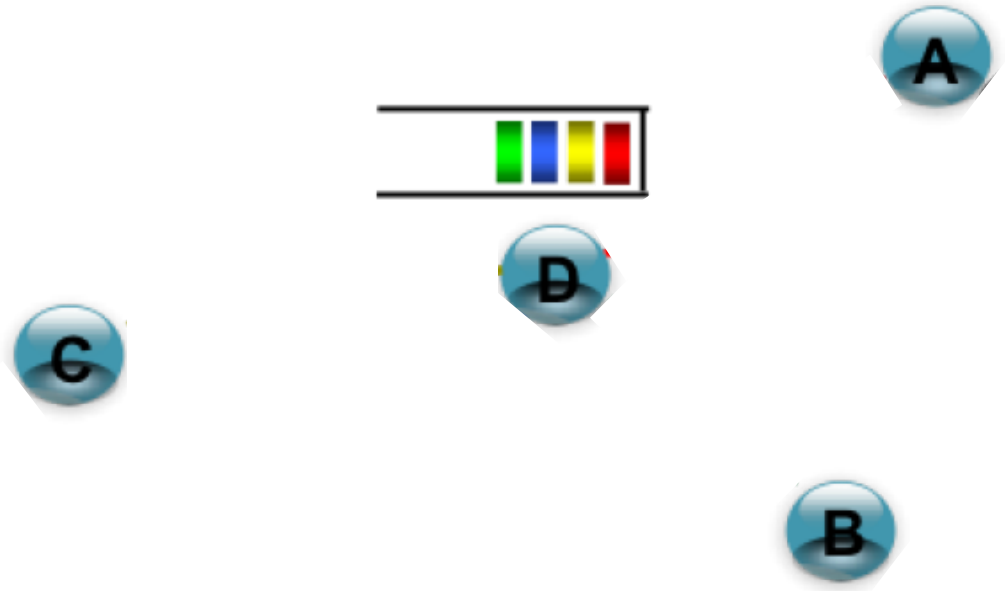
- Exploit wireless broadcast
- Every node snoops on all packets
- A node stores all heard packets for a limited time

- Node sends Reception Reports to tell its neighbors what packets it heard
  - Reports are piggybacked on packets
  - If no packets to send, periodically send reports

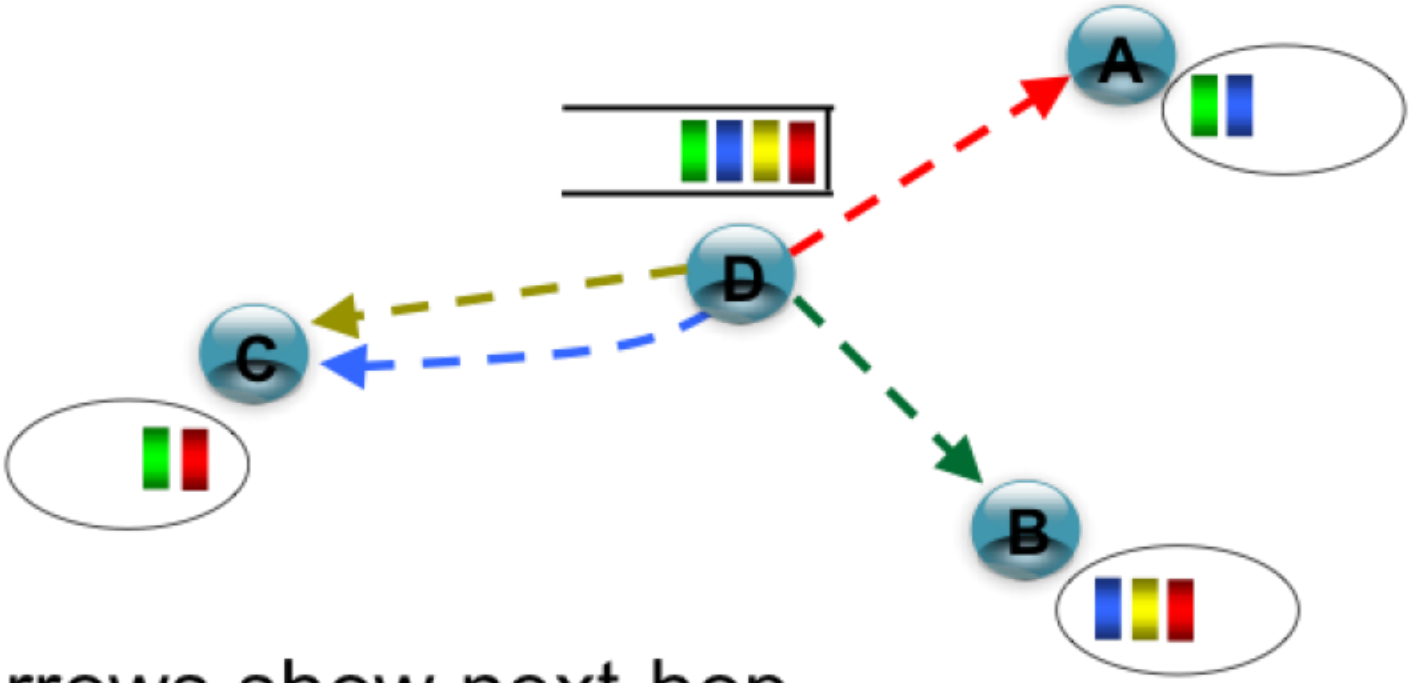
Opportunistic Coding

- To send packet *p* to neighbor *A*, XOR *p* with packets already known to *A*
  - Thus, *A* can decode

Which Packets to Code Together?

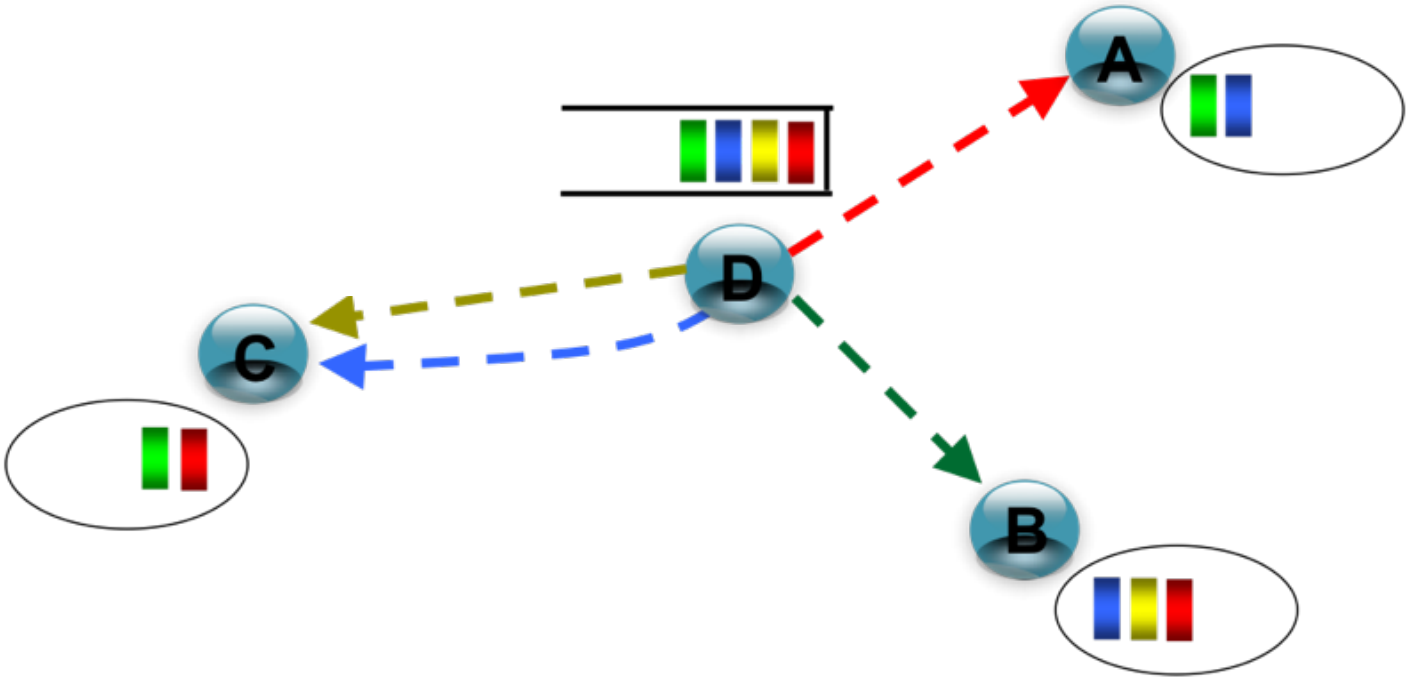


Which Packets to Code Together?

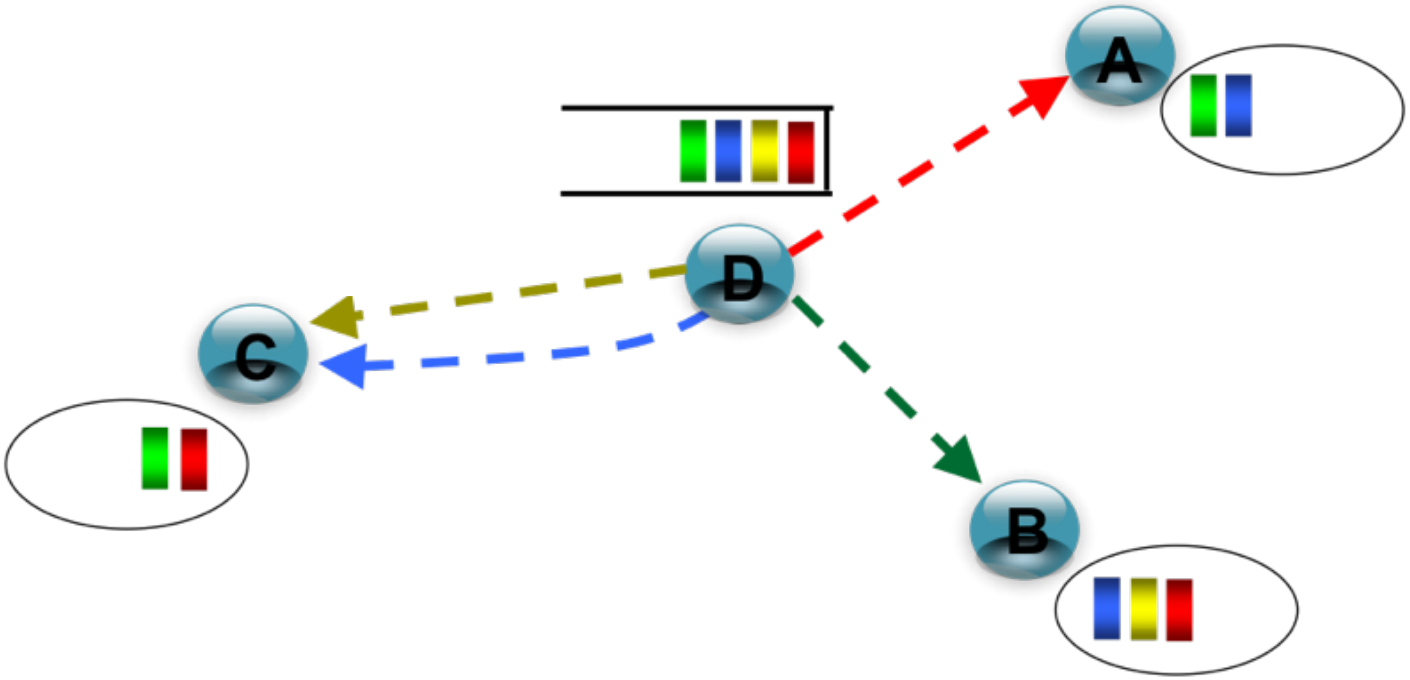


Arrows show next-hop

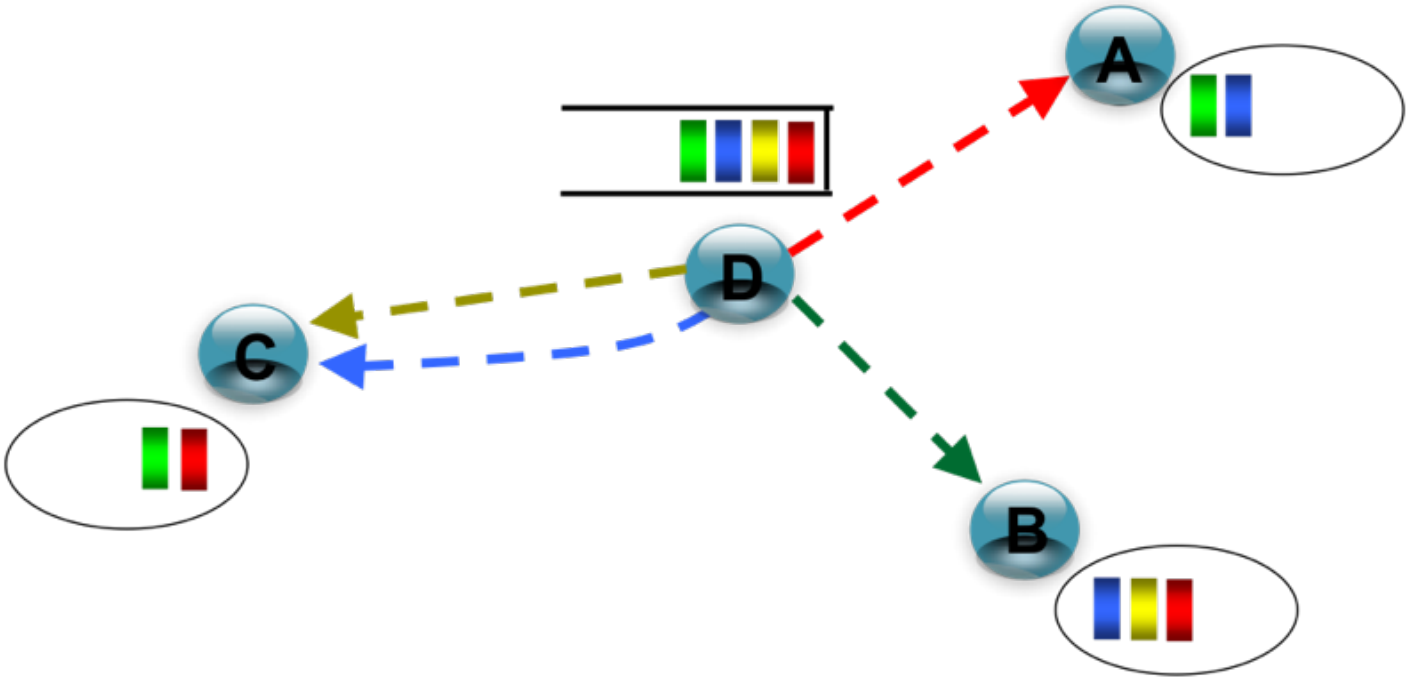
Which Packets to Code Together?



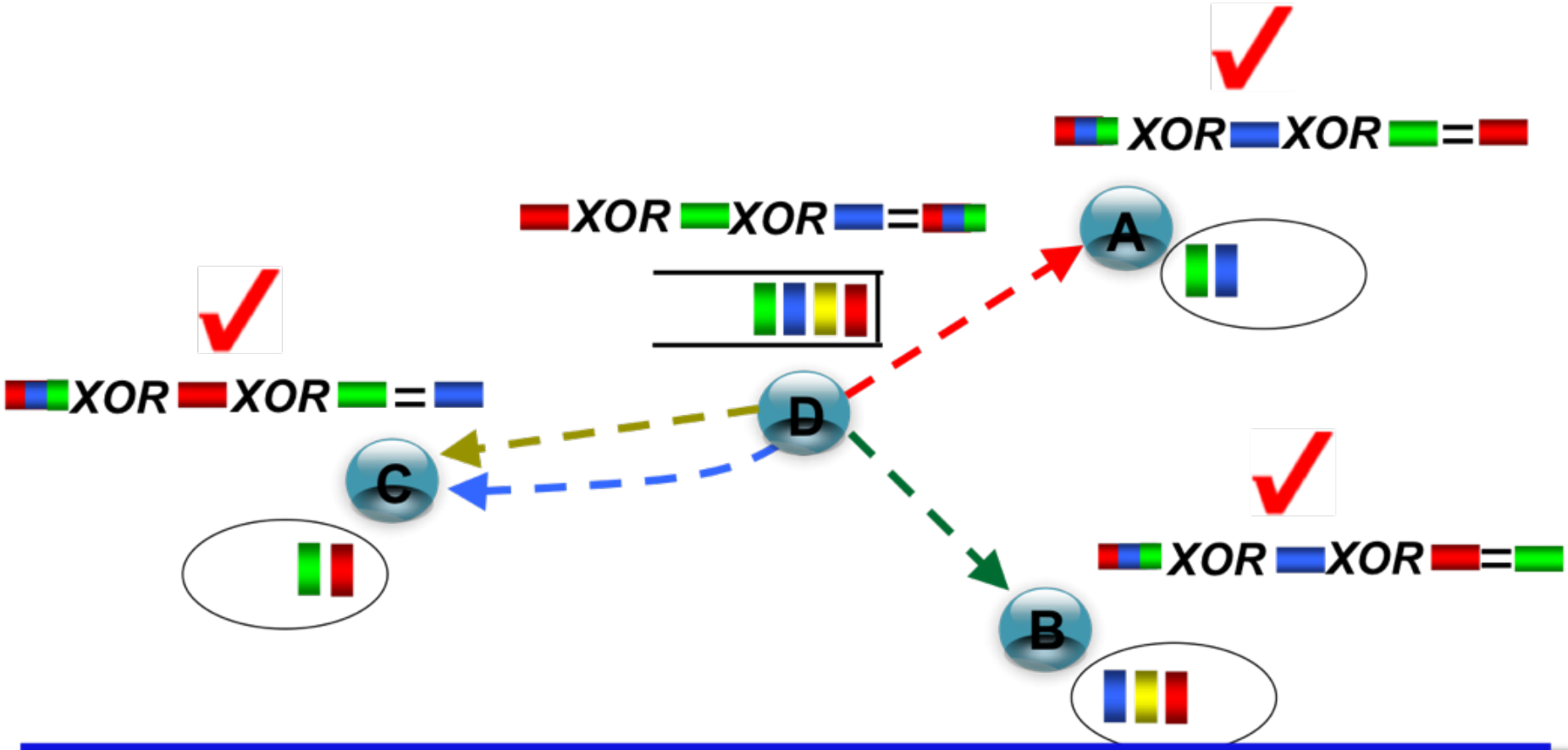
Which Packets to Code Together?



Which Packets to Code Together?



Which Packets to Code Together?



XOR n packets together iff the next hop of each packet already has the other ***n-1*** packets apart from the one it wants

But, to decode a node needs to know which packets are XOR-ed

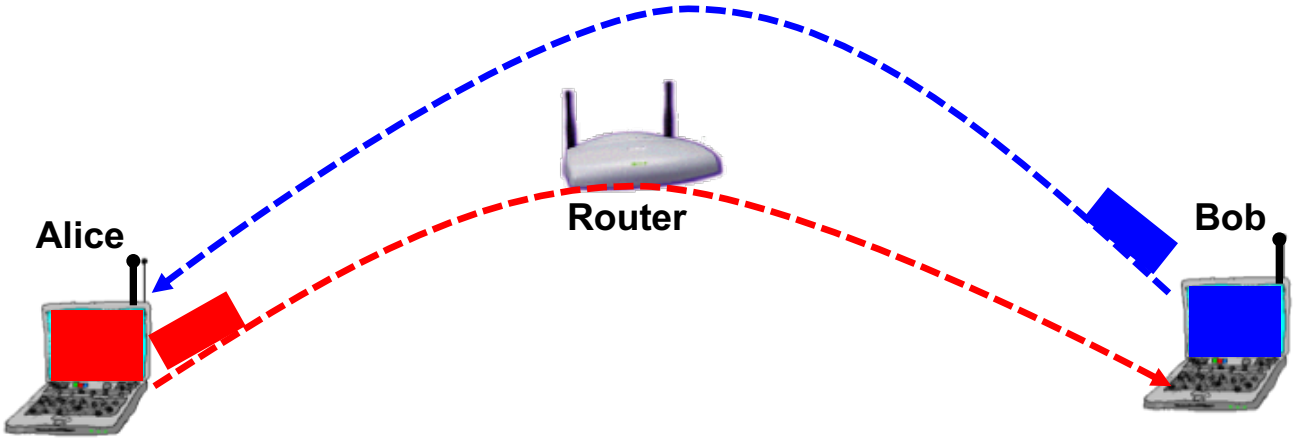
- Put that information in the header of the coded packet
- E.g., P = P1 +P2 → P's header will say P1,P2

COPE' s Characteristics

- COPE is a forwarding mechanism
  - It sits transparently between IP and MAC
  - Routing is unmodified (i.e., shortest path)
- Opportunistic → Code packets if possible, if not forward without coding
- Does not delay packets

Performance

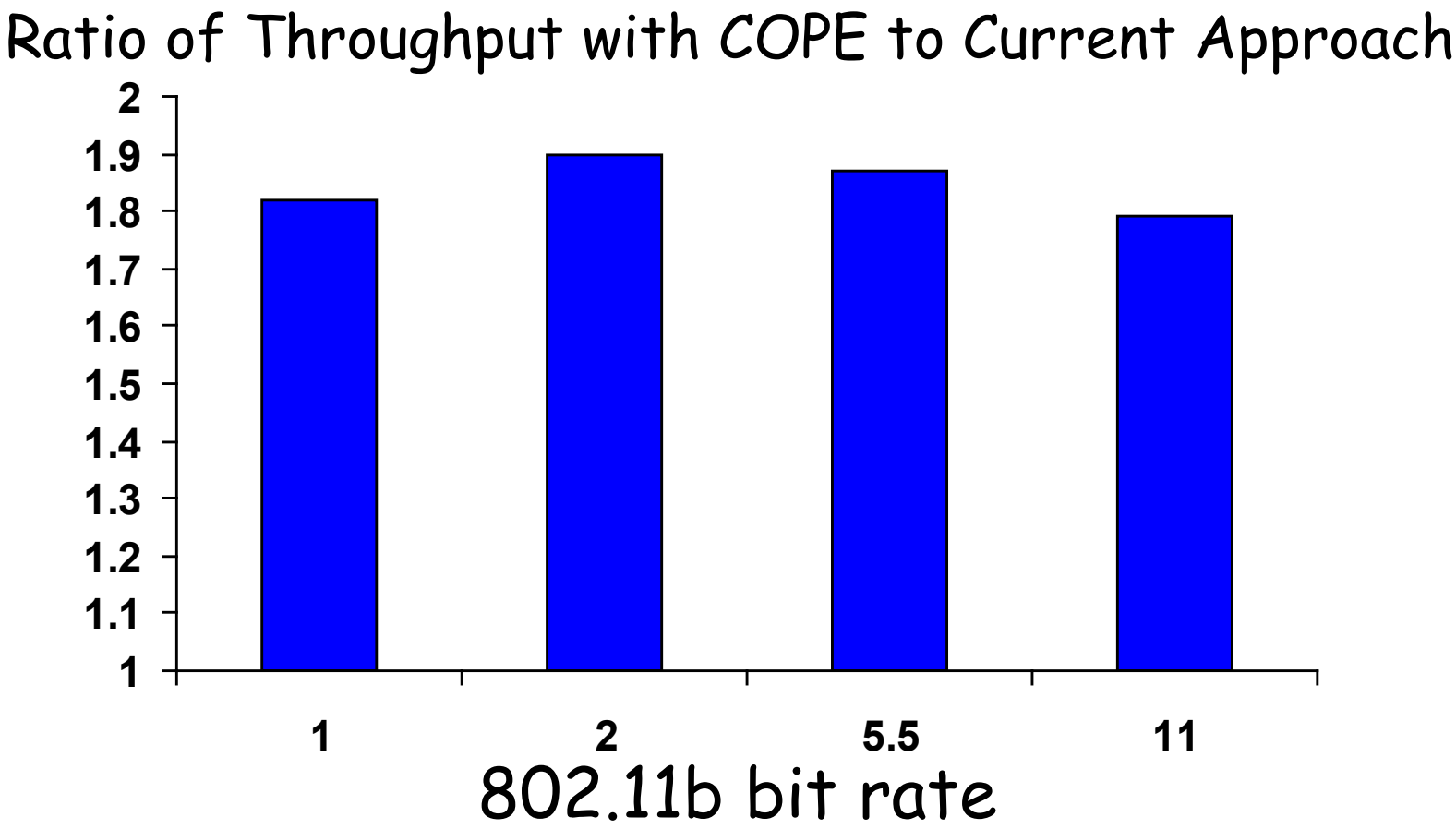
Alice and Bob Experiment



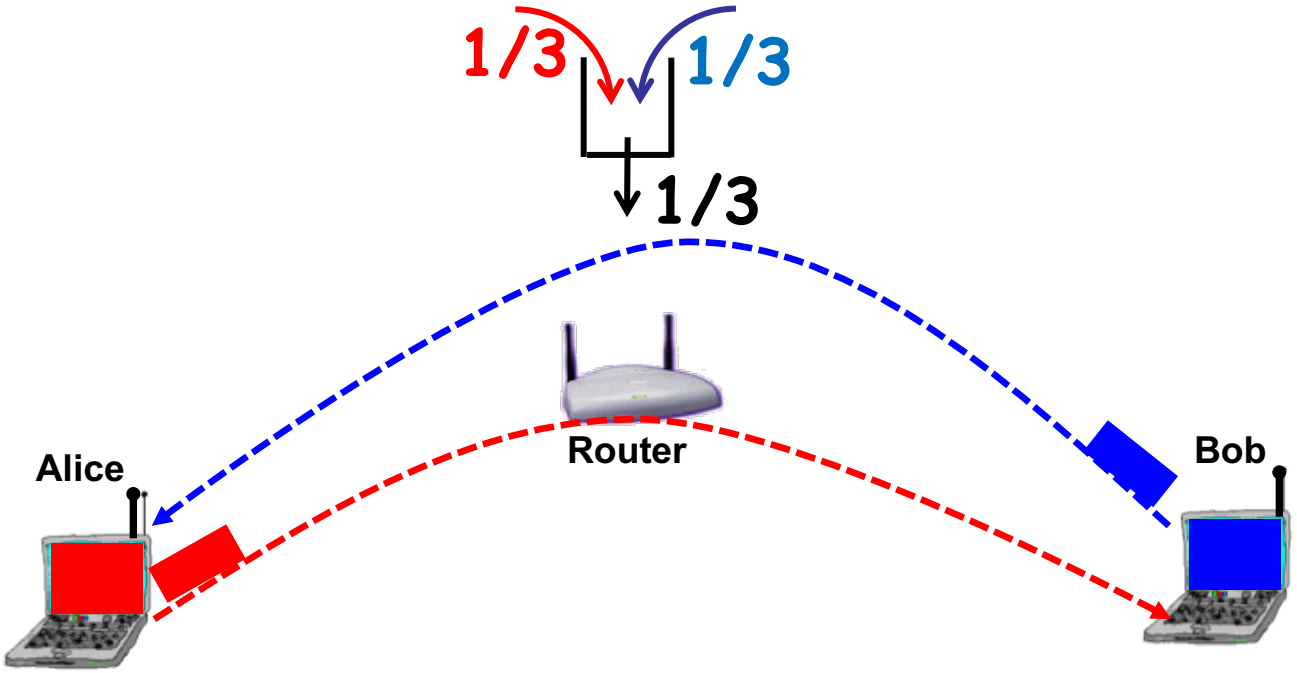
3 transmissions instead of 4

→ Throughput Gain = 4/3 = 1.3333

Results of the Alice-and-Bob



Why the Gain is more than 1.33 ?



802.11 is fair → Each node transmits 1/3

- Without COPE: Router needs to transmit twice as much
- With COPE: All nodes need equal rate.

COPE alleviates the mismatch between MAC's allocation and the congestion at a node

Coding Gain

Reduction in #Transmissions

In Alice-and-Bob scenario,
Coding Gain is 4/3 = 1.33

Nodes not backlogged

Coding+MAC Gain

Improvement of Draining Rate at Bottlenecks

In Alice-and-Bob scenario,
Coding+MAC Gain is 2

Nodes backlogged

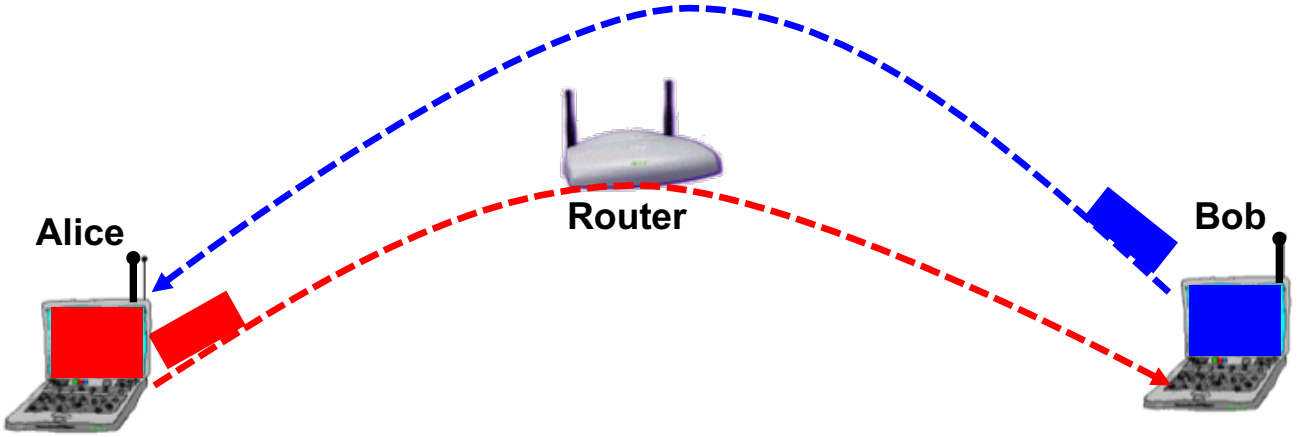
Can show that, in a plane

Coding gain is bounded by 2

Coding+MAC gain can be infinite

Limitations of COPE

- Like other protocols that exploit broadcast (e.g., ExOR, MORE), it assigns the same bit rate to all transmitters
  - Need new ideas for bit rate adaptation
- Applicable only in multi-hop networks, i.e., doesn't apply to WLANs
- The benefit of coding decreases if the traffic in the forward and reverse direction is not balanced



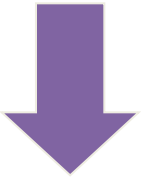
Traditional Approach: requires 4 transmissions

COPE: requires 3 transmissions

Can we do it in 2 transmissions?

Instead of router mixing packets…

Exploit that the wireless *channel naturally mixes signals*



Analog Network Coding (ANC)

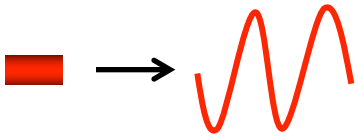
Lecture Outline

- Intra-Flow Network Coding with MORE
- Inter-Flow Network Coding with Cope
- Analog Networking Coding

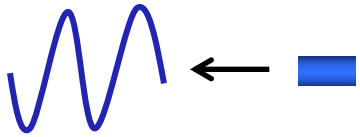
Analog Network Coding

Router

Alice



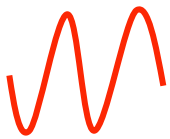
Bob



Analog Network Coding

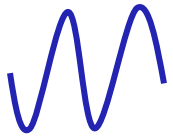
Router

Alice



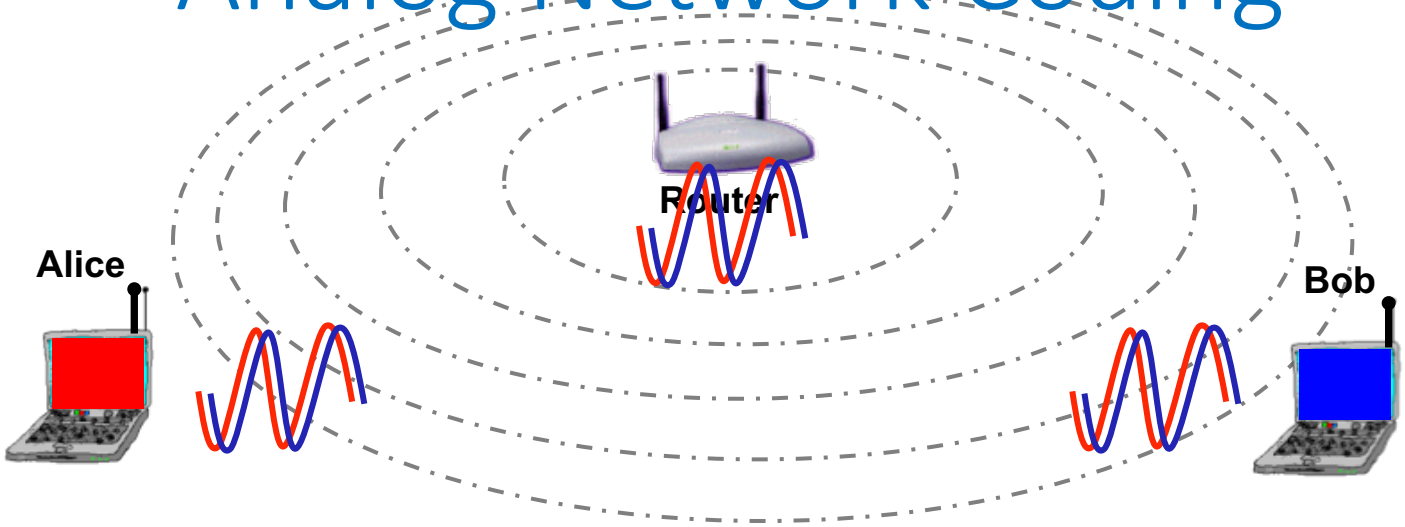
Interference

Bob



1) Alice and Bob transmit simultaneously

Analog Network Coding



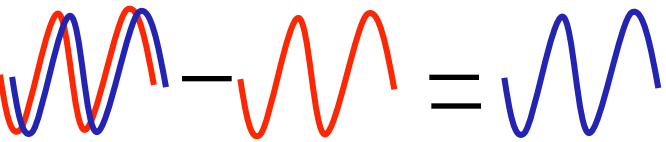
1) Alice and Bob transmit simultaneously
2) Router amplifies and broadcasts interfered signal

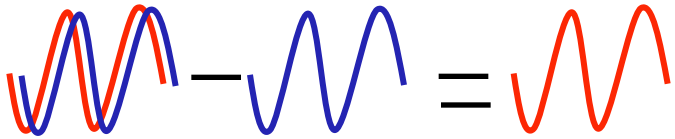
Analog Network Coding

Router

Alice

Bob





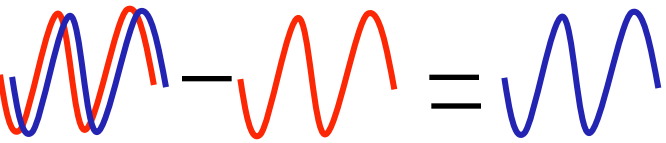
1) Alice and Bob transmit simultaneously
2) Router amplifies and broadcasts interfered signal
3) Alice subtracts known signal from interfered signal

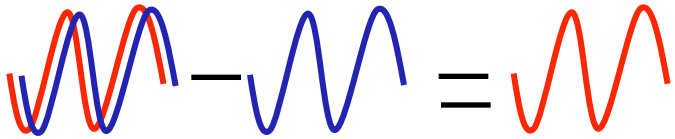
Analog Network Coding

Router

Alice

Bob

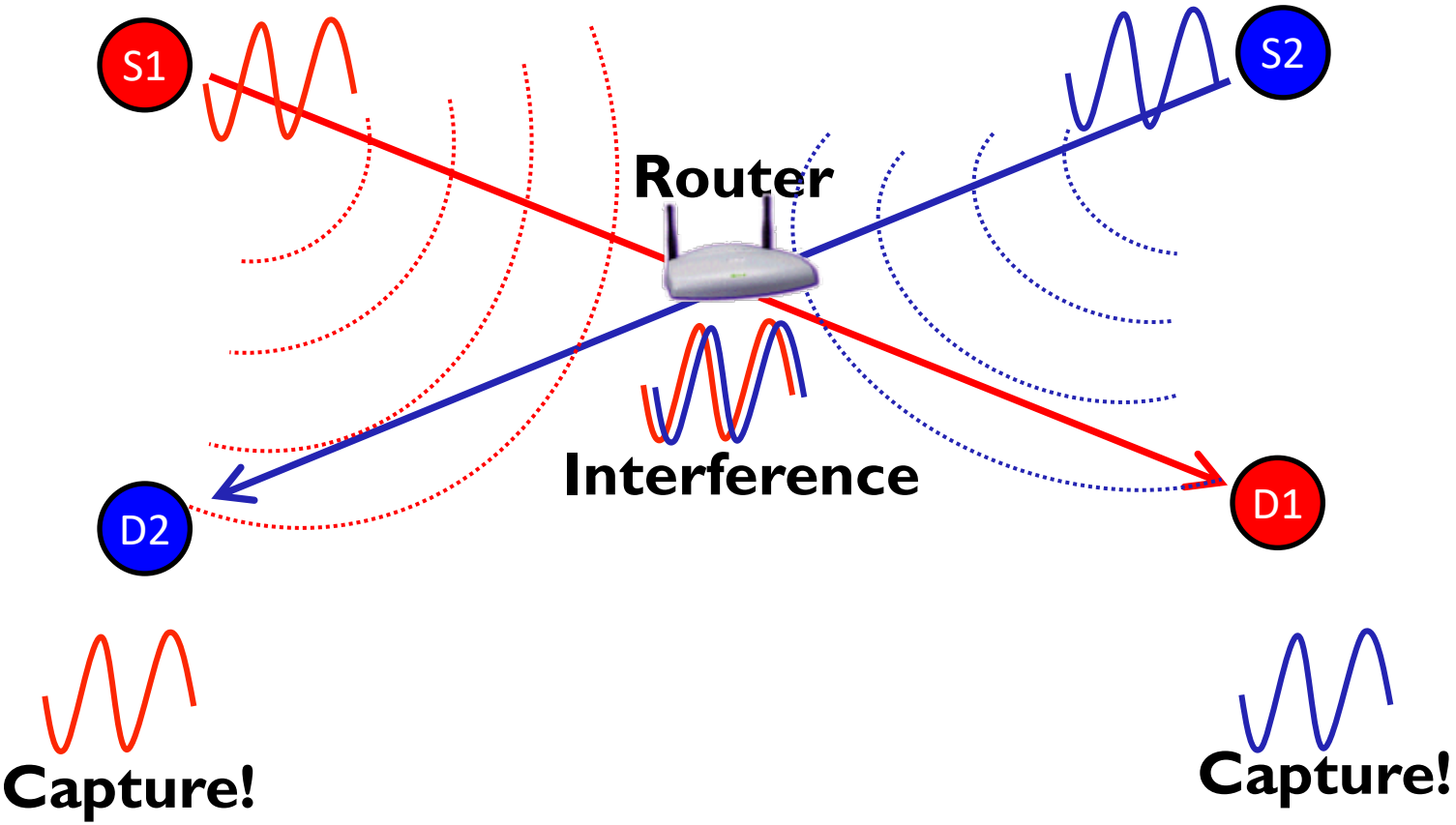




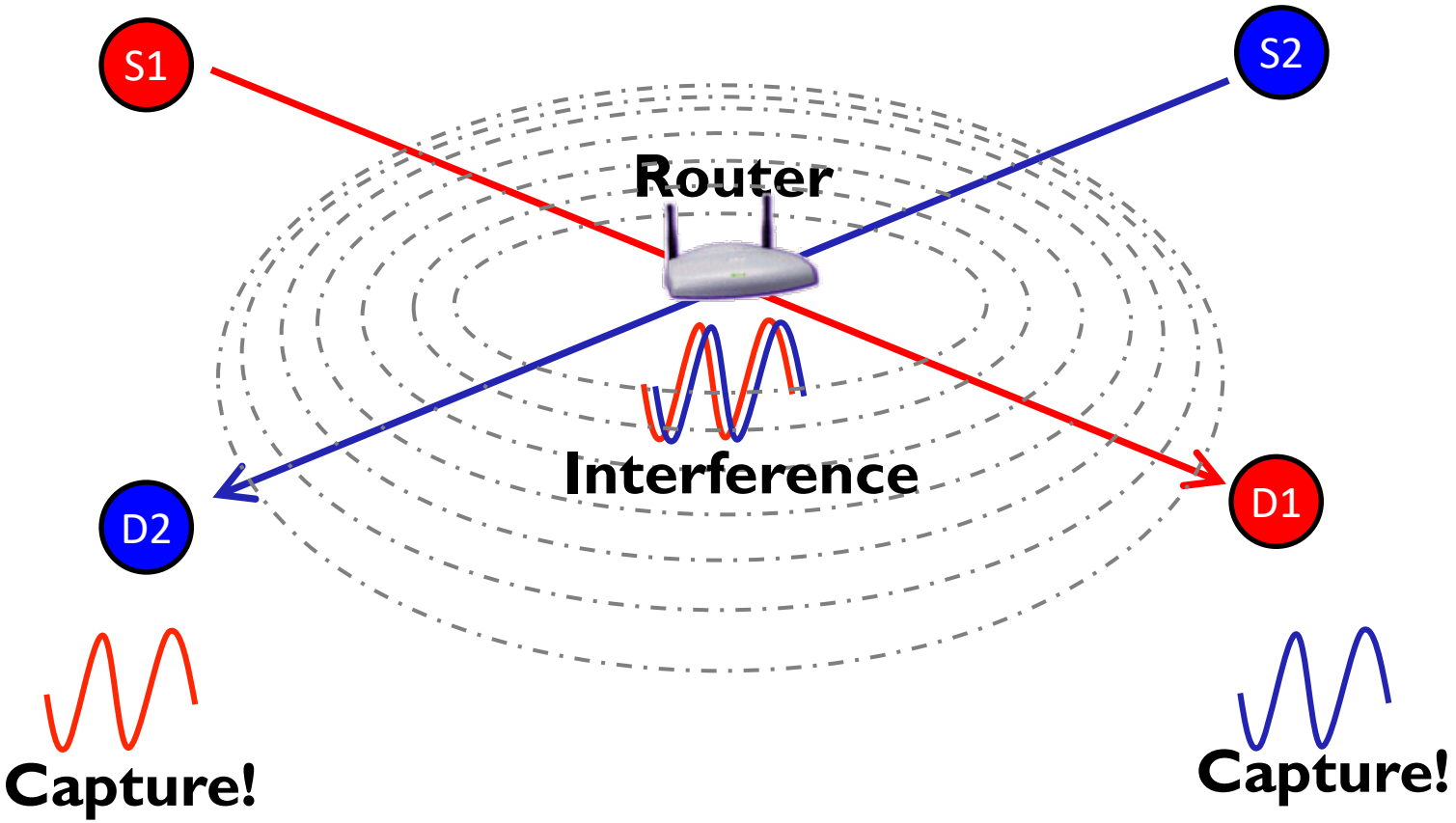
Analog Network Coding requires 2 time slots

→Higher throughput

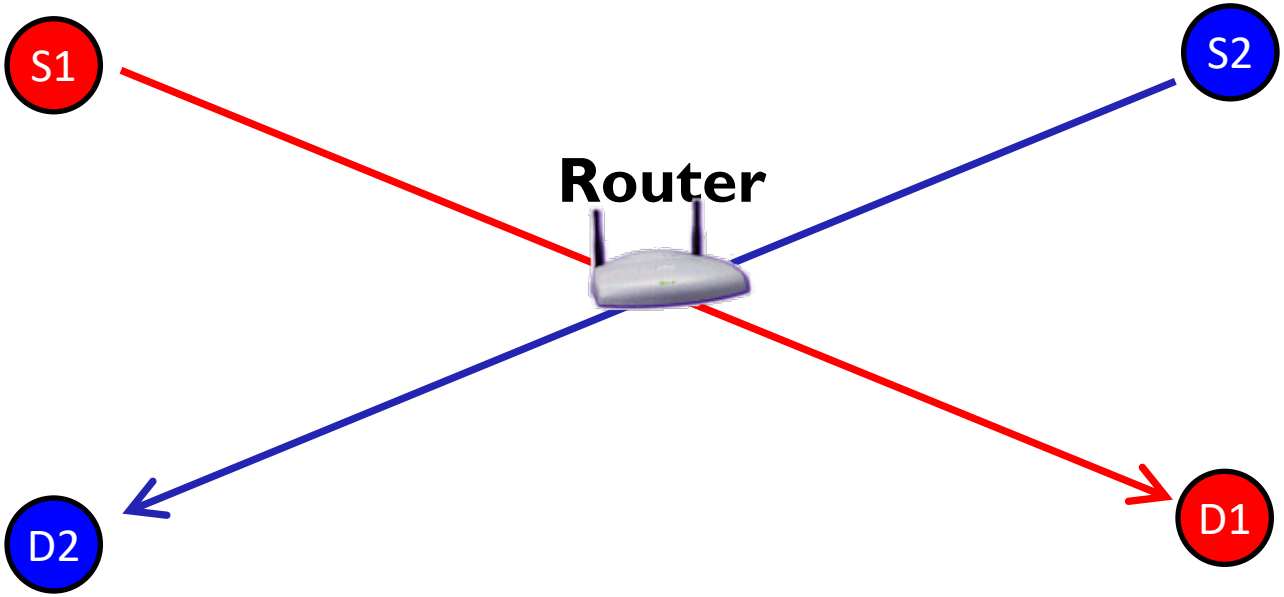
X topology

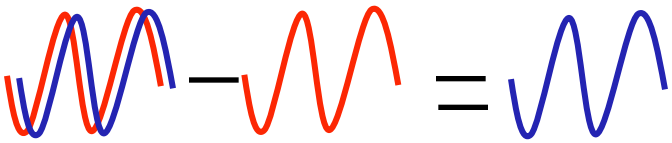


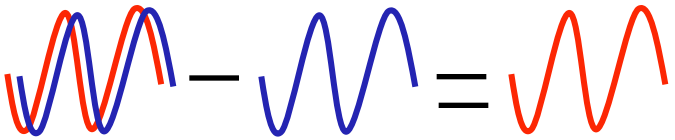
X topology



X topology





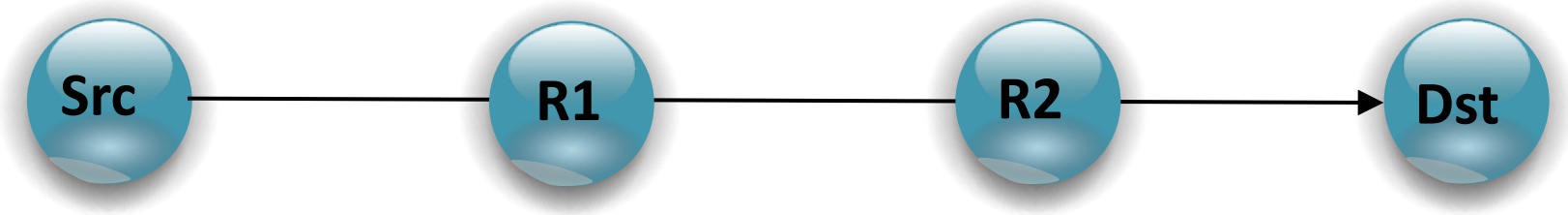


ANC decodes interference using overheard signals

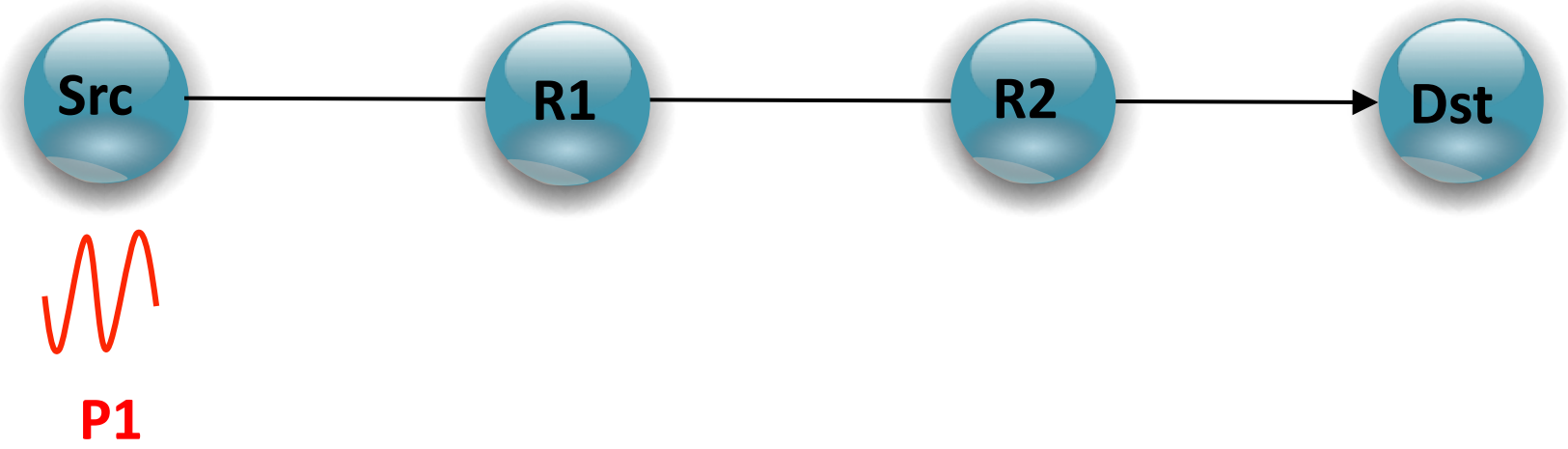
It Is More Than Going From 3 To 2!

- Philosophical shift in dealing with interference
  - Strategically exploit interference instead of avoiding it
- Promises new ways of dealing with hidden terminals

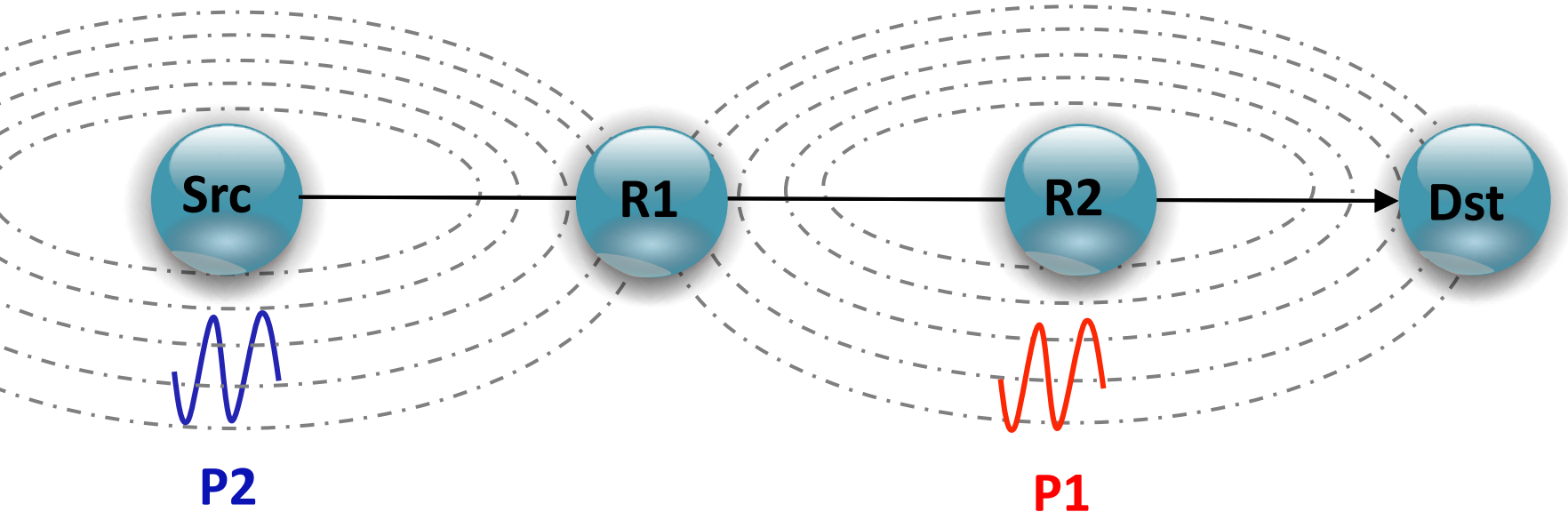
Hidden Terminal Scenario



Hidden Terminal Scenario

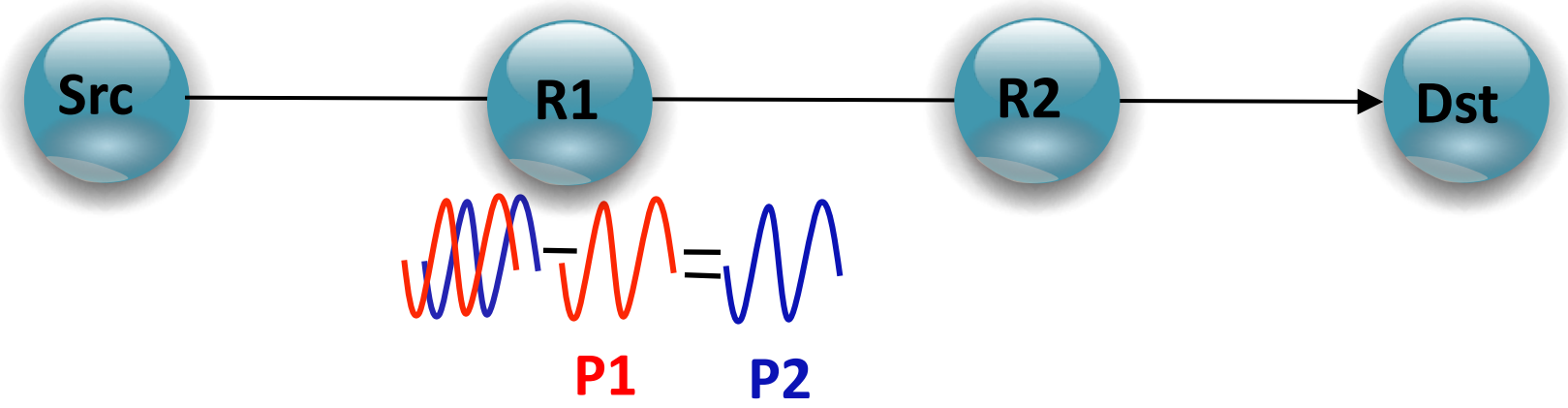


Hidden Terminal Scenario



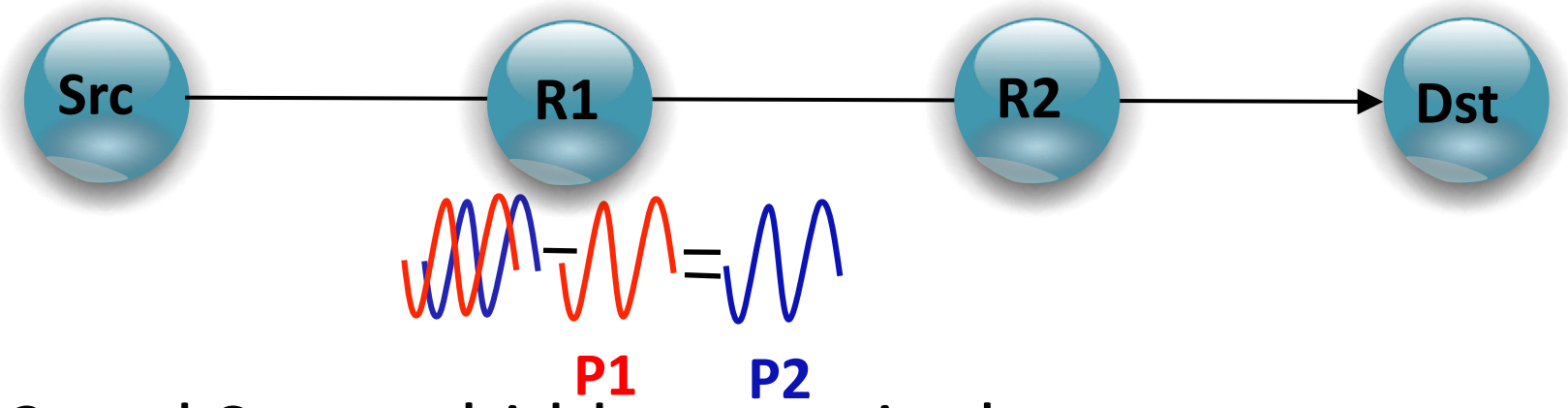
1) Src and R2 transmit simultaneously

Hidden Terminal Scenario



1) Src and R2 transmit simultaneously
2) R1 subtracts P1, which he relayed earlier to recover P2 that he wants

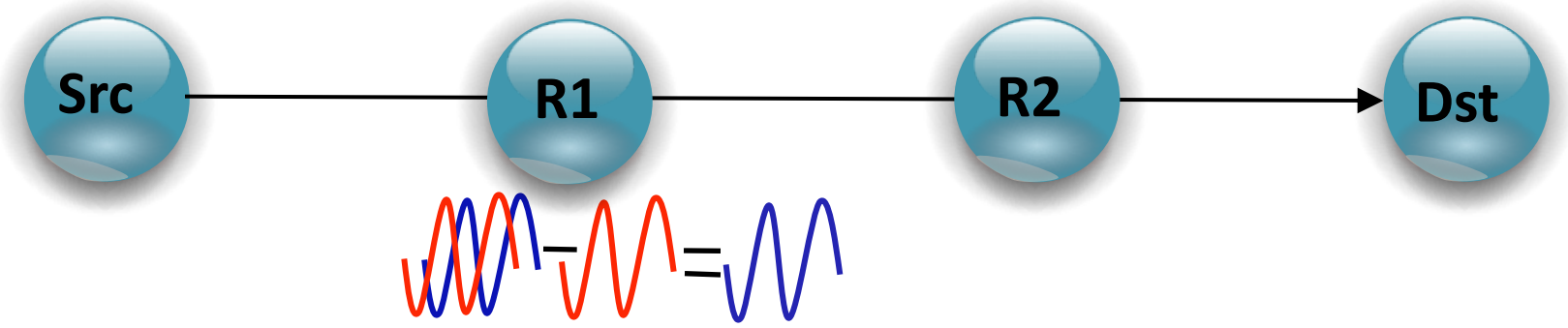
Hidden Terminal Scenario



R2 and Src are hidden terminals

- Today : Simultaneous transmission → Collision
- ANC : Simultaneous transmission → Success!

Hidden Terminal Scenario



Other Benefits of ANC:

- First step toward addressing hidden terminals
- ANC extends network coding to new scenarios

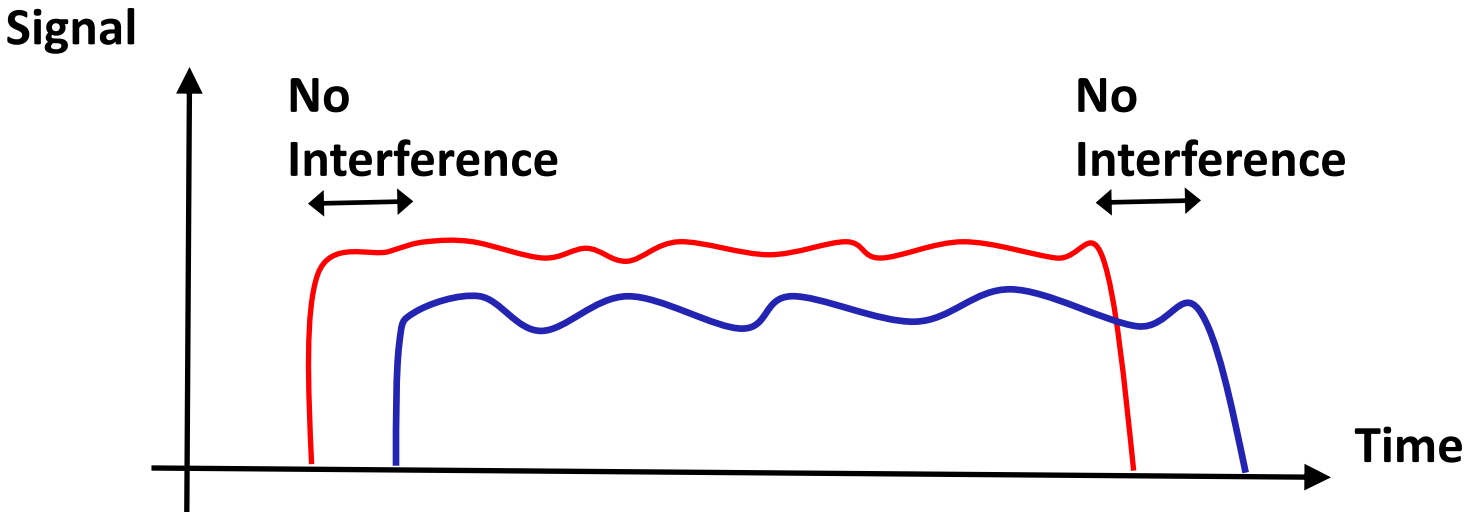
How do we make it work?

Practical Challenges

- Interfered signal is not exactly the sum
  - Channel distorts signals
  - Two signals are never synchronized
  - It is not $s_A(t) + s_B(t)$
    but $f_1(s_A(t)) + f_2(s_B(t-T))$

Key Idea: Exploit Asynchrony!

Key Idea: Exploit Asynchrony!



- Alice uses interference-free parts to estimate channel and timing
- Alice compensates for her interfering signal

Exploit asynchrony to make it practical

Protocol

- Router senses idle medium and broadcasts a trigger to Alice and Bob
- Alice and Bob jitter their start times randomly and transmit
- Router amplifies and forwards interfered signal
- Alice and Bob receive and decode

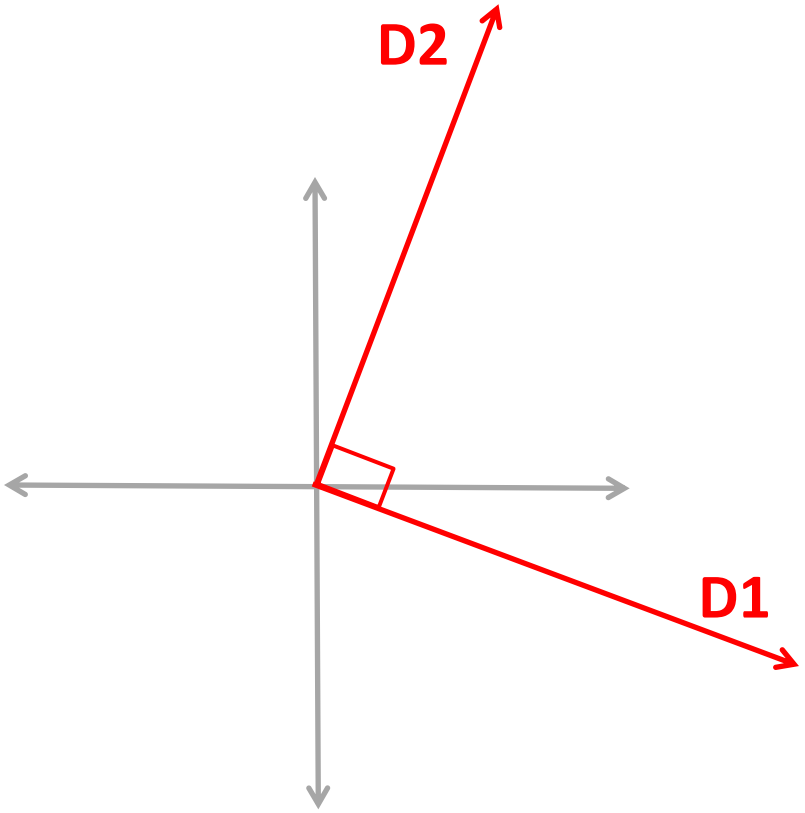
How do they decode?

Minimum Shift Keying

- Nodes transmit vectors on channel
- Focus on MSK (Minimum Shift Keying) modulation

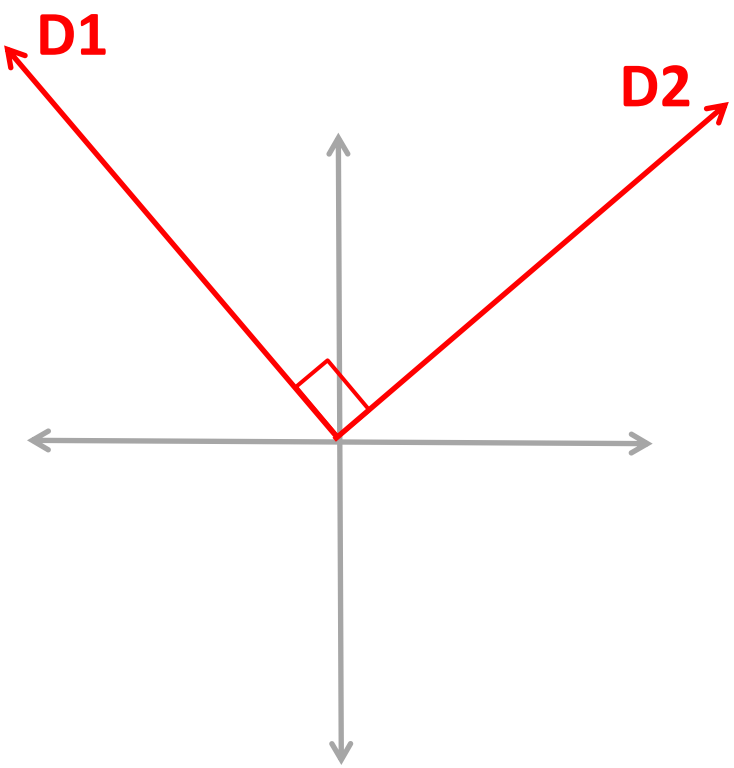
D2 leads **D1** by 90 degrees

→ Bit "1"



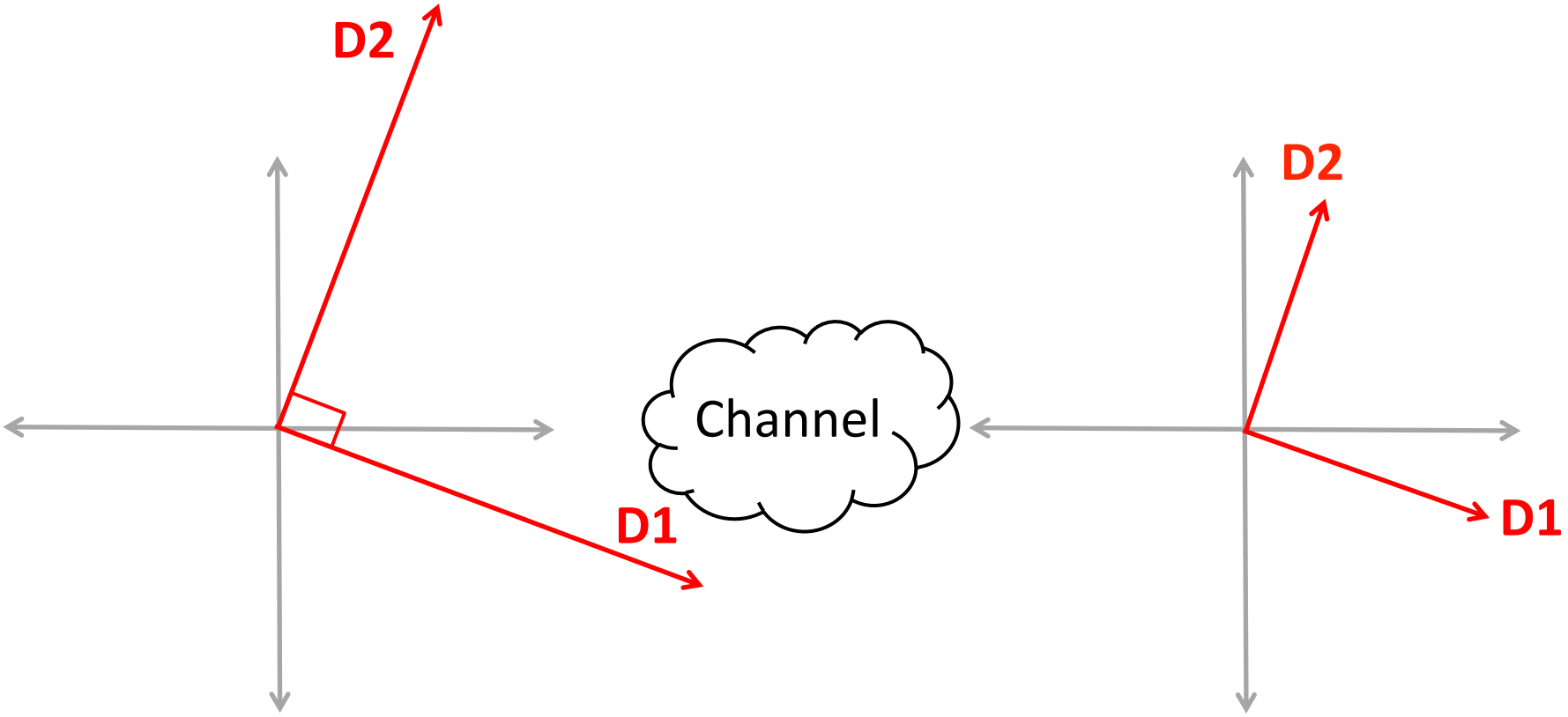
D2 lags **D1** by 90 degrees

→ Bit "0"



Channel Effects

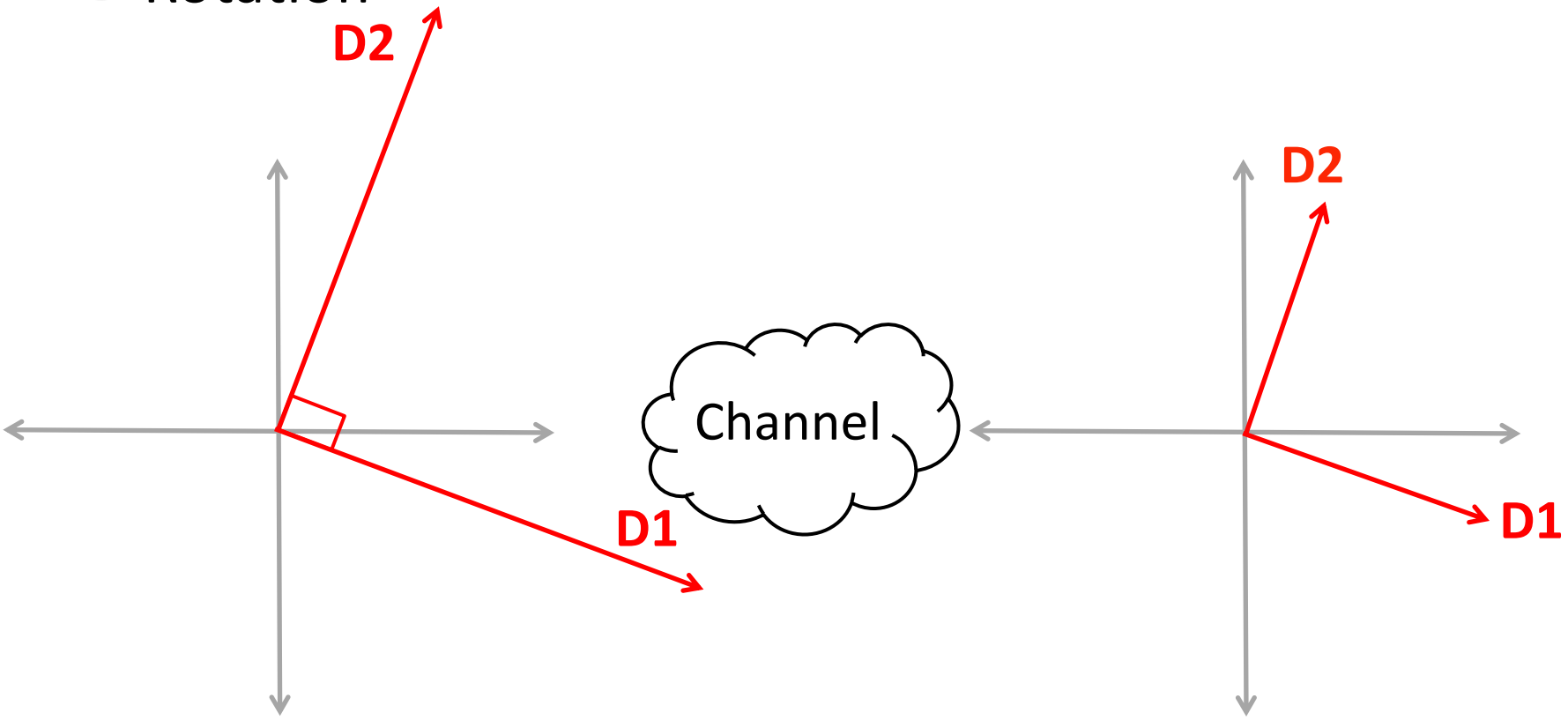
- Attenuation



D2 and **D1** are attenuated by the same amount

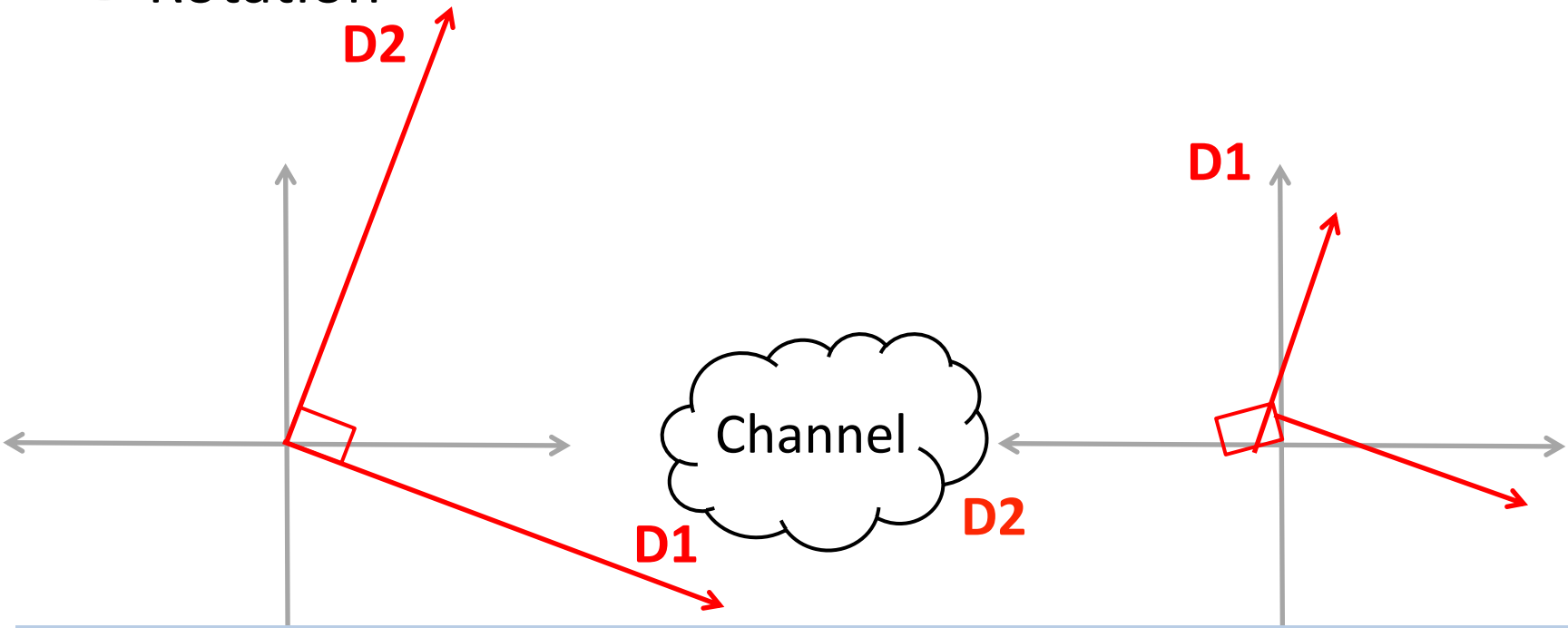
Channel Effects

- Attenuation
- Rotation



Channel Effects

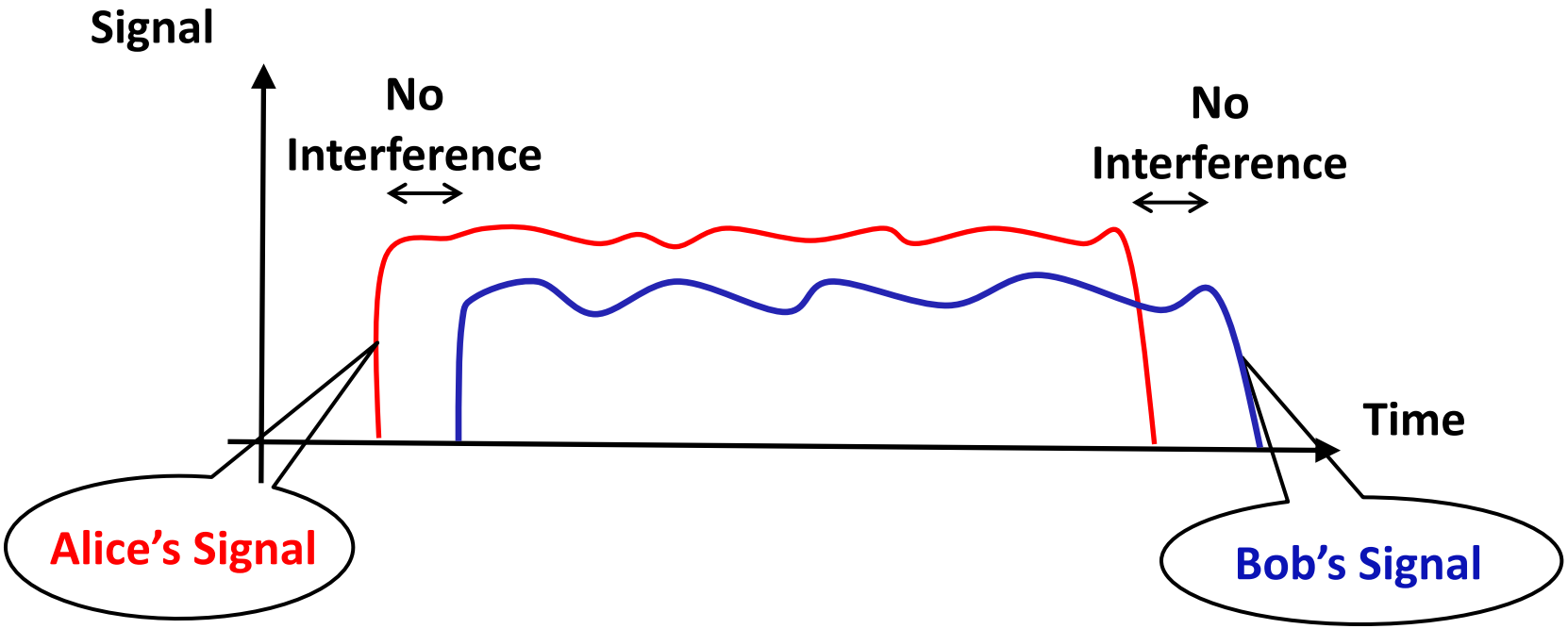
- Attenuation
- Rotation



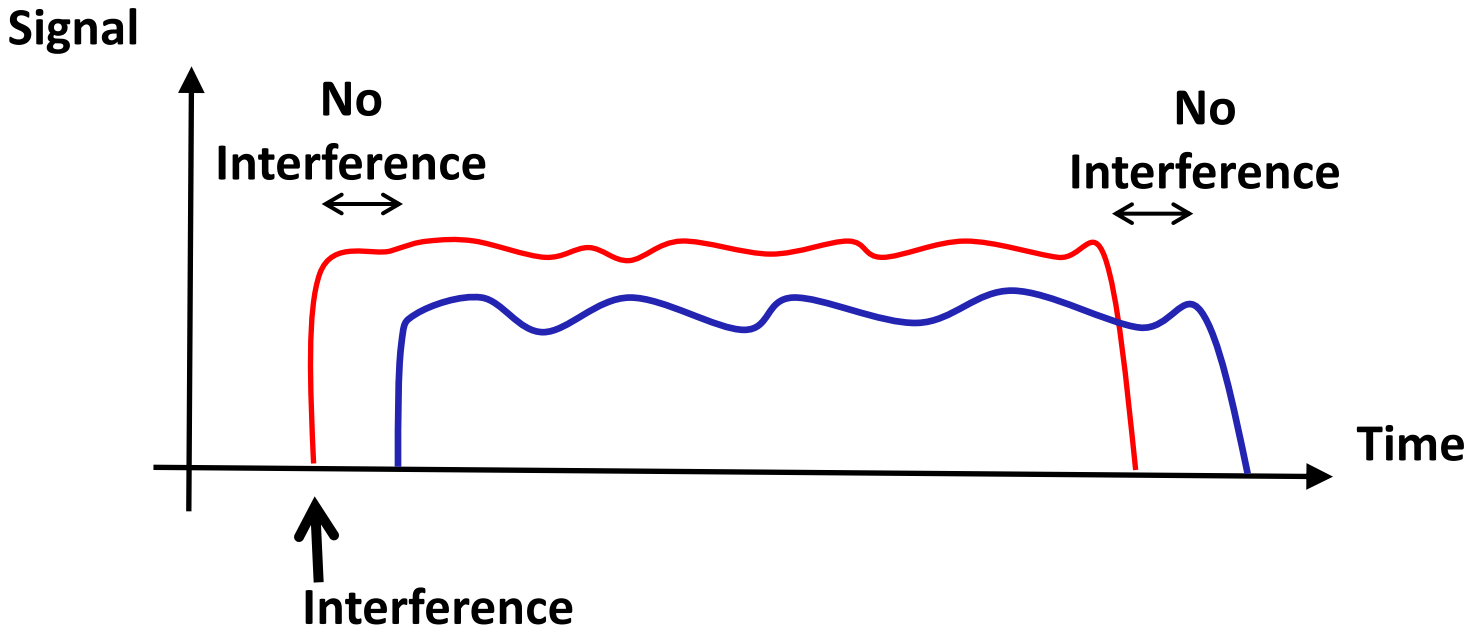
To decode, receiver computes angle between received vectors

Angle (D2, D1) = 90 degrees→ Bit "1" was transmitted

So, How Does Alice Decode?

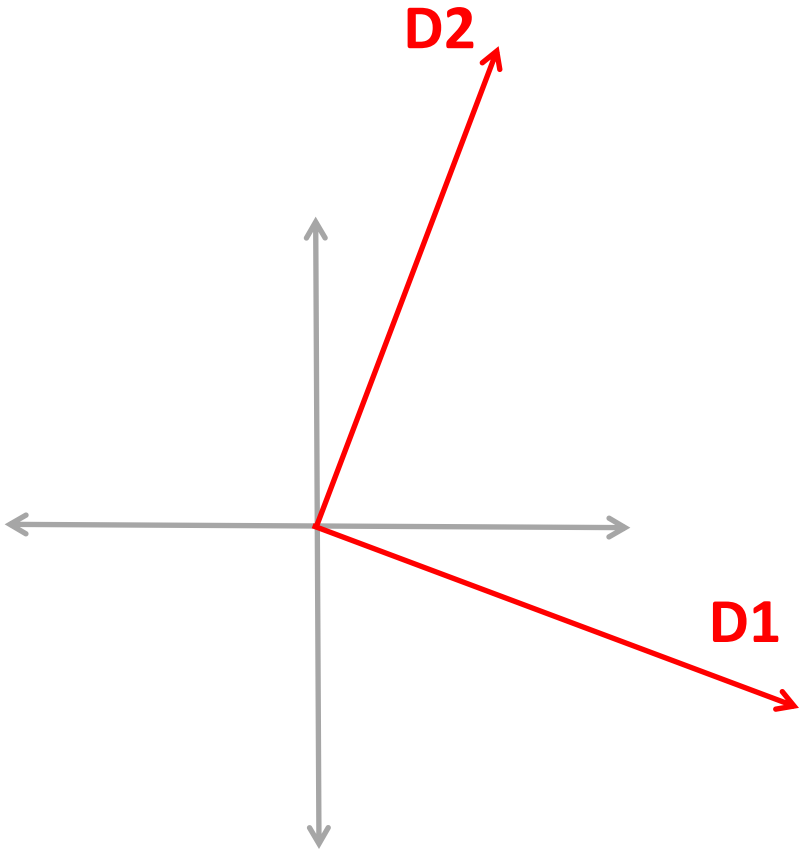


So, How Does Dina Decode?

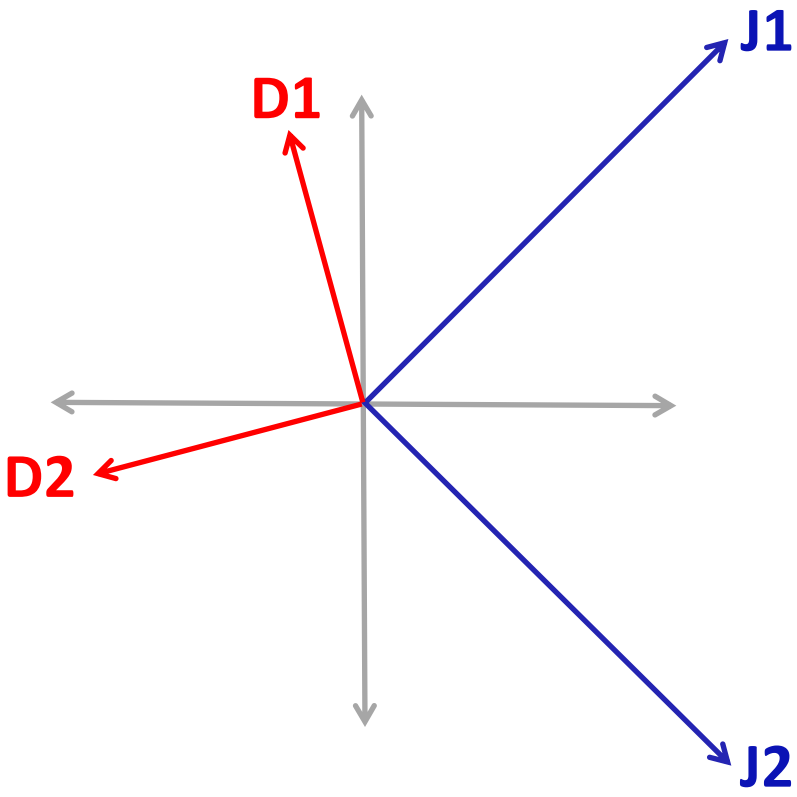


- Small uninterfered part at the start
- Decodes uninterfered part via standard MSK demodulation
- Once interference starts, Alice changes decoding algorithm

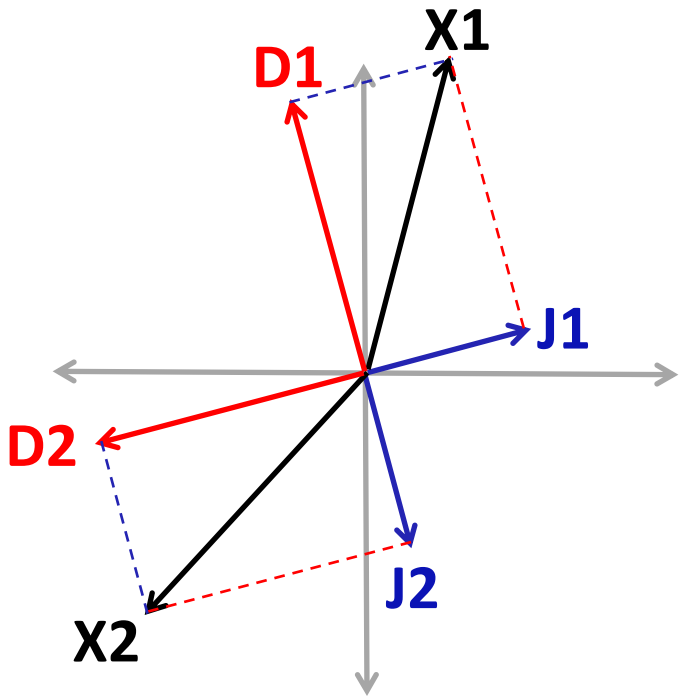
- What did Alice send?



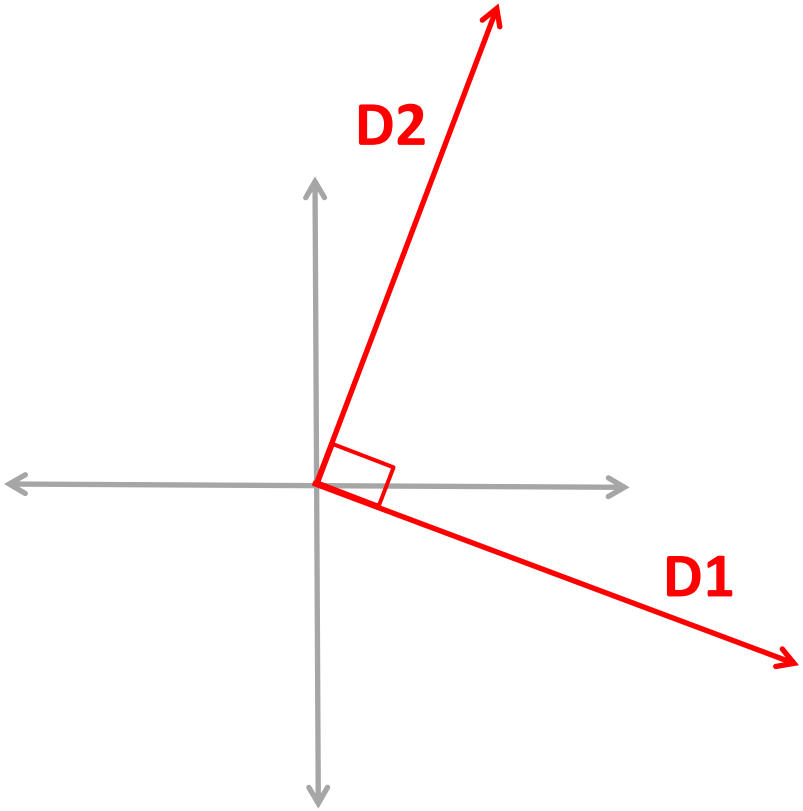
- What did Alice send?
- What did Bob send?

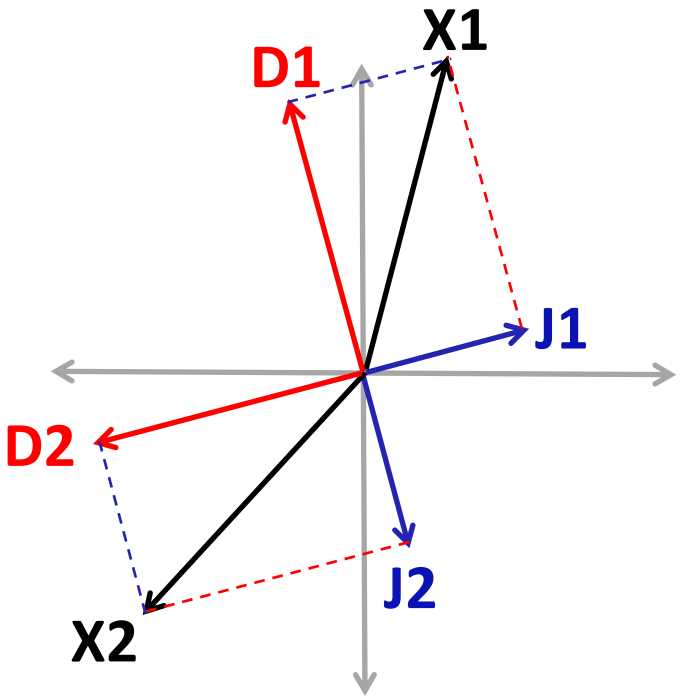


- **What is Interference → Vector addition**

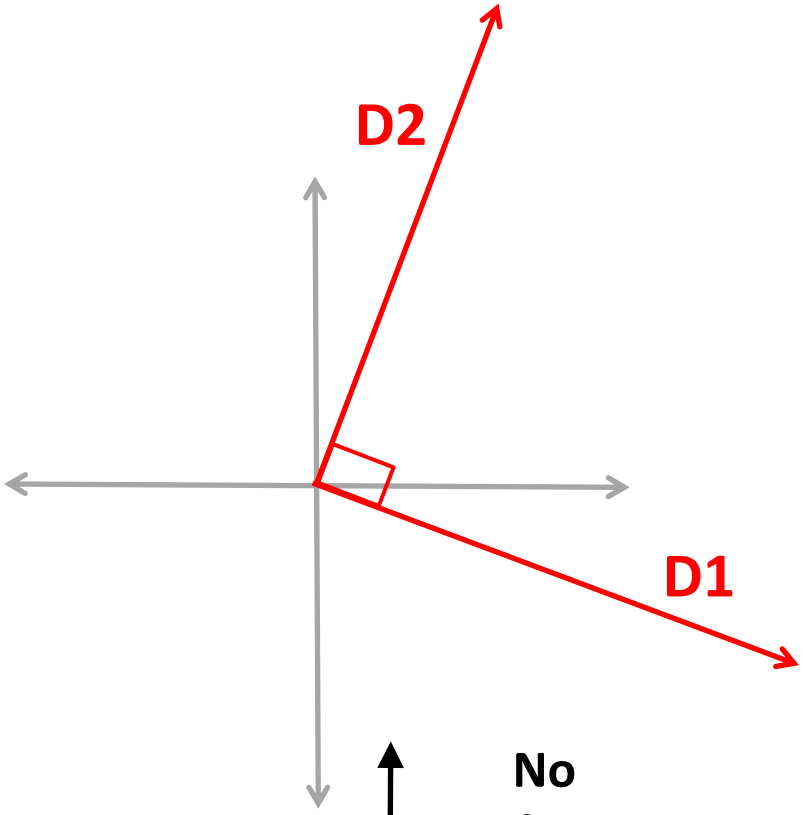


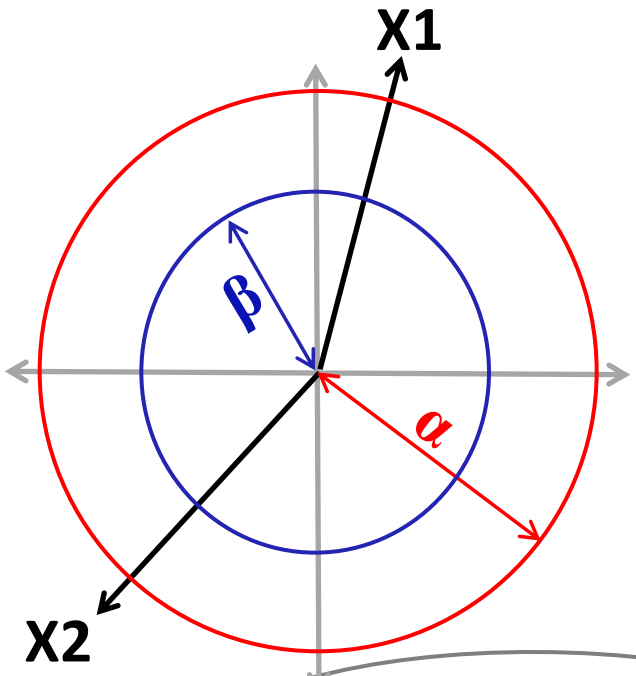
- What does Alice know?

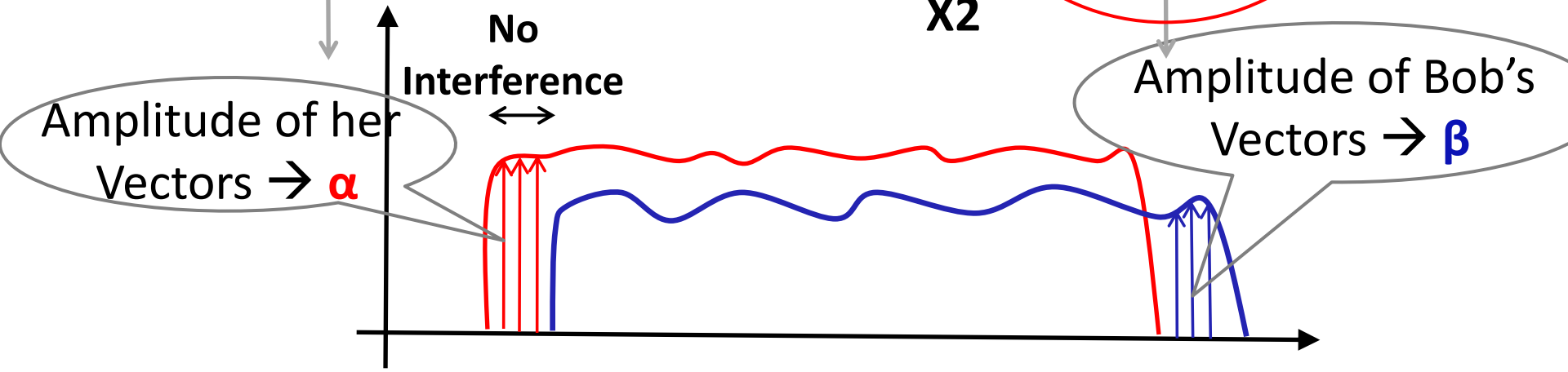




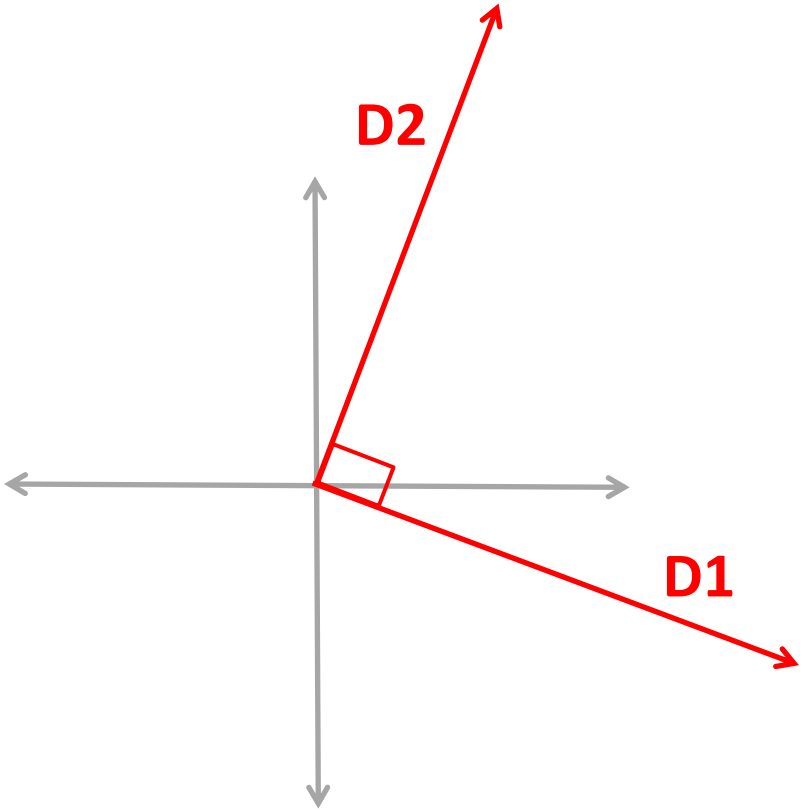
- What does Alice know?

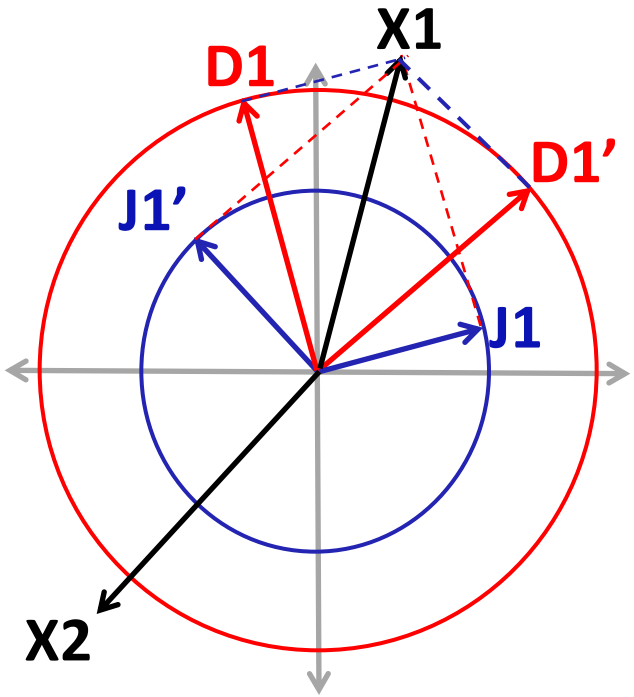






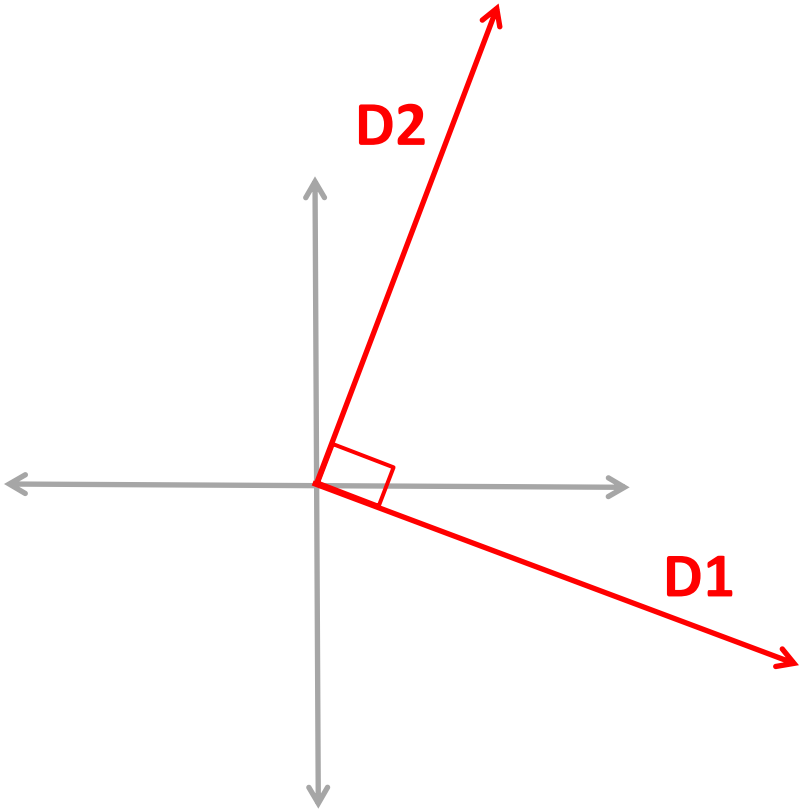
- What does Alice know?

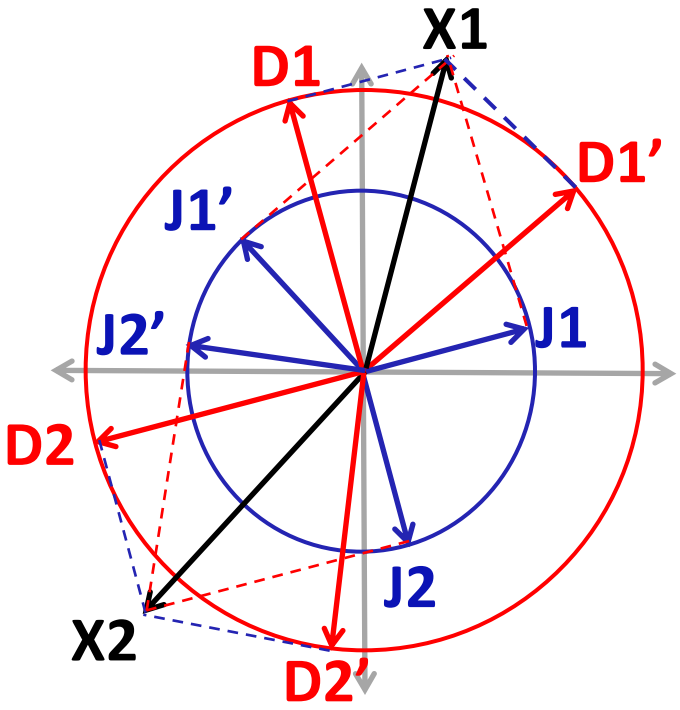




- Alice finds solutions for **X1** and **X2**

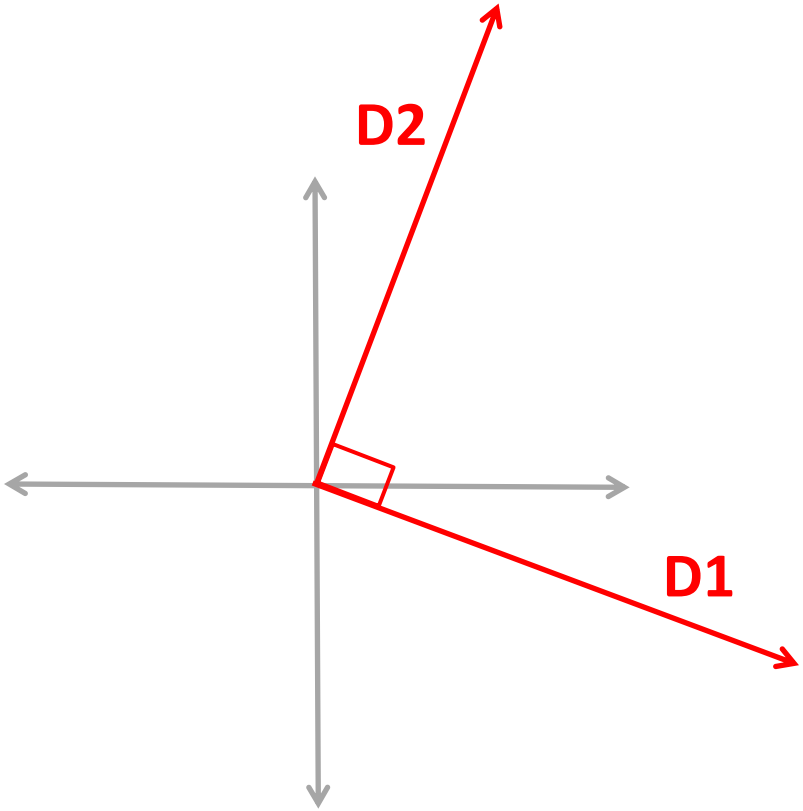
- What does Alice know?

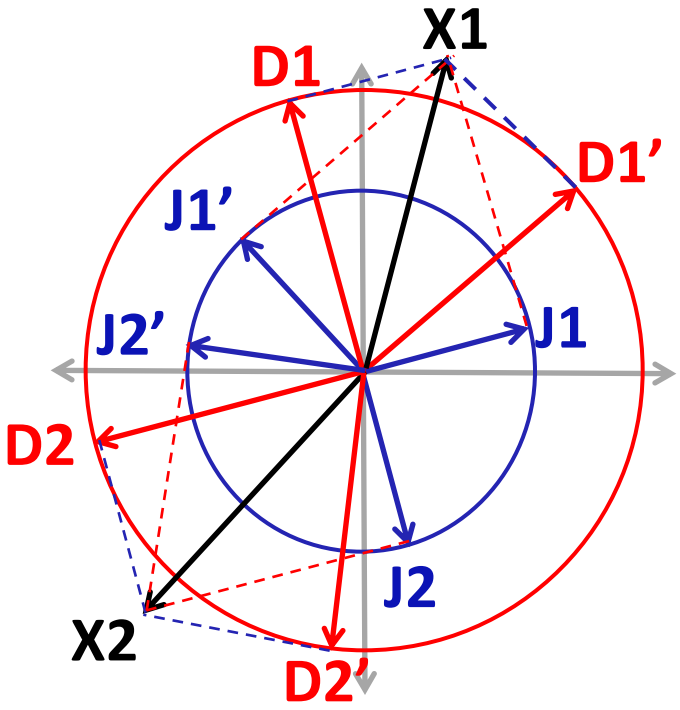




Two solutions for each interfered vector!

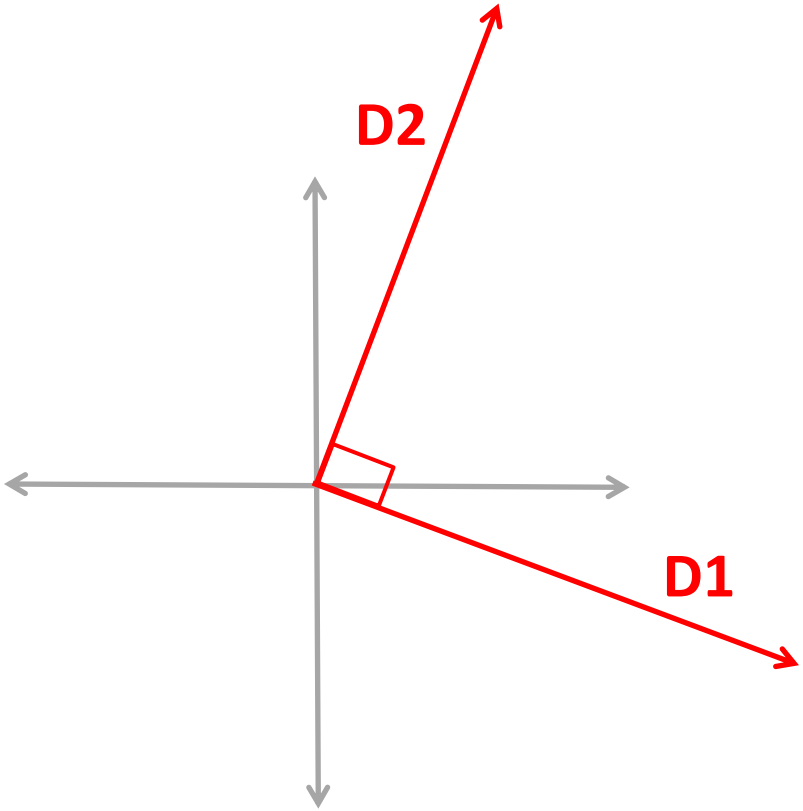
- What does Alice know?

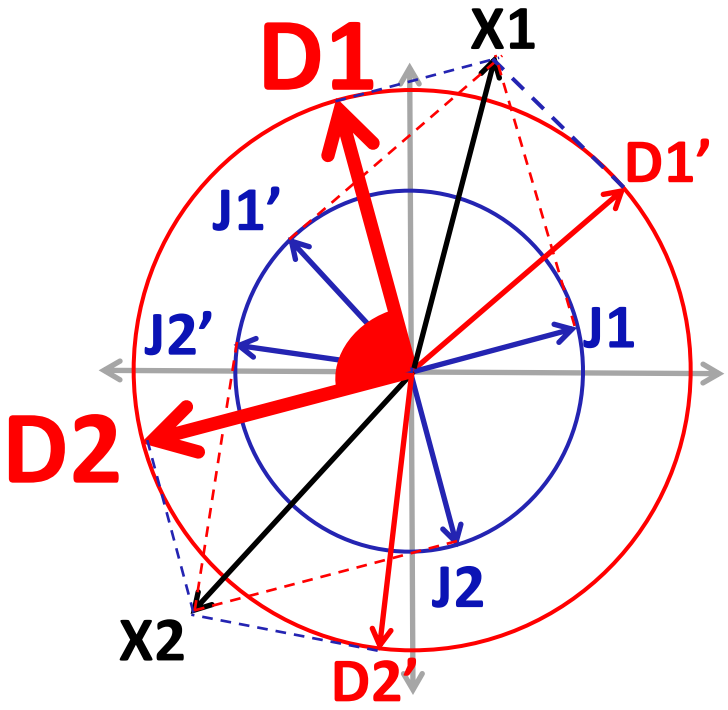




Four possible angles!

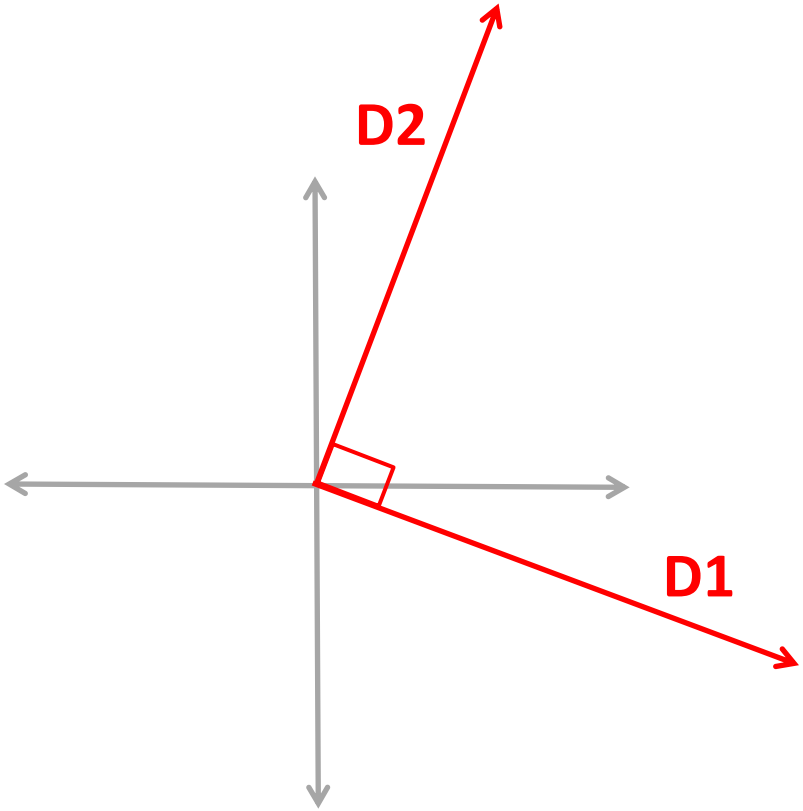
- What does Alice know?

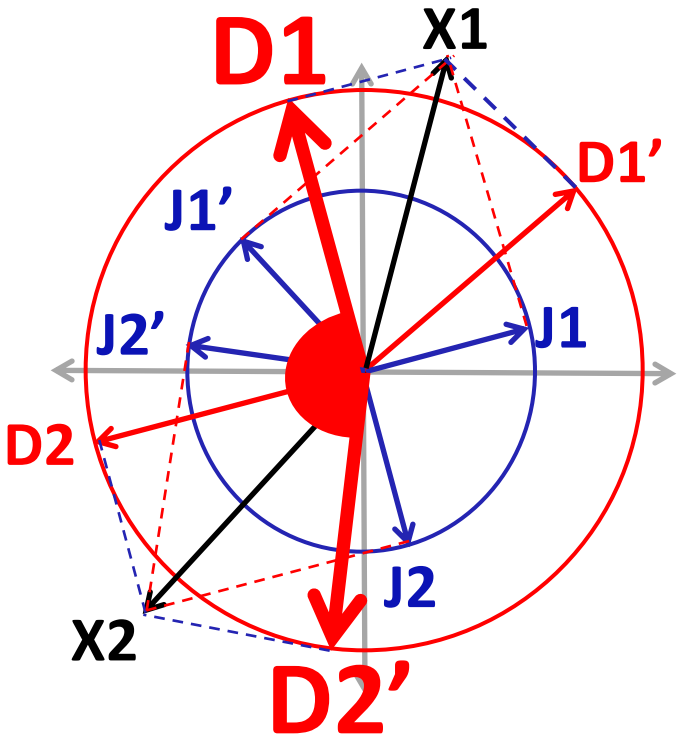




Four possible angles!

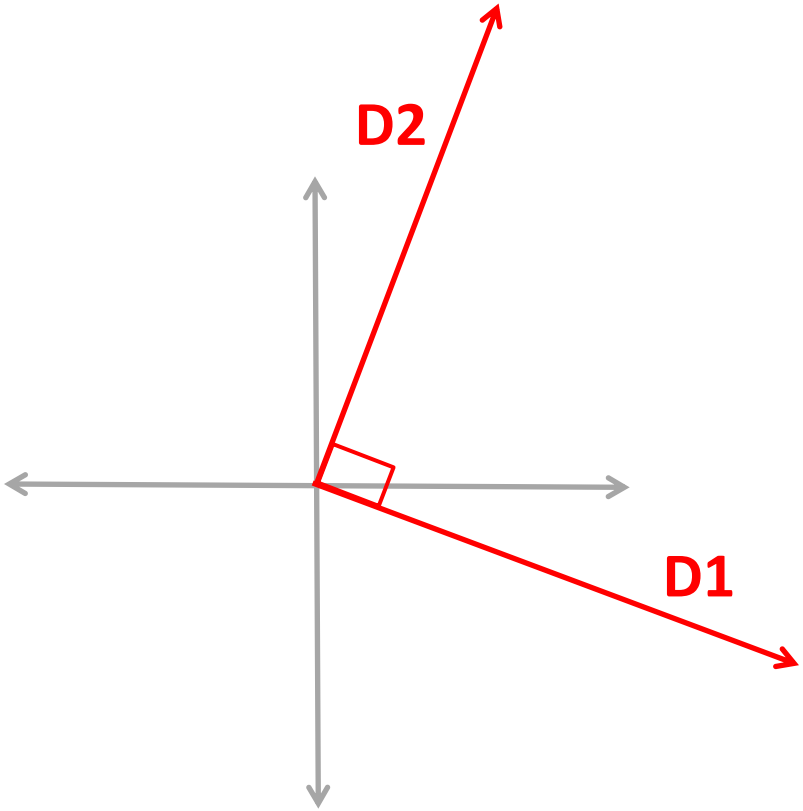
- What does Alice know?

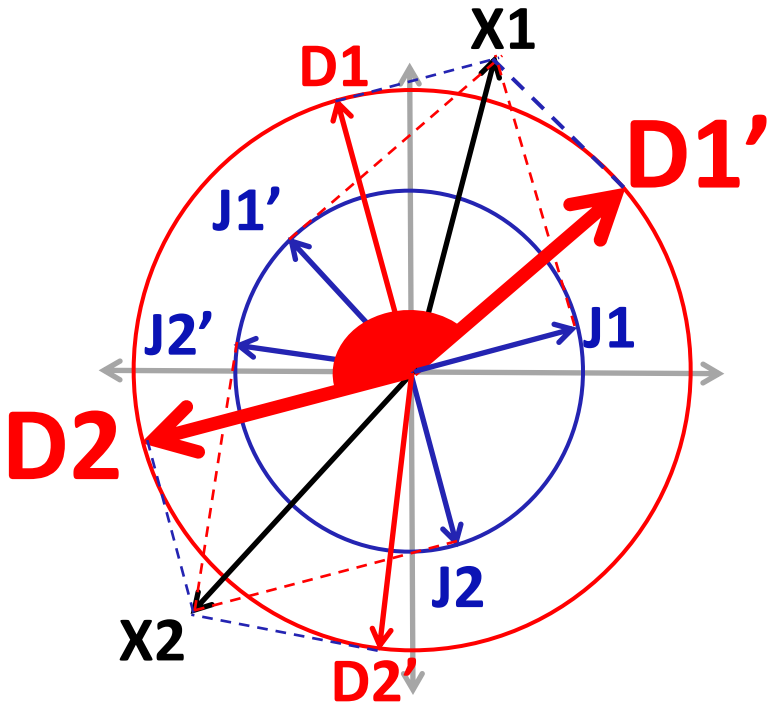




Four possible angles!

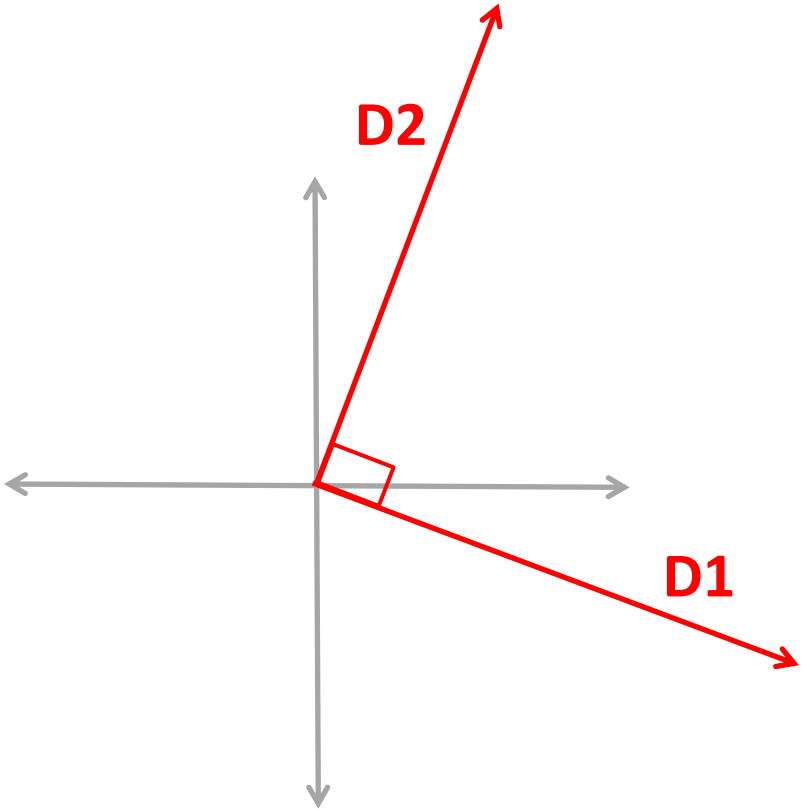
- What does Alice know?

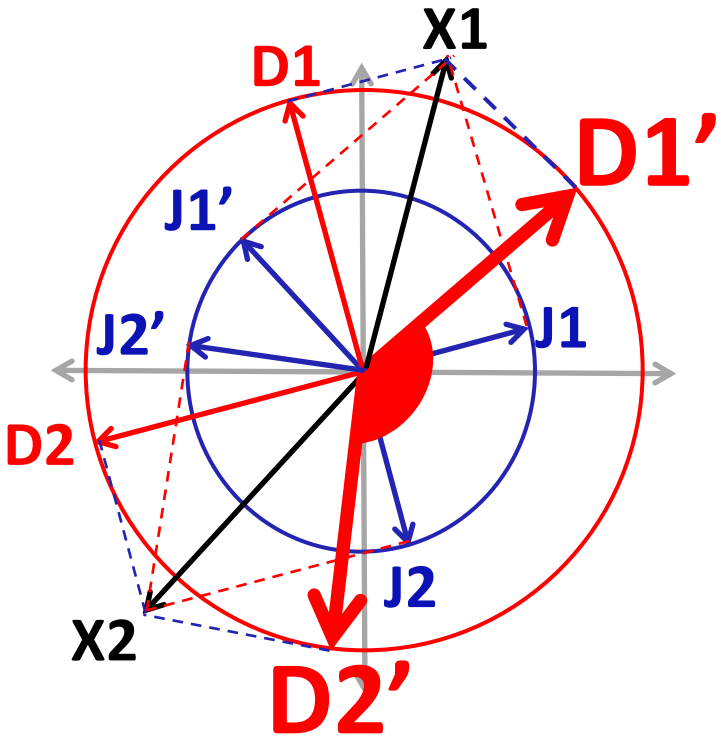




Four possible angles!

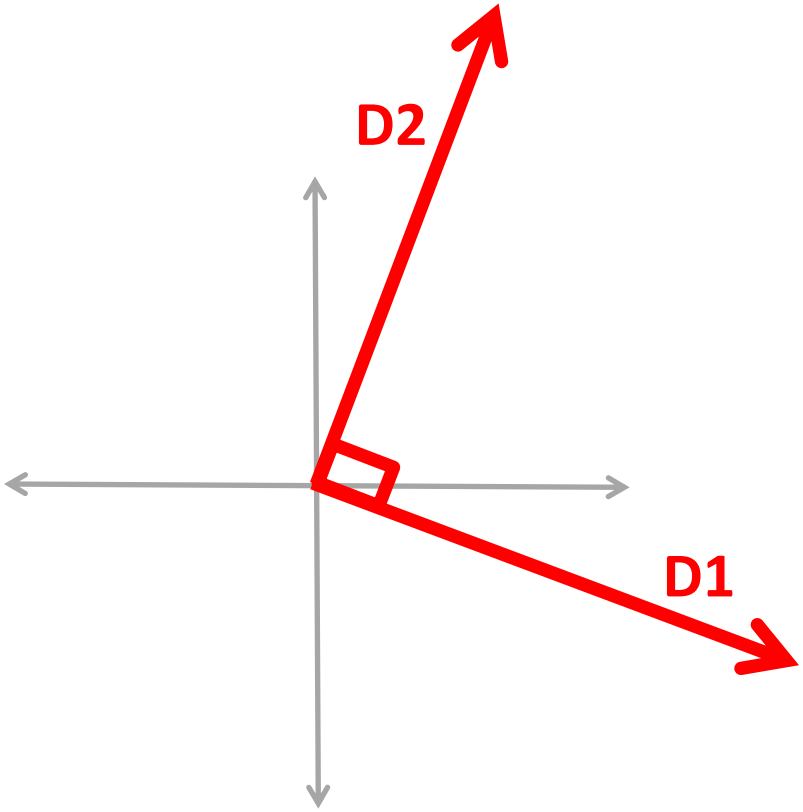
- What does Alice know?

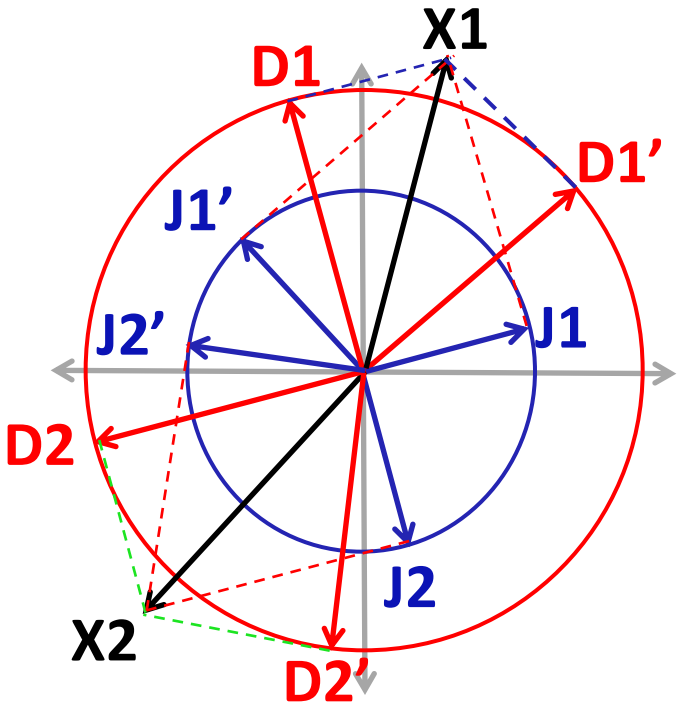




Four possible angles!

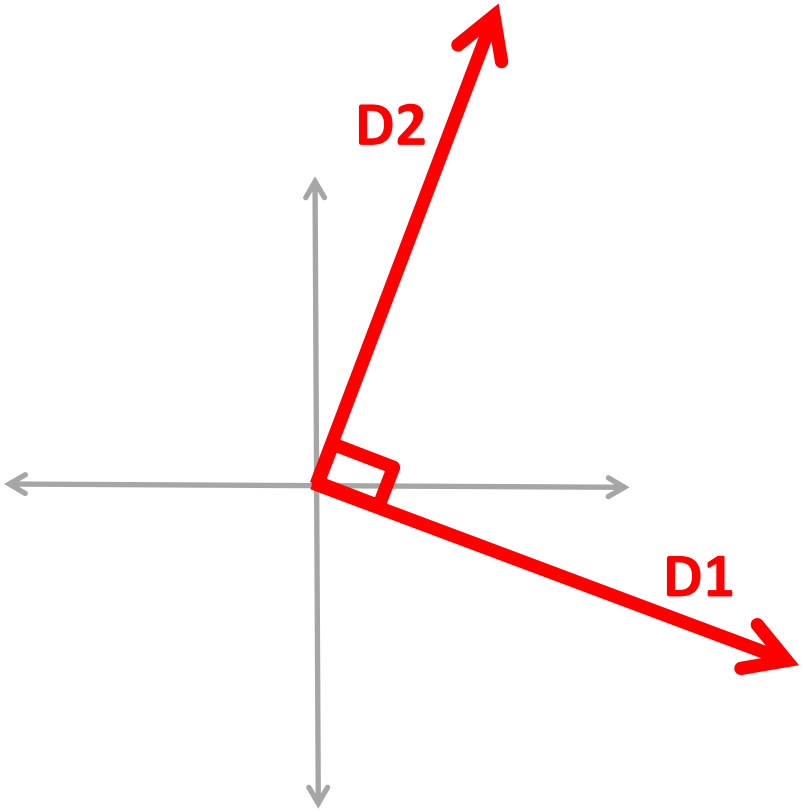
- What does Alice know?

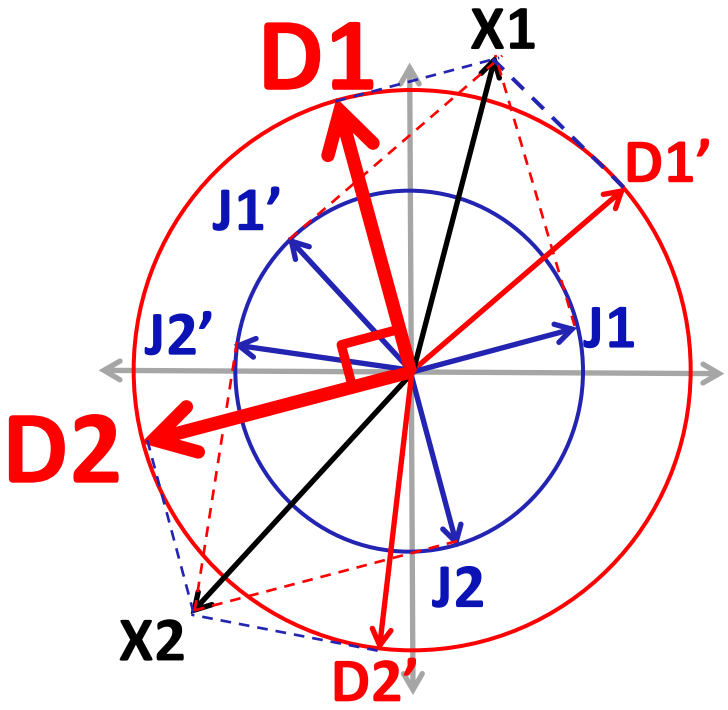




Pick the correct angle → 90 degrees

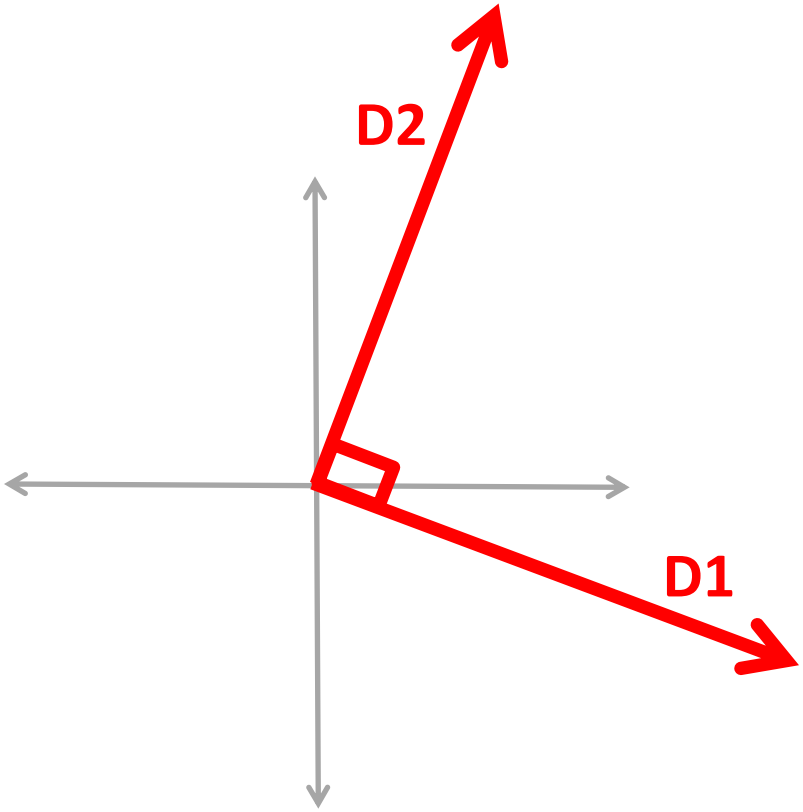
- What does Alice know?

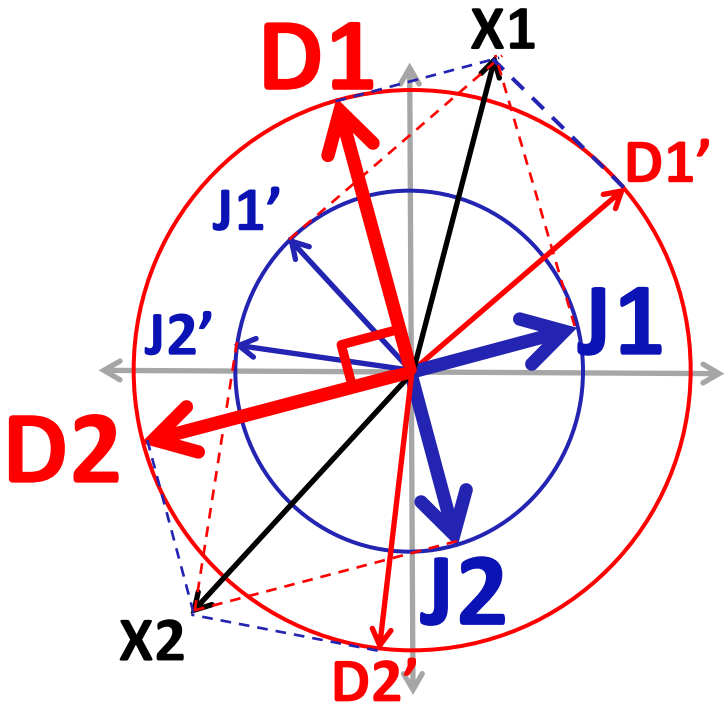




Pick the correct angle → +90 degrees

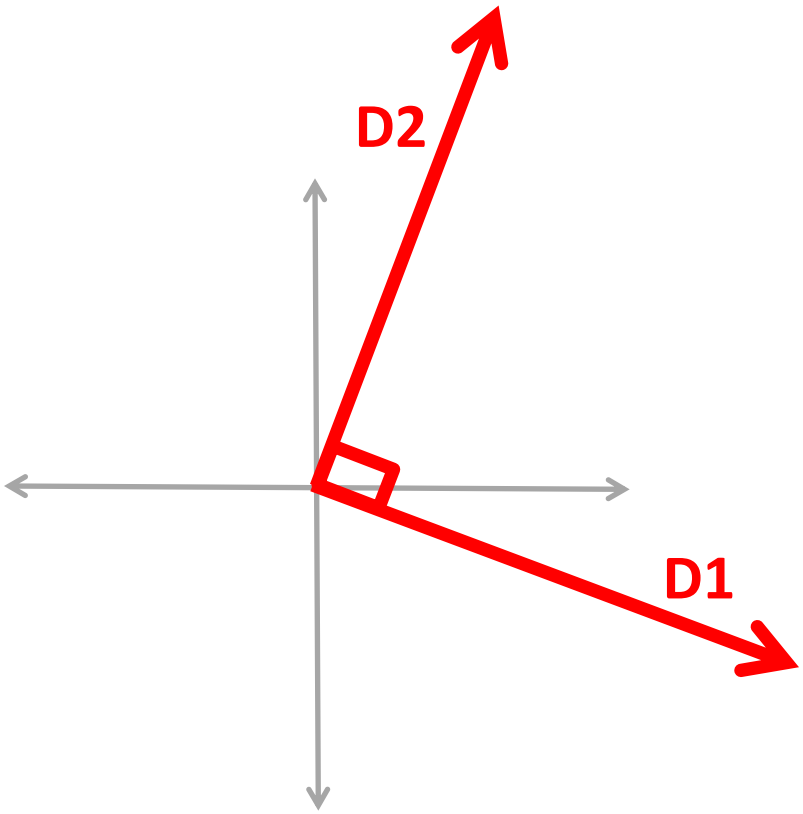
- What does Alice know?

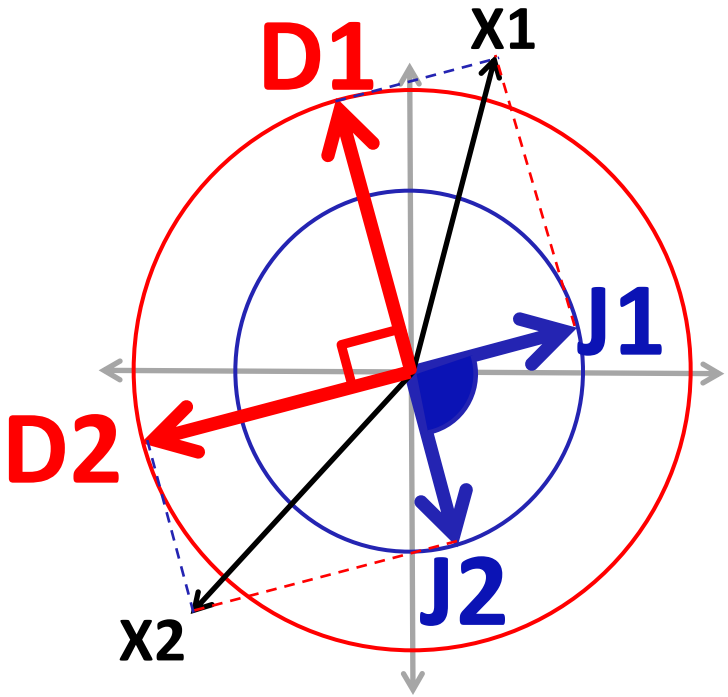




Dictates solution for Bob's vectors!

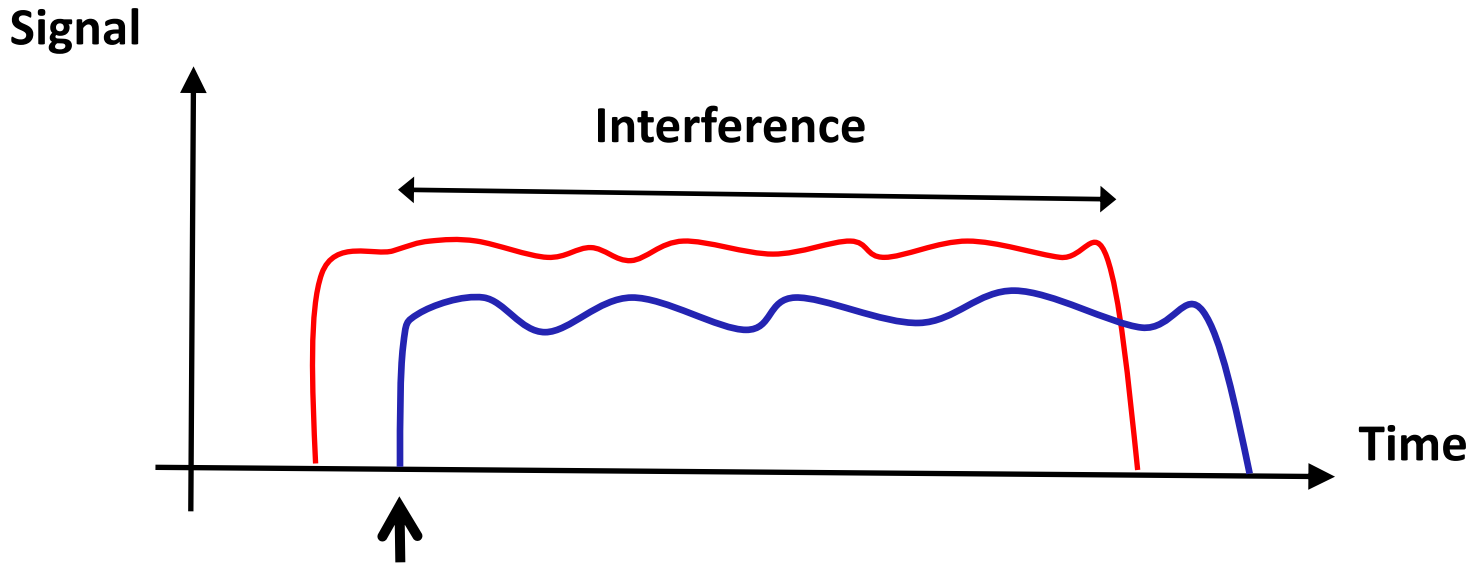
- What does Alice know?





- Alice finds angle between **J1** and **J2** and decodes

Decoding Algorithm – Decoding interference

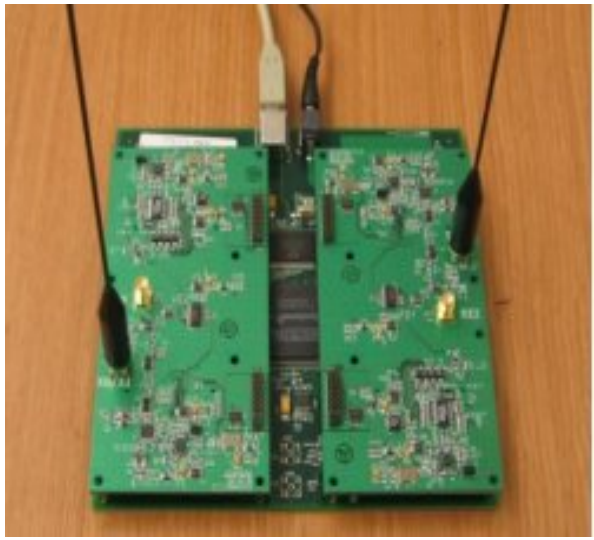


- Decode rest of the interfered part using this algorithm
- Decode final uninterfered part from Jon via standard MSK demodulation

Performance

ANC Implementation

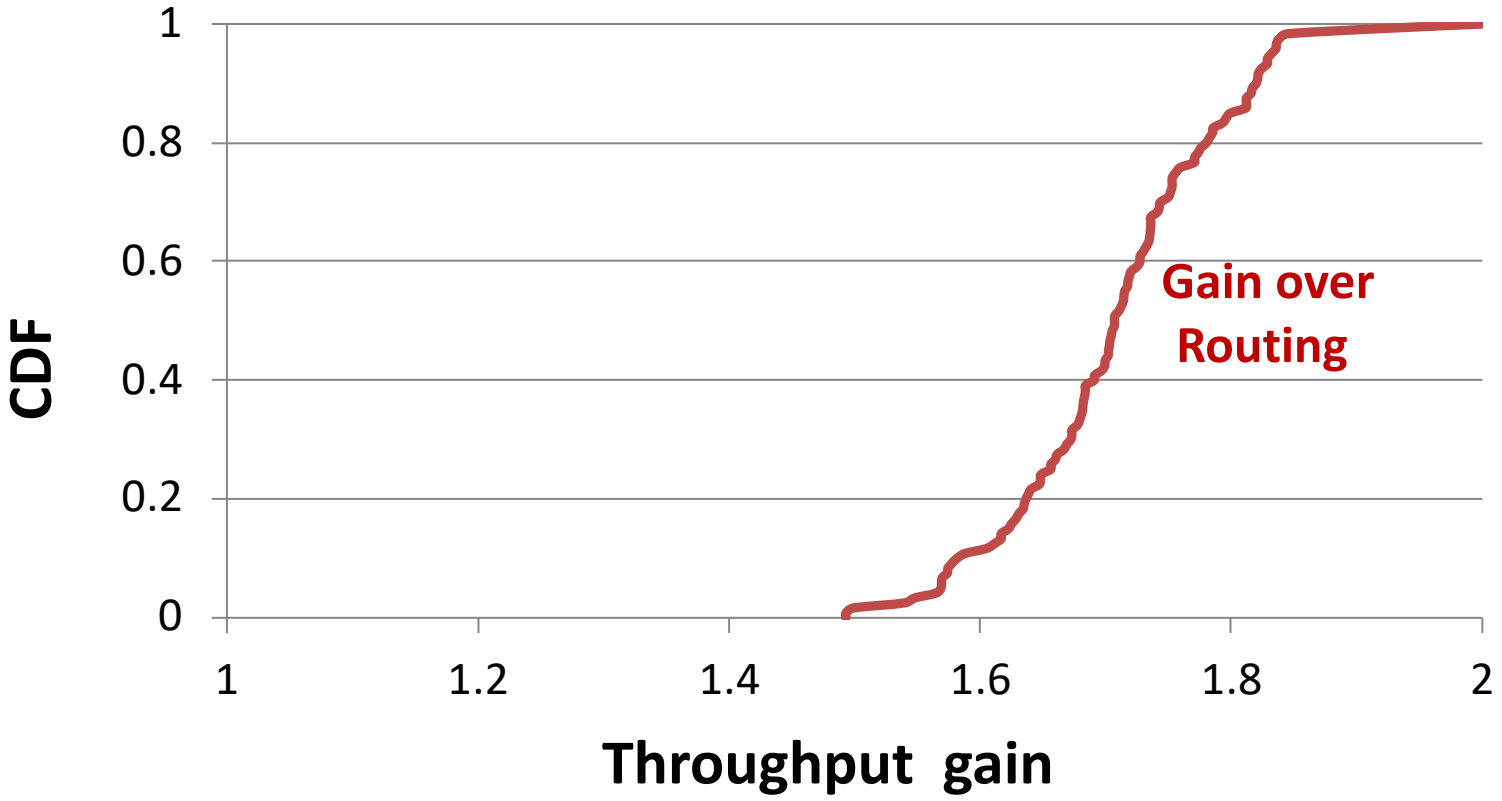
- Software – GNURadio codebase
- Hardware – USRP frontend
- 2.4-2.48 GHz frequency range
- SNR of 20-30 dB
- Canonical topologies in mesh networks



Alice and Bob

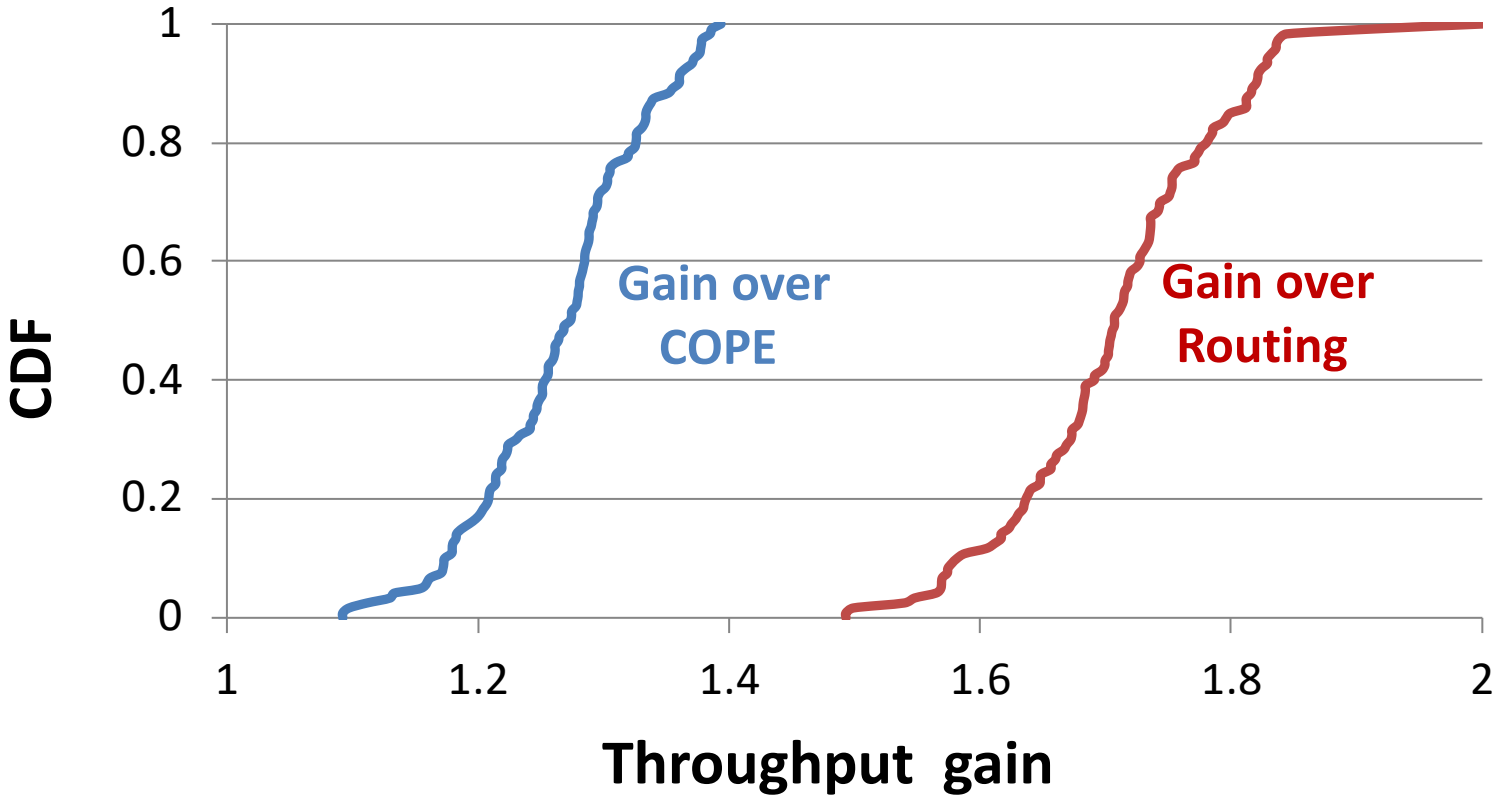
- ANC throughput gain over current 4/2 = 2
- ANC throughput gain over COPE 3/2 = 1.5

Throughput gain for Alice & Bob scenario



Median Gain over Routing – 70%

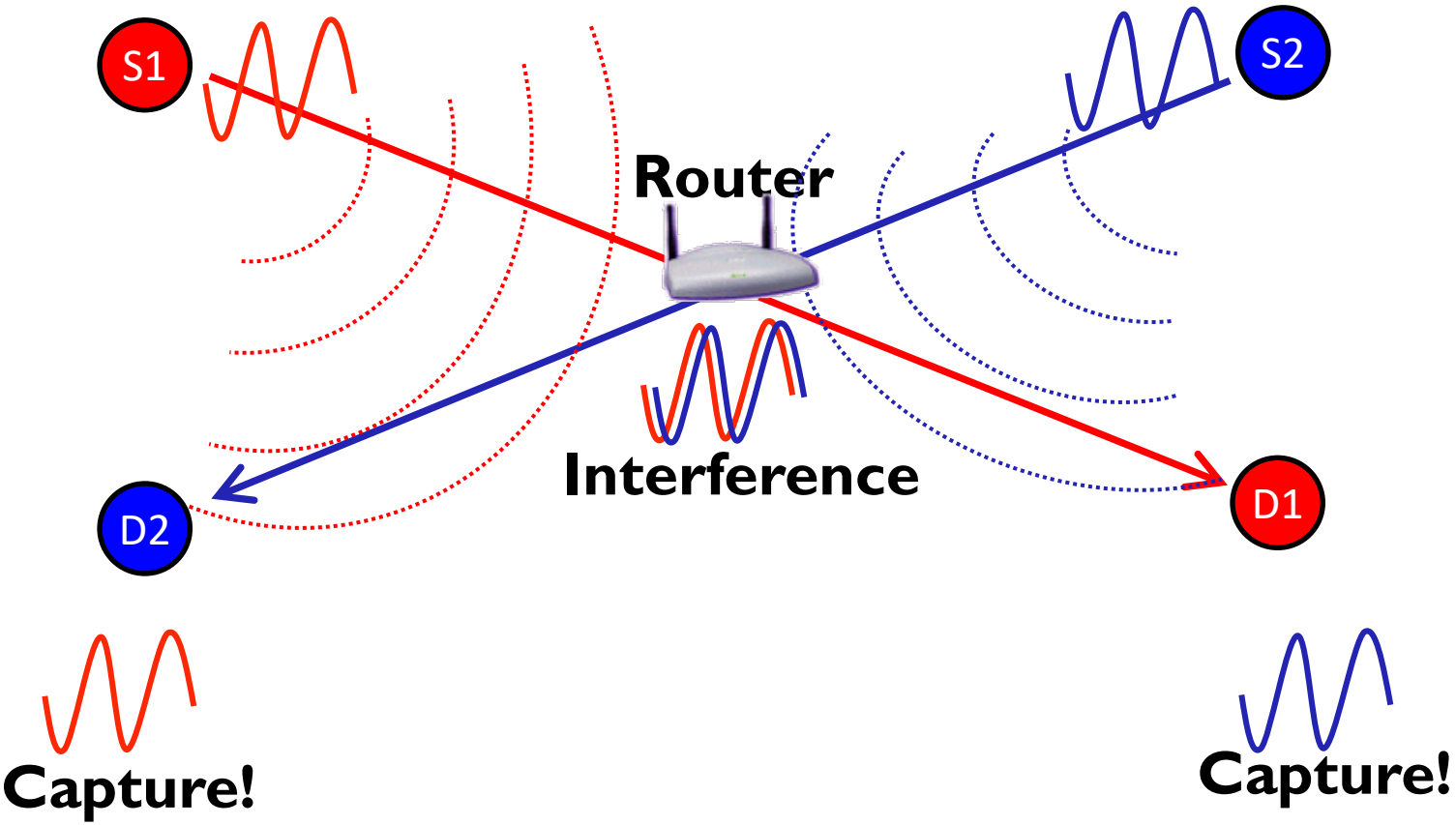
Throughput gain for Alice & Bob scenario



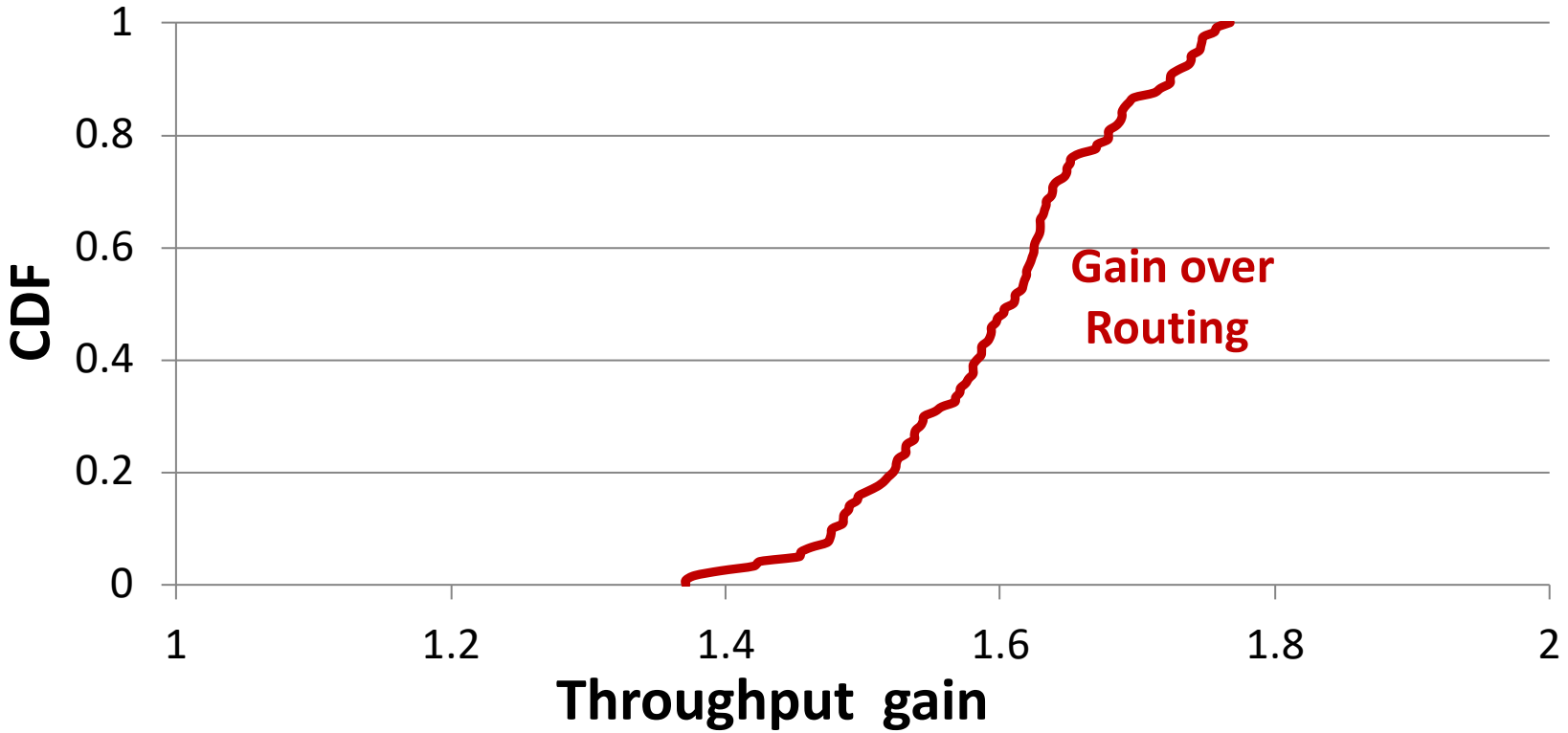
Median Gain over Routing – 70%

Median Gain over COPE – 30%

X topology

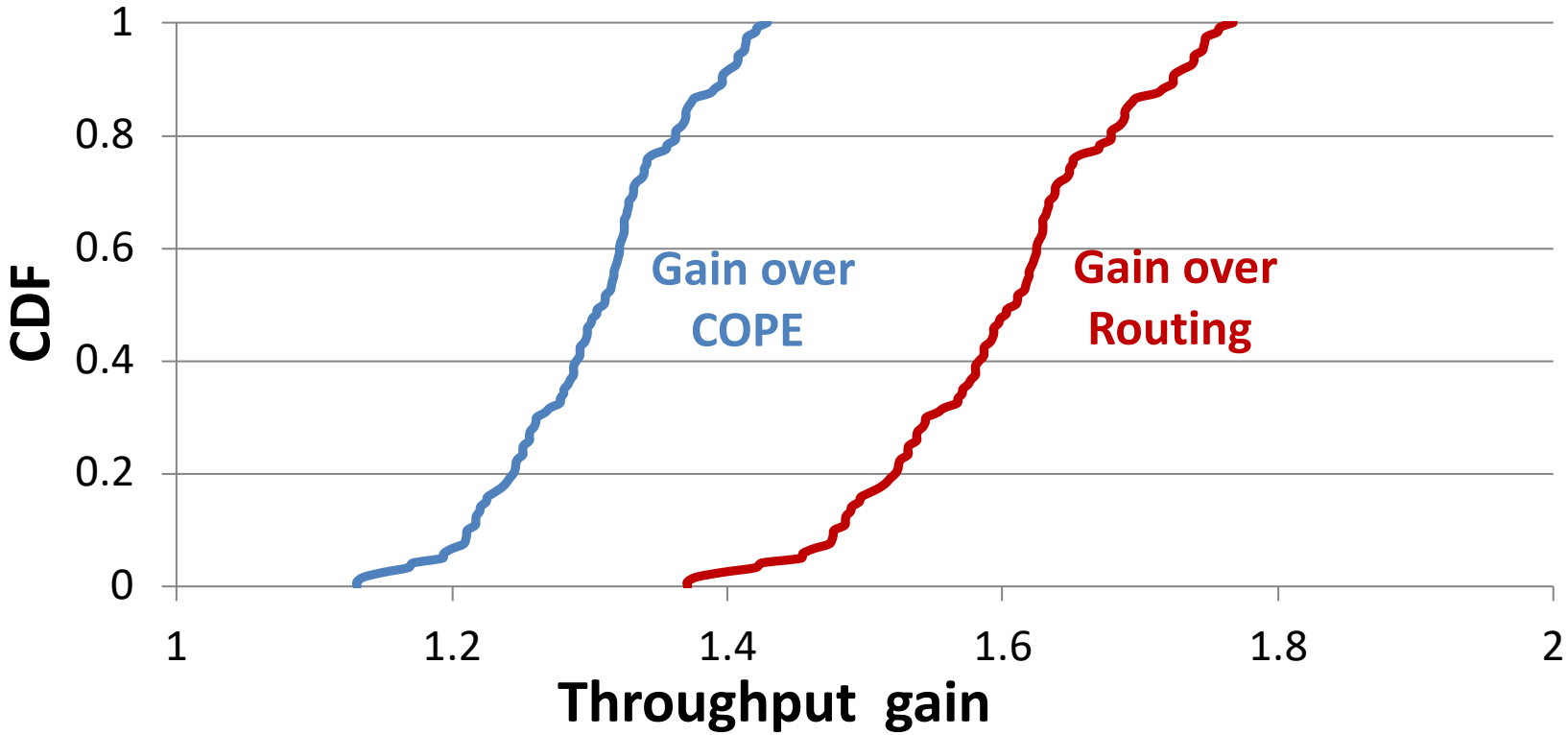


Throughput gain – X topology



Median Gain over Routing – 65%

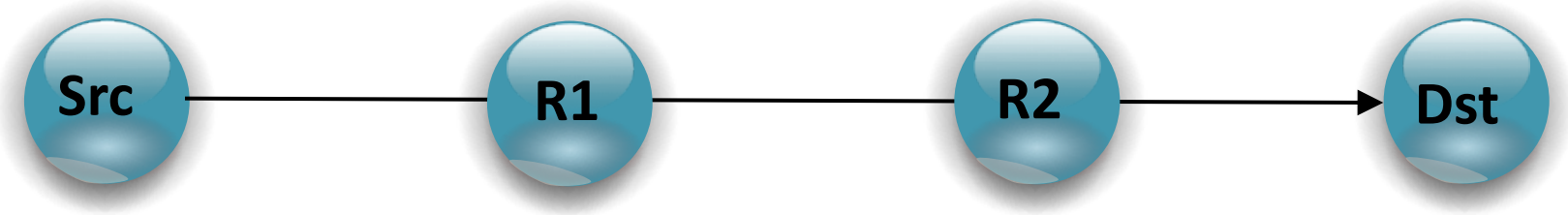
Throughput gain – X topology



Median Gain over Routing – 65%

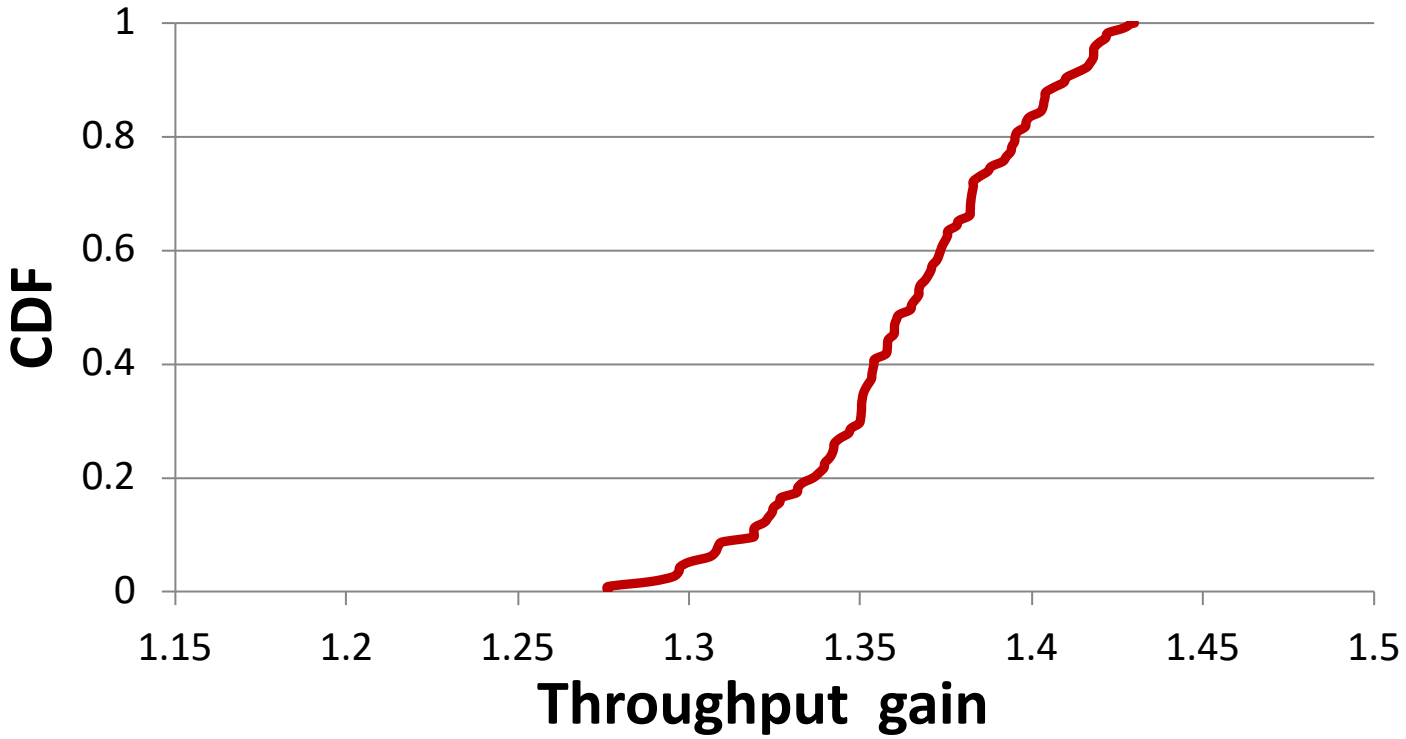
Median Gain over COPE – 28%

Chain topology



- ANC throughput gain over current 3/2 = 1.5

Throughput gain – Chain topology



Median Gain over Routing – 37%

ANC Limitations

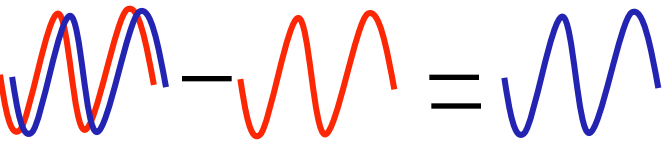
- Complexity.
- Buffering analog samples… expensive.
- Amplify noise!

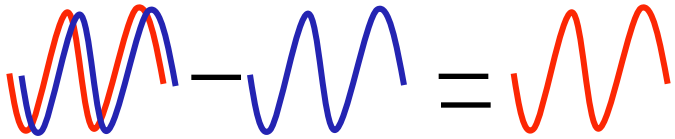
Analog Network Coding

Router

Alice

Bob





Analog Network Coding requires 2 time slots

Can we do it in 1 time slot?

Conclusion

- Network Coding :
  - Improve throughput & resilience to loss
  - Less coordination
  - Inter- & Intra- flow network coding
  - Analog coding using wireless channels

- Shifts in the design of wireless networks to recognize wireless for what it is:
  - Embrace Broadcast
  - Embrace Interference