Analog Network Coding

Sachin Katti

Shyamnath Gollakota and Dina Katabi

Current Wireless

Router

Current Wireless

Traditional Routing requires **4** time slots

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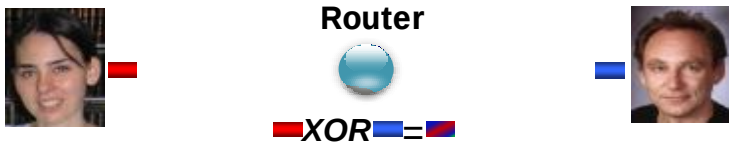
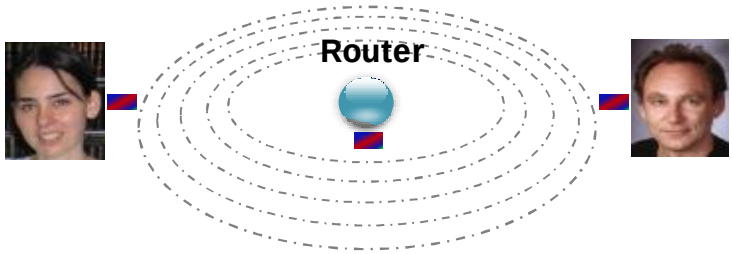
Last Year à Network Coding à COPE



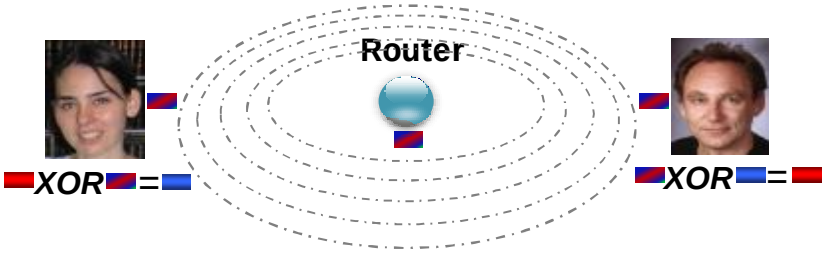
Traditional Routing requires **4** time slots

Last Year à Network Coding à COPE



Traditional Routing requires **4** time slots

Last Year à Network Coding à COPE



Traditional Routing requires **4** time slots

COPE requires **3** time slots

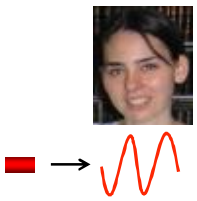
Can we do it in 2 time slots?

Instead of router mixing packets…

Exploit that the wireless *channel naturally mixes signals*

Analog Network Coding (ANC)

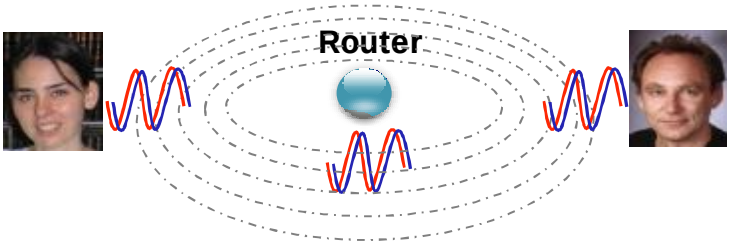
Analog Network Coding



Analog Network Coding

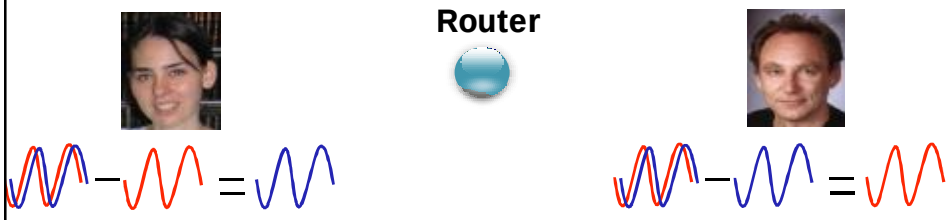
1) Dina and Jon transmit simultaneously

Analog Network Coding



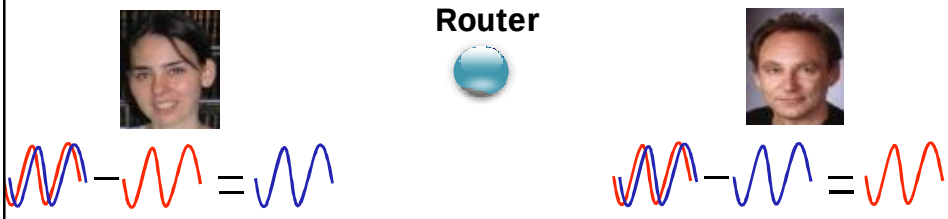
1) Dina and Jon transmit simultaneously
2) Router amplifies and broadcasts interfered signal

Analog Network Coding



1) Dina and Jon transmit simultaneously
2) Router amplifies and broadcasts interfered signal
3) Dina subtracts known signal from interfered signal

Analog Network Coding

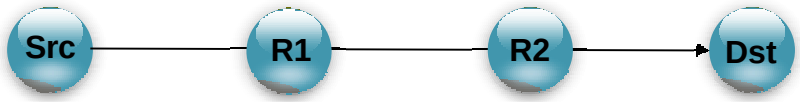


Analog Network Coding requires 2 time slots
à Higher throughput

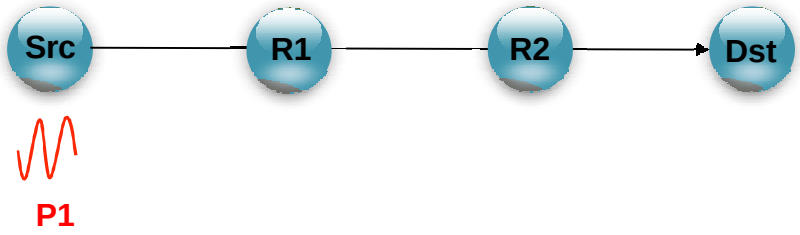
It Is More Than Going From 3 To 2!

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

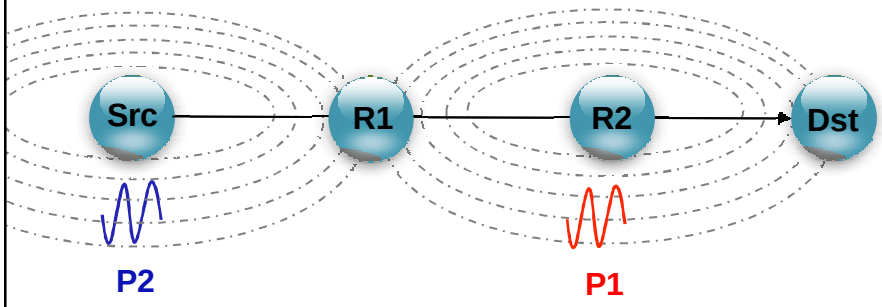
Hidden Terminal Scenario



Hidden Terminal Scenario

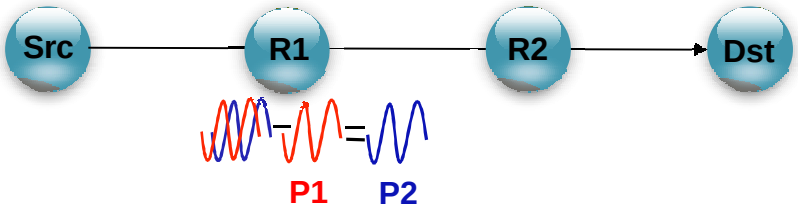


Hidden Terminal Scenario



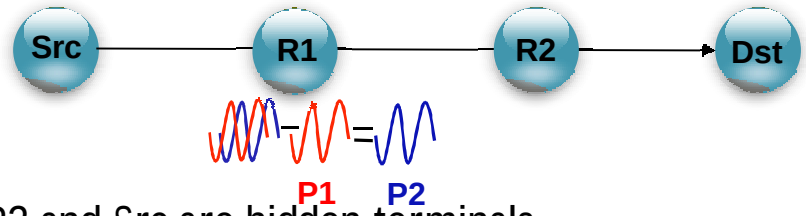
1) Src and R2 transmit simultaneously

Hidden Terminal Scenario



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

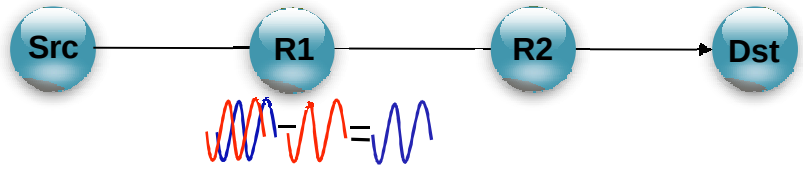
Hidden Terminal Scenario



R2 and Src are hidden terminals

- Today : Simultaneous transmission **à** Collision
- ANC : Simultaneous transmission **à** Success!

Hidden Terminal Scenario

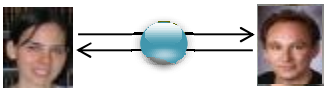


Other Benefits of ANC:

- **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 $s_D(t) + s_J(t)$ but $f1(s_D(t)) + f2(s_J(t-T))$
- Prior work assumes full synchronization and ignores channel distortion

Not Practical!

Key Idea: Exploit Asynchrony!

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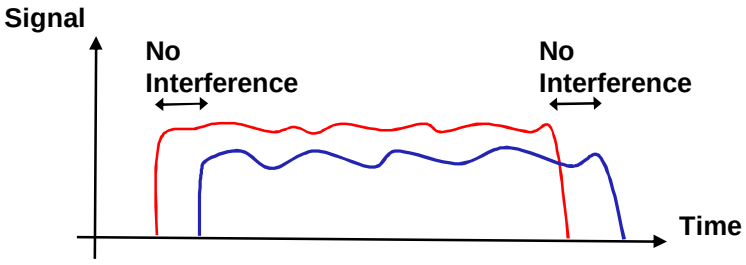


- Dina uses interference-free parts to estimate channel and timing
- Dina compensates for her interfering signal

Exploit asynchrony to make it practical

Cross layer realization of our idea

Protocol

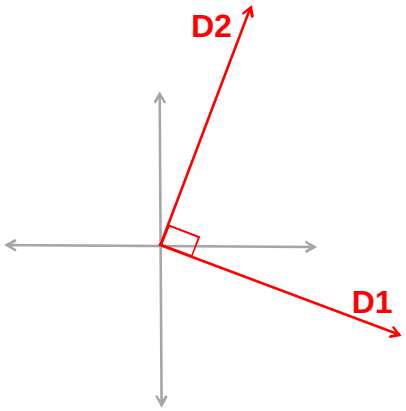
- Router senses idle medium and broadcasts a trigger to Dina and Jon
- Dina and Jon jitter their start times randomly and transmit
- Router amplifies and forwards interfered signal
- Dina and Jon receive and decode

How do they decode?

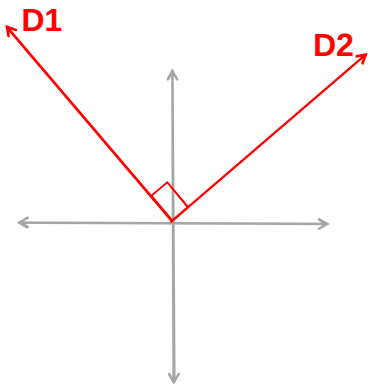
Primer on Modulation

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

D2 leads **D1** by 90 degrees
à Bit "1"

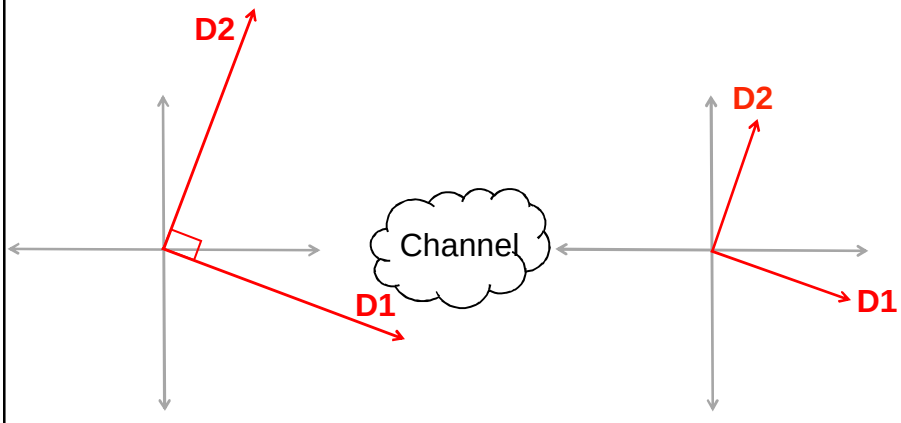


D2 lags **D1** by 90 degrees
à Bit "0"



Primer on Channel Effects

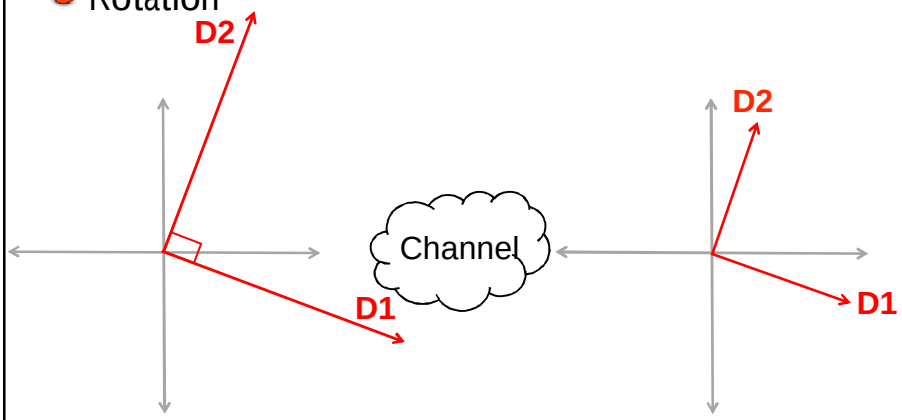
- Attenuation



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

Primer on Channel Effects

- Attenuation
- Rotation



Primer on Channel Effects

- Attenuation
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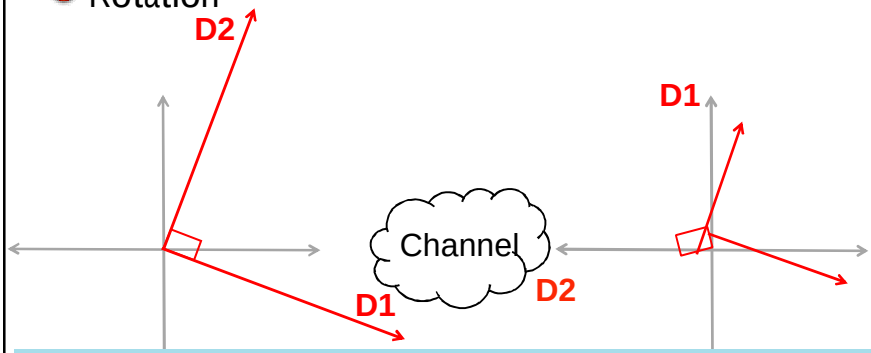
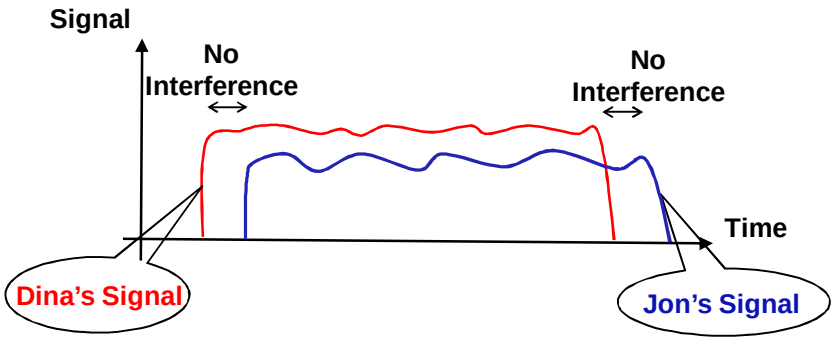


To decode, receiver computes angle between received vectors
Angle (D2, D1) = 90 degrees **à** Bit "1" was transmitted

So, How Does Dina Decode?



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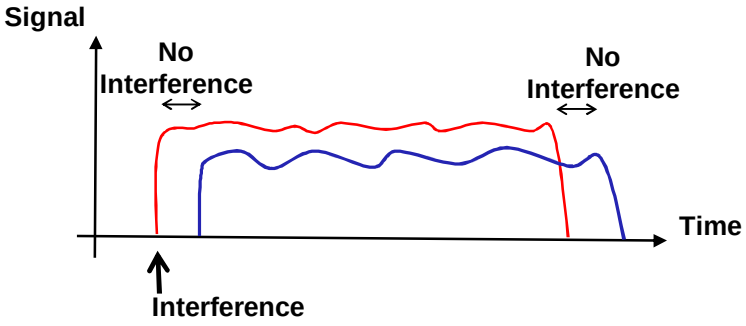
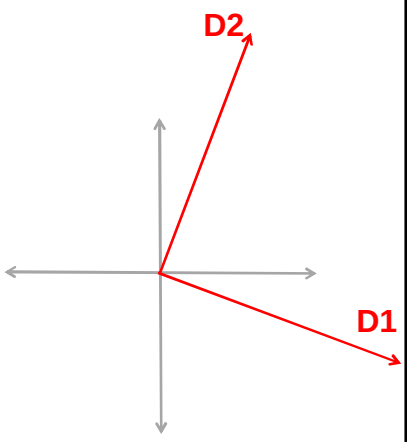
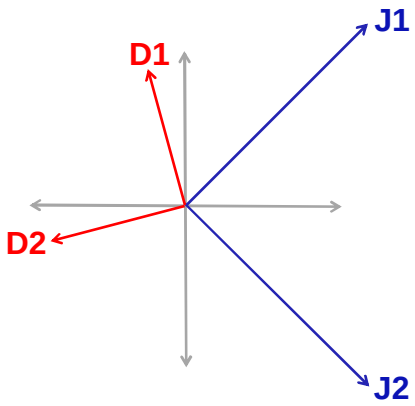


- Small uninterfered part at the start
- Decodes uninterfered part via standard MSK demodulation
- Once interference starts, Dina changes decoding algorithm

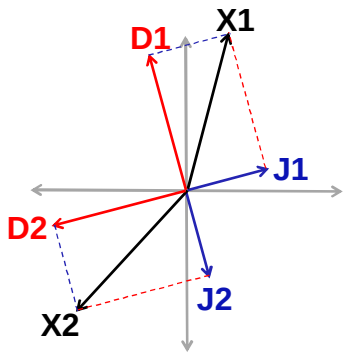
- What did Dina send?



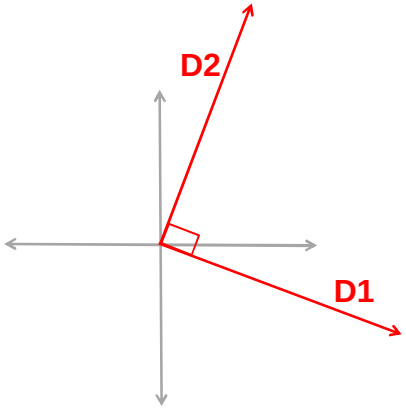
- What did Dina send?
- What did Jon send?

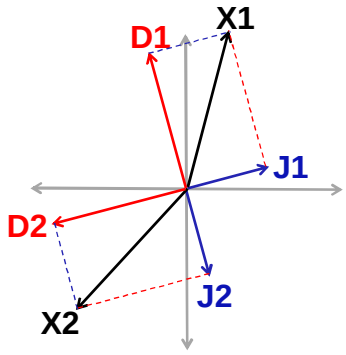


- **What is Interference à Vector addition**



- What does Dina know?





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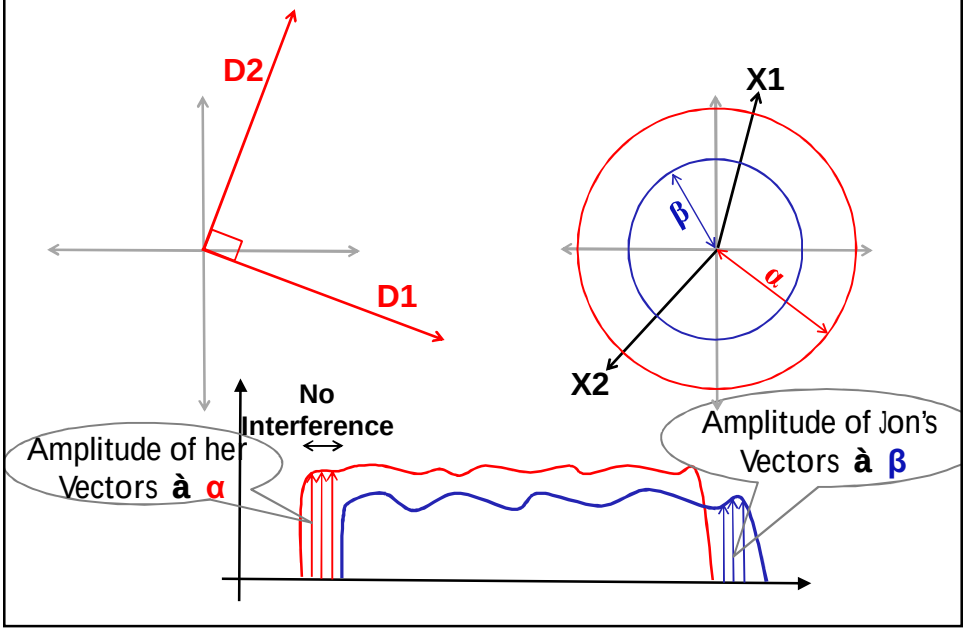

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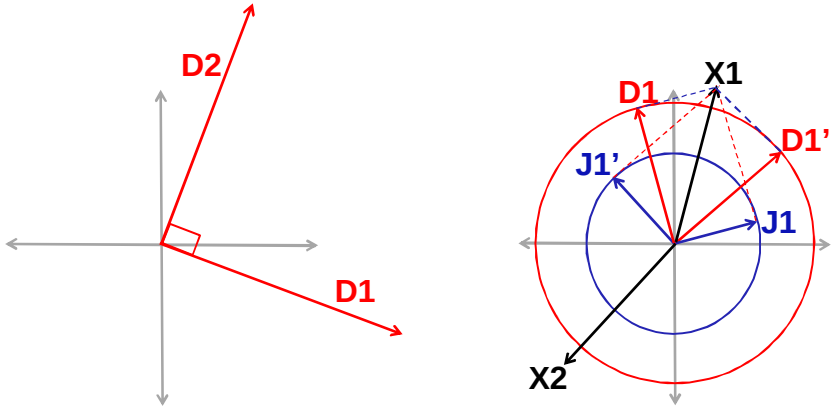
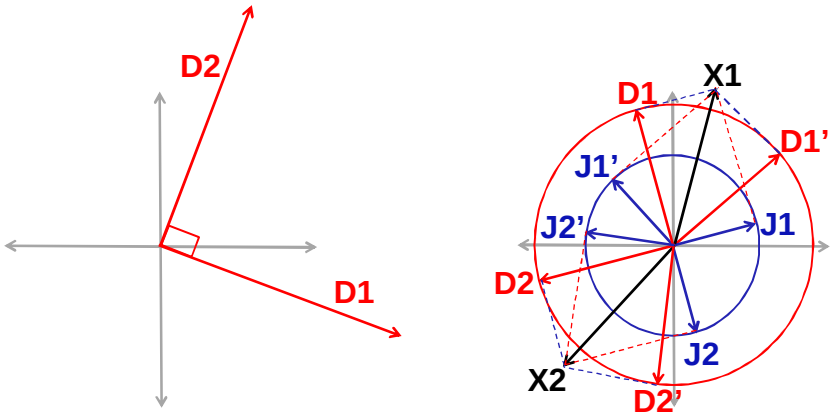


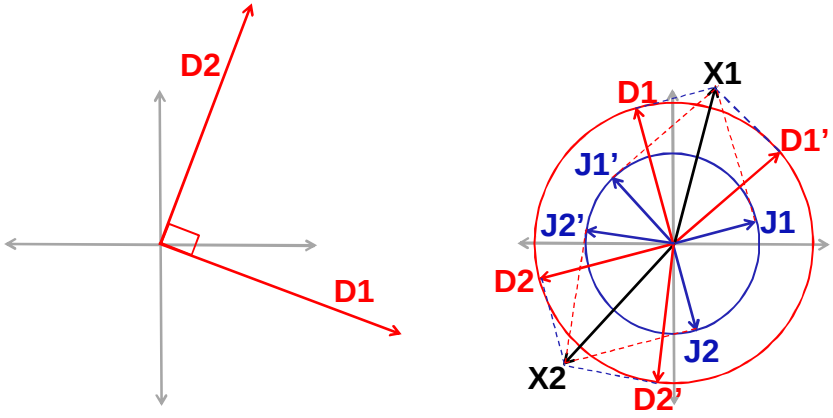
- Dina finds solutions for **X1** and **X2**

- What does Dina know?



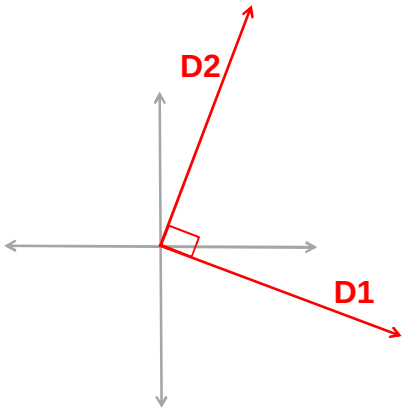
Two solutions for each interfered vector!

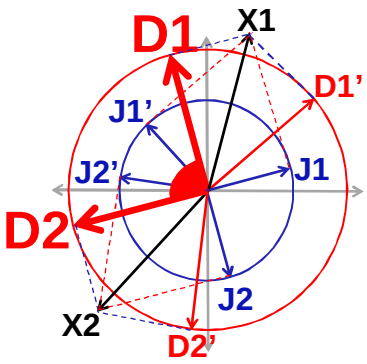
- What does Dina know?



Four possible angles!

- What does Dina know?





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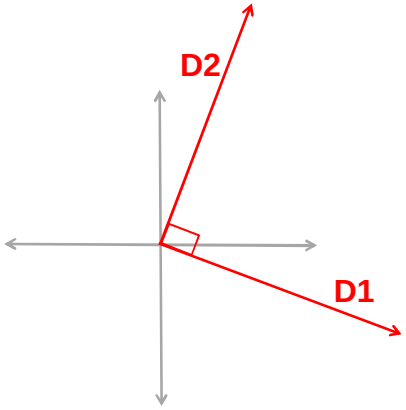

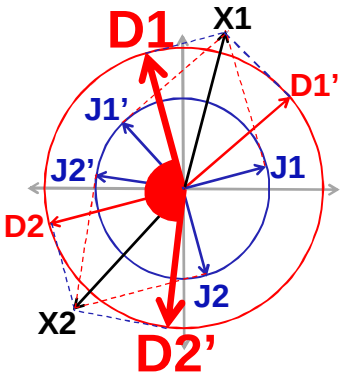

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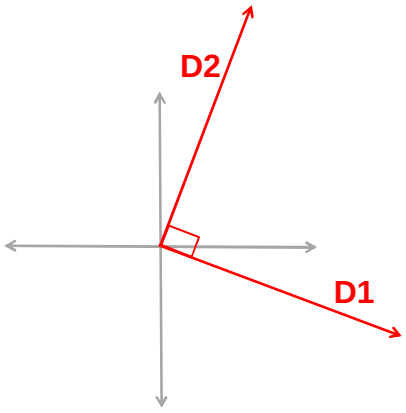

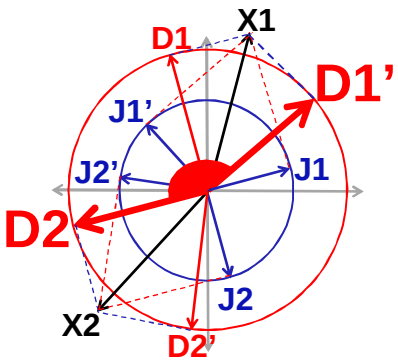

Four possible angles!

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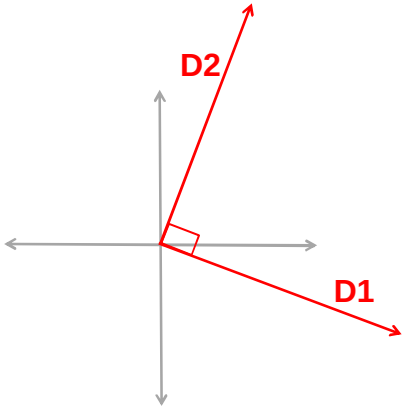

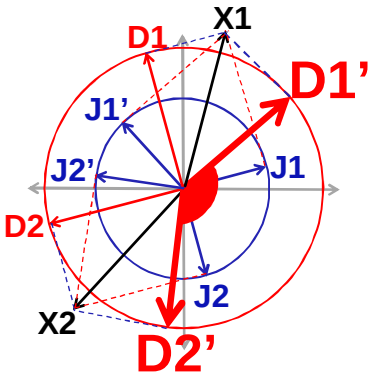

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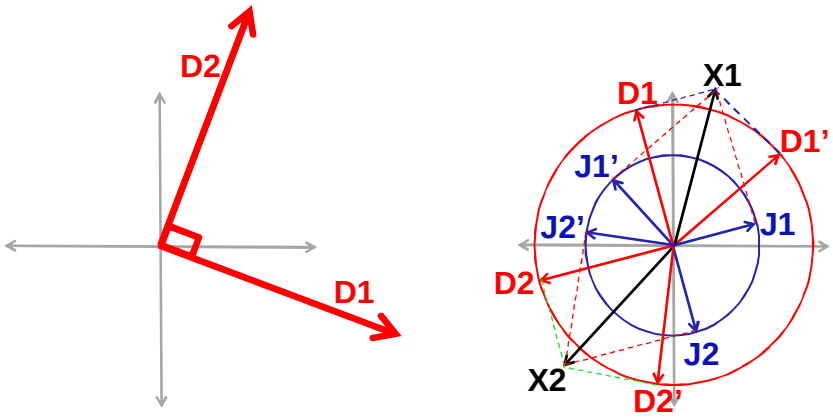
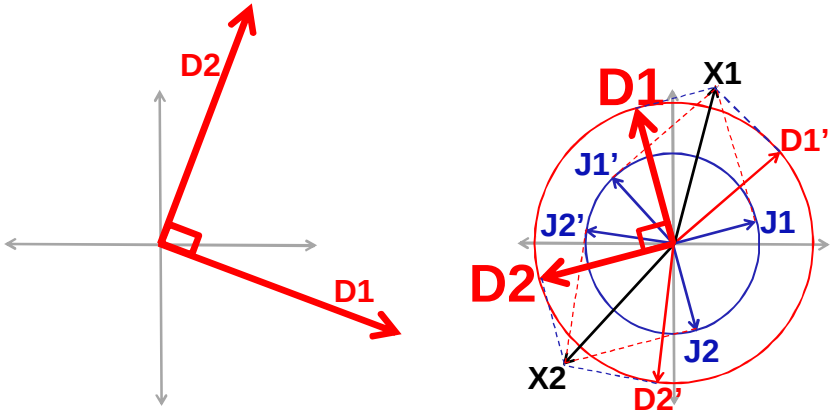


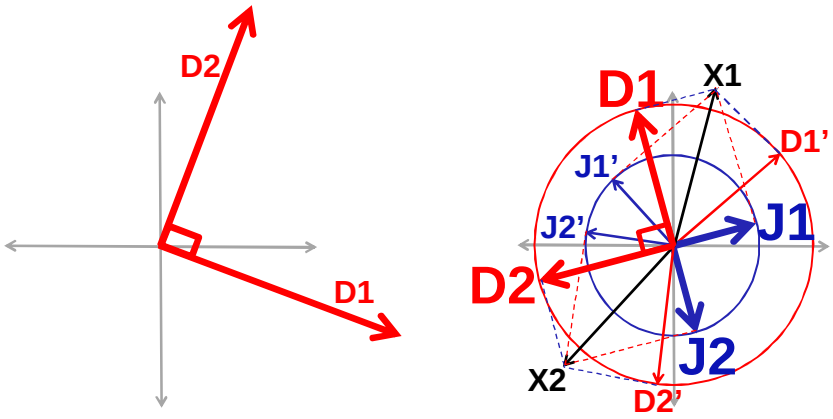
Pick the correct angle à 90 degrees

- What does Dina know?



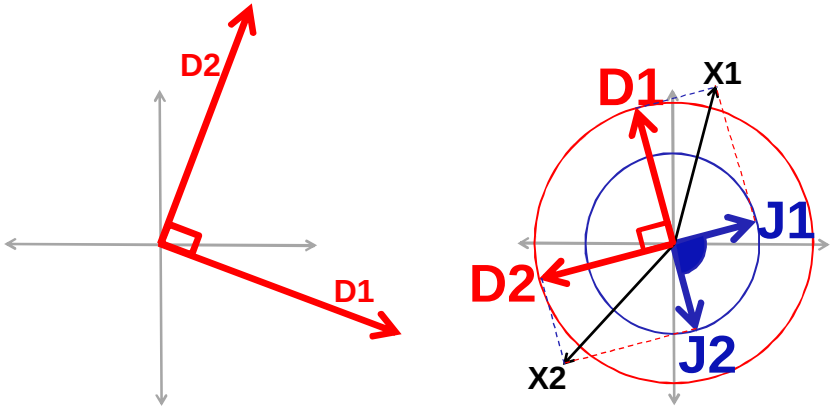
Pick the correct angle à +90 degrees

- What does Dina know?



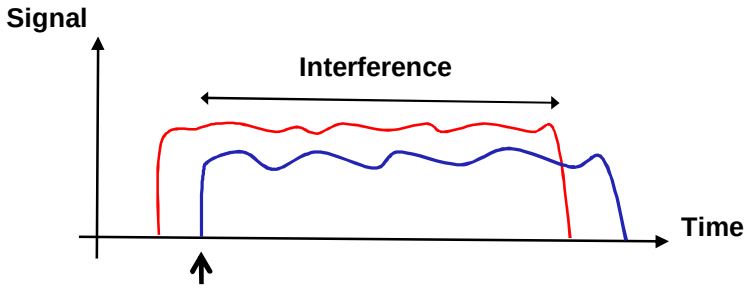
Dictates solution for Jon's vectors!

- What does Dina know?



- Dina 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

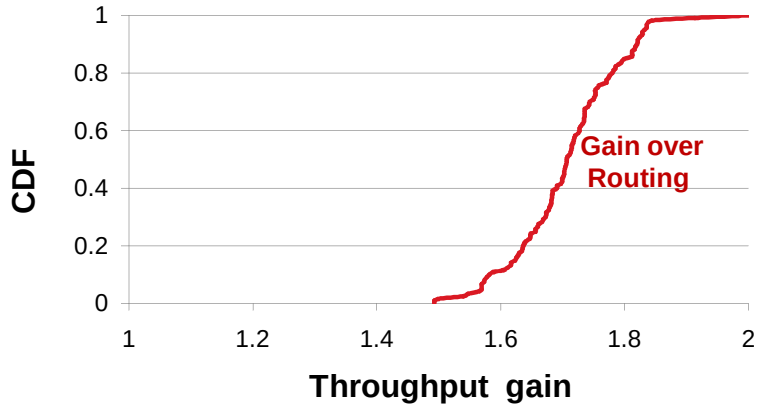
- Software – GNURadio codebase
- Hardware – USRP frontend
- 2.4-2.48 GHz frequency range
- SNR of 20-30 dB
- Canonical topologies in mesh networks

Dina and Jon

Router

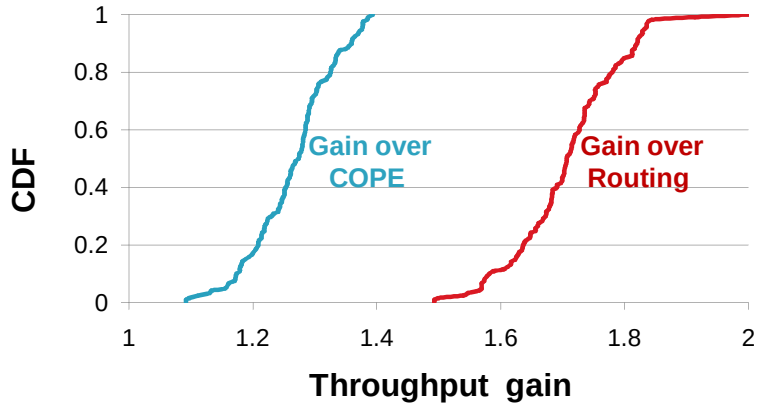
- ANC throughput gain over current 4/2 = 2
- ANC throughput gain over COPE 3/2 = 1.5

Throughput gain for Dina-Jon scenario



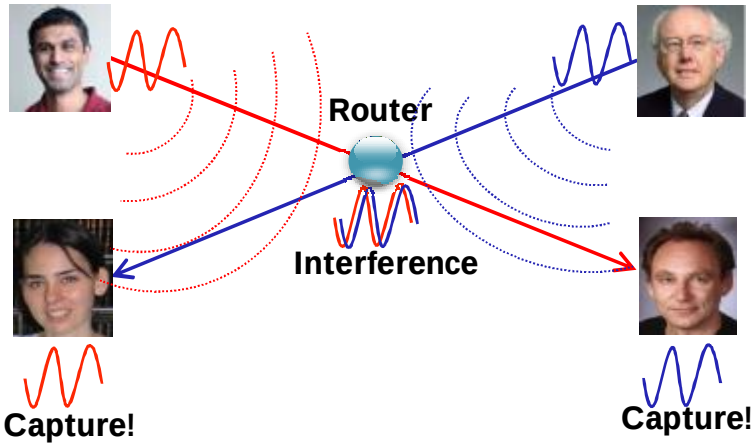
Median Gain over Routing – 70%

Throughput gain for Dina-Jon scenario



Median Gain over Routing – 70%
Median Gain over COPE – 30%

X topology



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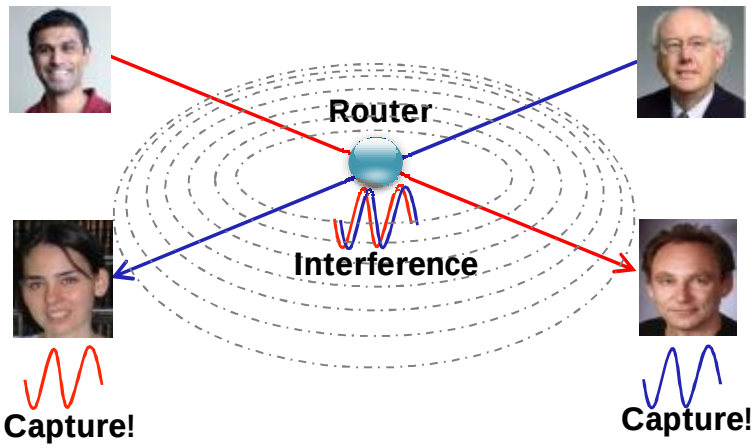
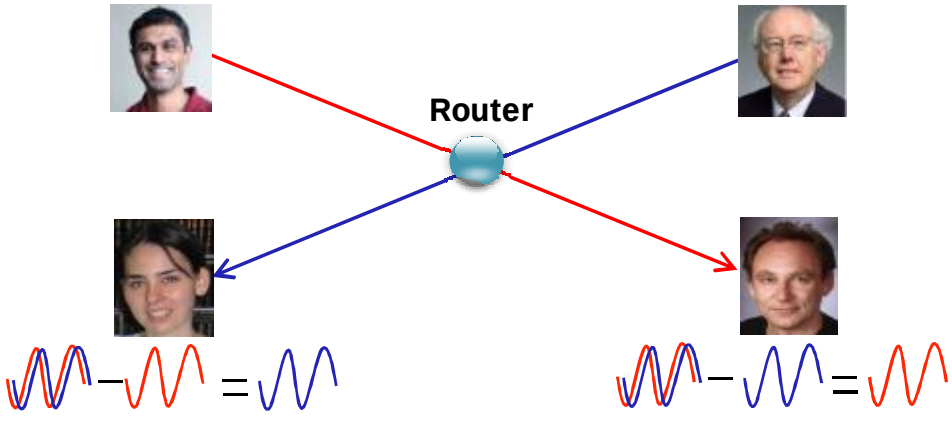
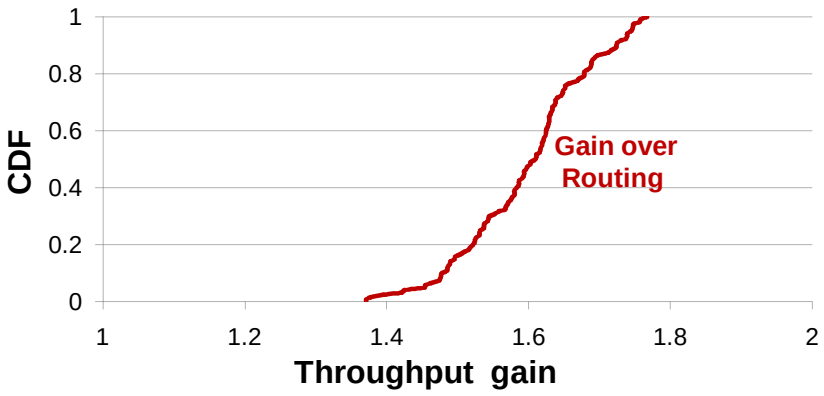


X topology



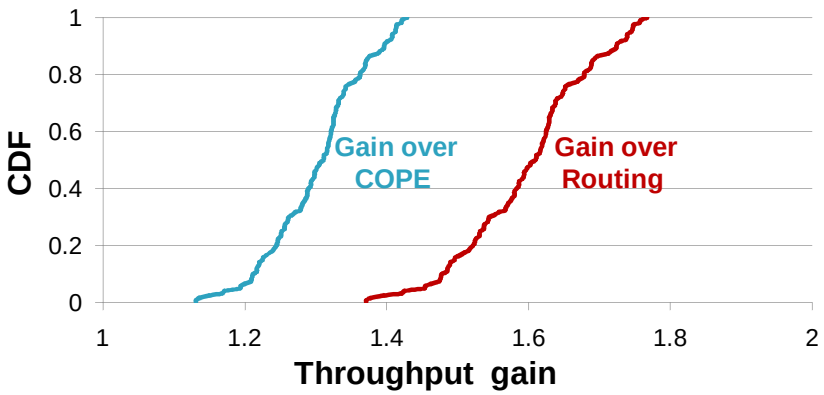
ANC decodes interference using overheard signals

Throughput gain – X topology



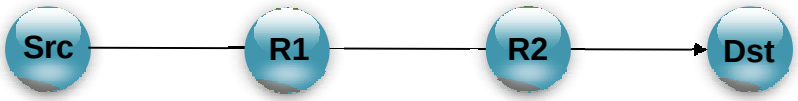
Median Gain over Routing – 65%

Throughput gain – X topology



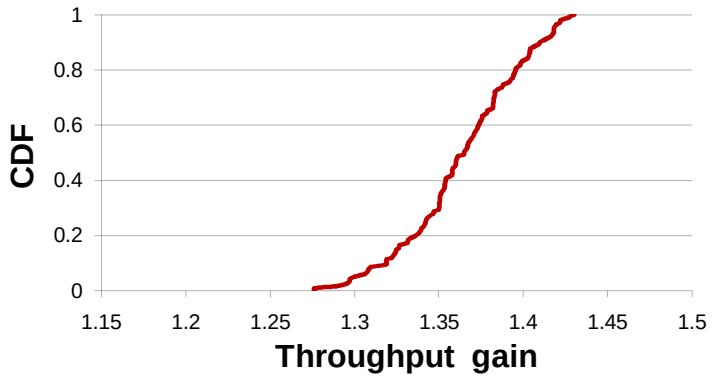
Median Gain over Routing – 65%
Median Gain over COPE – 28%

Chain topology



- ANC throughput gain over current 3/2 = 1.5

Throughput gain – Chain topology



Median Gain over Routing – 37%

Conclusion

- Shifts in the design of wireless networks to recognize wireless for what it is
  - Embrace Broadcast
  - Embrace Interference
- Implementation that yields large throughput gains