Analog Network Coding

Sachin Katti
Shyamnath Gollakota and Dina Katabi

Current Wireless
Current Wireless

Traditional Routing requires 4 time slots

Current Wireless

Traditional Routing requires 4 time slots
Traditional Routing requires 4 time slots
Last Year † Network Coding † 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)
1) Dina and Jon transmit simultaneously
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

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

Analog Network Coding requires 2 time slots
† 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

Src → R1 → R2 → Dst

Hidden Terminal Scenario

Src → R1 → R2 → Dst

P1
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!

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 $s_D(t) + s_I(t)$ but $f_1(s_D(t)) + f_2(s_I(t-T))$

- Prior work assumes full synchronization and ignores channel distortion

Not Practical!
Key Idea: Exploit Asynchrony!

- 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
- Bit “1”

D2 lags D1 by 90 degrees
- Bit “0”

---

**Primer on Channel Effects**

- Attenuation

D2 and D1 are attenuated by the same amount
Primer on Channel Effects

- Attenuation
- Rotation

Angle between vectors is preserved

To decode, receiver computes angle between received vectors

\[ \text{Angle (D2, D1)} = 90 \text{ degrees} \]

Bit “1” was transmitted
So, How Does Dina Decode?

- 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 Jon send?
What is Interference? Vector addition

What does Dina know?
What does Dina know?

Dina finds solutions for $X_1$ and $X_2$
What does Dina know?

Two solutions for each interfered vector!

Four possible angles!
What does Dina know?

Four possible angles!
What does Dina know?

Four possible angles!
What does Dina know?

Pick the correct angle $\pm 90$ degrees

What does Dina know?

Pick the correct angle $\pm 90$ degrees
What does Dina know?

Dina finds solutions for $X_1$ and $X_2$.

Dictates solution for Jon’s vectors!

What does Dina know?

Dina finds angle between $J_1$ and $J_2$ 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 - GNU Radio codebase
- Hardware - USRP frontend
- 2.4-2.48 GHz frequency range
- SNR of 20-30 dB
- Canonical topologies in mesh networks

Dina and Jon

- 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

Router

Interference

Capture!

Capture!
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 $\frac{3}{2} = 1.5$
Throughput gain - Chain topology

CDF

0 0.2 0.4 0.6 0.8 1
1 1.2 1.3 1.4 1.5

Throughput gain

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