From Shannon to 5G: Theory and Practice of Cooperative Wireless Networking

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November 21, 2016

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From Shannon

To 5G

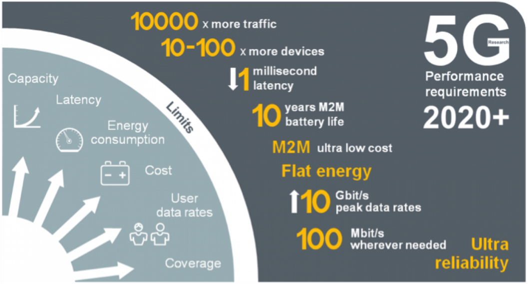
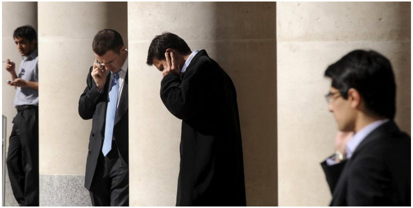


Figure curtesy of Nokia

The New York Times



- What 5G will mean for you
  - Downloading movies in seconds.
  - Networks that connect millions of new devices.
  - Driverless cars with extremely fast response times.

5G in the popular press

theguardian

- Get ready – 5G will create waves of innovation that disrupt every industry
  - 5G connectivity and the Internet of things create a platform for services, partnerships and businesses to be built on.

5G in the popular press

FORTUNE

- Why the FCC unanimously voted to advance 5G networks
  - Nearly 11 gigahertz of high-frequency spectrum for mobile, flexible, and fixed-use wireless broadband.
  - Process led by the private sector for producing technical standards.

But what exactly is 5G?

- Higher data rates: $1000\times$
  - More spectrum (licensed+unlicensed, mmWave).
  - More infrastructure density (small cells).
  - More antennas (massive MIMO).
  - Higher spectral efficiency (full-duplex).

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- Lower delay: 10$\times$
  - Integrated design of the protocol stack/core network (SDN).
  - Moving intelligence to the edge of the network (Fog RAN).

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- Heterogenous devices and applications
  - Mobile broadband.
  - Machine-type communications (IoT).
  - Ultra-reliable communications (vehicular networks).

Where is information theory in 5G?

Everywhere!

Where is information theory in 5G?

Wideband channels

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Where is information theory in 5G?

MIMO/massive MIMO

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Where is information theory in 5G?

Multiuser IT

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- Lower delay: $10\times$
  - Integrated design of the protocol stack/core network (SDN).
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- Heterogenous devices and applications
  - Mobile broadband.
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Where is information theory in 5G?

Joint source-channel coding

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Opportunities for IT in 5G

- Develop new results.
- Advanced technologies $\Rightarrow$ Old ideas can be practical.
  - Computational power, cheap storage, higher degrees of freedom.
- Today: Cooperative networks.
  - Terminals helping one another communicate.

Roadmap

- Theoretical foundations of cooperation
  - 70's-80's: Gen X and Y, "oldies but goldies"
- Extensions to the theory
  - Late 90's-21st century: Gen Z, driven by wireless
- Applications in 5G
  - Gen α?

Roadmap

- Theoretical foundations of cooperation
  - 70's-80's: Gen X and Y, "oldies but goldies"

- Extensions to the theory
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- E.C. van der Meulen, "Three terminal communication channels," 1971.

- $T1$ communicates with $T3$ with help of $T2$.
- Examples, bounds.

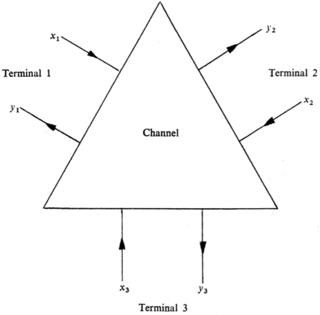
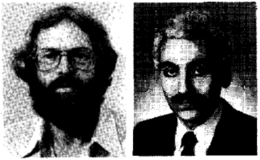


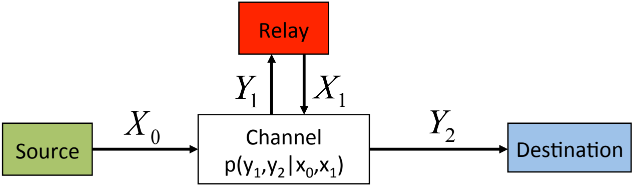
Figure 1

Then came the relay channel..

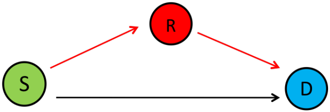
- T.M. Cover and A.A. El Gamal, "Capacity theorems for the relay channel," 1979.



- Key results, achievable schemes, capacity in special cases



The relay channel



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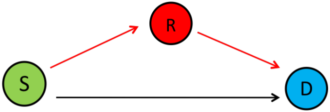
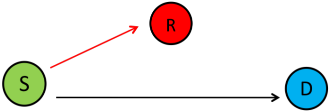
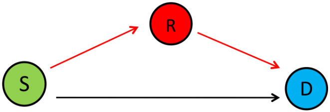


- Broadcast: Source to relay and destination.



The relay channel



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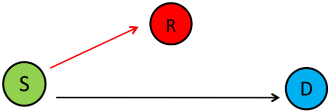
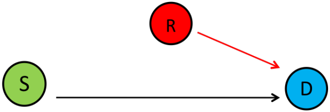


- Multiple access: Source and relay to destination.



Model assumptions

- Relay is *causal*.
- Relay is *full-duplex.*
    - Relay can receive and transmit at the same time.

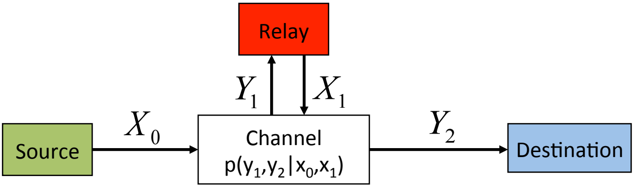
Capacity of the relay channel

- Capacity not known in general, only in some special cases.
- Cutset upper bound.
- Achievable schemes.

Decode-and-Forward (DF)

- Achievable strategy.
- Destination cannot decode by itself.
- Relay fully decodes source information and re-encodes.
- Source and relay transmit "cooperatively" to resolve the ambiguity at the destination.

Optimality of DF

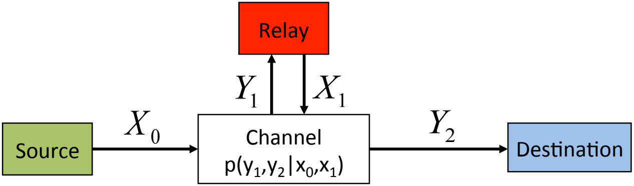


- DF is optimal for the physically degraded relay channel.

$$p(y_2, y_1|x_1, x_0) = p(y_1|x_1, x_0)p(y_2|y_1, x_1).$$

  - Relay can decode whatever the destination can decode.

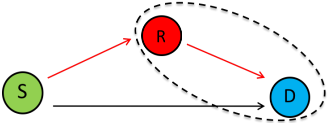
Compress-and-Forward (CF)



- Compress Y_1 as $\hat{Y}_1$ and send to destination.
- Compression makes use of the correlated destination signal Y_2.
  - Wyner-Ziv (WZ) compression.

Comments on CF

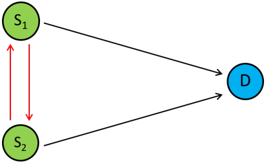
- CF works well when relay cannot decode and relay-to-destination channel is “good.”



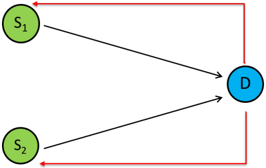
- Major improvements to CF (came much later)
  - Quantize-map-forward [Avestimehr, Diggavi, Tse, 2007].
  - Noisy network coding [Lim, Kim, El Gamal, Chung, 2010].
  - Also work well in *relay networks.*

Another Dutch master

- Frans Willems in the 80's.
- Cribbing/conferencing encoders.



- MAC with generalized feedback.



Roadmap

- Theoretical foundations of cooperation
  - 70's-80's
- Extensions to the theory
  - Late 90's-21st century: Gen Z, driven by wireless

- Applications in 5G

Theory – driven by wireless

- Wireless channel: Cooperation under fading.
- Practical constraints: Half-duplex.
- Cooperation in multiuser channels.
- Cooperation in cellular networks.
- Cooperation in large networks.

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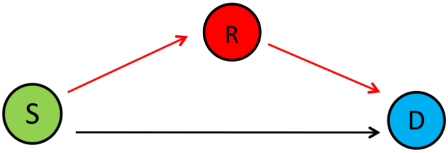
Cooperation in fading channels

- Cooperation can mitigate fading: Creates diversity.
- User-cooperation diversity.
  [Sendonaris, Erkip, Aazhang, 1998]
- Cooperative diversity.
  [Laneman, Tse, Wornell, 2000]
- Motivated wireless researchers to study cooperation.
- Scope expanded beyond IT.

Cooperation diversity



- If only one link fails, transmission is successful.
- If two links fail, transmission may fail.
  $\rightarrow$ Diversity $= 2$.
- Same as 2-antenna source.

Full-duplex

- Common assumption in IT.
- Transmit and receive signals 100dB apart.
- Not possible in practice (until recently).

"Use your inside scream"

Half-duplex

- Either transmit or receive, but not both.
- Can adapt DF, CF to work in half-duplex.
- Gaussian channel: Amplify-and-forward (AF).
  [Laneman, Tse, Wornell, 2004]
- For all strategies
  - Diversity $\uparrow$ at the expense of spectral efficiency.
- Diversity-multiplexing tradeoff of cooperative communications.
  [Yuksel, Erkip, 2007]

Theory – driven by wireless

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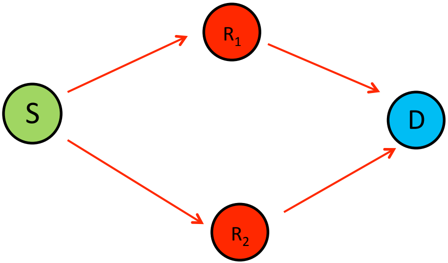
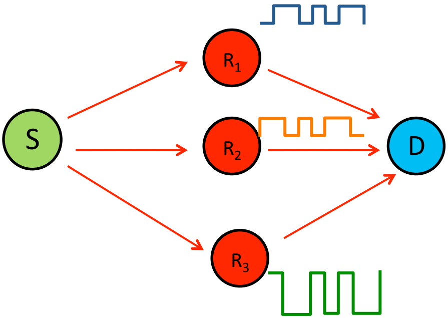
Multiple relays

- Single source-destination.
- Diamond relay channel.
  [Schein, Gallager, 2000]

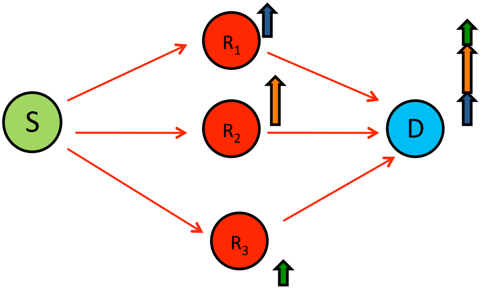


Multiple relays

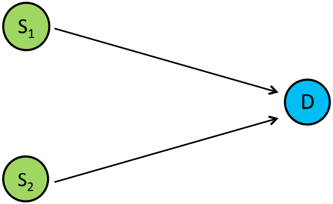
- Distributed space-time coding.
- Relays act as antennas of a space-time code. [Laneman, Wornell, 2003]



- Distributed beamforming.
- Need phase information and synchronization among relays. [Mudumbai, Brown, Madhow, Poor, 2009]



Multiple access relay channel



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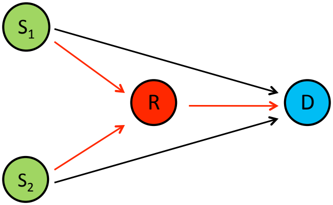
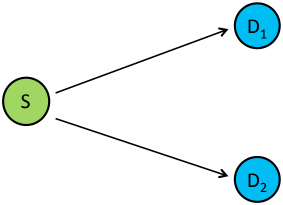
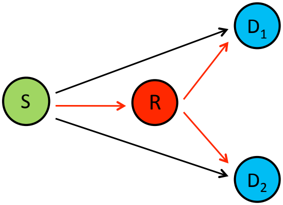


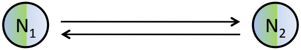
Broadcast relay channel



Broadcast relay channel

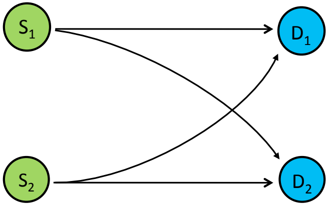


Two-way relay channel

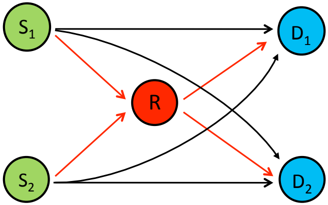


Two-way relay channel

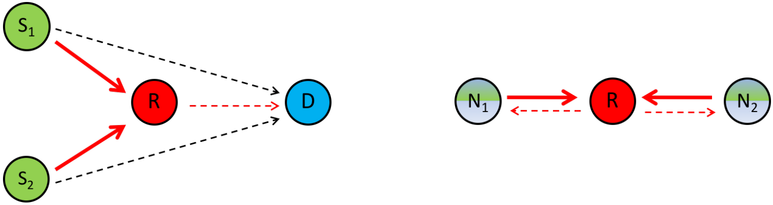
Interference relay channel



Interference relay channel

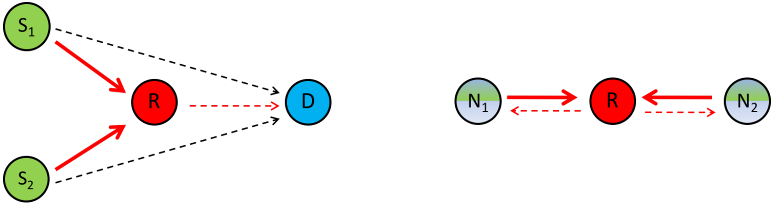


New ideas



- Relay does not have to decode each source individually.
- Relay can decode *functions* of source messages and forward.

New ideas



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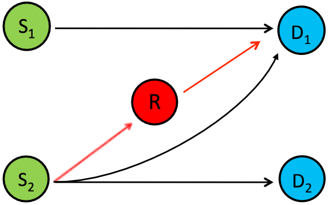
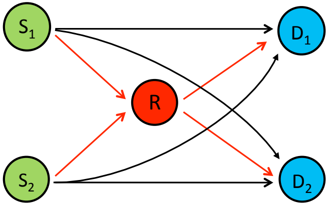
- Relay can decode *functions* of source messages and forward.
- Analog network coding, compute-and-forward.
- *Structured codes.*
  [Zhang, Liew, Lam 2006], [Popovski, Yomo, 2006], [Nazer, Gastpar, 2006]

New ideas



- Signal forwarding not possible.
- Interference cancellation: Transmit $-X_2$ to cancel interference at D_1.
- Interference forwarding: Transmit X_2 to boost and help decode interference at D_1.

New ideas



- Relay can do
  - Signal forwarding.
  - Interference forwarding.
  - Interference cancellation.

[Sahin, Simeone, Erkip, 2009]

Theory – driven by wireless

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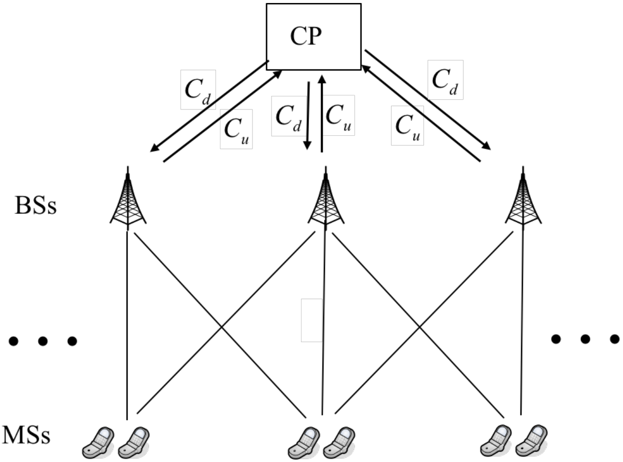


- Cooperation of BSs.

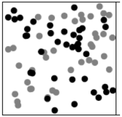
How do BSs cooperate?

- BSs have baseband processing capability.
  - Backhaul.
  - Hard information, DF.
  - 4G LTE: Coordinated Multi-Point (CoMP).
- Baseband processing done centrally.
  - Fronthaul.
  - Soft information, CF.
  - Cloud-RAN (CRAN).

BS cooperation

- Tools from Wyner's cellular model.
  [Wyner, 1994]
- Tools from MIMO broadcast/multiple access channels.
- Tools from multiuser cooperation.
- Mitigate/exploit inter-cell interference.
  [Gesbert, Hanly, Huang, Shamai, Simeone, Yu, 2010]

Cooperation in large networks



- Large ad-hoc network with n nodes.
- Rather than the *exact* capacity region, study how capacity scales with n.
- Scaling laws.
  [Gupta, Kumar, 2000]
- Operating regimes: Area $\sim n^{\nu}$.
  [Ozgur et. al. 2010]
- Multi hop essential for communication among distant nodes.

Roadmap

- Theoretical foundations of cooperation.
  - 70's-80's.
- Extensions to the theory.
  - Late 90's-21st century.
- Applications in 5G.
  - Gen α?

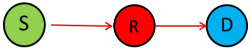
"No, you weren't downloaded.
Your were born."

"No you weren't downloaded. You were born."

Cooperative networking in 5G

- Relaying in 5G.
- Full duplex cellular and impact of BS cooperation.

Relaying in 4G

- Multihop mode. 

- Used for: Shadowing, hotspots, coverage.

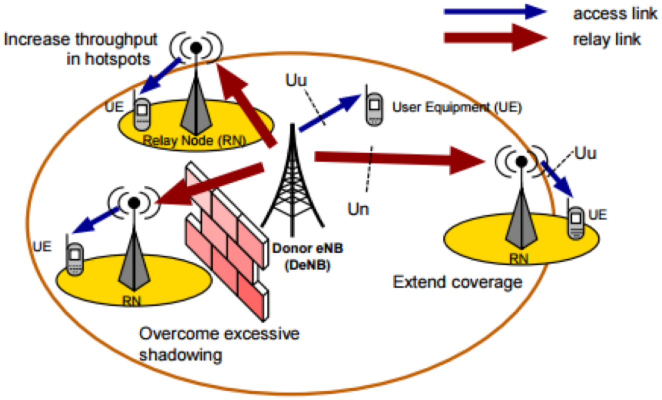


Figure courtesy of Nokia.

Commercial 4G relaying

S4GRU Sprint 4G Rollout Updates

Bringing you info about ***Network Vision, LTE, and WiMAX***

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Sprint enters the Relay race

Posted by **lilotimz**, in Author: Tim Yu 18 January 2016 · 6,355 views

Flexi Zone Band 41 | B41 small cell | NSN | Nokia Networks B41 | 2.5 GHz backhaul

Airspan

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AirRAN Products » **iRelay**

iRelay - Using LTE Relay as a Backhaul for Small Cells

iRelay is Airspan's innovative new portfolio of backhaul solutions, based on LTE Relay. LTE Relay is an out of band relay solution, using different frequencies for the backhaul and access links. The backhaul link leverages existing LTE macro networks to provide a backhaul solution for small cell deployments.

Issues with 4G relaying

- 4G is limited in degrees of freedom (DoF).
  - Spectrum scarce.
  - Small number of antennas.
- Relaying mainly used for *power gain.*
- Half-duplex: Need to give up DoF for relaying.
- Net impact on throughput may be limited.

What about 5G?

- Abundant DoF.
    - More spectrum (licensed+unlicensed, mmWave).
    - More antennas (massive MIMO).
- Full-duplex implementations.

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Capacity as a function of bandwidth

$$C(W) = W \log\left(1 + \frac{P}{WN_0}\right).$$

- Low SNR: Power limited.

$$C(W) \approx \frac{P}{N_0}.$$

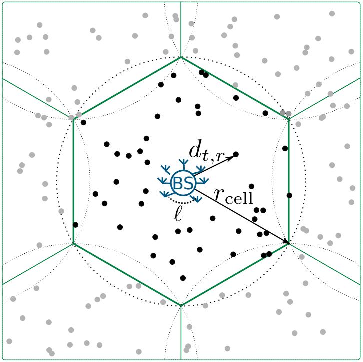
- High SNR: Bandwidth limited

$$C(W) \approx W \log\left(\frac{P}{WN_0}\right).$$

Cellular network and bandwidth

- When does a cellular network become power/ bandwidth limited?
- What is the role of relaying?
- Use capacity scaling as a metric.
- Incorporate bandwidth into the formulation.
- Cellular network.
- Investigated in [Gomez-Cuba, Rangan, Erkip, González-Castaño, 2014, 2016]

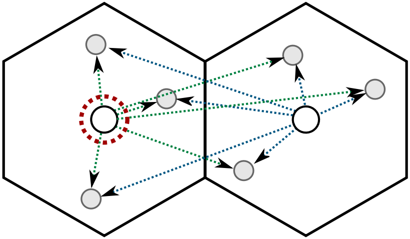
Model



- Cellular traffic.
  - Uplink/downlink.
- $n \to \infty$ nodes.
- Path loss exponent α.
- Uniform in area $A \sim n^{\nu}$.
- Served by $m \sim n^{\beta}$ BSs.
- BS has $\ell \sim n^{\gamma}$ antennas.
- Non-cooperative BSs.
  - Each BS serves $\approx n/m$ users.
- Bandwidth $W \sim n^{\psi}$.

DL upper bound: Cut around each BS

- One BS $\rightarrow$ All nodes, remaining BSs.
- Perfect cooperation on each side.
  - Single transmitting BS with receiver cooperation.
  - Equivalent to a $\ell \times n$ MIMO.
- Upper bounds feasible rate in one cell; repeat for all cells.



Achievable rates

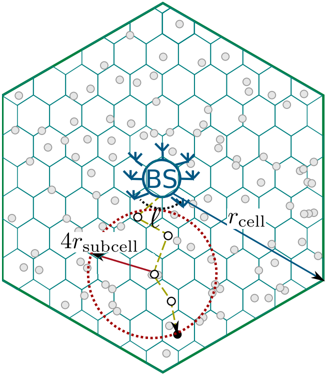
- Two protocols, leading to achievable rates.
- Infrastructure Single Hop (ISH).
- Infrastructure Multi Hop (IMH).

Infrastructure single hop

- Each BS directly transmits to nodes in its cell.
- BS-node transmission
  - Divide users into groups of ℓ.
  - $\ell \times \ell$ MIMO-BC within each group.
  - Each group in orthogonal subchannel.
  - Out of cell interference treated as noise.

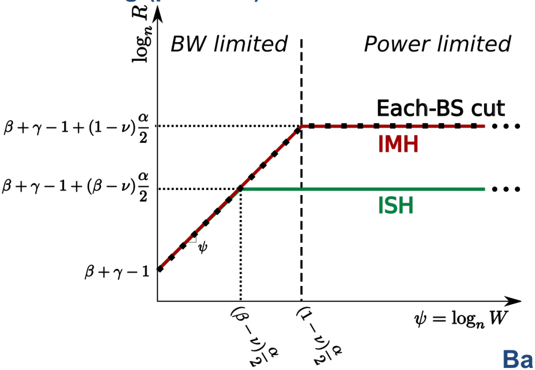
Infrastructure multi hop

- BS transmits to nodes by multihop.
  - Divide each cell into *routing sub-cells*.
  - BS initiates ℓ routes simultaneously using MIMO-BC.
  - Each sub-cell forwards data to the next.
  - Multiple routes at the same time.



Upper bound versus protocols

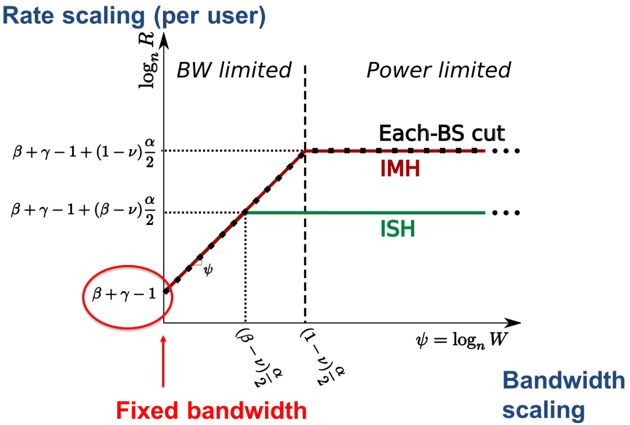
Rate scaling (per user)

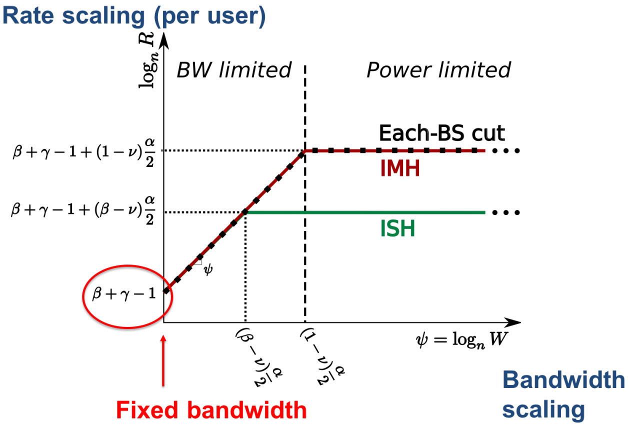


Bandwidth scaling

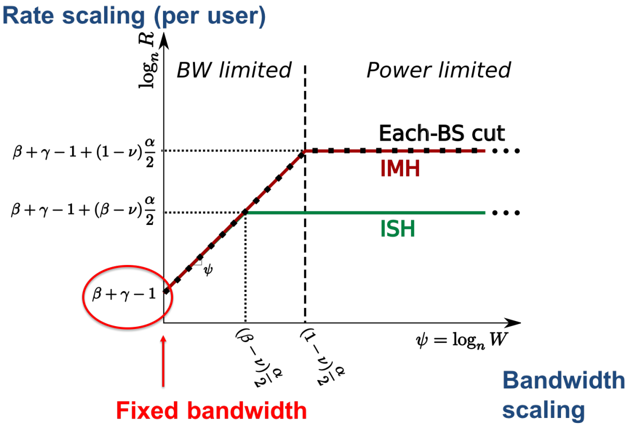
Exponent	Parameter
α	$P_r = P_t r^{-\alpha}$
ψ	BW $W \sim n^{\psi}$
ν	Area $A \sim n^{\nu}$
β	BSs $m \sim n^{\beta}$
γ	BS ant's $\ell \sim n^{\gamma}$

4G: Fixed bandwidth



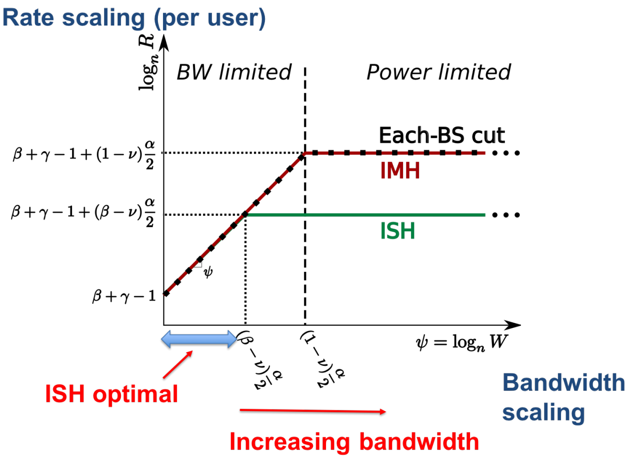


- BSs $\sim n^{\beta}$, BS ant's $\sim n^{\gamma}$, $\beta + \gamma \leq 1$.
- Rate decreases (is constant) with n.
- More infrastructure $(\beta + \gamma) \rightarrow$ Slower decrease.

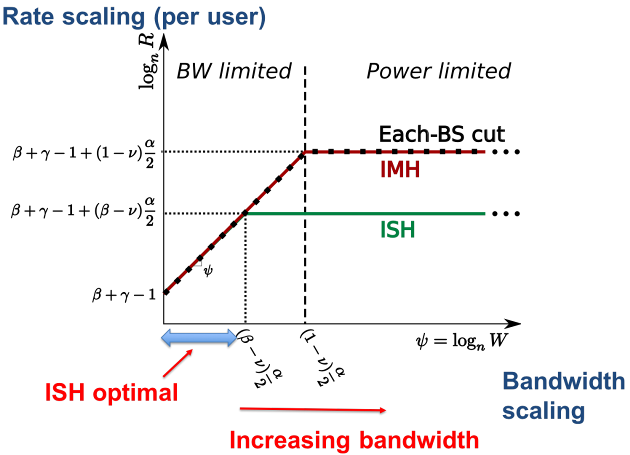


- ISH optimal, no need for IMH.

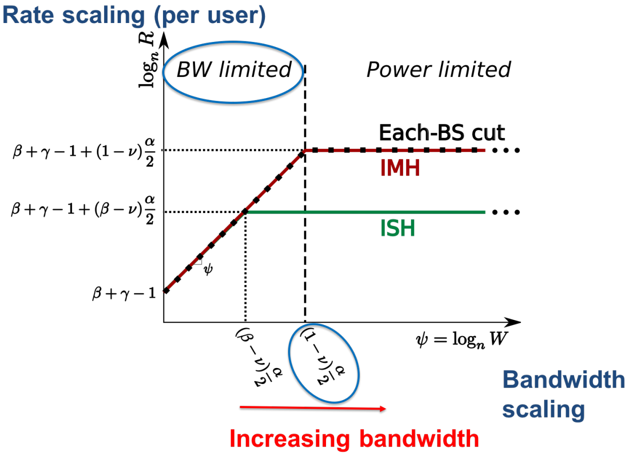
5G: Increasing bandwidth and ISH



5G: Increasing bandwidth and ISH



- BSs $\sim n^{\beta}$, area $\sim n^{\nu}$, path loss α.
- ISH optimal until edge nodes become power limited.
- Cannot exploit BW for $\psi > (\beta-\nu)\frac{\alpha}{2}$.



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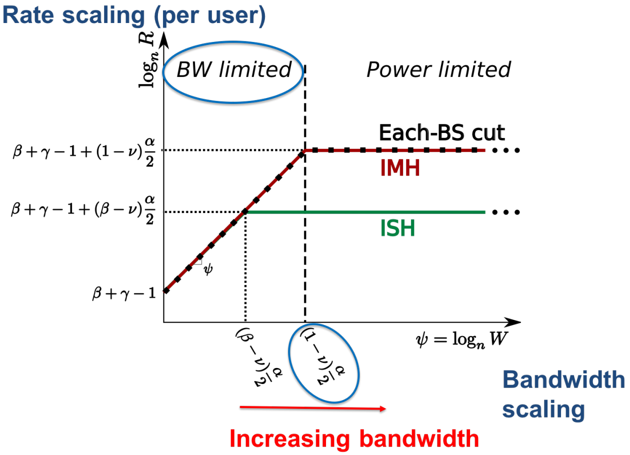

- BSs $\sim n^{\beta}$, area $\sim n^{\nu}$, path loss α.
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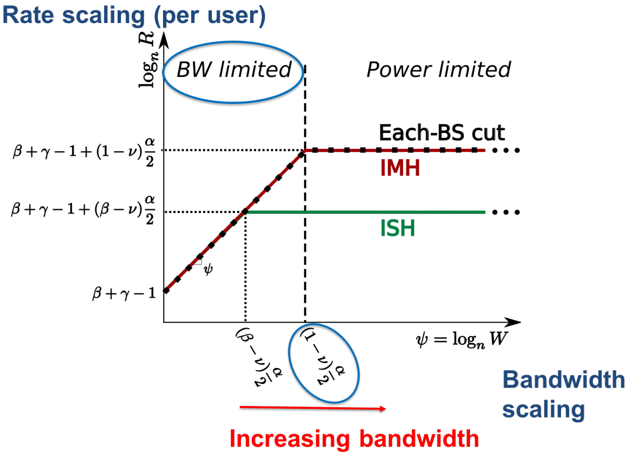
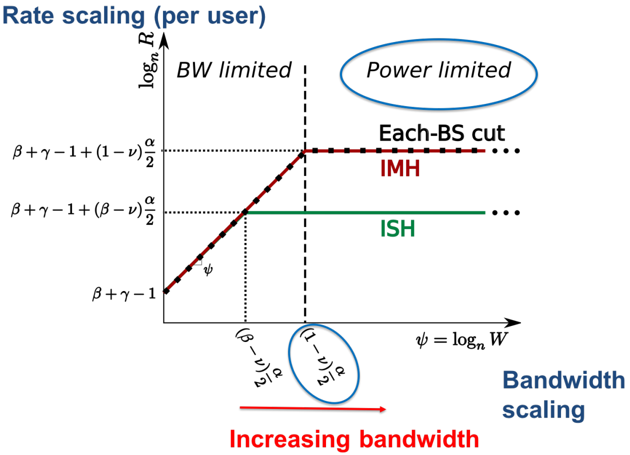
5G: Increasing bandwidth and IMH



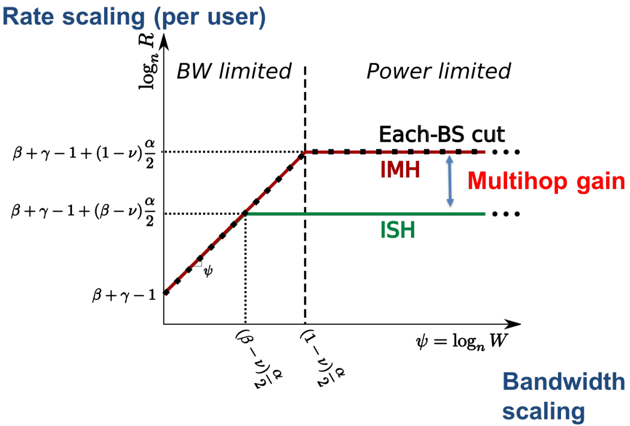
- BSs $\sim n^{\beta}$, area $\sim n^{\nu}$, path loss α.
- IMH always optimal.
- Network/IMH is BW limited for a larger range of ψ.

5G: Increasing bandwidth and IMH



- Network/IMH becomes power limited when nearest neighbor node becomes power limited.

5G: Impact of multihop

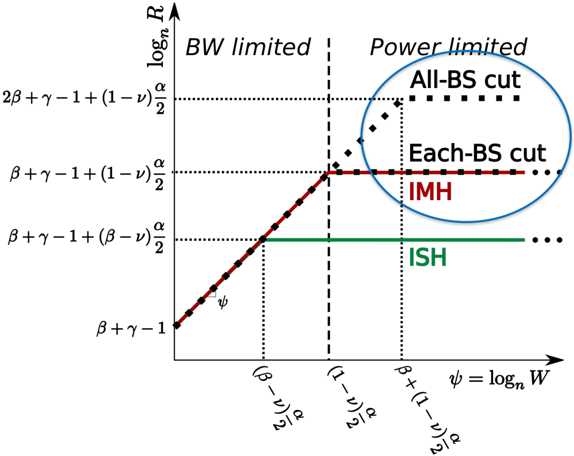


- Multihop more effective when BW is large.
- Multihop gain $1-\beta$ higher for smaller BS densities.

Discussion

- Protocols for
  - Infrastructure relays.
  - Infrastructure hierarchical cooperation.
  - Hierarchical cooperation not as useful as in the ad-hoc setting.

What about BS cooperation?



- BS cooperation potentially useful.
- Protocols for capacity limited backhaul/fronthaul?

- Relaying in 5G.
- Full duplex cellular and impact of BS cooperation.

5G: Full duplex is practical

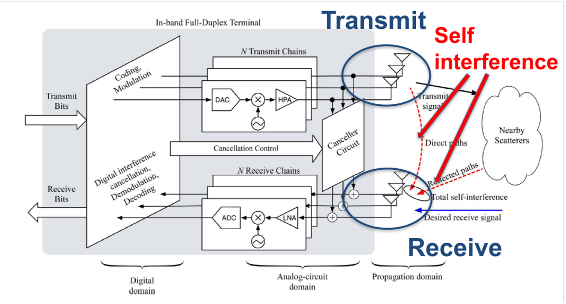
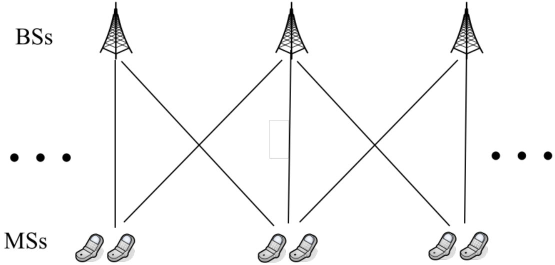


Figure from [Sabharwal et. al., 2014]

- Analog and digital cancellation of SI.
- Cancelation using: Polarization, antenna separation.
- Residual self-interference.
  [Sabharwal et. al., 2014]

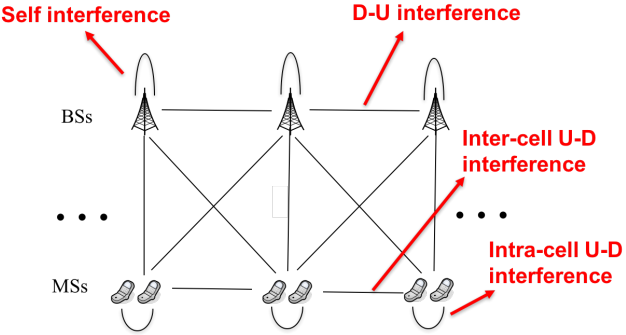
- Start-up founded by Levis and Katti, Stanford EE and CS professors.

Half duplex cellular



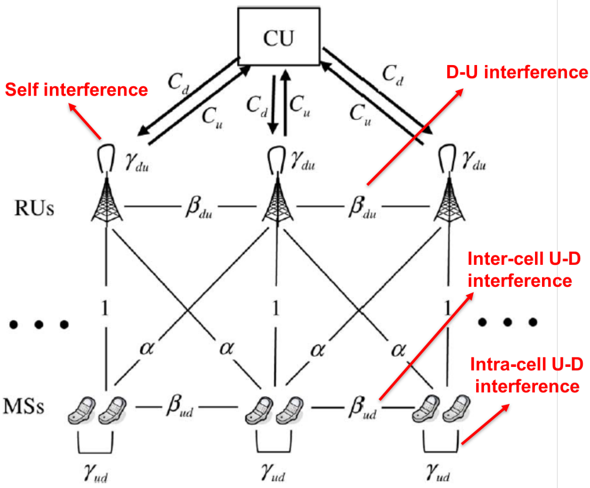
- Standard cellular operation:
  - Uplink and downlink operated in TDD or FDD.

Full duplex cellular



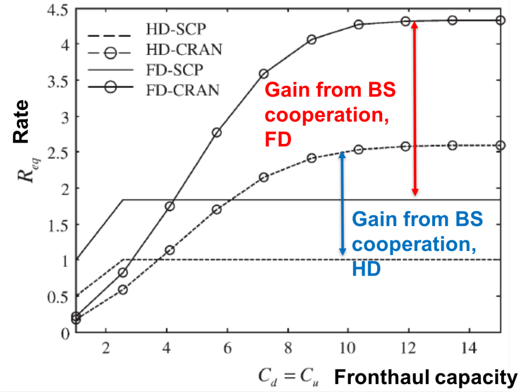
- Full duplex BSs, half duplex mobiles:
  - Self interference at BSs.
  - DL-UL interference: Interference among BSs.
  - UL-DL interference: Interference among mobiles.

Full duplex cellular with BS cooperation



- A study showing potentials of full duplex under BS cooperation. [Simeone, Erkip, Shamai, 2014]

Impact of BS cooperation



- BS cooperation more valuable in full duplex.
  - DL-UL interference (among BSs) can be mitigated.

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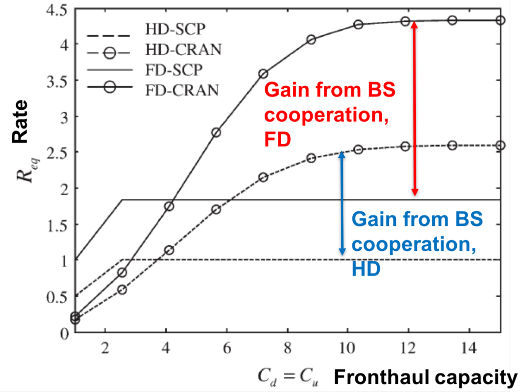
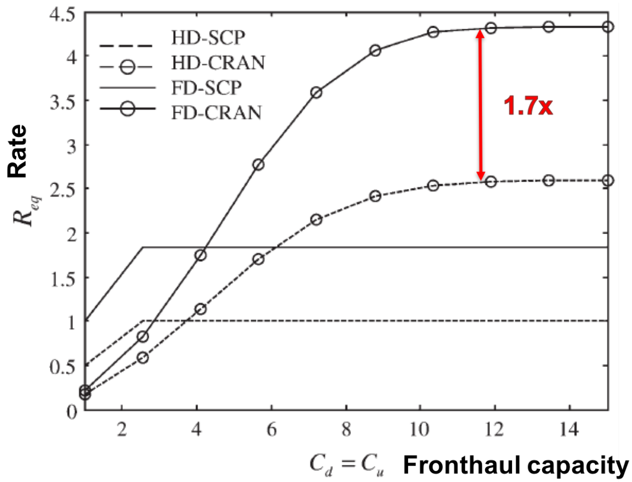


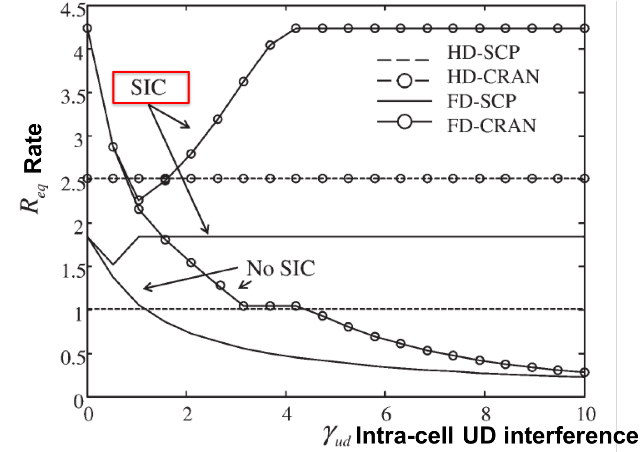
- BS cooperation more valuable in full duplex.
  - DL-UL interference (among BSs) can be mitigated.
- Intra-cell UL-DL interference: SIC at mobiles.

Full duplex gain



- Net gain of FD 1.7×, less than 2×.
    - Due to inter-cell UL-DL interference.

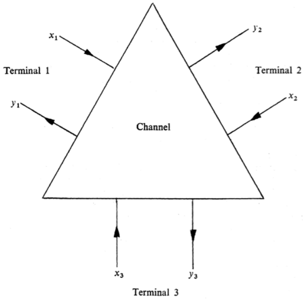
Intra-cell UL-DL interference



- SIC essential to get full duplex benefits.
- Alternative: User scheduling: [Goyal et. al., 2013]

Shannon theory

5G applications



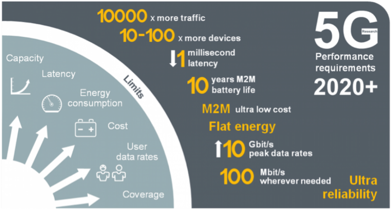


Figure curtesy of Nokia

40+ years of rich theory and applications of cooperative communications.

What's next?

- For researchers
  - Still many interesting open problems.
  - New problems inspired by technology.
  - Old techniques now practical.

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Even more than what you think, how you think matters.
Atul Gawande, *The Mistrust of Science*, Caltech graduation speech, 2016.

Thank you Shannon for teaching us how to think!