Networks with Mixed Delay-Constraints

Michèle Wigger
Telecom ParisTech

joint work with Homa Nikbakht and Shlomo Shamai

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Different Types of Communications in 5G

- Enhanced Mobile Broadband (eMBB) requires high rates
- Ultra-Reliable Low-Latency Communication (URLLC) requires low delays
- Massive Machine-Type Communications (MTC)

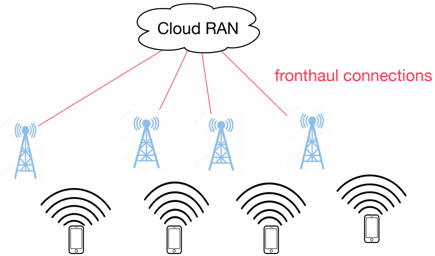
Coexistence of eMBB and URLLC $\rightarrow$ Mixed-Delays

- Standard propositions: time-sharing with smart scheduling

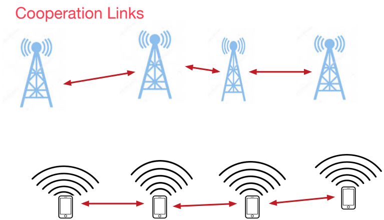
In this talk: Benefits from joint coding

High Rates Achieved Through Cooperation

Cloud Radio Access Networks (C-RAN)



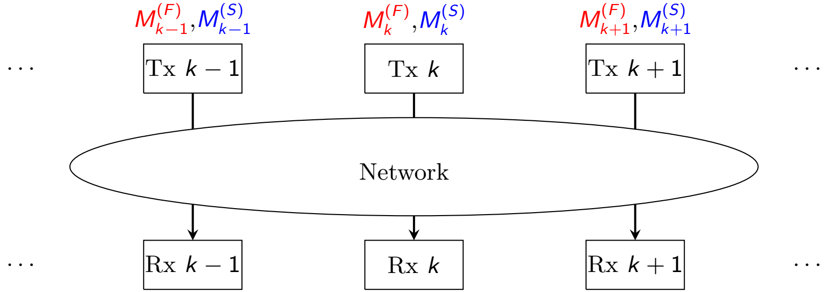
Direct Communication



- Cooperation requires additional hops
  $\rightarrow$ Low-latency communication cannot benefit from cooperation!

Mixed Delay Constraints in a Cooperative Network

- Each Tx k sends independent messages $(M_k^{(F)}, M_k^{(S)})$



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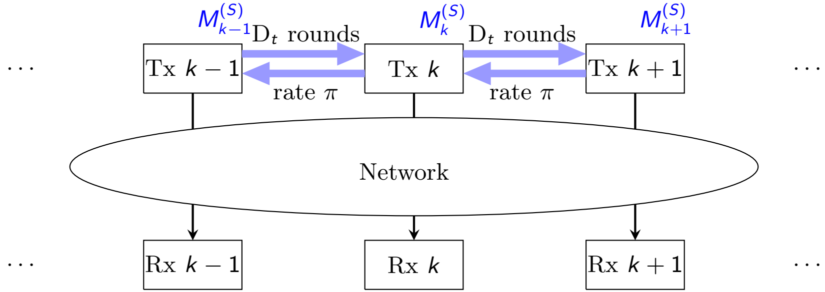

- Txs exchange information about "slow" messages during D_t conferencing rounds

Mixed Delay Constraints in a Cooperative Network

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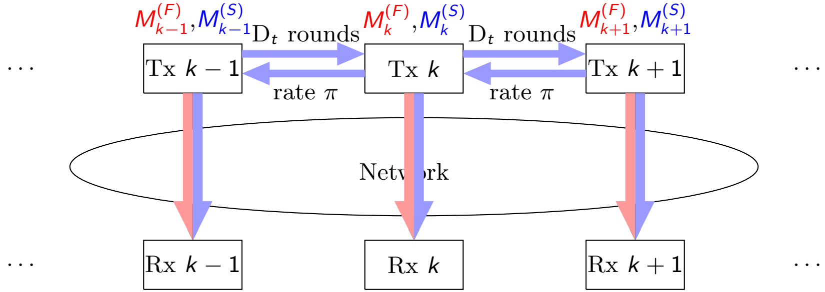

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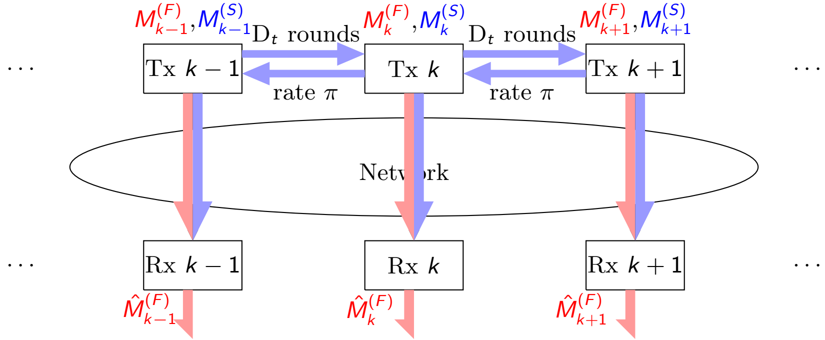

- Txs exchange information about "slow" messages during D_t conferencing rounds

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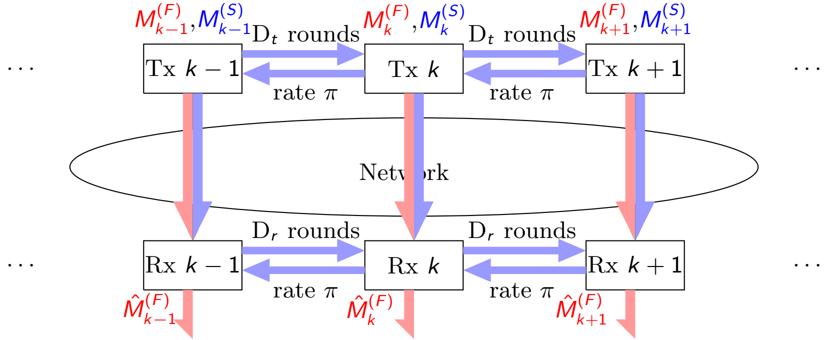
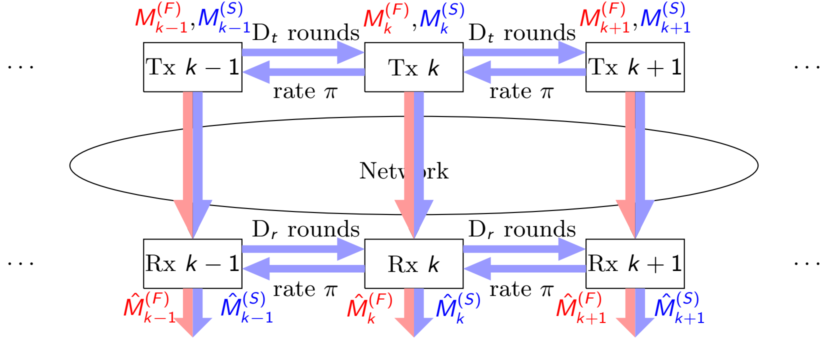


- Txs exchange information about “slow” messages during D_t conferencing rounds
- Rxs communicate over D_r rounds before decoding “slow” messages

Mixed Delay Constraints in a Cooperative Network

- Each Tx k sends independent messages $(M_k^{(F)}, M_k^{(S)})$



- Total delay constraint on "slow" messages: $\mathrm{D}_r + \mathrm{D}_t \leq \mathsf{D}_{\mathsf{max}}$
- "fast" messages cannot profit from cooperation because they are subject to stringent delay constraints

Some Related Works

- M. Wigger, R. Timo, and S. Shamai (Shitz), "Conferencing in Wyners Asymmetric Interference Network: Effect of Number of Rounds ," *IT-Trans*, Feb. 2017.

  → Only $\mathsf{D}_{\mathsf{max}}$ cooperation rounds allowed

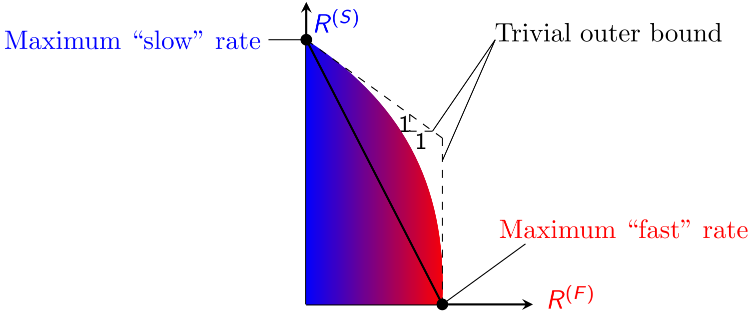
- W. Huleihel and Y. Steinberg,"Channels with cooperation links that may be absent," *IT-Trans*, Sep. 2017.

  → Additional message can be sent if cooperation link present

- K. Cohen, A. Steiner and S. Shamai (Shitz), "The broadcast approach under mixed delay constraints," *ISIT* 2012.

Mixed-Delays Capacity Region

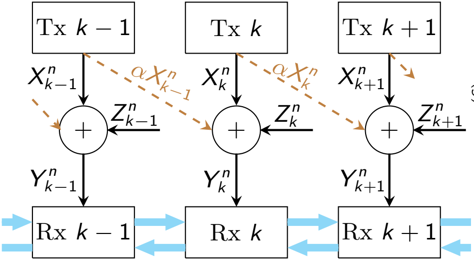
- $(R^{(F)}, R^{(S)})$: average achievable "fast" and "slow" rates



Timesharing: large $R^{(F)}$ harms overall performance (sum-rate)
$\rightarrow$ Inherent or artefact of time-sharing?

Wyner's Soft-Handoff Network with Rx-Conferencing

- $\mathrm{D}_t = 0$



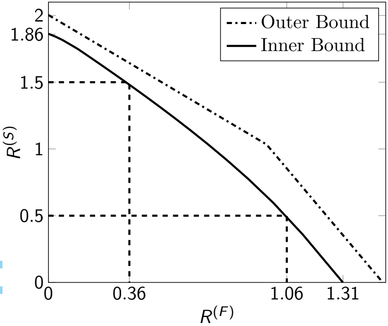
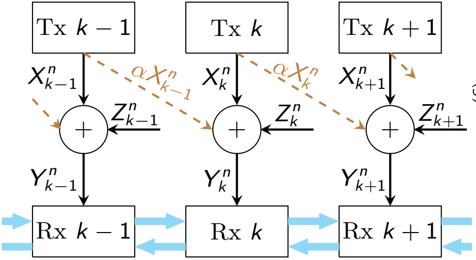


Figure: $P = 5$, $\alpha = 0.2$, $\pi = 0.346$, and $\mathrm{D}_t = 16$.

Wyner's Soft-Handoff Network with Rx-Conferencing

- $\mathrm{D}_t = 0$



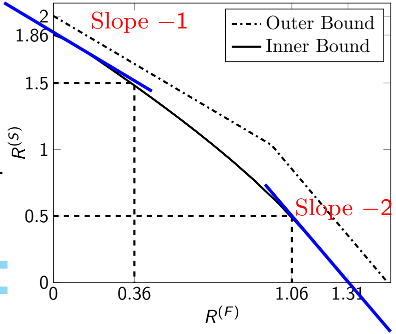


Figure: $P = 5$, $\alpha = 0.2$, $\pi = 0.346$, and $\mathrm{D}_t = 16$.

- Small $R^{(F)}$ → Small penalty in sum-rate
- Large $R^{(F)}$ → 1 "fast" bit costs 2 "slow" bits

High SNR Regime

- Conferencing rate $\pi = \mu \cdot \frac{1}{2} \log P$
- Degrees of Freedom (DoF):

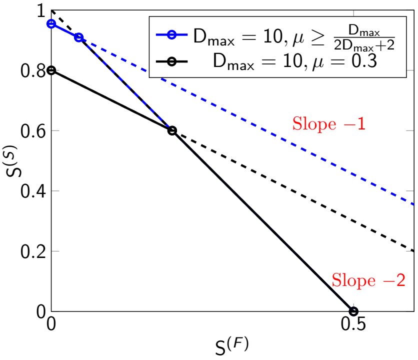
$$\mathsf{S}^{(F)} := \overline{\lim_{K\to\infty}} \ \overline{\lim_{P\to\infty}} \ \frac{R^{(F)}}{\frac{1}{2}\log(1+P)}$$

$$\mathsf{S}^{(S)} := \overline{\lim_{K\to\infty}} \ \overline{\lim_{P\to\infty}} \ \frac{R^{(S)}}{\frac{1}{2}\log(1+P)}$$

Soft-Handoff Network with Rx-Conferencing: High SNR

Theorem (DoF Region)

$$(\mathsf{S}^{(F)}, \mathsf{S}^{(S)}) \text{ achievable iff: } \begin{cases} 2\mathsf{S}^{(F)} + \mathsf{S}^{(S)} & \leq 1 \\ \mathsf{S}^{(F)} + \mathsf{S}^{(S)} & \leq \min\left\{\frac{1}{2} + \mu, \ \frac{2\mathsf{D}_{\max}+1}{2\mathsf{D}_{\max}+2}\right\} \end{cases}$$



- Small $S^{(F)}$: sum-rate not decreased by insisting on fast decoding
- Large $S^{(F)}$: 1 "fast" bit costs 2 slow "bits"

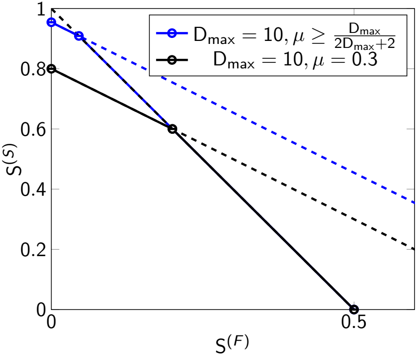
Capacity Upper Bound $2R^{(F)} + R^{(S)} \leq \frac{1}{2}\log(P) + o(1)$

$$
\begin{aligned}
& n(R_k^{(F)} + R_k^{(S)} + R_{k+1}^{(F)}) \\
& \overset{(a)}{\leq} I(M_k; Y_k^n, Y_{k+1}^n | M_{k-1}, M_{k+1}) + I(M_{k+1}^{(F)}; Y_{k+1}^n | M_{k+1}^{(S)}) + \epsilon_n \\
& \overset{(b)}{=} I(M_k; Y_k^n | M_{k-1}) + I(M_k; Y_{k+1}^n | Y_k^n, M_{k-1}, M_{k+1}) \\
& \qquad\qquad + I(M_{k+1}^{(F)}; Y_{k+1}^n | M_{k+1}^{(S)}) + \epsilon_n \\
& \overset{(c)}{\leq} \frac{1}{n}\Big[h(X_k^n + Z_k^n) - h(Z_k^n) + h(\alpha X_k^n + Z_{k+1}^n | X_k^n + Z_k^n) \\
& \qquad - h(Z_{k+1}^n) + h(Y_{k+1}^n | M_{k+1}^{(S)}) - h(\alpha X_k^n + Z_{k+1}^n)\Big] + \frac{\epsilon_n}{n} \\
& \overset{(d)}{\leq} \frac{1}{2}\log(1 + (1 + |\alpha|^2)P) + \frac{1}{2}\log(1 + \alpha^2) + \max\{-\log|\alpha|, 0\} + \frac{\epsilon_n}{n}.
\end{aligned}
$$

Soft-Handoff Model with Tx-Conferencing: High SNR

Theorem (DoF Region)

$(\mathsf{S}^{(F)}, \mathsf{S}^{(S)})$ achievable iff: $\begin{cases} 2\mathsf{S}^{(F)} + \mathsf{S}^{(S)} & \leq 1 \\ \mathsf{S}^{(F)} + \mathsf{S}^{(S)} & \leq \min\left\{\frac{1}{2} + \mu, \ \frac{2\mathsf{D}_{\max}+1}{2\mathsf{D}_{\max}+2}\right\} \end{cases}$



Tx-Rx Duality!

Soft-Handoff Model with Tx-Conferencing: High SNR

Theorem (DoF Region)

$(\mathsf{S}^{(F)}, \mathsf{S}^{(S)})$ achievable iff:

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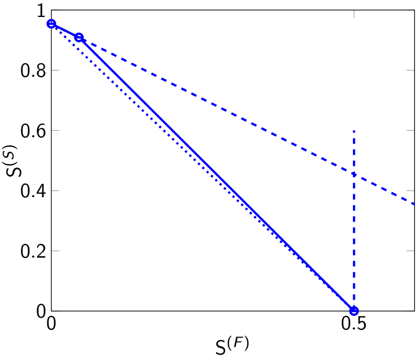
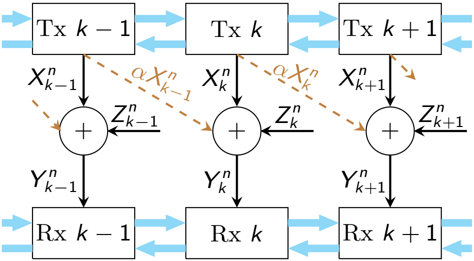
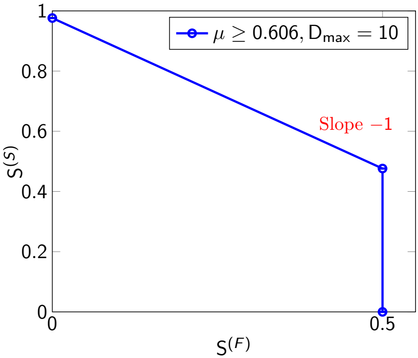


- If $\mu \geq \frac{\mathrm{D}_{\mathsf{max}}}{2\mathrm{D}_{\mathsf{max}}+2}$

Significant Gains with Tx- and Rx- Conferencing

- $D_t, D_r \geq 0$





- When $\mu \geq \frac{2D_{max}}{3(D_{max}+1)}$: max sum-rate achievable for full $S^{(F)}$ $\rightarrow$ no tradeoff
- Full $S^{(F)}$ possible with positive $S^{(S)}$

Significant Gains with Tx- and Rx- Conferencing

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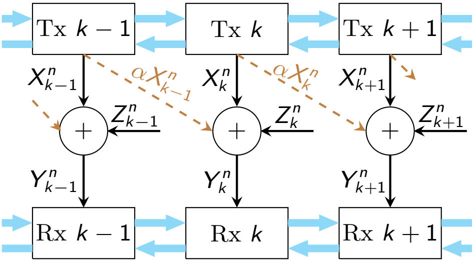

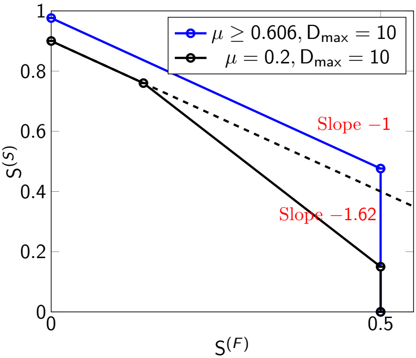

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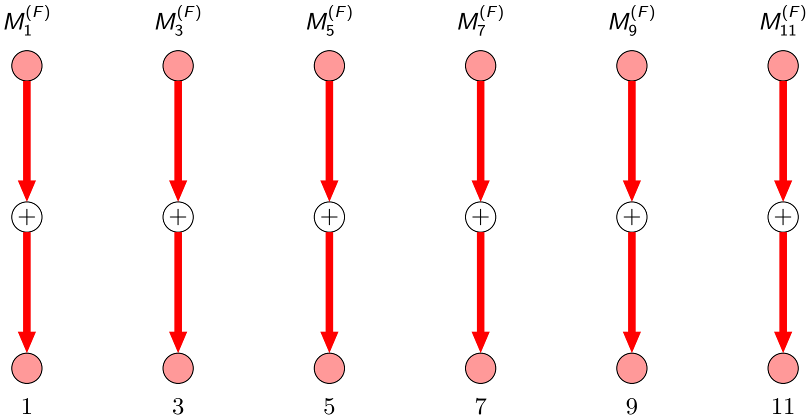
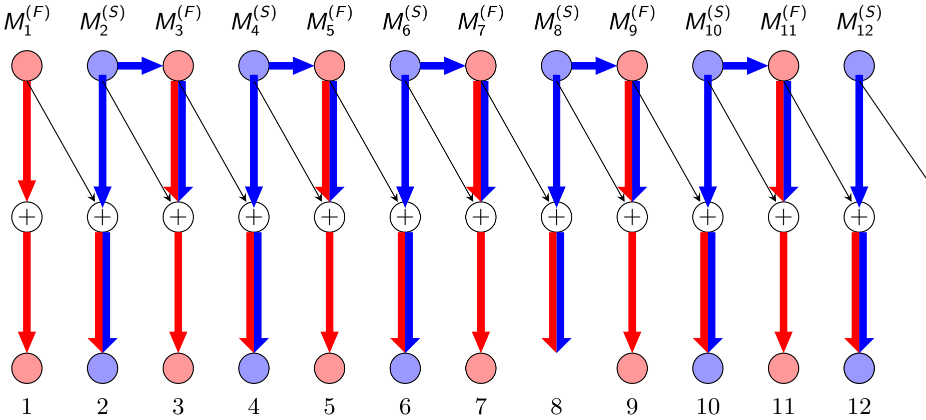
Scheme Combining "Fast" and "Slow" Transmissions

- Getting $\mathsf{S}^{(F)} = \frac{1}{2}$



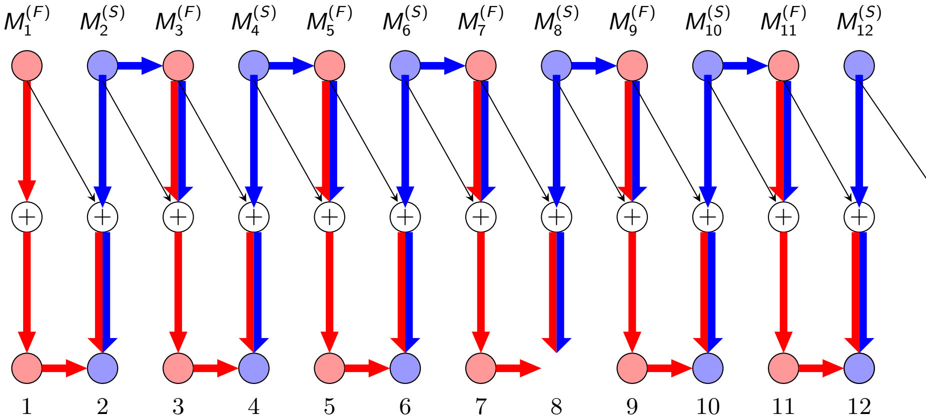
Scheme Combining "Fast" and "Slow" Transmissions

- Adding "slow" messages and mitigating their interference



Scheme Combining “Fast” and “Slow” Transmissions

- @Rxs mitigate interference from “fast” messages



Scheme Combining "Fast" and "Slow" Transmissions

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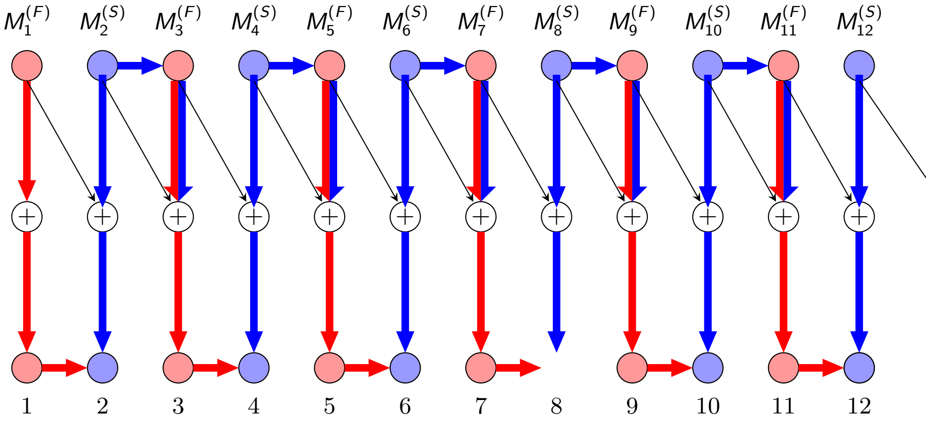
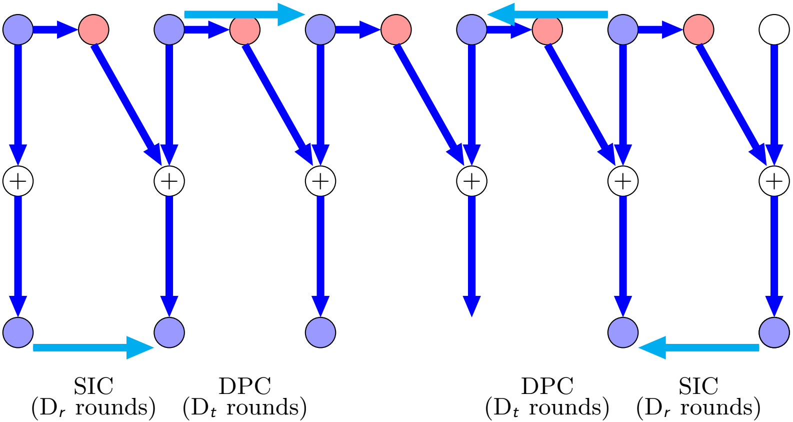
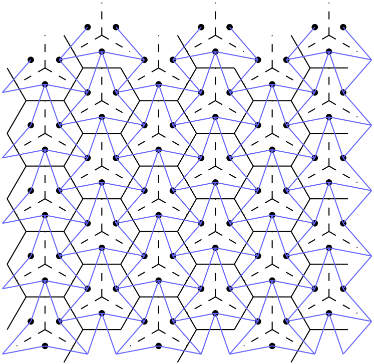


Scheme Combining “Fast” and “Slow” Transmissions

- Design scheme for “slow” messages

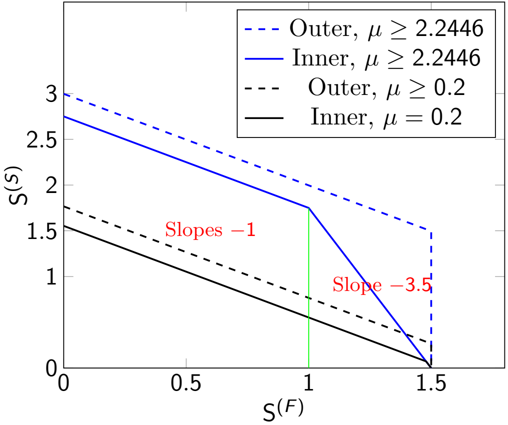


Sectorized Hexagonal Model



- 1 cell = 3 sectors
- BSs have $3M$ directional antennas
- 1 user per sector
- 3 users of a cell do not interfere
- static channels, Gaussian noise
- Cooperation between neighbouring users / BSs

Degrees of Freedom for Hexagonal Model

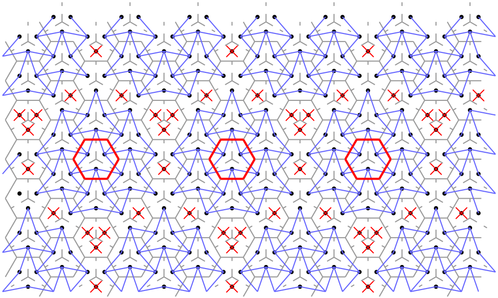


D = 20
$M = 3$

- $S^{(F)}$ without IA: sum-DoF not decreased

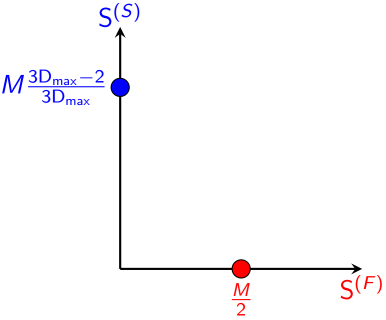
Transmitting only “slow” messages

- Silence some mobile users → non-interfering clusters
- Virtual-MIMO in a cluster where center cell decodes all messages



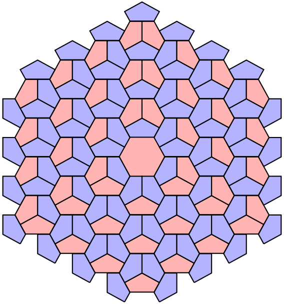
$D_{max} = 4$

Gelincik et al. 2018

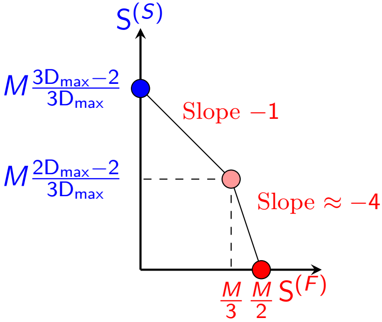


Alternating "fast" and "slow" messages

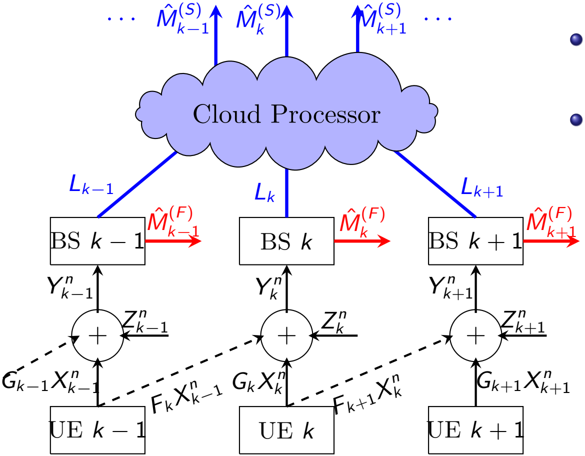
- Silence users as before → clusters
- Blue sectors send "slow" messages, red sectors "fast" messages
- "Fast" Txs precancel interference from "slow" messages
- "Slow" Rxs cancel interference from "fast" messages
- "Slow" messages sent using virtual MIMO scheme from before



$D_{max} = 8$



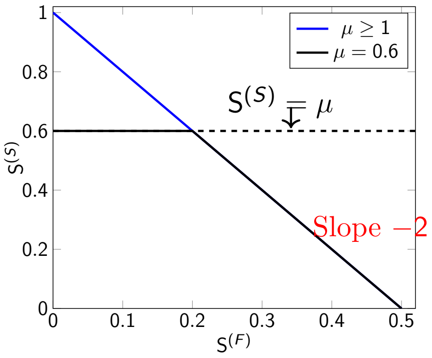
Cloud Radio Access Network



- $\{G_k\}$ and $\{F_k\}$ are fading processes.
- Fronthaul rate π (DoF μ)

R. Kassab, O. Simeone, P. Popovski, and T. Islam, "Non-orthogonal multiplexing of ultra-reliable and broadband services in fog-radio architectures," *IEEE Access*, 2019.

Mixed-Delays DoF Region for C-RAN



No better than time-sharing!

- When $\mu < 1$ and $S^{(F)} \leq \frac{1}{2} - \frac{\mu}{2}$ $\rightarrow S^{(S)}$ is constant.
- When $\mu < 1$ and $S^{(F)} > \frac{1}{2} - \frac{\mu}{2}$, or when $\mu \geq 1$:
  $\rightarrow$1 bit of “fast” DoF costs 2 bits of “slow” DoF

Capacity Region of a C-RAN

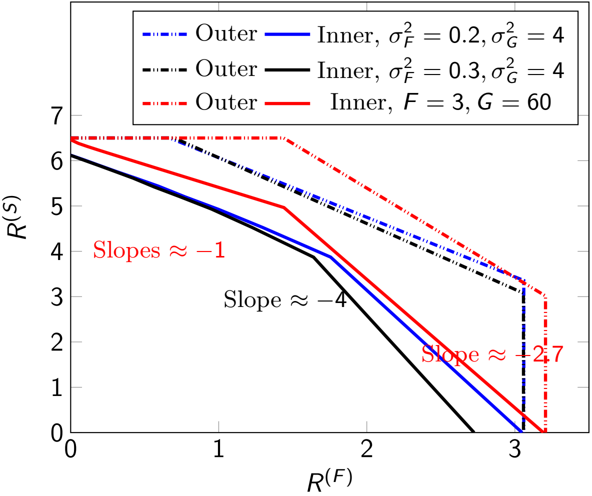


Figure: Capacity inner and outer bounds for $P = 100$, $\pi = 6.5$, and different variances σ_F^2 and σ_G^2 of F and G, and for static values G and F.

Conclusions

- Jointly designing mixed-delay systems can yield significant performance benefits in networks with cooperation
- Benefits are much larger when txs and rxs can cooperate
- For certain configurations, there is no loss in overall performance due to stringent delay constraints

Future works:

- Finer measure for delay (finite blocklength)
- Random arrivals of "fast" messages

Some References

- H. Nikbakht, M. Wigger, and S. Shamai Shitz, "Mixed delay constraints in Wyner's soft-handoff network," *ISIT 2018*.
- H. Nikbakht, M. Wigger, and S. Shamai Shitz, "Mixed delay constraints at maximum sum-multiplexing gain," *ITW 2018*.
- H. Nikbakht, M. Wigger, and S. Shamai Shitz, "Multiplexing gain region of sectorized cellular networks with mixed delay constraints," *SPAWC 2019*, `https://arxiv.org/abs/1902.11231`.
- H. Nikbakht, M. Wigger, W. Hachem, and S. Shamai Shitz, "Mixed delay constraints on a fading C-RAN uplink," submitted to *ITW 2019*.