atlanTTic research center for Telecommunication Technologies

Universidade Vigo

Rate-Splitting and Space Communications, a Robust Alliance

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IEEE ComSoc WTC SIG on Rate Splitting Multiple Access (RSMA)

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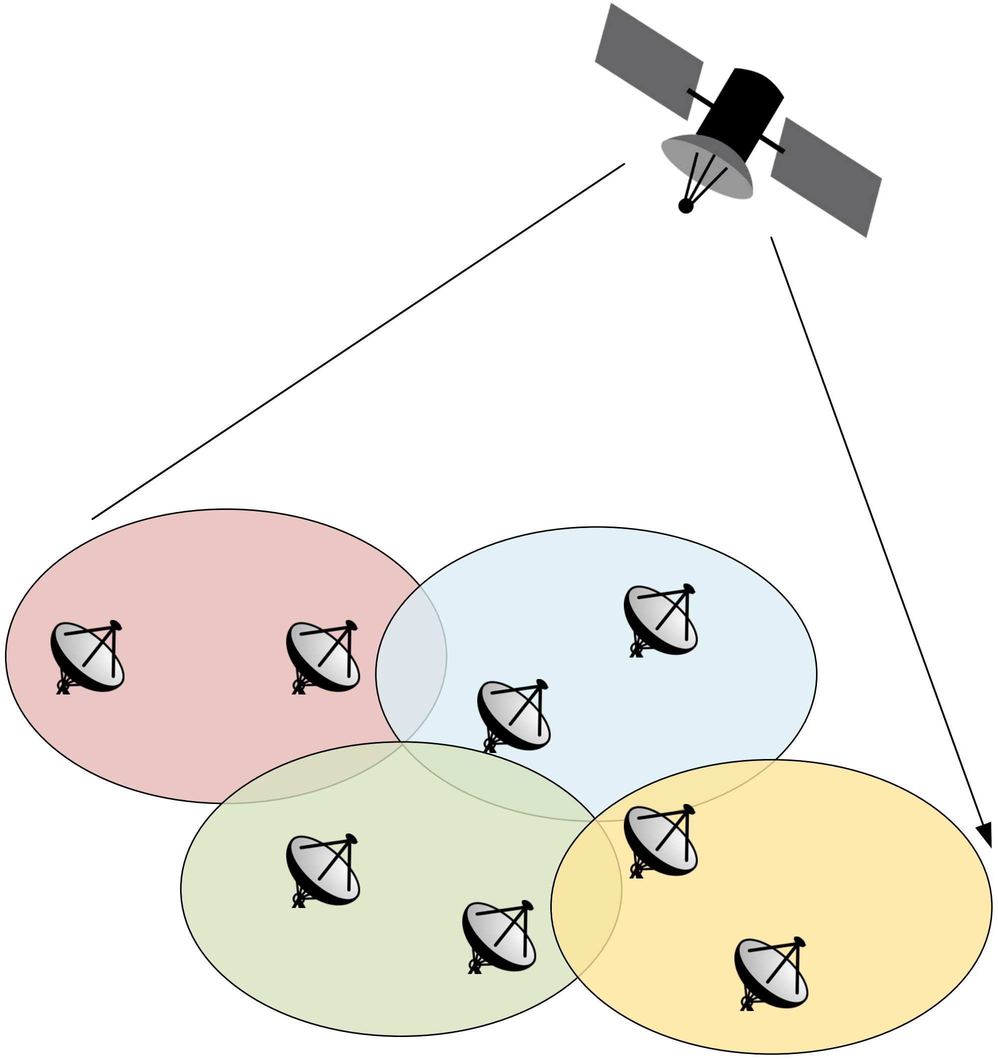
Outline

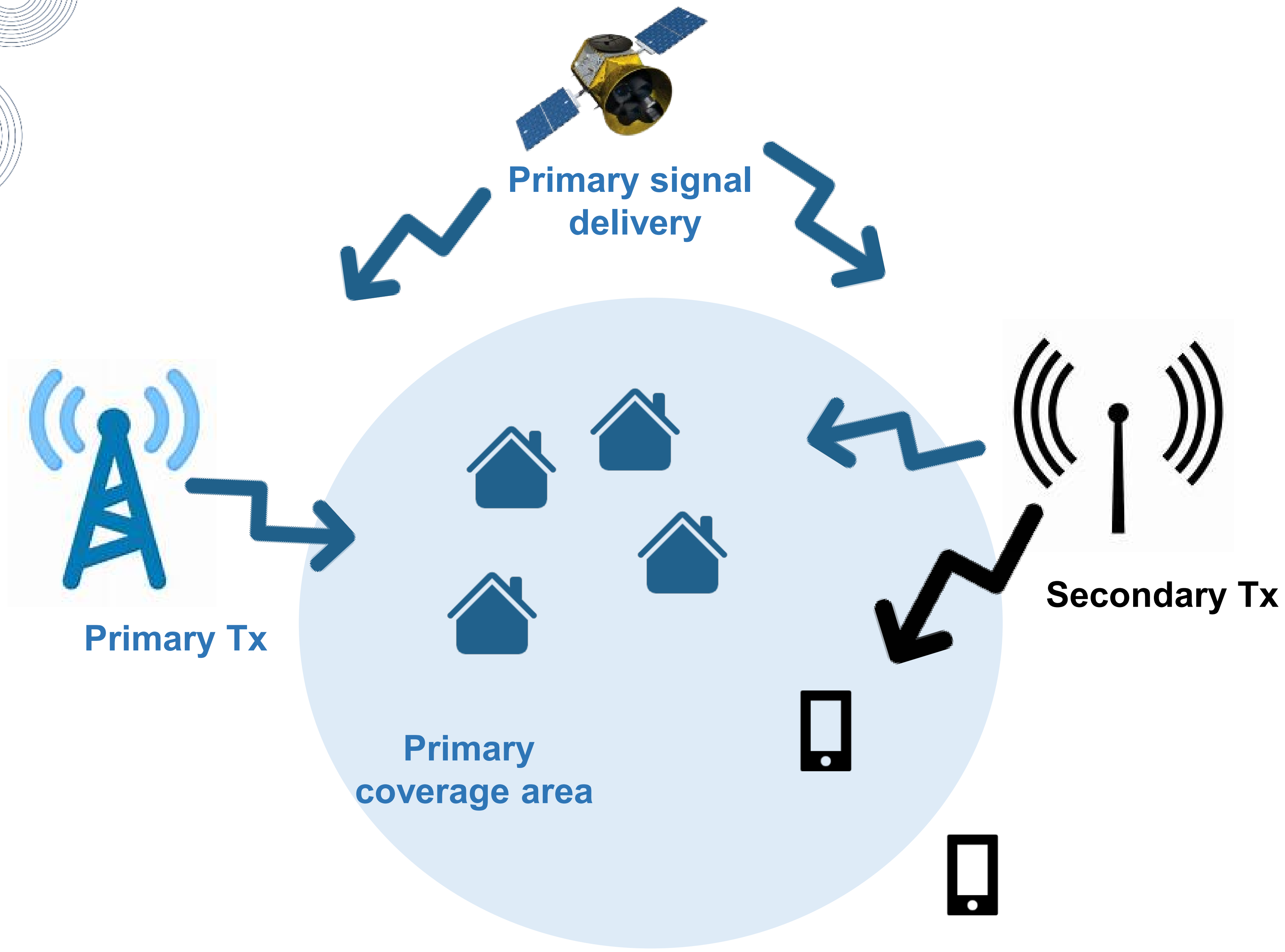
1. **Overlay Cognitive** Radio over Broadcast Networks
2. **MISO Broadcast** Channel with Magnitude CSIT
3. **Beam free** approaches

Joint works with:

- Alberto Rico (Qualcomm)
- Tomás Ramírez (University of Vigo)
- Nele Noels (University of Ghent)
- Marius Caus, Adriano Pastore (CTTC)
- Nader Alagha (European Space Agency)

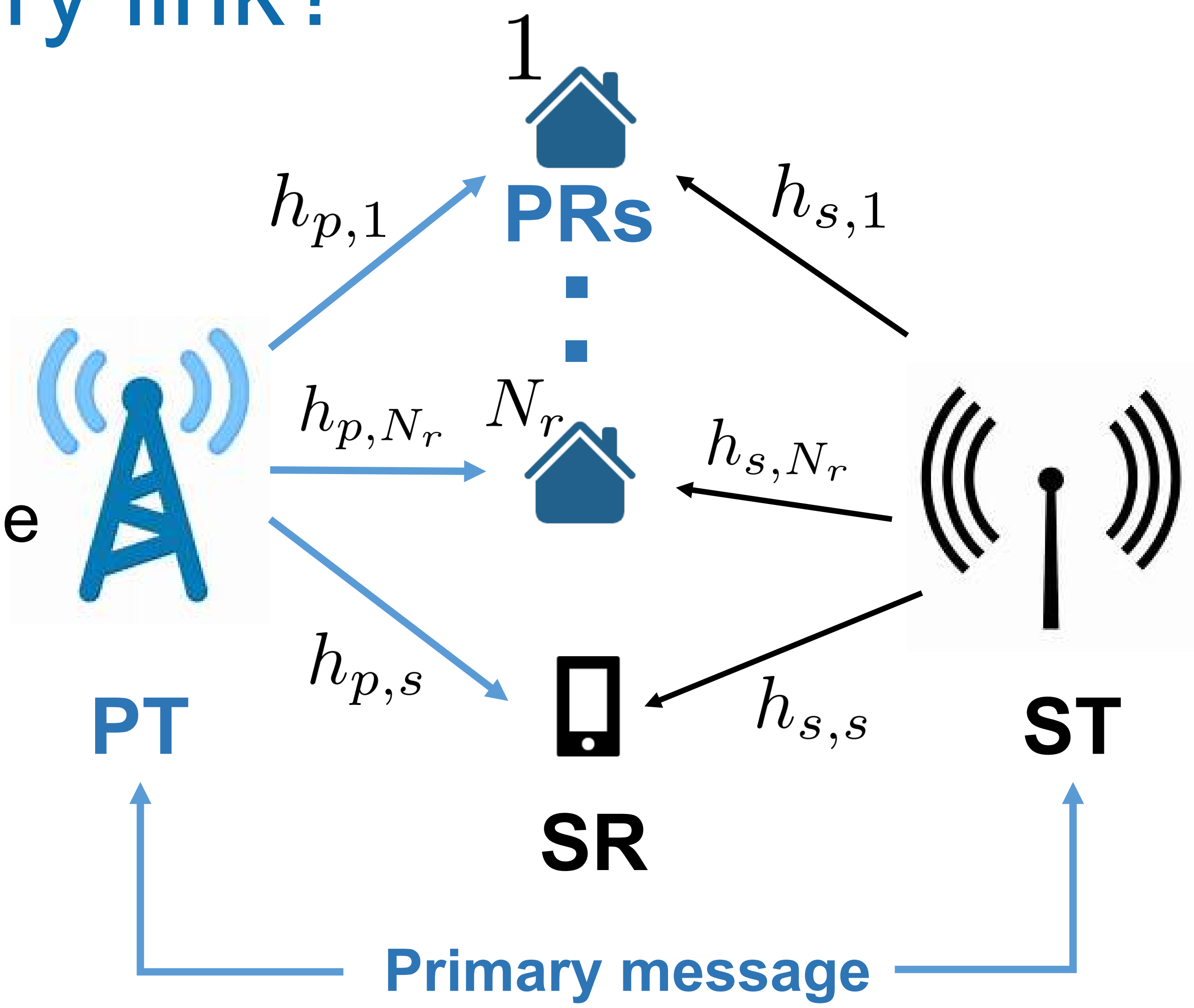


Overlay Cognitive Radio over Broadcast Networks


Primary signal
delivery
Secondary Tx
Primary Tx
Primary
coverage area

Capacity of secondary link?

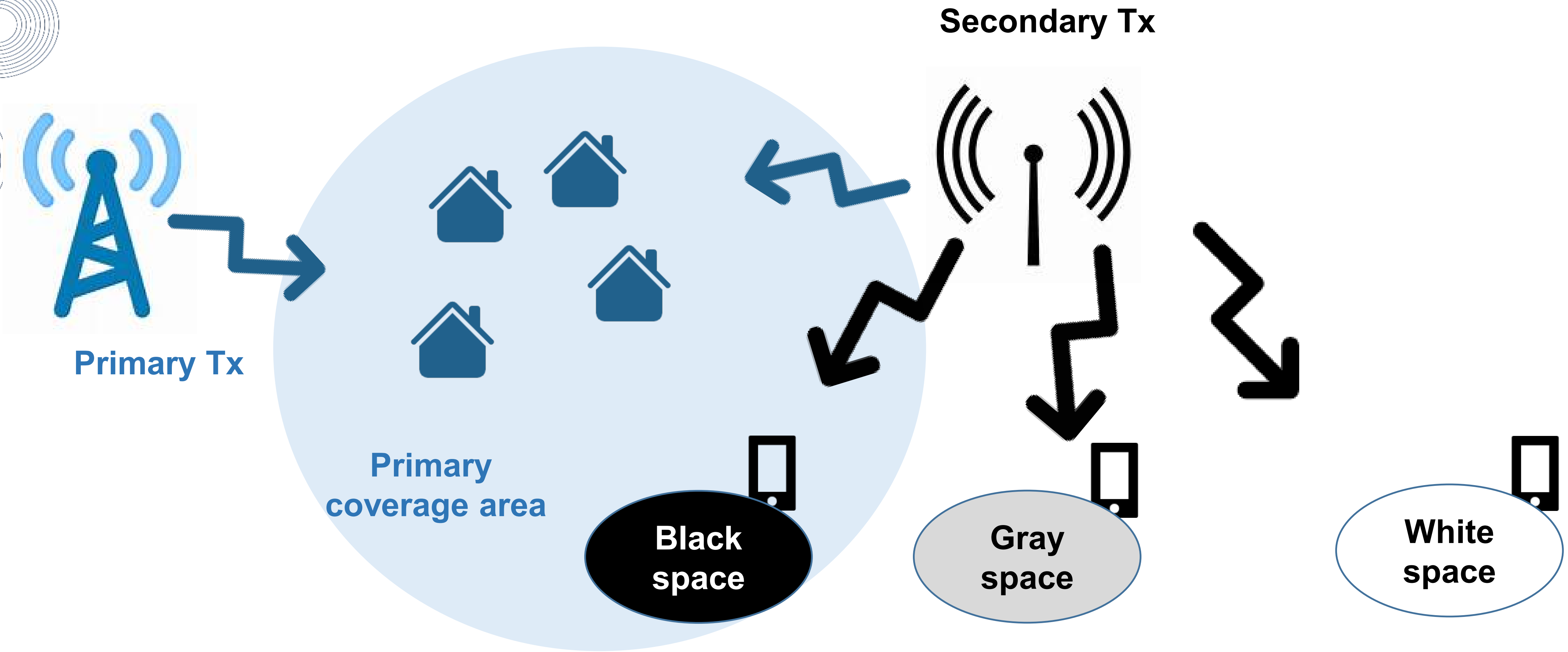
- Secondary Tx (ST) knows the transmit primary message
- **ST cannot use DPC** to cancel the interference (unknown channel)
- Relevant metric: **coverage area**



Design parameters

message splitting

- Power splitting at secondary Tx: $P_s = P_s^{pr} + P_s^{sec}$
- Required SINR at primary Rx: $\Upsilon_0 = 2^{R_p} - 1$
- Power margin of most restrictive primary Rx: $\mathcal{M}$
- Preservation of primary coverage: $P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M}$



Power allocated to primary:	✓	✓	✗
Decoding strategy:	**Decode primary**	**Decode primary**	**Treat as noise**

Coding/decoding strategies

- Regimes:
  - Treat primary interference as noise: $$\frac{|h_{p,s}|^2 P_p + |h_{s,s}|^2 P_s^{pr}}{\sigma^2} < \Upsilon_0$$ $$(\mathcal{N})$$
  - Strong interference (primary is decodable) $$\frac{|h_{p,s}|^2 P_p + |h_{s,s}|^2 P_s^{pr}}{\sigma^2 + P_s^{sec} |h_{s,s}|^2} \geq \Upsilon_0$$ $$(\mathcal{S})$$

Optimization

Single secondary receiver

- **Treat as noise: linear fractional program**

$$P_s$$

P_s^{pr}	P_s^{sec}

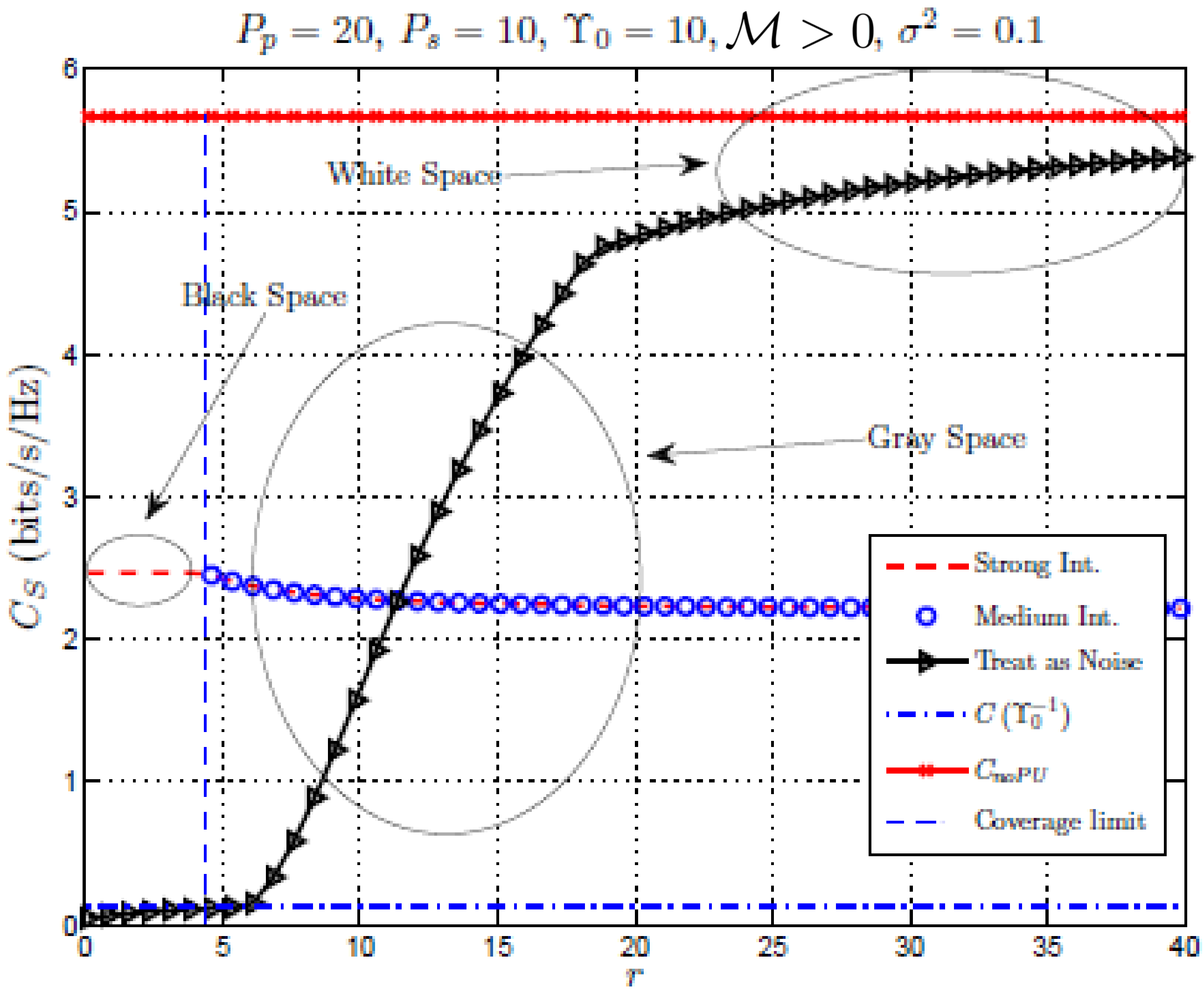
$$\begin{aligned} \max. \quad & f(P_s^{pr}, P_s^{sec}) \triangleq \frac{P_s^{sec}\left|h_{s,s}\right|^2}{\sigma^2 + P_s^{pr}\left|h_{s,s}\right|^2 + P_p\left|h_{p,s}\right|^2} \\ \text{s.t.} \quad & P_s^{pr} + P_s^{sec} \leq P_s \\ & P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M} \\ & P_s^{pr}, P_s^{sec} \geq 0 \end{aligned}$$

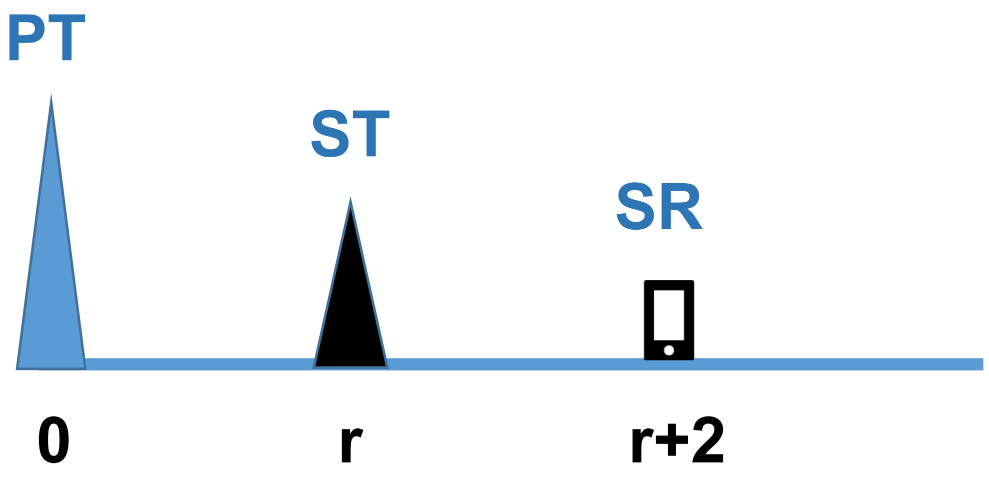
- **Strong interference: LP**

$$\begin{aligned} \max. \quad & P_s^{sec}\left|h_{s,r}\right|^2 \\ \text{s.t.} \quad & P_s^{pr} + P_s^{sec} \leq P_s \\ & P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M} \\ & P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M}^s \\ & P_s^{pr}, P_s^{sec} \geq 0 \end{aligned}$$

The coverage area of the primary system is extended!

Channel capacity for a single SR





Free space propagation model

Multiple Receivers

- **Unicast:** orthogonal allocation, and consideration of one SR at a time
- **Multicast/Broadcast** with several SRs
- **Goal**: given N_s receivers, maximize the common rate R_s such that no PR is compromised

- **Design variables:**
  - **Power allocation weights:**

$$\left(P_s^{pr}, P_s^{sec}\right)$$

  - **Vector of decoding strategies:**

$$\boldsymbol{\mathcal{D}} = (\mathcal{D}_1, \ldots, \mathcal{D}_{N_s}) \in \{\mathcal{N}, \mathcal{S}\}^{N_s}$$

Optimization problem

Generalized linear fractional program

Channel capacity at *k* receiver

We can go down from 2^{N_s} to $N_s + 1$ decoding strategies:

$$\begin{aligned}
\boldsymbol{\mathcal{D}}^{(0} &= (\mathcal{N}, \mathcal{N}, \ldots, \mathcal{N}) \\
\boldsymbol{\mathcal{D}}^{(1} &= (\mathcal{S}, \mathcal{N}, \ldots, \mathcal{N}) \\
\boldsymbol{\mathcal{D}}^{(2} &= (\mathcal{S}, \mathcal{S}, \ldots, \mathcal{N}) \\
&\vdots \\
\boldsymbol{\mathcal{D}}^{(N_s} &= (\mathcal{S}, \mathcal{S}, \ldots, \mathcal{S})
\end{aligned}$$

$$\begin{aligned}
\max \quad & \min_{k=1,\ldots,N_s} \left\{ C_k^{\mathcal{D}_k}(P_s^{pr}, P_s^{sec}) \right\} \\
\text{s.t.} \quad & P_s^{pr} + P_s^{sec} \leq P_s \\
& P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M} \\
& P_s^{pr} \geq P_s^{sec}\Upsilon_0 - \mathcal{M}_{r_k}^{s}, k = 1, \ldots, N_s \\
& P_s^{pr}, P_s^{sec} \geq 0
\end{aligned}$$

If $\mathcal{D}_k = \mathcal{S}$

and solve $N_s + 1$ quasiconvex optimization problems.

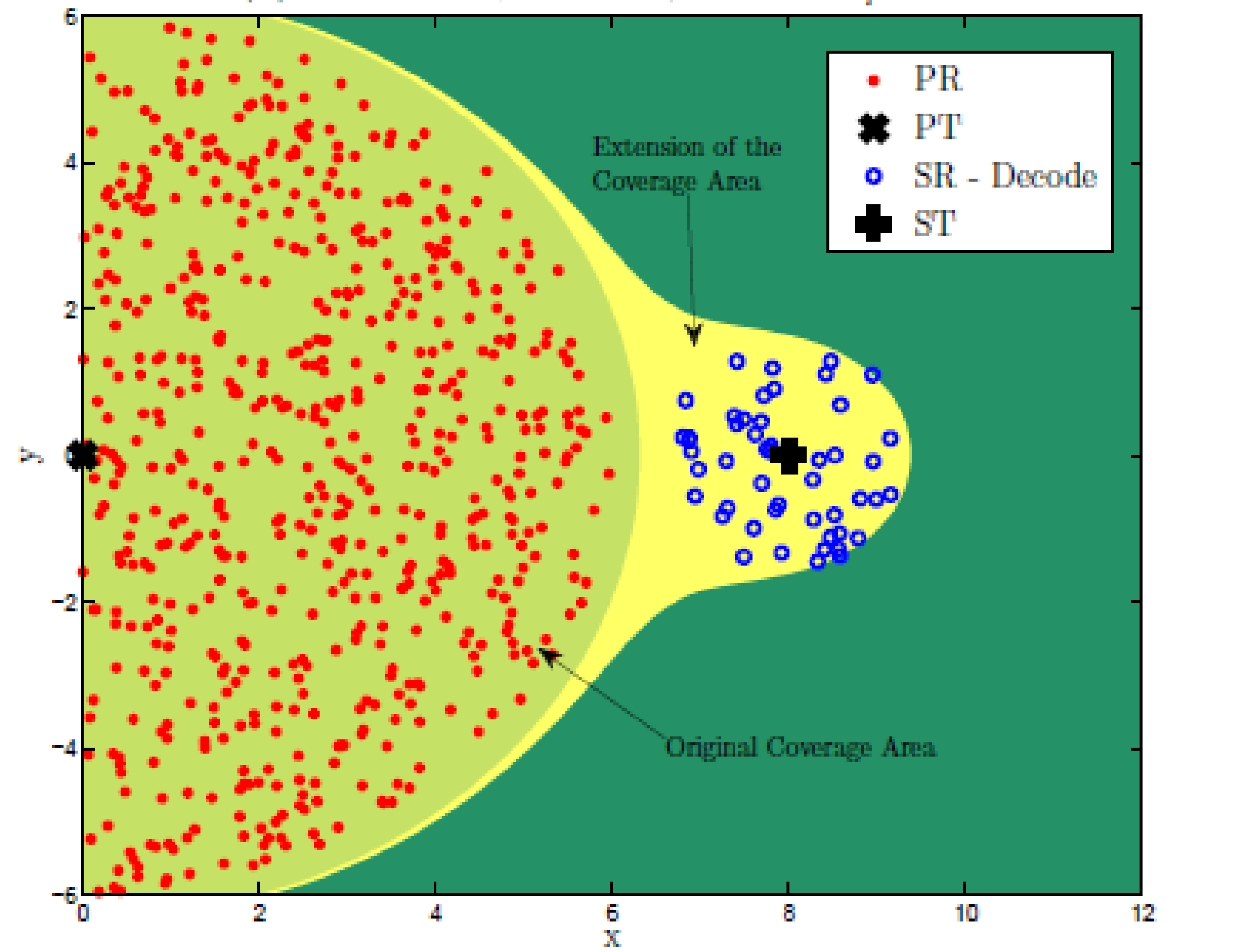
Gray space

- Decoding strategy (all receivers):

$$(\mathcal{S})$$

$$P_s = 10$$

9.14	0.86



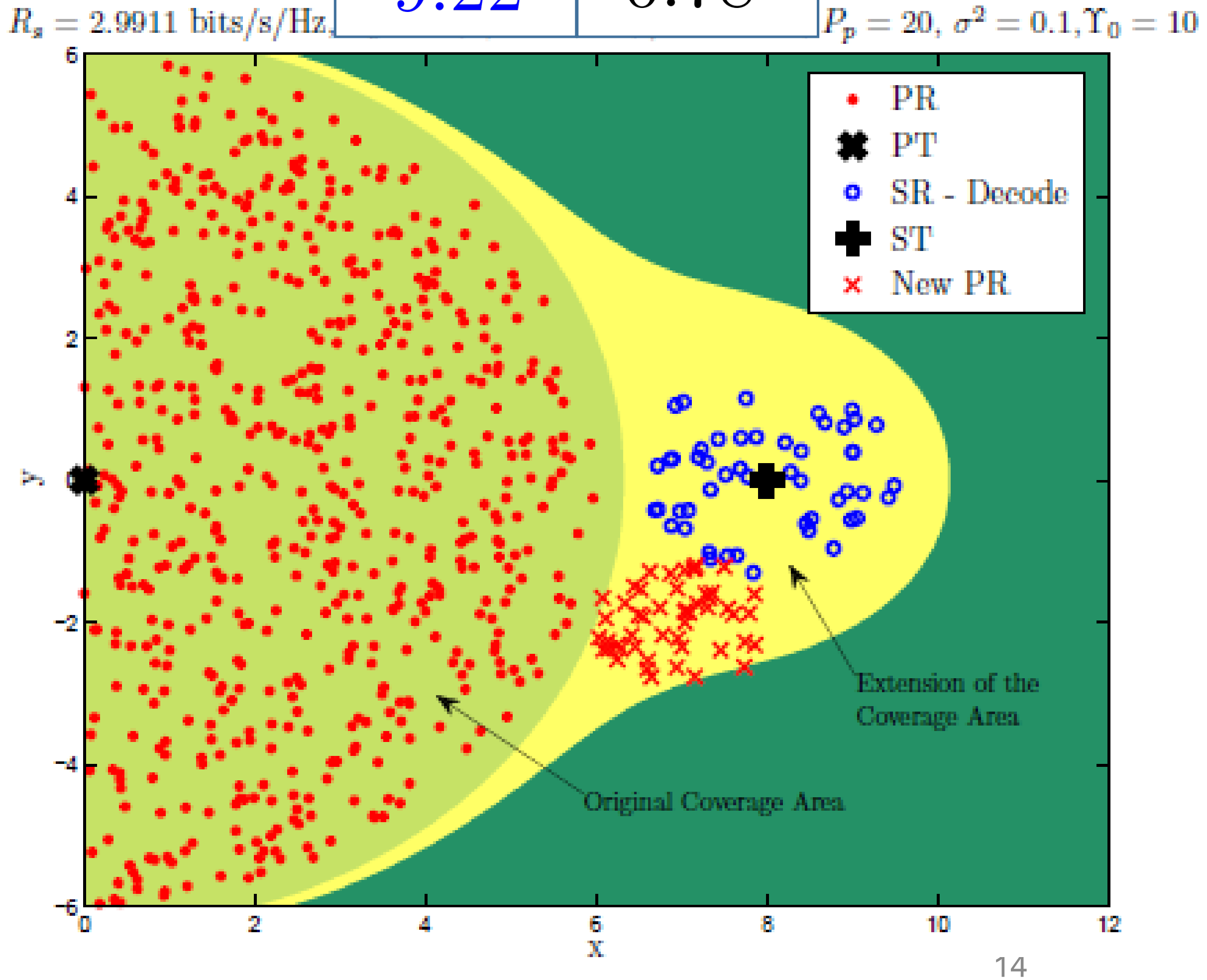
Extension of initial coverage

- Decoding strategy (all receivers):

$$(\mathcal{S})$$

$$P_s = 10$$

9.22	0.78



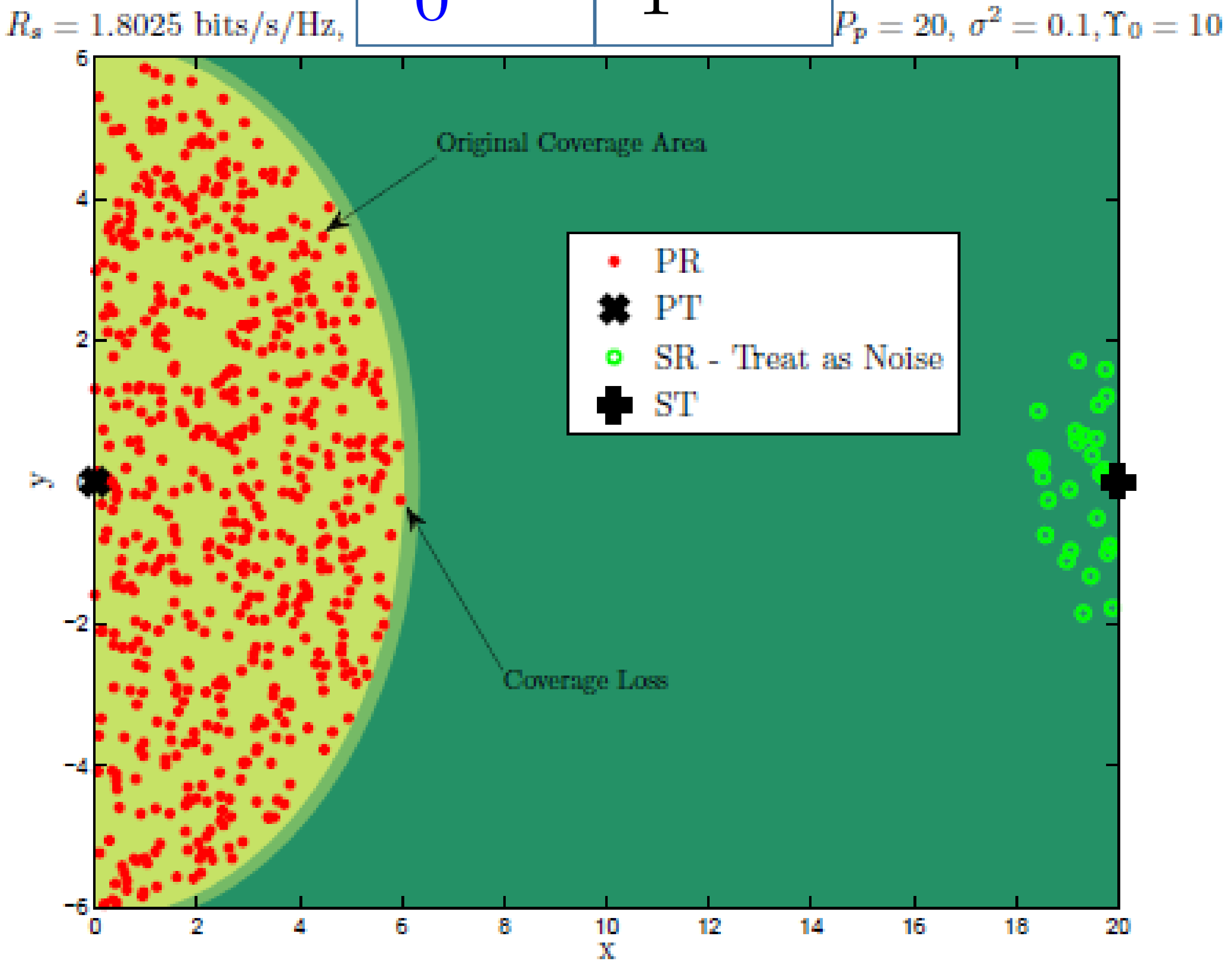
White Space

- Decoding strategy (all receivers):

$$(\mathcal{N})$$

$$P_s = 1$$

0	1



Rate Splitting for the MISO Broadcast Channel with Magnitude CSIT

Motivation

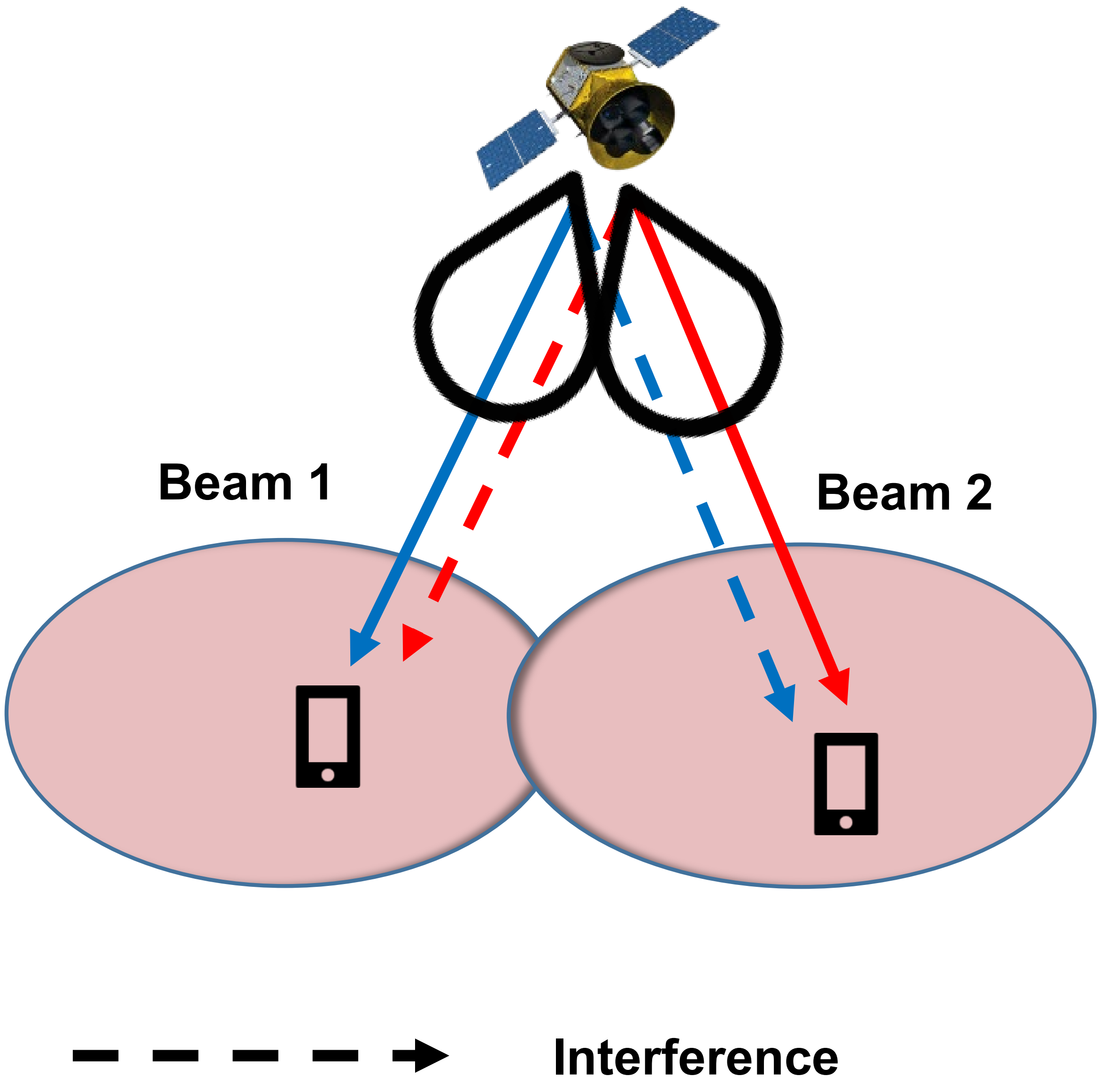
- Block-fading channel:

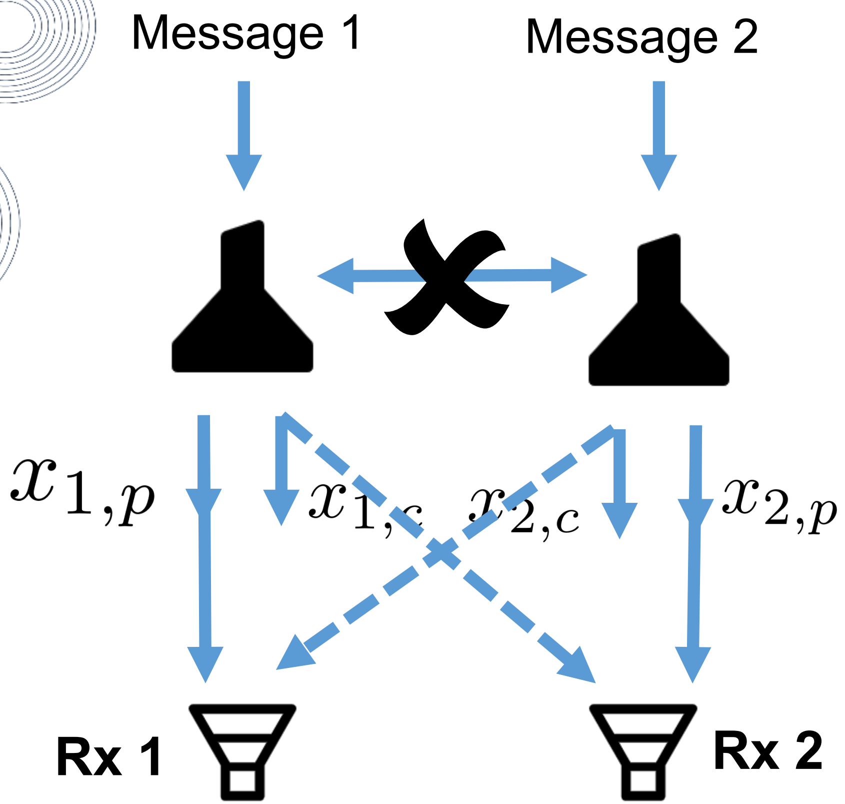
$$y_1 = h_{1,1}x_1 + h_{1,2}x_2 + w_1,$$
$$y_2 = h_{2,1}x_1 + h_{2,2}x_2 + w_2.$$

- **No phase information** available at the transmitter, only the channel quality of the links:

$$\gamma_{j,k} = \frac{P}{2}|h_{j,k}|^2.$$

- Per-antenna power constraint
- Perfect CSIR



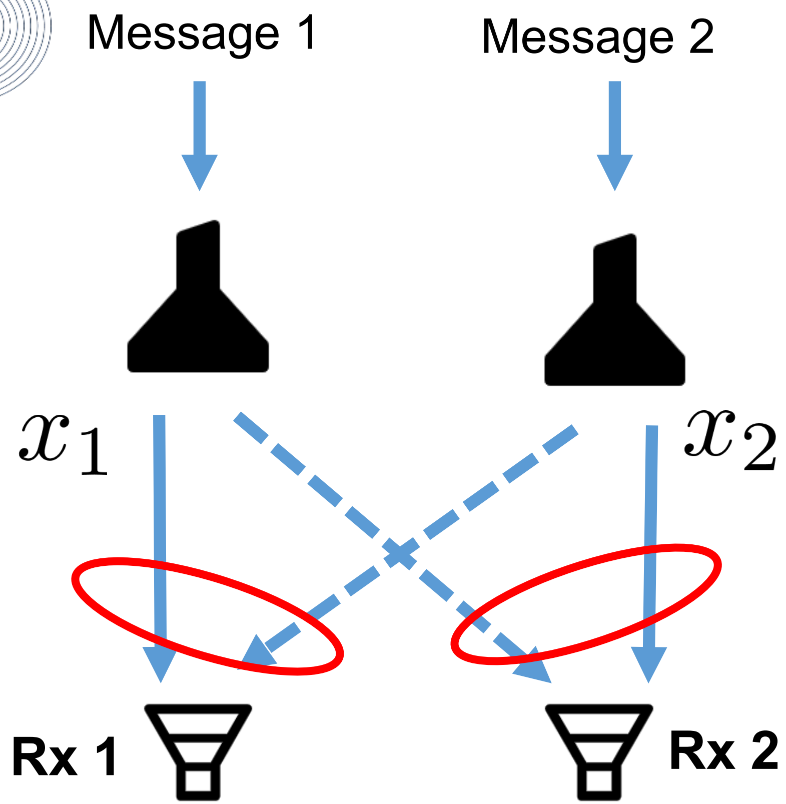


Some seminal works

- **Interference channel: no antenna cooperation (MISO-IC)**
- Han-Kobayashi achievable rate, based on **rate-splitting**
- For the Gaussian case, additive superposition

Te Han and Kingo Kobayashi. "A new achievable rate region for the interference channel." IEEE Transactions on Information Theory 27.1 (1981): 49-60.

Some seminal works



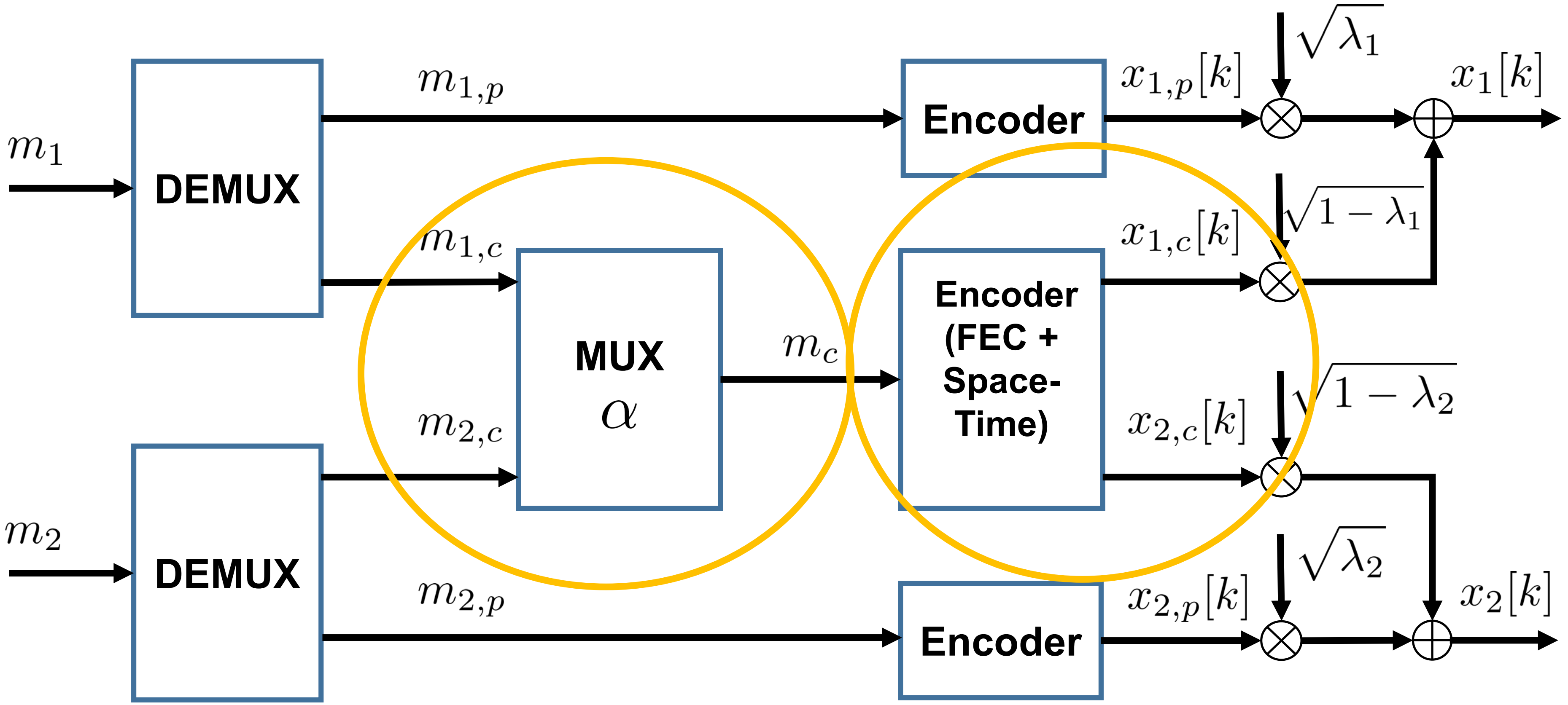
- **MISO-BC with vector-magnitude CSIT**
- **Superposition coding** and successive decoding. Capacity region achieved with:

$$\boldsymbol{x} = [x_1, x_2] = \boldsymbol{u}_1 + \boldsymbol{u}_2$$

$$\boldsymbol{u}_1 \text{ and } \boldsymbol{u}_2 \text{ independent Gaussian vectors}$$

Jafar, Syed Ali, and Andrea J. Goldsmith. "Isotropic fading vector broadcast channels: The scalar upper bound and loss in degrees of freedom." IEEE Transactions on Information Theory 51.3 (2005): 848-857.

Space-Time RS



Space-Time RS

$$
\begin{aligned}
x_1[k] &= \sqrt{\frac{P}{2}(1-\lambda_1)}\, x_{1,c}[k] + \sqrt{\frac{P}{2}\lambda_1}\, x_{1,p}[k], \\
x_2[k] &= \sqrt{\frac{P}{2}(1-\lambda_2)}\, x_{2,c}[k] + \sqrt{\frac{P}{2}\lambda_2}\, x_{2,p}[k]
\end{aligned}
$$

- With Gaussian codebooks:

$$R_{1,p} = \log_2\left(1 + \frac{\lambda_1 \gamma_{1,1}}{1+\lambda_2\gamma_{1,2}}\right),$$

$$R_{2,p} = \log_2\left(1 + \frac{\lambda_2 \gamma_{2,2}}{1+\lambda_1\gamma_{2,1}}\right),$$

$$R_c = \min_{j\in\{1,2\}} \log_2\left(1 + \frac{(1-\lambda_1)\,\gamma_{j,1} + (1-\lambda_2)\,\gamma_{j,2}}{1+\lambda_1\gamma_{j,1}+\lambda_2\gamma_{j,2}}\right)$$

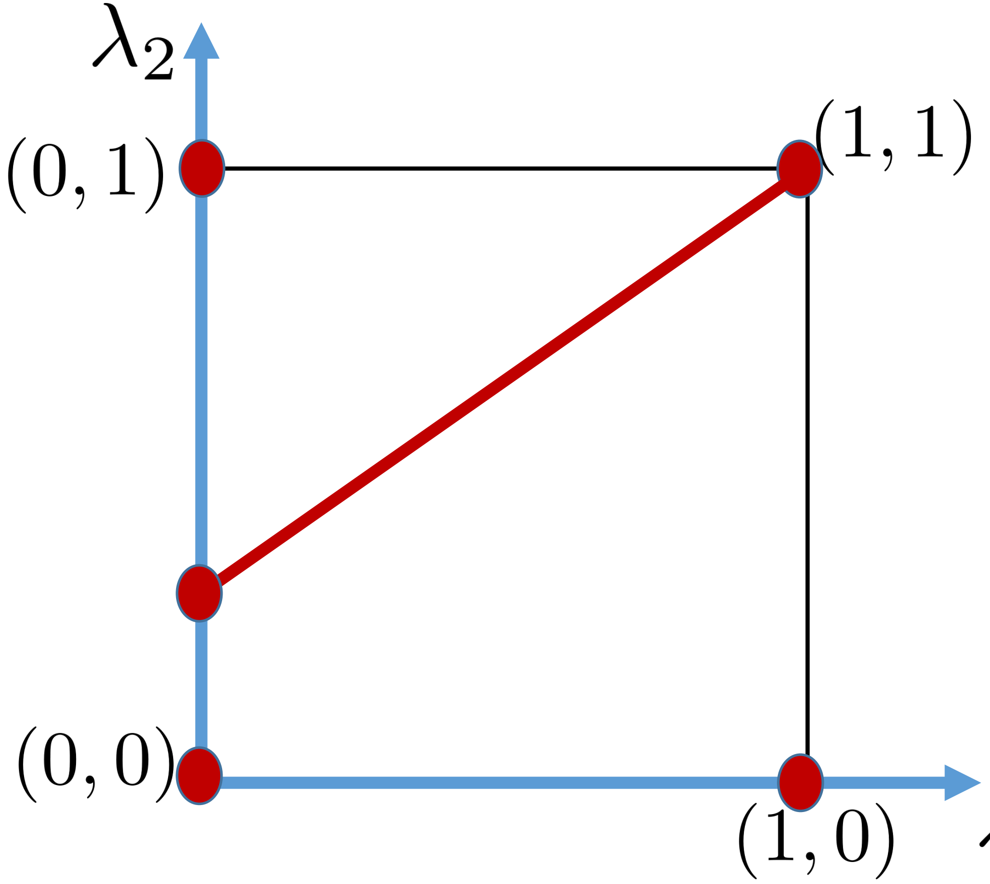
Link adaptation: achievable rates do not depend on the channel phase

$$
\begin{aligned}
R_1 &= R_{1,p} + \alpha \cdot R_c \\
R_2 &= R_{2,p} + (1-\alpha) \cdot R_c
\end{aligned}
$$

Multicast: Alamouti → simple decoding of common message

Achievable Sum-Rate Maximization

$$(\lambda_1, \lambda_2) = \arg\max\{R_{1,p} + R_{2,p} + R_c\}, \quad 0 \leq \lambda_1 \leq 1, \quad 0 \leq \lambda_2 \leq 1,$$



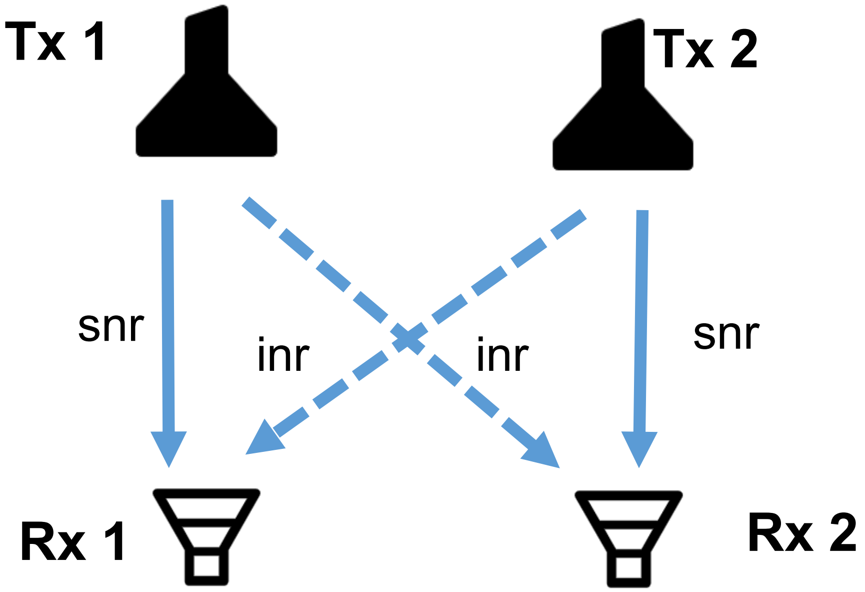
Generalized Degrees of Freedom

- STRS achieves the sum-GDoF of the 2-user MISO BC under finite precision CSIT.

- Our main driver is the performance in the finite SNR regime

$$\mathrm{GDoF}_{sum} = \lim_{P\to\infty} \frac{C_{sum}(P)}{\log_2 P}$$

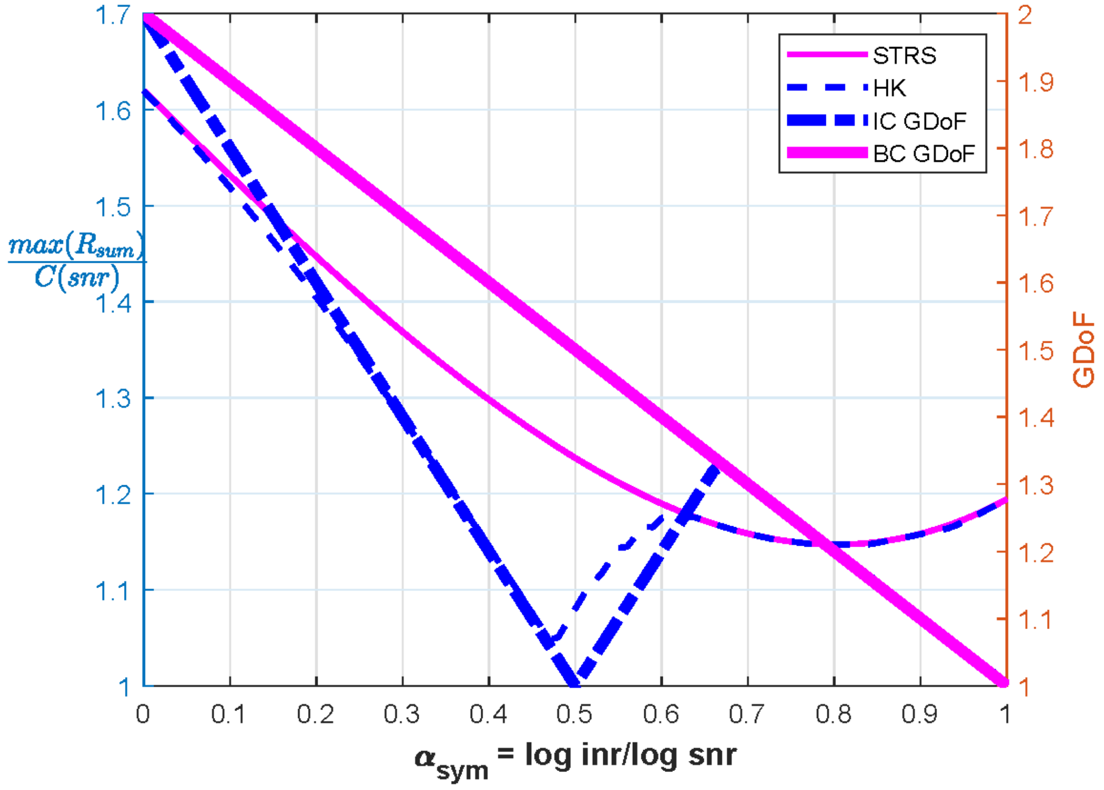
STRS: Numerical Results, Symmetric Case



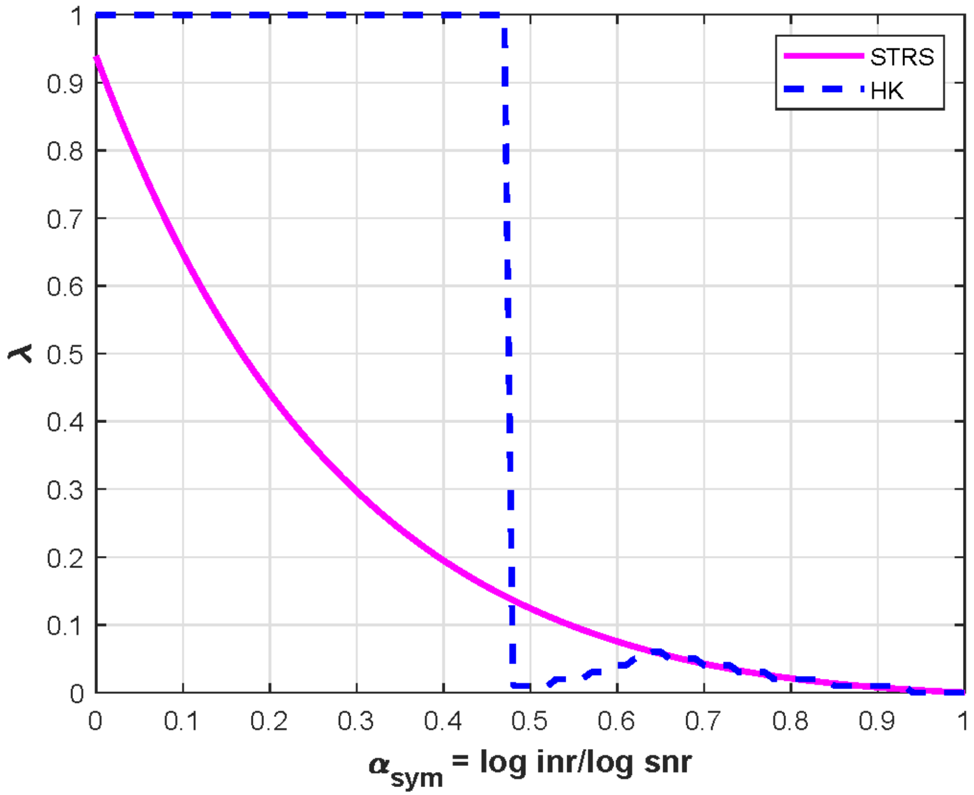
STRS: Numerical Results, Symmetric Case

Symmetric case, 2 users, snr = 15 dB

Sum-rate and GDoF

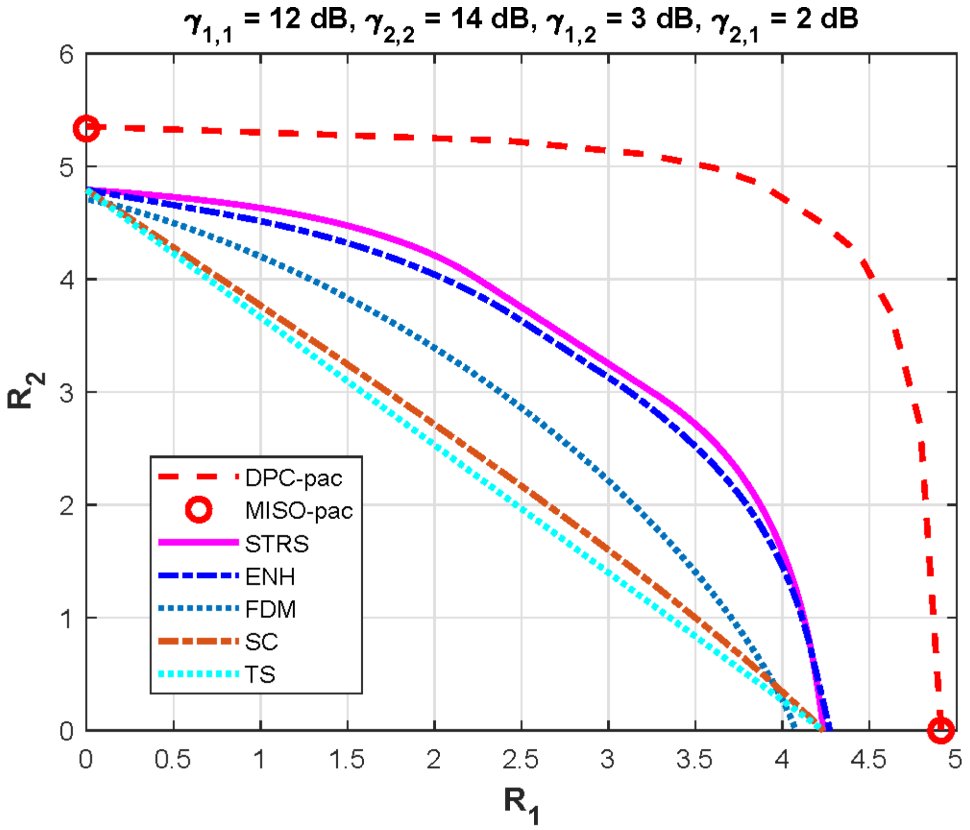


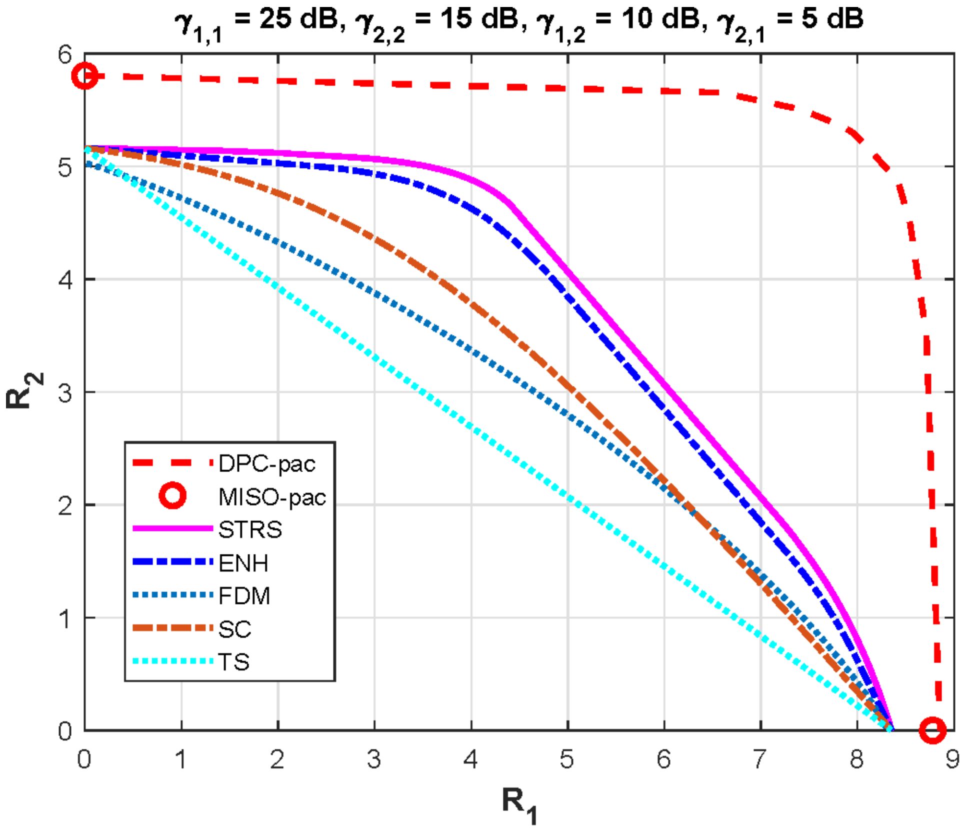
Weighting factor



STRS: Numerical results

Two users. Channel coefficients: random phases

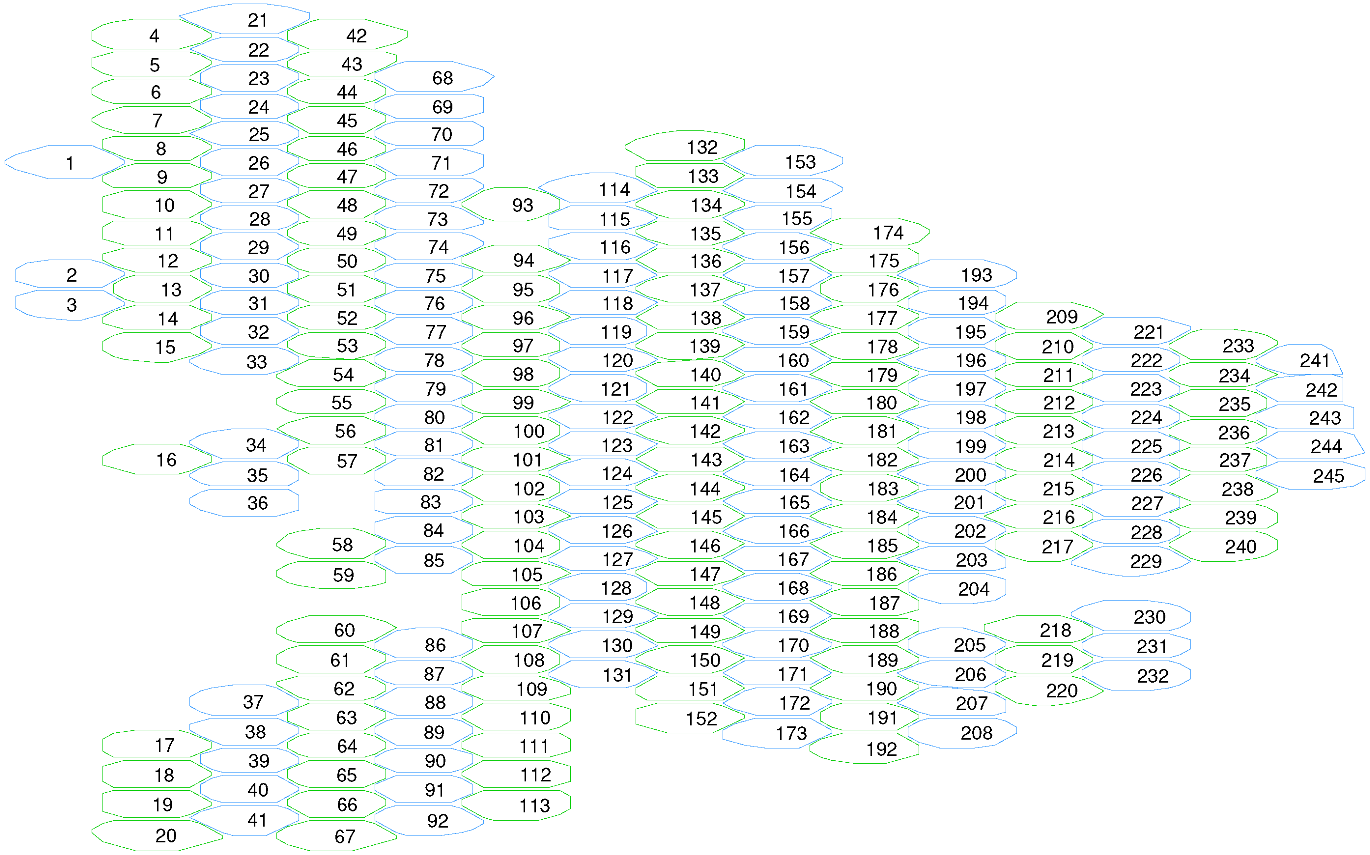


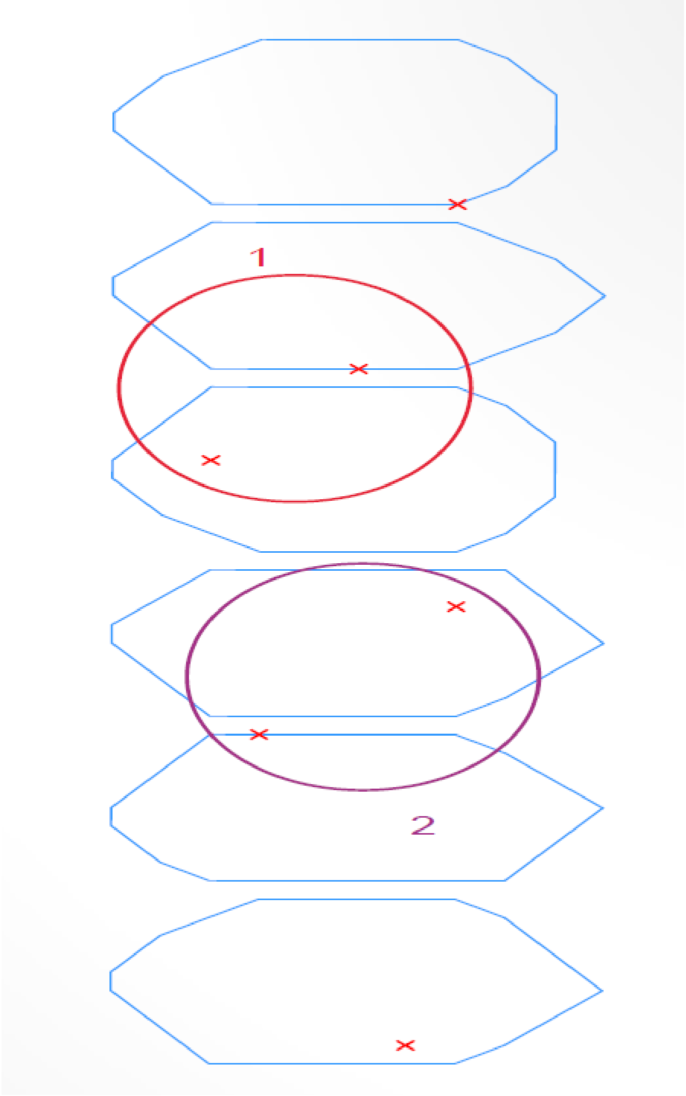


pac: per-antenna power constraint

ENH: A. Gholami Davoodi and S. A. Jafar, "*Transmitter cooperation under finite precision CSIT: A GDoF perspective*," IEEE Trans. Inf. Theory, vol. 63, no. 9, pp. 6020–6030, Sep. 2017.

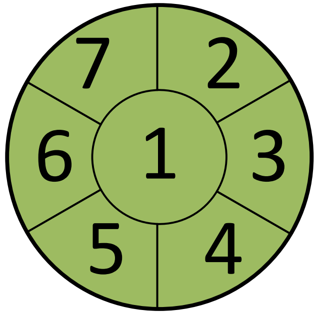
Satellite scenario: system level design



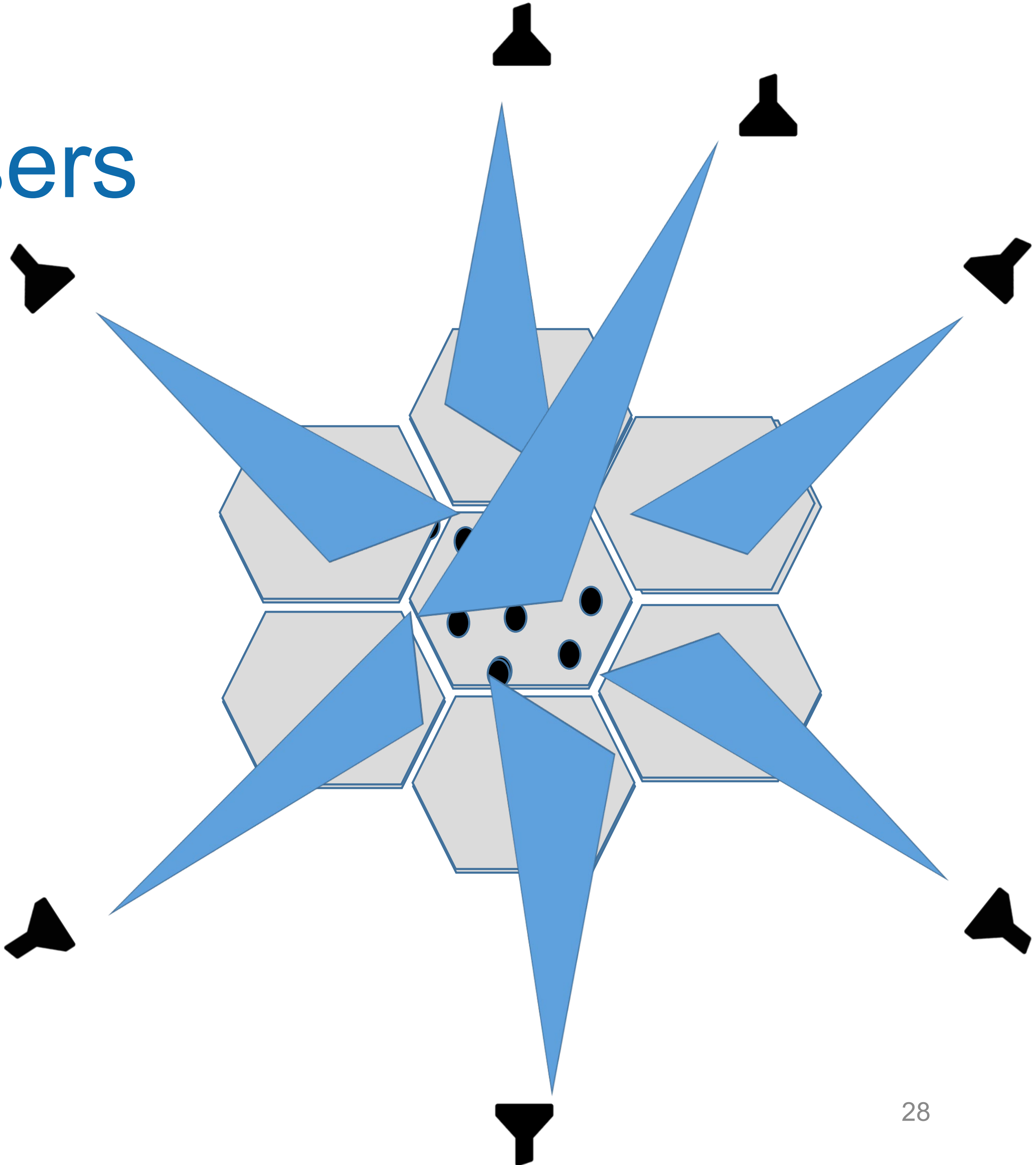


Extension to n>2 users

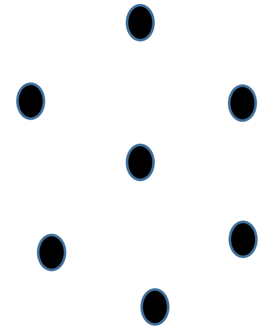
- Traffic non-uniformly distributed
- Hot-spot case
- Sectorization:



$$n = 7 = (6 + 1)$$



Analysis: we assume symmetry



$$\gamma_{11} > \gamma_{22} = \ldots = \gamma_{nn}$$
$$\gamma_{12} = \gamma_{13} = \ldots = \gamma_{1n}$$
$$\gamma_{21} = \gamma_{31} = \ldots = \gamma_{n1}$$

$$\gamma_{ij} = \frac{P}{n}|h_{ij}|^2$$

Central beam

$$x_1 = \sqrt{(1-\lambda_1)\frac{P}{n}}x_{1,c} + \sqrt{\lambda_1\frac{P}{n}}x_{1,p}$$

Outer beams

$$x_j = \sqrt{(1-\lambda_2)\frac{P}{n}}x_{j,c} + \sqrt{\lambda_2\frac{P}{n}}x_{j,p}, j = 2,\ldots,n$$

Optimal solution close to **NOMA:**

$$\boxed{\lambda_1 = 0, \lambda_2 = 1}$$

$$x_1 = \sqrt{\frac{P}{n}}x_{1,c}$$
$$x_j = \sqrt{\frac{P}{n}}x_{j,p}, j = 2,\ldots,n$$

Precoding (full CSIT)

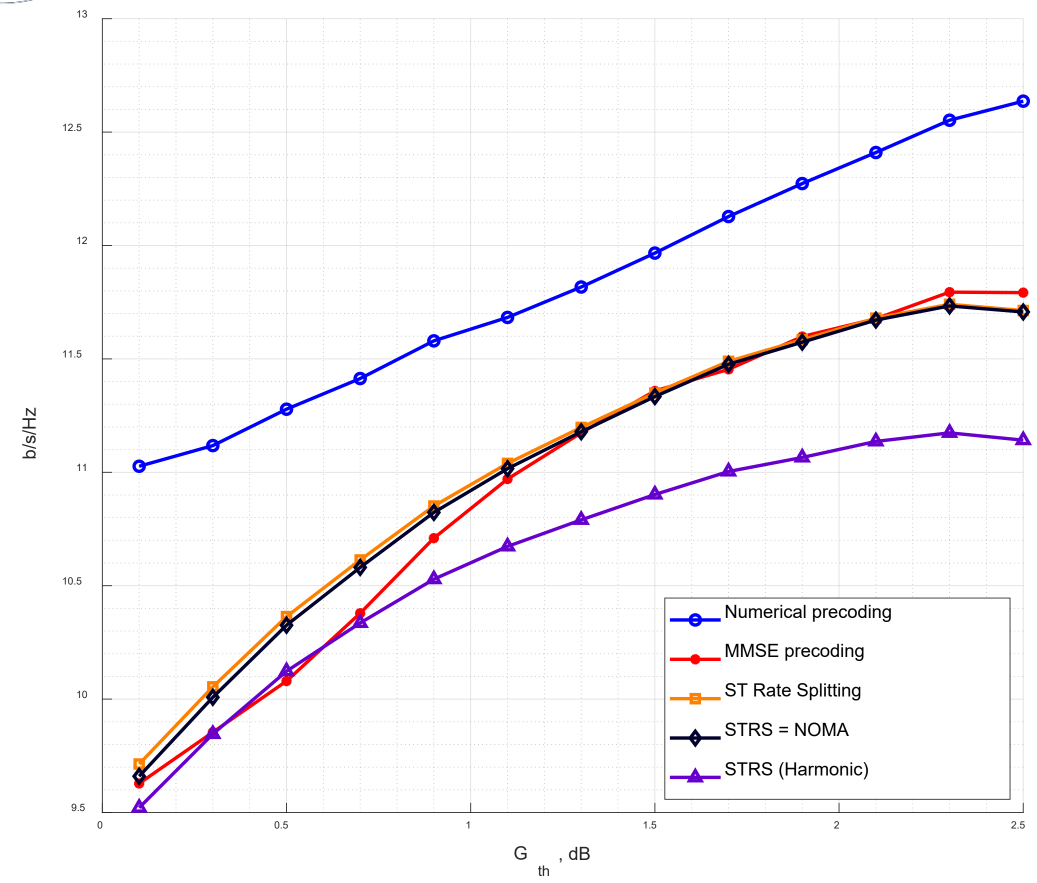
- MMSE precoder (closed form): $\mathbf{F} = \sqrt{\nu}\mathbf{H}^{\mathrm{H}}\left(\mathbf{H}\mathbf{H}^{\mathrm{H}} + \frac{n}{P}\sigma^2\mathbf{I}\right)^{-1}$

- Performance precoder (numerical solution):

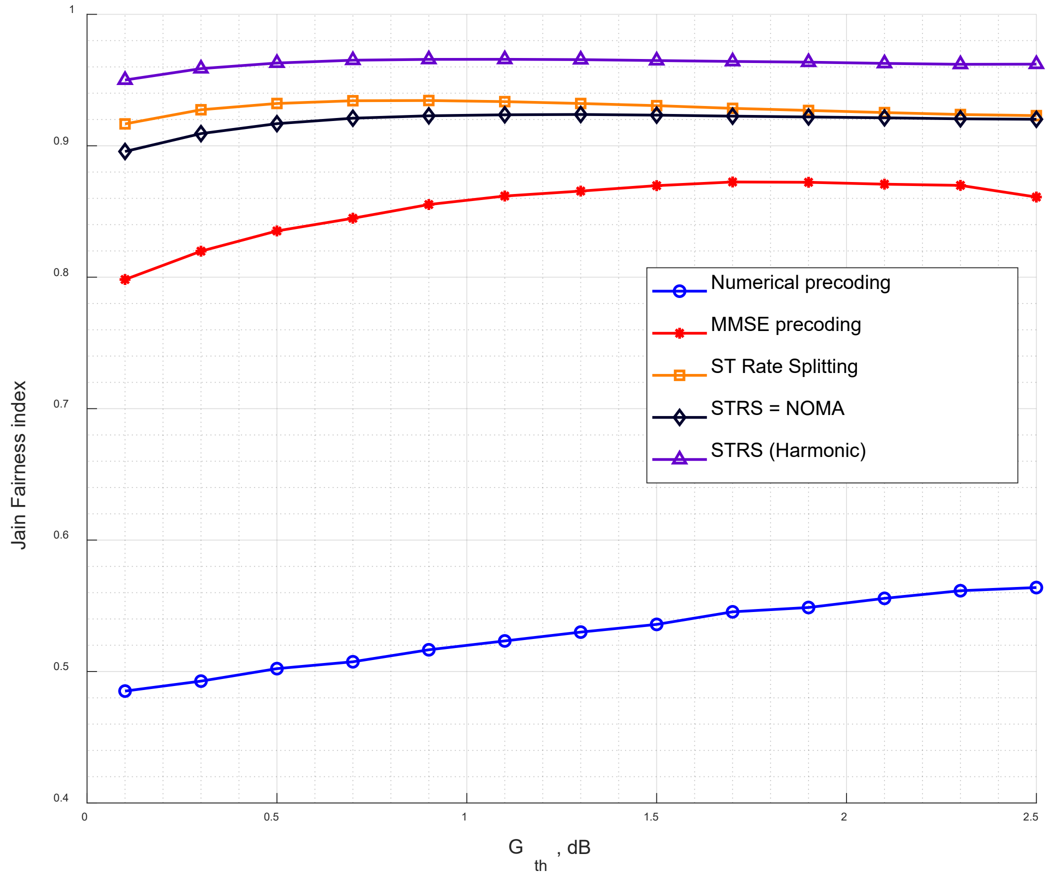
$$\begin{aligned} \boldsymbol{F}_{\mathrm{opt}} \; &= \underset{F}{\operatorname{argmax}} \quad \textstyle\sum_{m=1}^{n} R_m \\ \text{s.t.} \quad & \quad \left\|F_i\right\|^2 \leq \tfrac{P}{n} \\ & \quad R_m = W \log_2\left(1 + \tfrac{|H_m f_m|^2}{\sigma^2 + \sum_{l \neq m} |H_l f_i|^2}\right) \end{aligned}$$

Numerical comparison

Achievable spectral efficiency

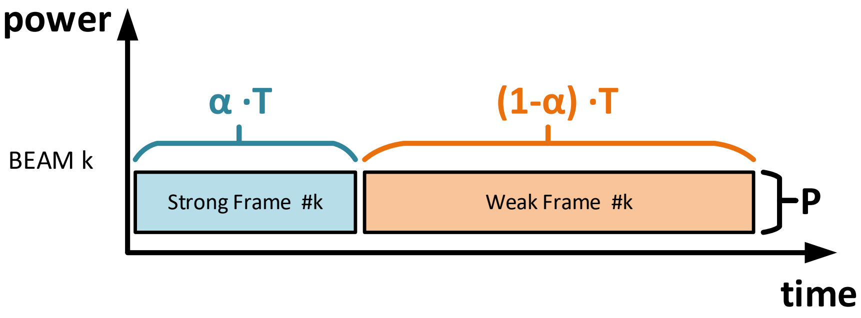


Fairness (Jain index)

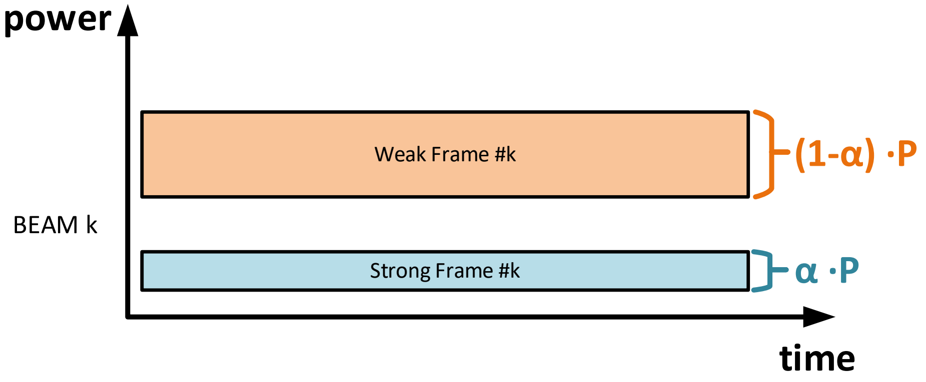


Beam-free approach

NOMA and SNR unbalance

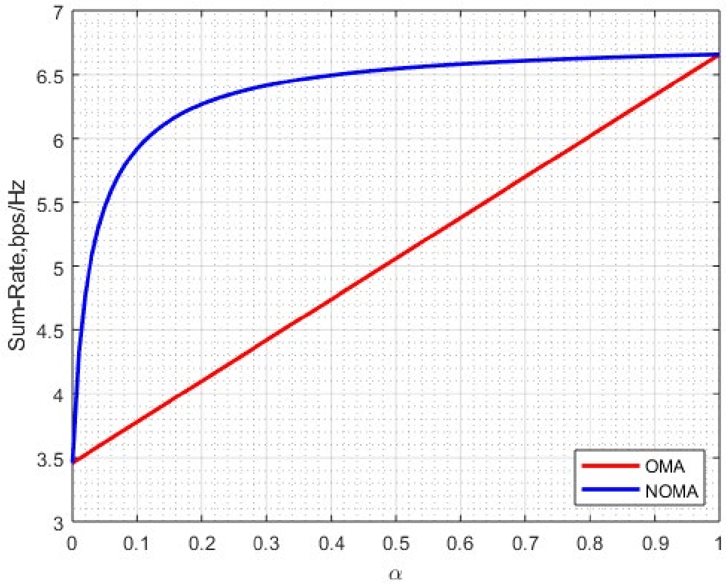


ORTHOGONAL MULTIPLE ACCESS (OMA)



NON-ORTHOGONAL MULTIPLE ACCESS (NOMA)

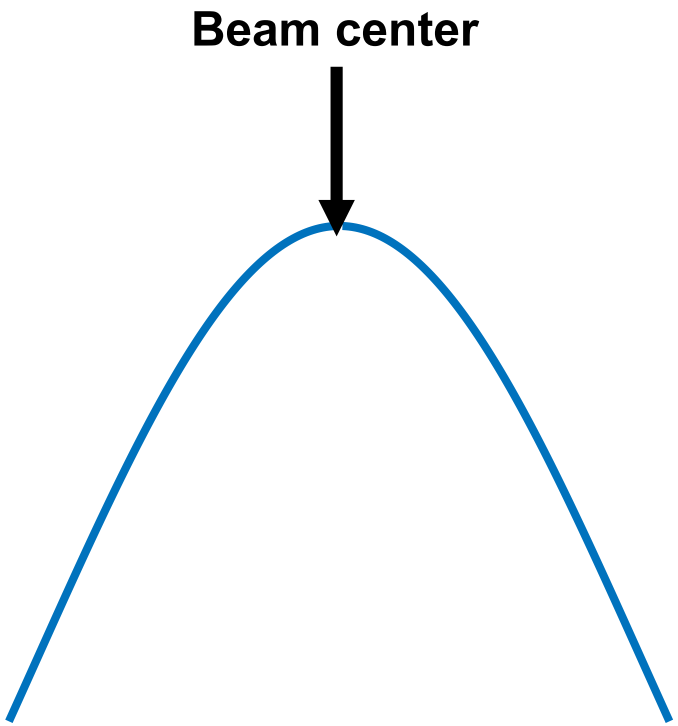
More efficient rate allocation

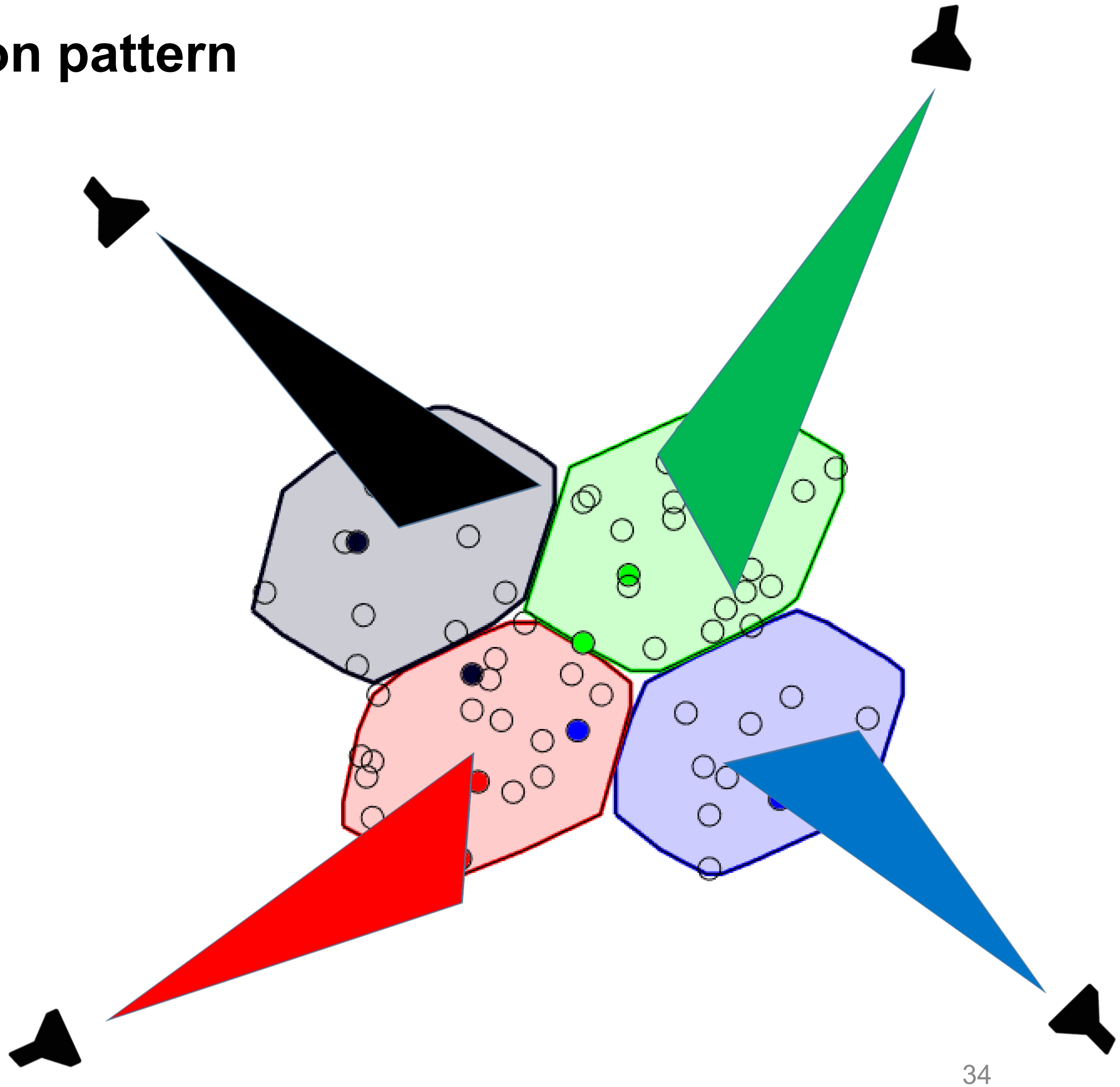


SNR1= 20 dB
(Strong user)

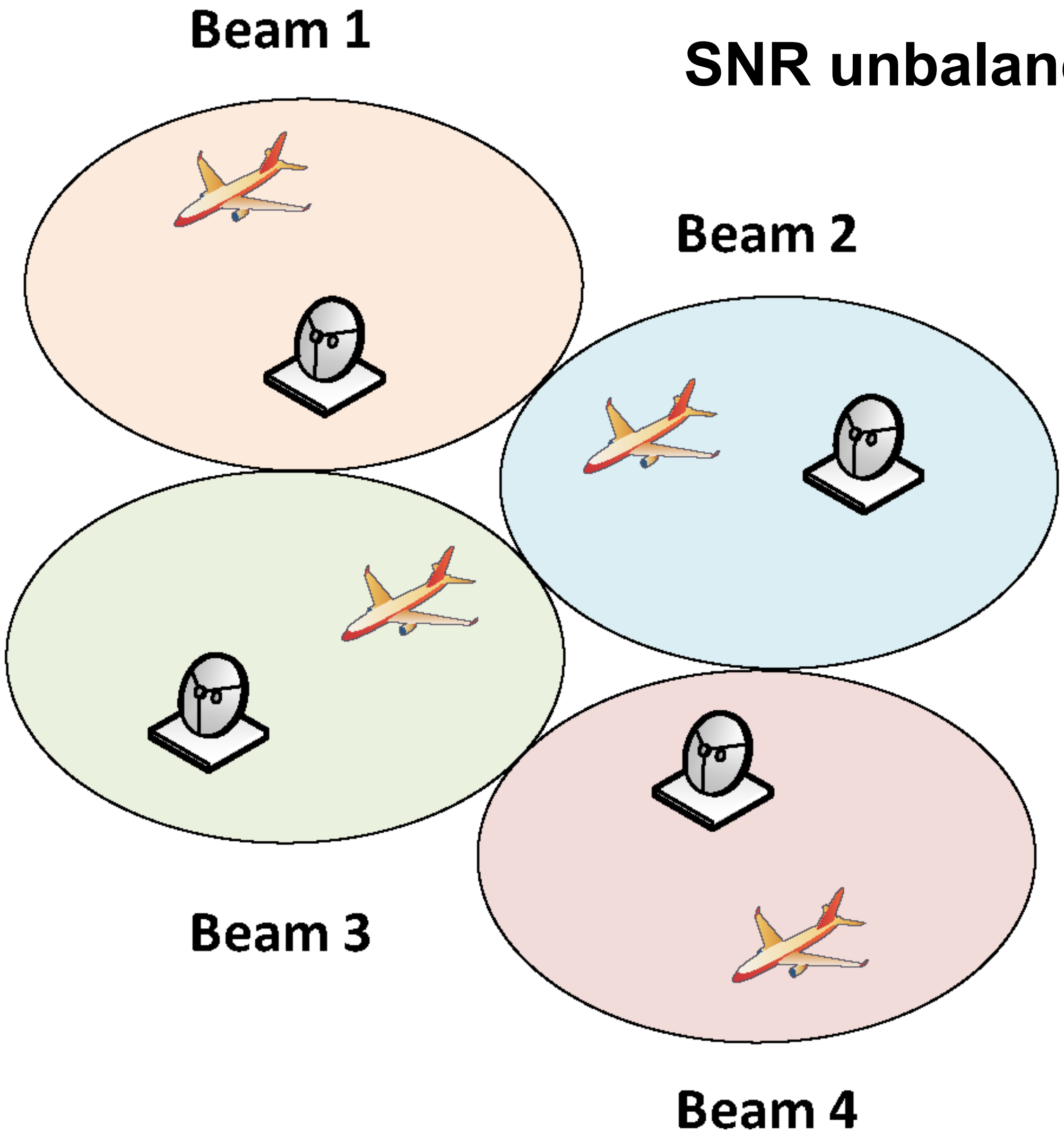
SNR2= 10 dB
(Weak user)

SNR unbalance: beam radiation pattern

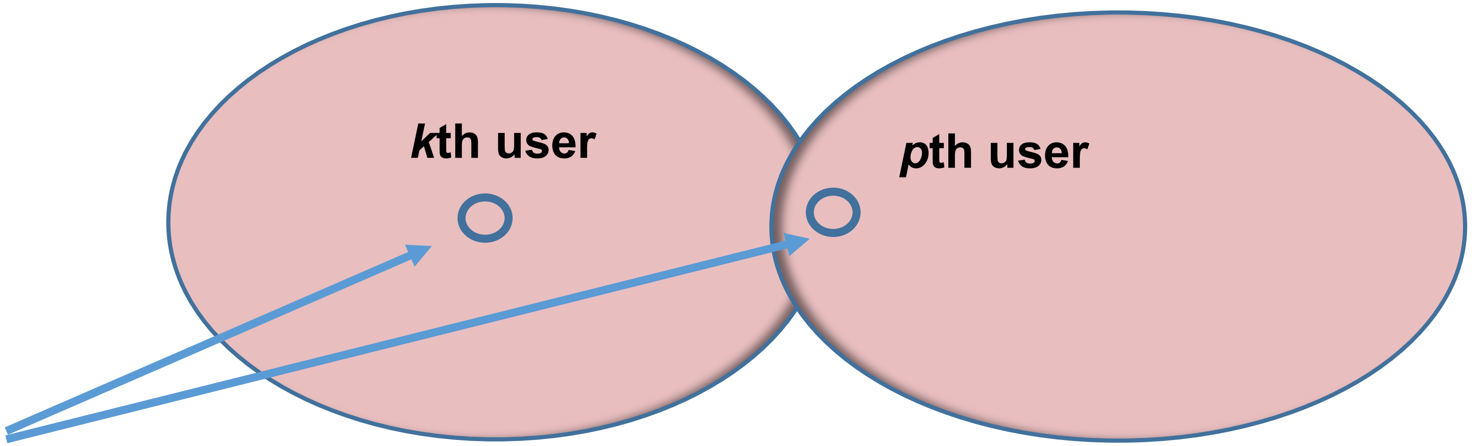




SNR unbalance: different types of terminals



Optimization process



Resource allocation
(user pairing)

Rate optimization: closed form expression for the optimum power allocation to maximize the Weighted Sum Rate

$$\max_{\alpha} w_k r_k(t) + w_p r_p(t)$$

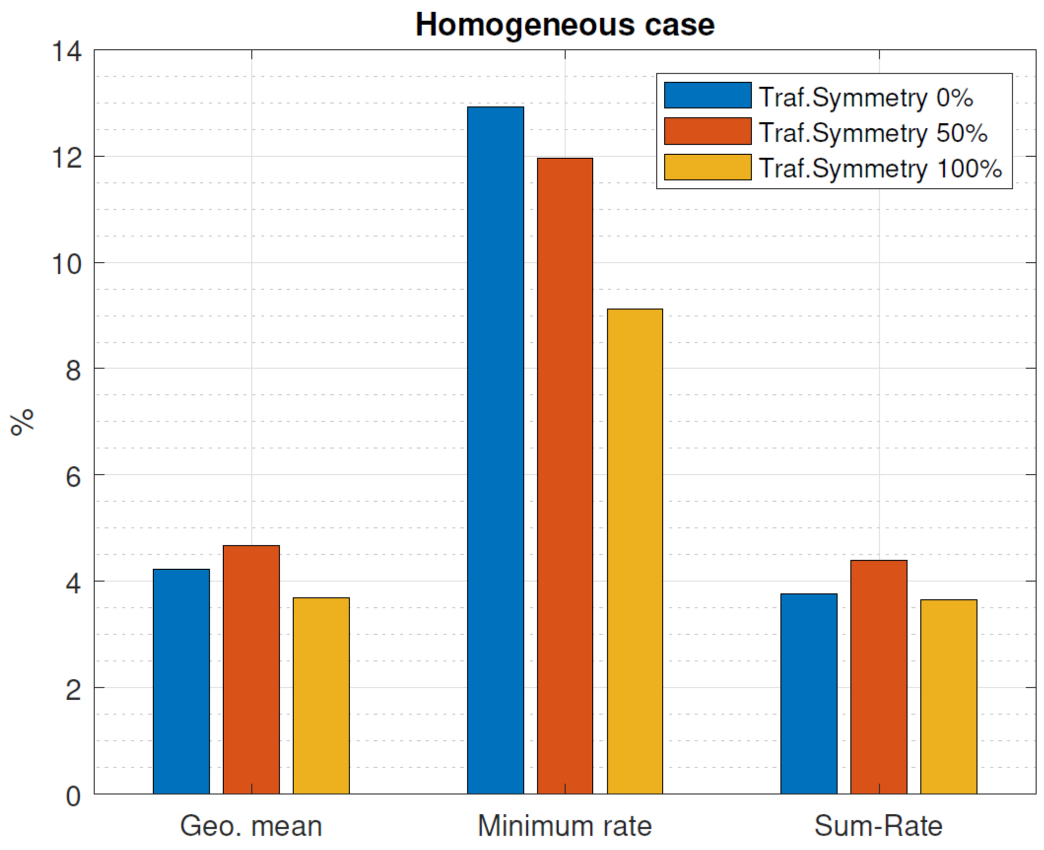
Proportional Fair Scheduling (PFS) policy

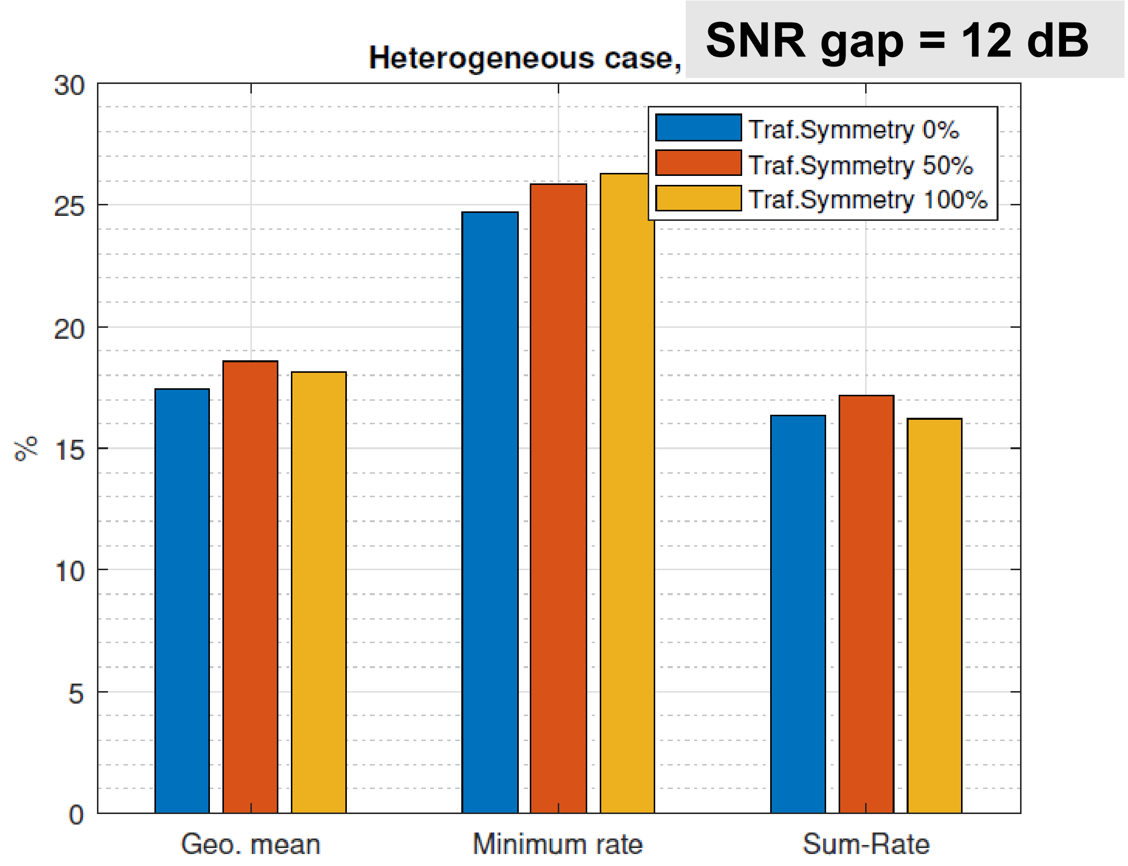
$$F(t) = \sum_{k=1}^{K} \frac{r_k(t)}{R_k(t)} = \sum_{k=1}^{K} w_k(t) r_k(t)$$

Simulations

Number of beams	16
Frequency band	20 GHz
EIRP per beam	62 dBW
Bandwidth per beam	250 MHz
Number of time slots	300
Monte-Carlo simulations	1200
Traffic distribution	Uniform

Numerical results





Sum-rate improvement with respect to Orthogonal Multiple Access

Conclusions

- **Rate Splitting** plays a major role also in phase-blind settings:
  - Overlay cognitive radio
  - MISO broadcast channel
  - Beam-free (cell-free approaches)
- In some specific case, its particular instance, **NOMA**, suffices
- **Link adaptation** can be jointly applied with the exposed techniques
- The selection of users is particularly relevant
- Drawback: users need to apply at least one stage of interference cancellation

References

- C. Mosquera, N. Noels, T. Ramírez, M. Caus and A. Pastore, **"Space-Time Rate Splitting for the MISO BC With Magnitude CSIT,"** in IEEE Transactions on Communications, vol. 69, no. 7, pp. 4417-4432, July 2021.
- T. Ramírez and C. Mosquera, **"Resource Management in the Multibeam NOMA-based Satellite Downlink,"** IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2020, pp. 8812-8816.
- T. Ramírez, Mosquera, C., Caus, M., Pastore, A., Alagha, N., and Noels, N., **“Adjacent Beams Resource Sharing to Serve Hot Spots : A Rate Splitting Approach”**, in 36th International Communications Satellite Systems Conference (ICSSC), 2018.
- Ramírez, T., Mosquera, C., Caus, M., Pastore, A., Navarro, M., and Noels, N. **“Message-splitting for interference cancellation in multibeam satellite systems”.** In 9th Advanced Satellite Multimedia Systems Conference and the 15th Signal Processing for Space Communications Workshop (ASMS/SPSC), IEEE, 2018.
- Alberto Rico-Alvariño and Carlos Mosquera. **"Overlay spectrum reuse in a broadcast network: covering the whole grayscale of spaces."** IEEE International Symposium on Dynamic Spectrum Access Networks, 2012.