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Optimal Resource Allocation in Distributed Heterogeneous 5G Wireless Networks

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Communications Theory

5G Lab GERMANY

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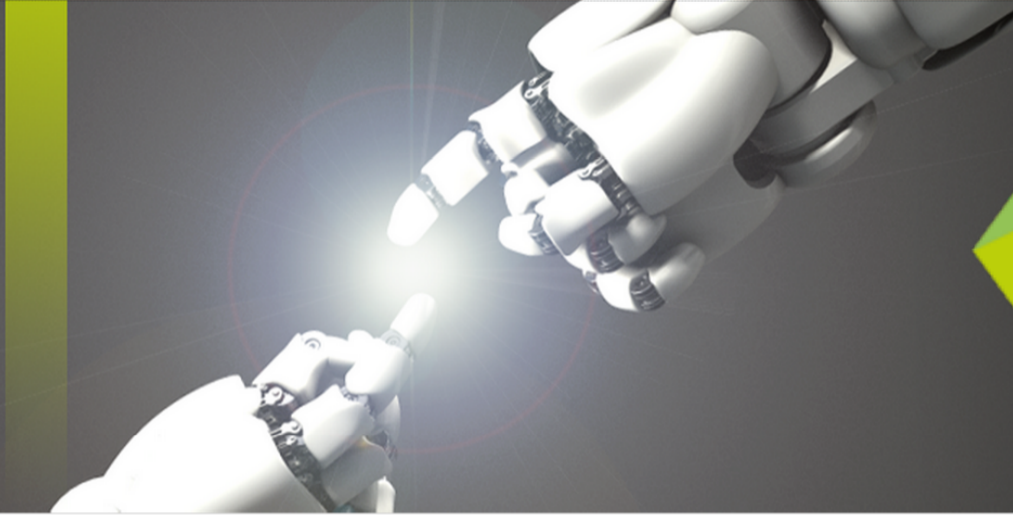
Holistic View on 5G



5G LAB GERMANY

5G *Use Cases*

5G *Requirements*

Wireless

Network

Silicon

Cloud

5G *Holistic View*

20 Profs.;500 Researchers ;25+ Start Ups

Data Rate

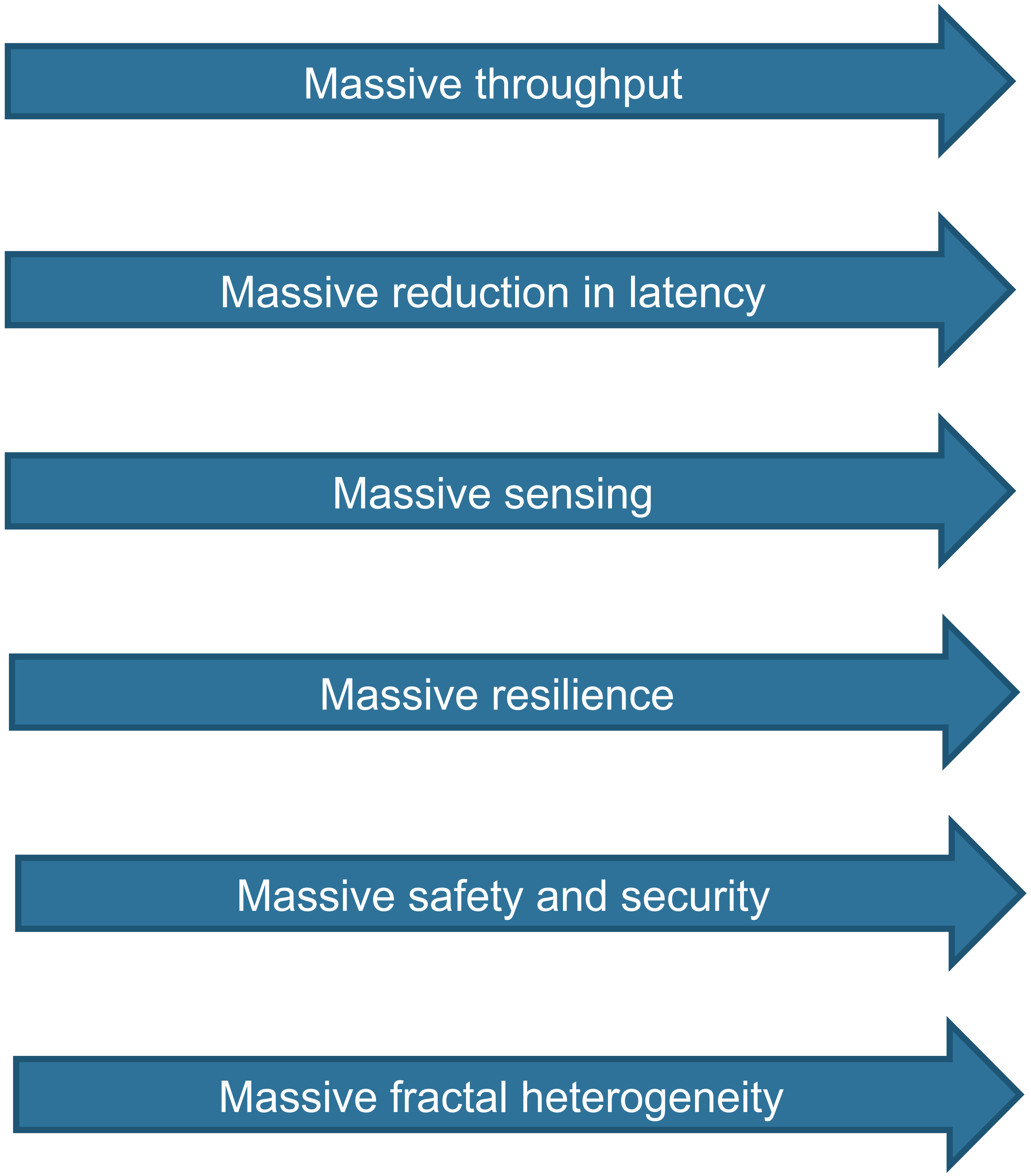
Latency

Security

Reliability

Heterogeneity

5G Massive Challenges - Solutions Approaches



5G Massive Challenges - Solutions Approaches

Massive throughput

Massive MIMO, Full-Duplex

Massive reduction in latency

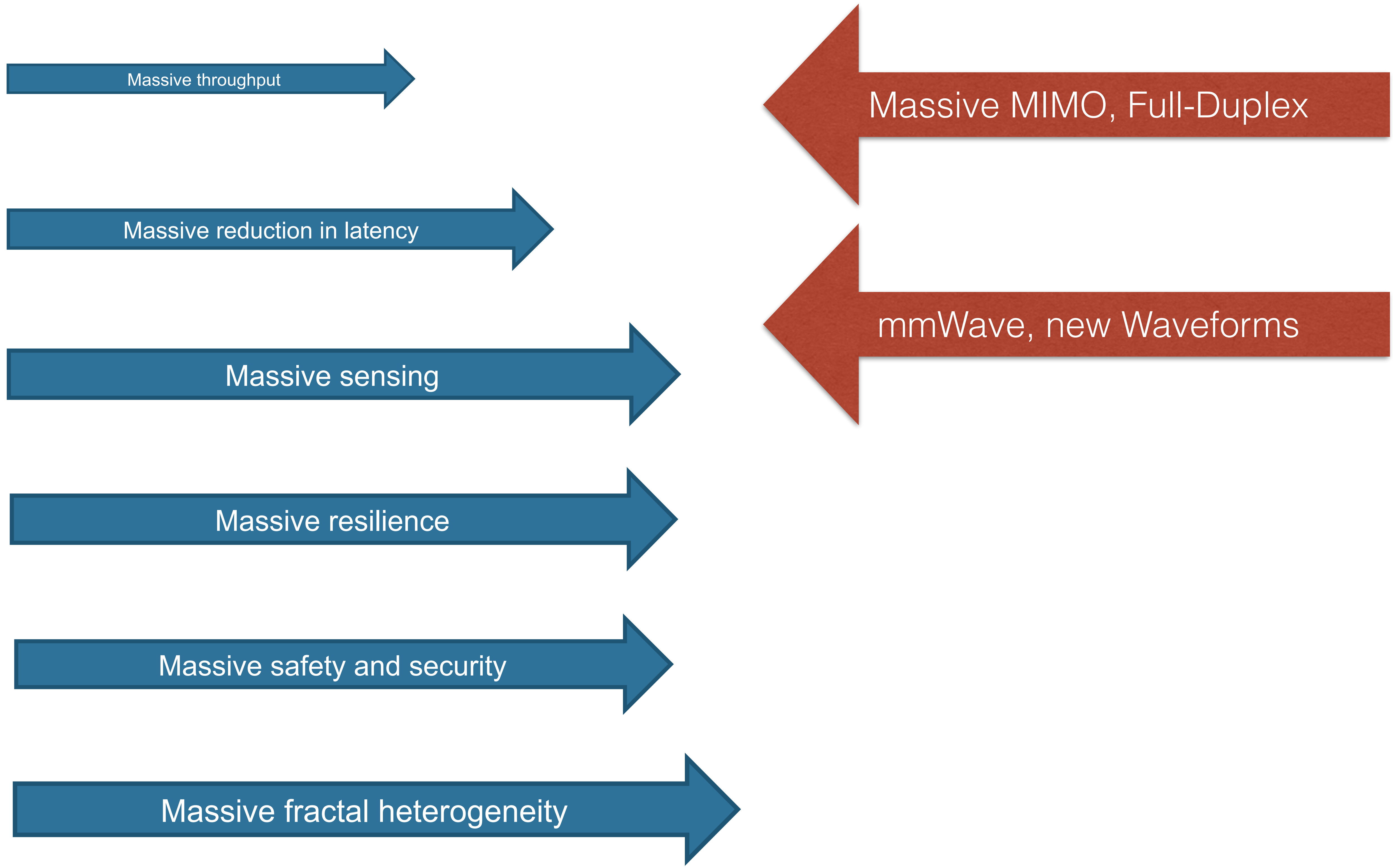
Massive sensing

Massive resilience

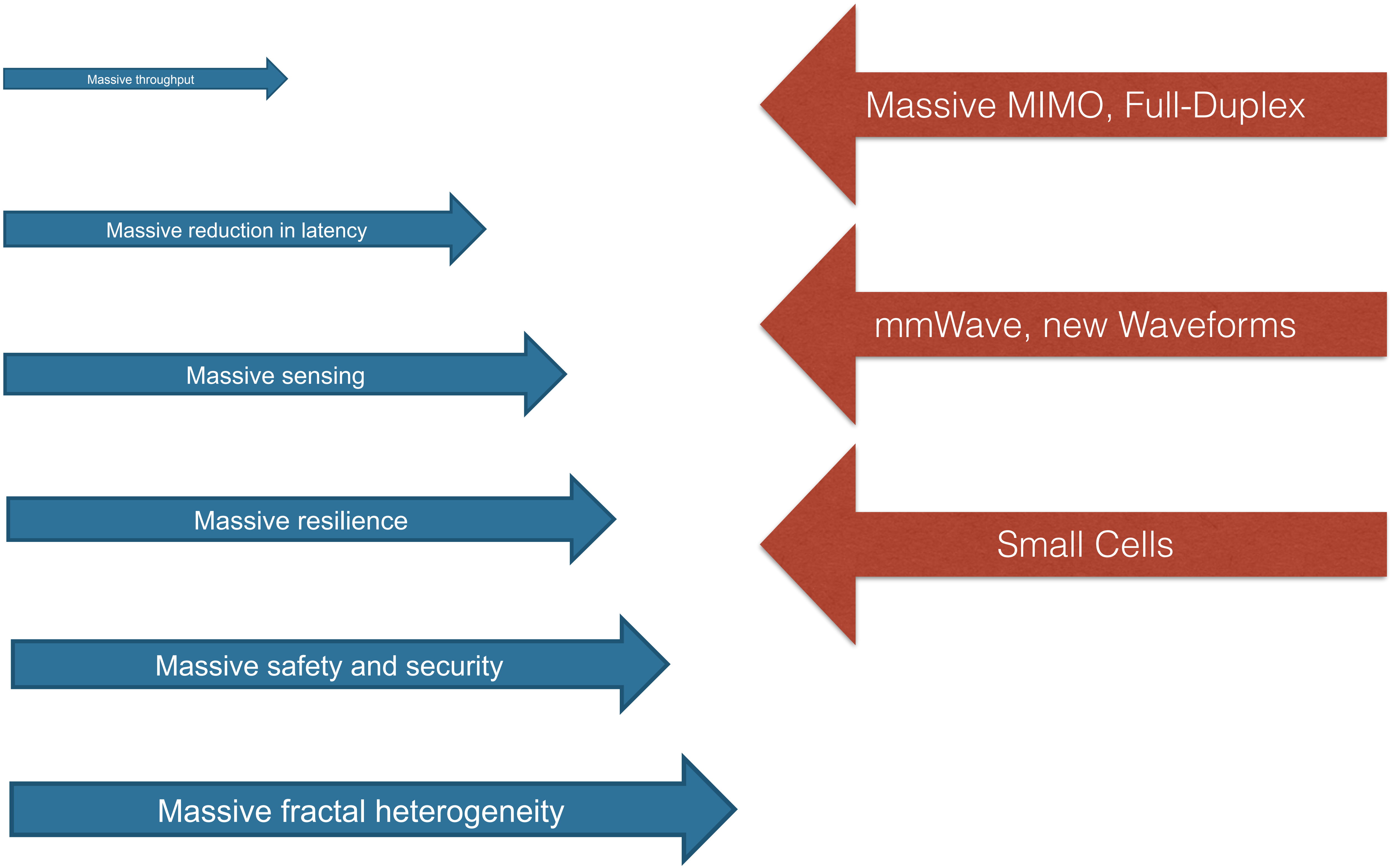
Massive safety and security

Massive fractal heterogeneity

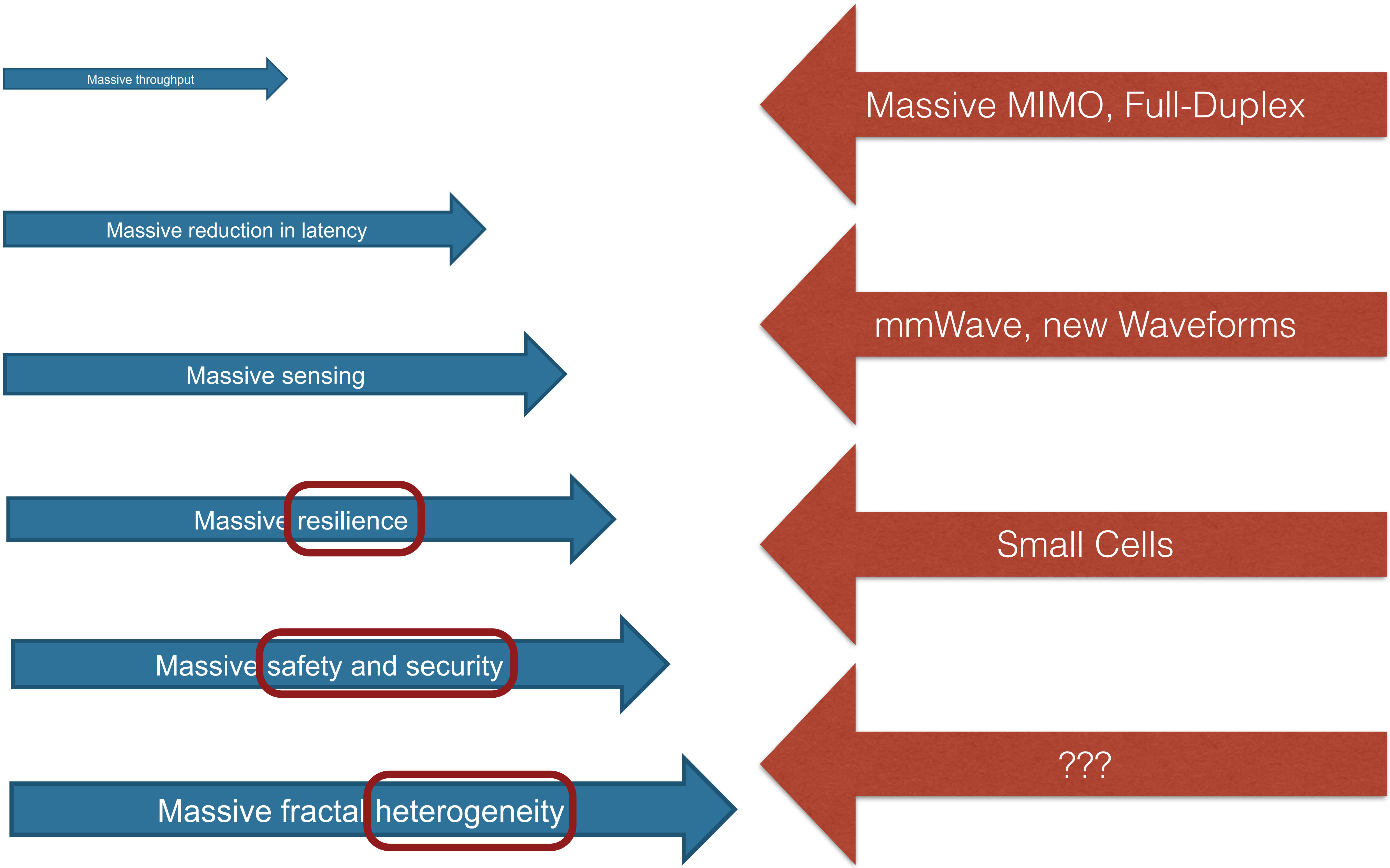
5G Massive Challenges - Solutions Approaches



5G Massive Challenges - Solutions Approaches



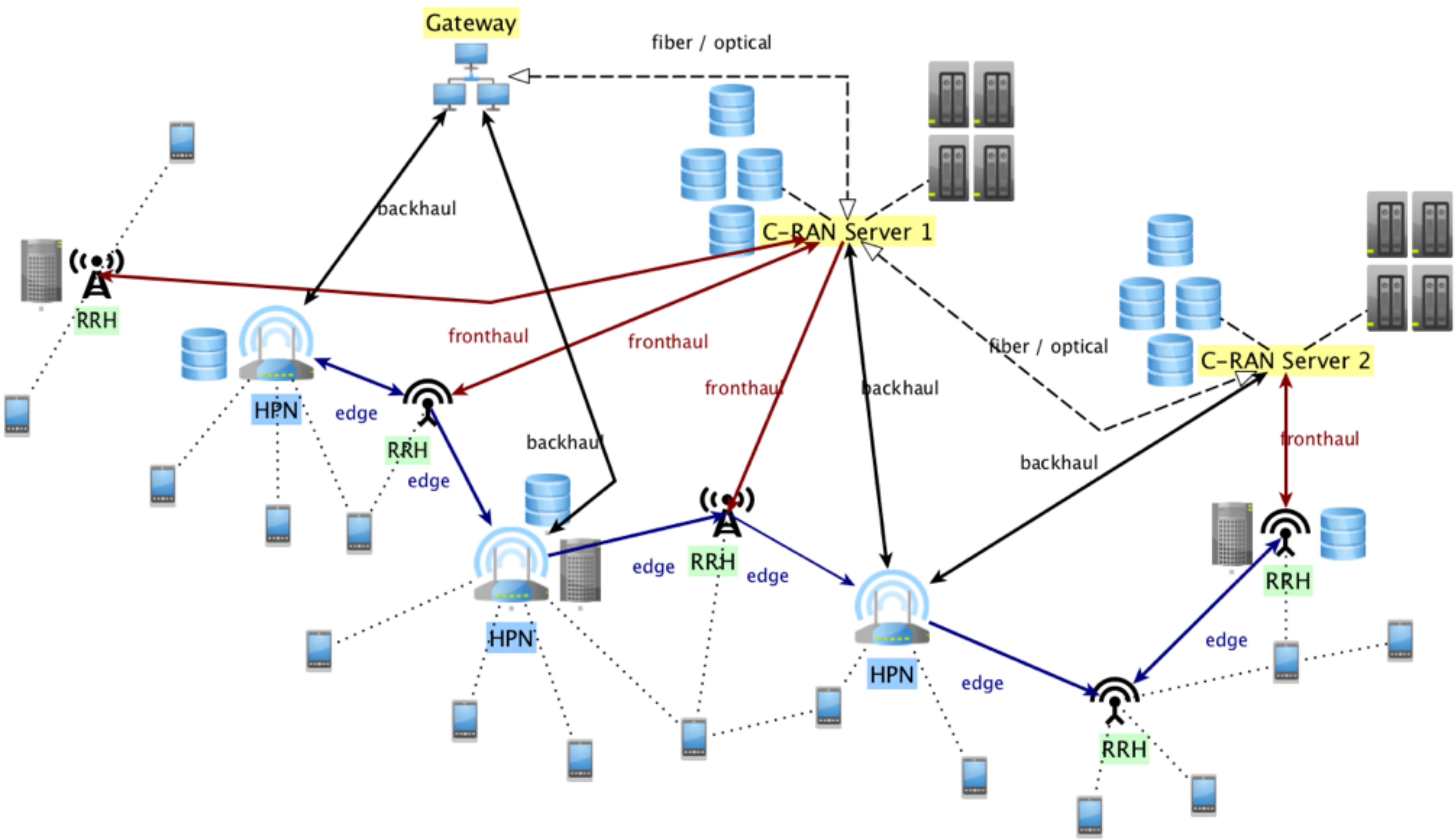
5G Massive Challenges - Solutions Approaches



Outline

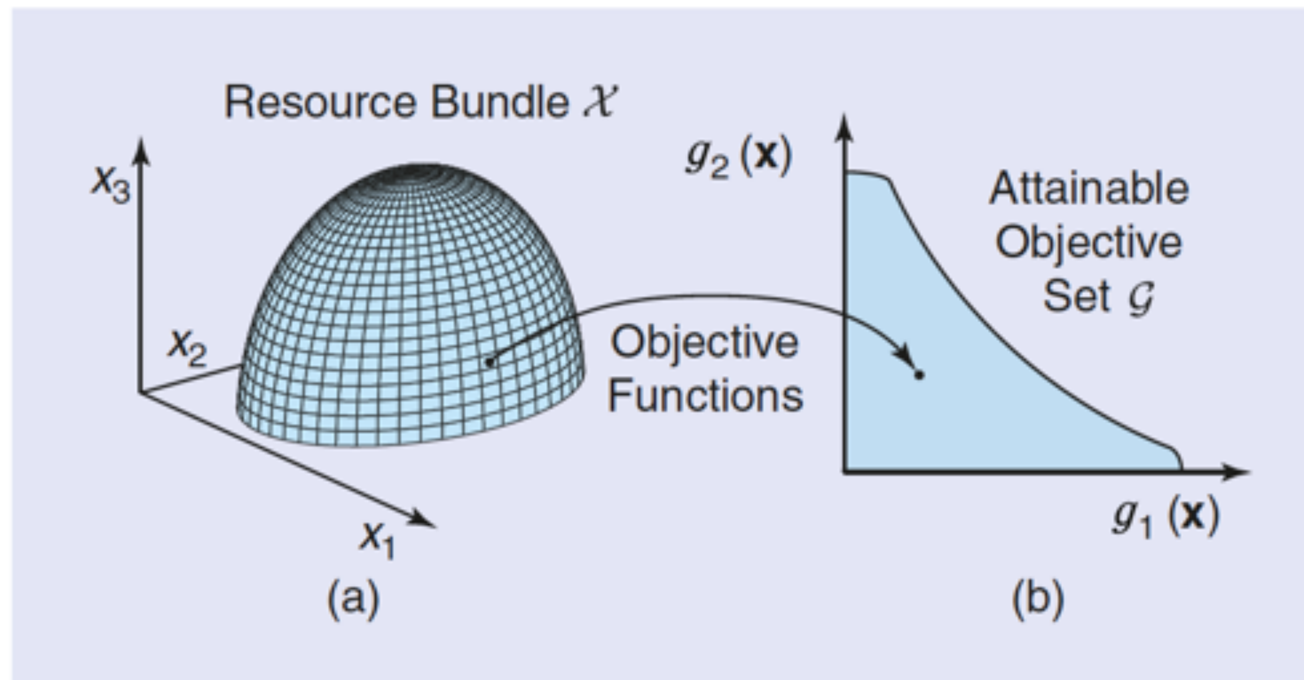
- **Introduction**
  - Heterogeneity (networks, users, services, …)
  - Multi-Objective Optimization
- **Framework for Energy-Efficient Resource Allocation**
  - Centralized and Distributed Power Control
- **Conclusions**

Heterogenous Networks



Heterogeneous Services

- **Conflicting** performance metrics/requirements:
  - Data rate / throughput
  - Delay / latency
  - Energy efficiency
  - Security



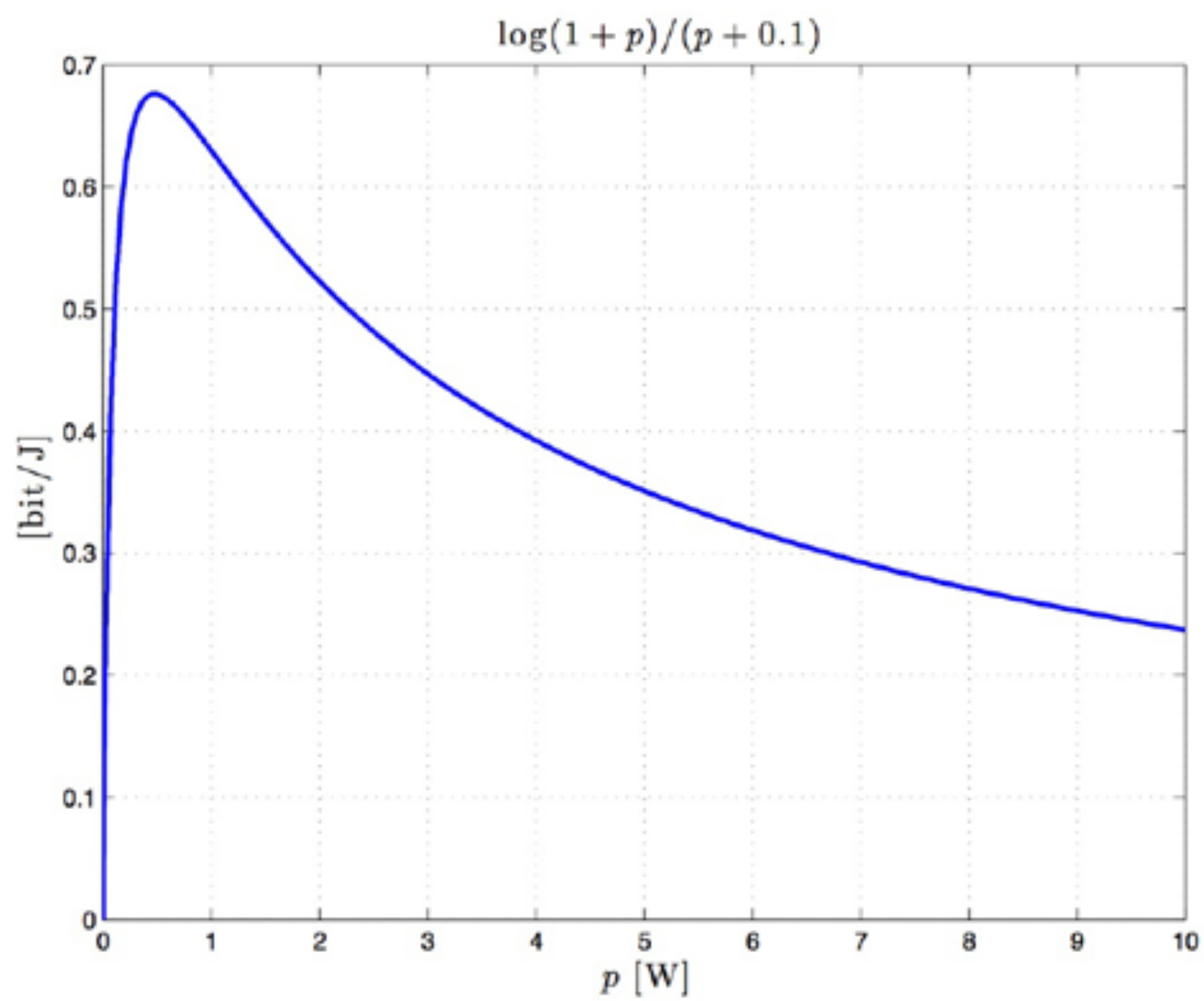
- **Multi-Objective Programming** (MOP) problem

E. Björnson, E. Jorswieck, M. Debbah, B. Ottersten, "Multi-Objective Signal Processing Optimization: The Way to Balance Conflicting Metrics in 5G Systems", IEEE Signal Processing Magazine, vol. 31, no. 6, pp. 14-23, Nov. 2014.

Energy-efficiency of a link

In line with the physical meaning of efficiency, the **energy efficiency is defined** as the system benefit-cost ratio in terms of amount of data reliably transmitted over the energy that is required to do so.

$$EE = \frac{f(\gamma(p))}{\alpha p + P_c}$$



Energy-efficiency of a network

- Global Energy-efficiency

$$\text{GEE} = \frac{\sum_{k=1}^{K} f(\gamma_k(\{p_k\}_{k=1}^{K}))}{\sum_{k=1}^{K} \alpha_k p_k + P_{c,k}}$$

- Weighted arithmetic mean

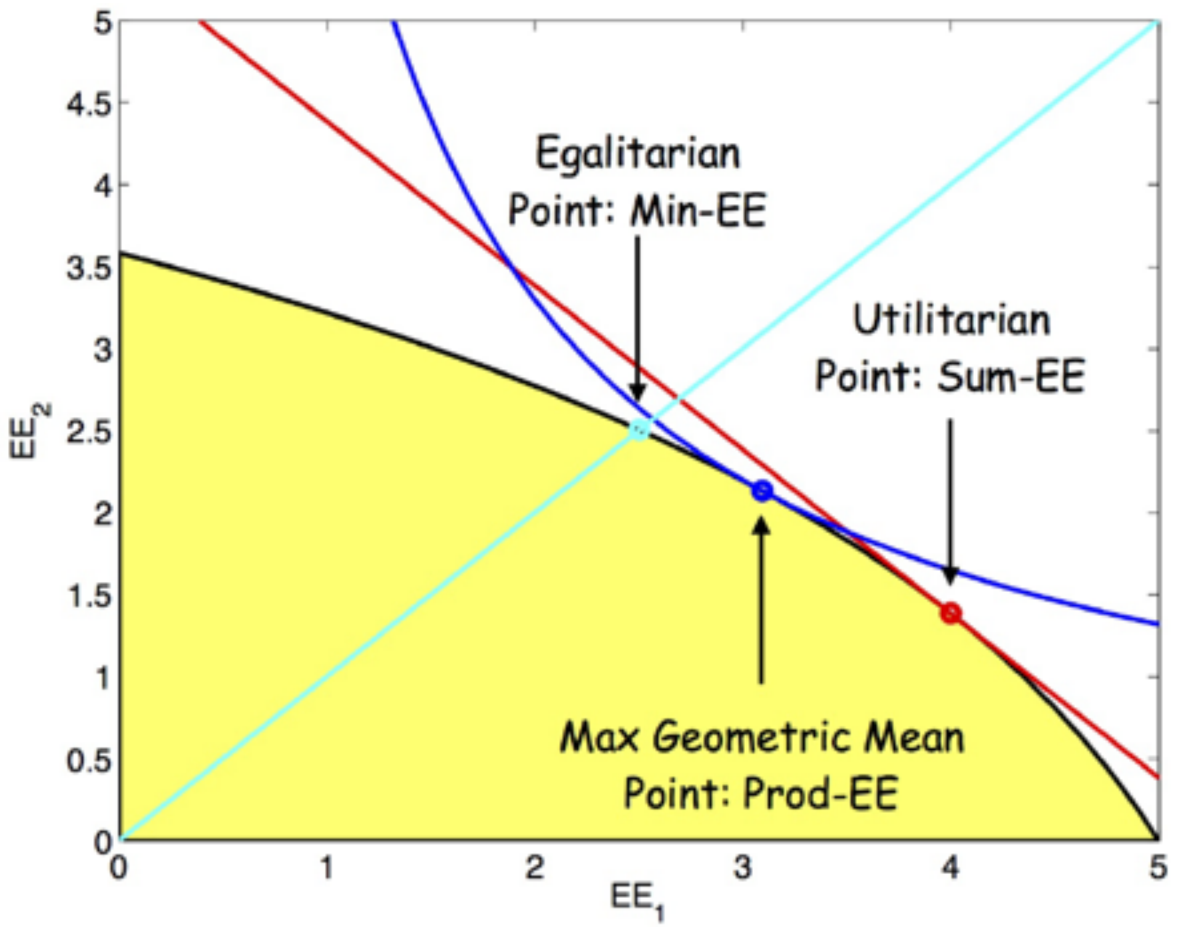
$$\text{Sum-EE} = \sum_{k=1}^{K} w_k \frac{f(\gamma_k(\{p_k\}_{k=1}^{K}))}{\alpha_k p_k + P_{c,k}}$$

- Weighted geometric mean

$$\text{Prod-EE} = \prod_{k=1}^{K} \left(\frac{f(\gamma_k(\{p_k\}_{k=1}^{K}))}{\alpha_k p_k + P_{c,k}} \right)^{w_k}$$

- Weighted minimum EE

$$\text{Min-EE} = \min_k \left(w_k \frac{f(\gamma_k(\{p_k\}_{k=1}^{K}))}{\alpha_k p_k + P_{c,k}} \right)$$



Observation: always ratios

Fractional Programming

Single ratio: concave fractional problems

CFP

$f(\boldsymbol{x}) \geq 0$, $g(\boldsymbol{x}) > 0$, differentiable functions. f, concave, g, h_k convex for all $k = 1, \ldots, K$.

$$\begin{cases} \max_{\boldsymbol{x}} \dfrac{f(\boldsymbol{x})}{g(\boldsymbol{x})} \\ \text{s.t. } h_k(\boldsymbol{x}) \leq 0 \ , \ \forall\, k = 1, \ldots, K \end{cases}$$

- The objective is **pseudo-concave**.
- A local maximum is also a global maximum and **KKT conditions are necessary and sufficient**.

C. Isheden, Z. Chong, E. Jorswieck, G. Fettweis, "Framework for Link-Level Energy Efficiency Optimization with Informed Transmitter", IEEE Trans. on Wireless Communications, vol. 11, no. 8, pp. 2946-2957, Aug. 2012.

Parametric approach: Dinkelbach's algorithm

Consider the function

$$F(\lambda) = \max_{\boldsymbol{x}}\{(f(\boldsymbol{x}) - \lambda g(\boldsymbol{x})) \;:\; h_k(\boldsymbol{x}) \leq 0\;,\; \forall\, k = 1, \ldots, K\} \tag{1}$$

There exists a unique, positive λ^* such that $F(\lambda^*) = 0$ and an optimal solution of (1) with $\lambda = \lambda^*$ solves the CFP.

- This method allows to solve a CFP by converting it into a **sequence of convex problems**

- Solving a CFP is equivalent to **finding the zero** of the function $F(\lambda)$.

Dinkelbach's algorithm

$\epsilon > 0$; $n = 0$; $\lambda_n = 0$;
repeat
  $\boldsymbol{x}_n^* = \arg\max_{\boldsymbol{x}} \{f(\boldsymbol{x}) - \lambda_n g(\boldsymbol{x}) \;:\; h_k(\boldsymbol{x}) \leq 0\;,\; \forall\, k = 1, \ldots, K\}$;
  $F(\lambda_n) = f(\boldsymbol{x}_n^*) - \lambda_n g(\boldsymbol{x}_n^*)$;
  $\lambda_{n+1} = \dfrac{f(\boldsymbol{x}_n^*)}{g(\boldsymbol{x}_n^*)}$;
  $n = n + 1$;
until $F(\lambda_n) < \epsilon$

W. Dinkelbach, „On nonlinear fractional programming,"
Management Science, vol. 13, no. 7, pp. 492 - 498, March 1967

Insights into Dinkelbach's algorithm

- The update rule for λ follows **Newton's method**.

$$\lambda_{n+1} = \lambda_n - \frac{F(\lambda_n)}{F'(\lambda_n)} = \lambda_n - \frac{f(\mathbf{x}_n^*) - \lambda_n g(\mathbf{x}_n^*)}{-g(\mathbf{x}_n^*)} = \frac{f(\mathbf{x}_n^*)}{g(\mathbf{x}_n^*)}$$

- **Super-linear convergence** rate.

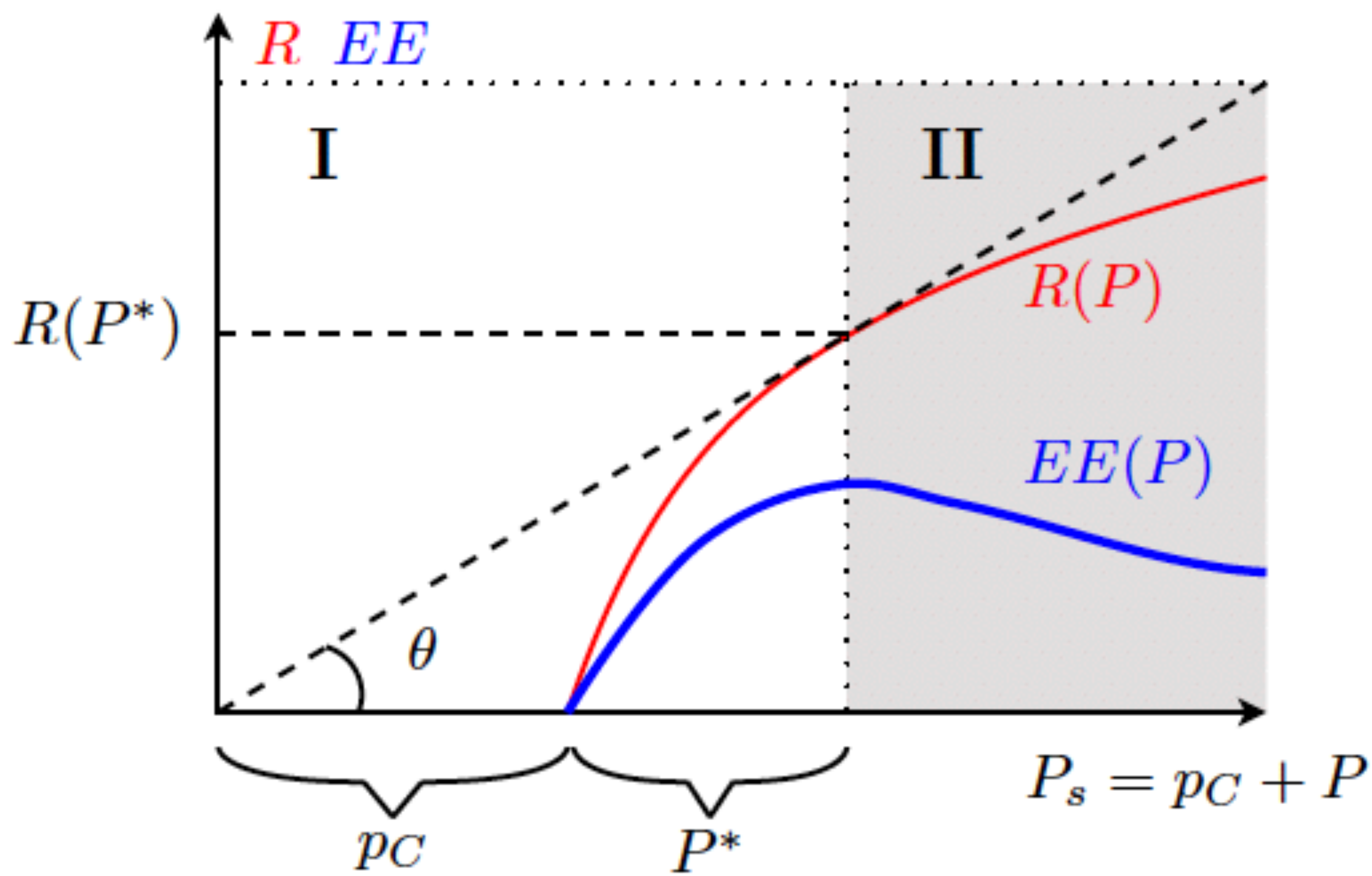
- The algorithm works for **general FP**, too. However, we have to compute F(λ)…

- … if the problem is not a CFP, we can still use Dinkelbach, but in each iteration we need to **globally solve a non-convex problem**

$$F(\lambda) = \max_{\mathbf{x}} \{ f(\mathbf{x}) - \lambda g(\mathbf{x}) : h_k(\mathbf{x}) \leq 0, \forall k = 1, ..., K \}$$

Application

Energy-Efficient Power Control in 5G



Power Control for Energy Efficiency

- Power control for energy efficiency can be performed in a **centralized** or **decentralized** manner. Both approaches are of interest in the context of 5G networks, for which
    - **network centric techniques** like Cloud-RAN and cooperative multipoint (CoMP) [1], as well as
    - **user-centric techniques** like device-to-device (D2D) [2] and the use of femto-cells [3], have been proposed.

[1] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," IEEE J. Sel. Areas Commun., vol. 28, no. 9, Dec. 2010.

[2] F. Boccardi, R. W. H. Jr., A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," IEEE Communications Magazine, vol. 52, no. 2, pp. 74–80, February 2014.

[3] J. Hoydis, M. Kobayashi, and M. Debbah, "Green small-cell networks," IEEE Vehicular Technology Magazine, vol. 6, no. 1, pp. 37 – 43, March 2011.

Network-centric GEE Model

SINR of transmitter *k* on resource *n*

received signal power channel gain times transmit power

$$\gamma_{k,n} = \frac{\alpha_{k,n} p_{k,n}}{\sigma^2_{k,n} + \phi_{k,n} p_{k,n} + \sum_{j \neq k} \omega_{kj,n} p_{j,n}}$$

noise power

self-interference

interference from other active links

bandwidth

SINR tx *k* rs *n*

Global energy efficiency

$$\psi \triangleq \frac{\sum_{k=1}^{K} \sum_{n=1}^{N} B \log_2 (1 + \gamma_{k,n})}{p_c + \sum_{k=1}^{K} \mathbf{1}^T \mathbf{p}_k}$$

total circuit power dissipated

transmit power allocation

Applications to 5G Technologies I

- **Massive MIMO** (uplink, *S* cells, *M* antennas, *K* users)
  - Channel of UE *j* in cell *l* to BS *i* : $\mathbf{h}_{ilj}$
  - MMSE-based **channel estimation**
  - **SINR expression** holds with

large scale fading

$$\rho_{iik} = \frac{d_{iik}}{\tau + \sum_l d_{ilk}}$$

pilot sequence parameter

$$\alpha_k = \rho_{iik}^2 \ , \quad \omega_{kj} = d_{ilj}\rho_{iik}$$

$$\phi_k = d_{iik}\rho_{iik} + \sum_{l \neq i} \rho_{ilk}^2$$

J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?" IEEE Journal on Selected Areas in Communications, vol. 31, no. 2, pp. 160 – 171, February 2013.

Applications to 5G Technologies II

- **Two-hop multi-point to multi-point network** with S BSs with M antennas using N subcarriers, K UEs, exploiting a SISO AF relay.

- **SINR model** applies with $\sigma_{k,n}^2 = \sigma_n^2(p_{r,n}|\mathbf{c}_{k,n}^H \mathbf{h}_{i_k,n}|^2 + \sigma_{i_k,n}^2 \|\mathbf{c}_{k,n}\|^2)$

$$\alpha_{k,n} = p_{r,n}|h_{k,n}|^2 |\mathbf{c}_{k,n}^H \mathbf{h}_{i_k,n}|^2 \ , \quad \phi_{k,n} = \sigma_{i_k,n}^2 |h_{k,n}|^2 \|\mathbf{c}_{k,n}\|^2$$

$$\omega_{kj,n} = \left(p_{r,n}|\mathbf{c}_{k,n}^H \mathbf{h}_{i_k,n}|^2 + \sigma_{i_k,n}^2 \|\mathbf{c}_{k,n}\|^2\right)|h_{j,n}|^2$$

A. Zappone, E. A. Jorswieck, and S. Buzzi, "Energy efficiency and interference neutralization in two-hop MIMO interference channels," IEEE Transactions on Signal Processing, vol. 62, no. 24, pp. 6481– 6495, December 2014.

Y. Pei and Y.-C. Liang, "Resource allocation for device-to-device communications overlaying two-way cellular networks," IEEE Transactions on Wireless Communications, vol. 12, no. 7, pp. 3611–3621, July 2013.

Centralized Algorithm for N=1

- GEE optimal **power control**: $$\max_{\mathbf{p}\in\mathcal{P}} \frac{\sum_{k=1}^{K} B\log_2(1+\gamma_k)}{p_c+\sum_{k=1}^{K} p_k}$$
- **Feasibility**

Let $\mathbf{F}\in\mathbb{C}^{K\times K}$ be a matrix whose (k,j)-th element is defined as

$$[\mathbf{F}]_{k,j} \triangleq \begin{cases} 0 & j=k \\ \frac{\omega_{kj}\underline{\gamma}_k}{\alpha_k-\phi_k\underline{\gamma}_k} & j\neq k \end{cases} \quad (1)$$

and denote by $\rho_{\mathbf{F}}$ its spectral radius. The solutions to GEE problems exist if and only if

$$\rho_{\mathbf{F}}<1 \quad \text{and} \quad (\mathbf{I}-\mathbf{F})^{-1}\underline{\mathbf{s}}\leq\overline{\mathbf{p}} \quad (2)$$

where $\overline{\mathbf{p}}=[\overline{p}_1,\overline{p}_2,\ldots,\overline{p}_K]^T\in\mathbb{R}_+^{K\times 1}$ and $\mathbf{s}\in\mathbb{R}_+^K$ has elements given by $[\underline{\mathbf{s}}]_k\triangleq\sigma_k^2\underline{\gamma}_k(\alpha_k-\phi_k\underline{\gamma}_k)^{-1}$.

First-order Optimal Solution by Sequential Convex Programming

The general idea of sequential convex programming is to find **local optima of a difficult problem** with objective f to maximize, by **solving a sequence of easier problems** with objectives f_i

1. $f_i(\mathbf{x}) \le f(\mathbf{x})$, for all $\mathbf{x}$;
2. $f_i(\mathbf{x}^{(i-1)}) = f(\mathbf{x}^{(i-1)})$;
3. $\nabla f_i(\mathbf{x}^{(i-1)}) = \nabla f(\mathbf{x}^{(i-1)})$.

Bound $\log_2(1+\gamma) \ge a \log_2 \gamma + b$ works well and **iterative algorithm** can be developed that **converges** to stationary point

- B. R. Marks and G. P. Wright, "A general inner approximation algorithm for nonconvex mathematical programs," Operations Research, vol. 26, no. 4, pp. 681–683, July-Aug. 1978.
- M. Chiang, C. Wei, D. P. Palomar, D. O'Neill, and D. Julian, "Power control by geometric programming," IEEE Trans. Wireless Commun., vol. 6, no. 7, pp. 2640–2651, Jul. 2007.
- L. Venturino, N. Prasad, and X. Wang, "Coordinated scheduling and power allocation in downlink multicell OFDMA networks," IEEE Trans. Veh. Technol., vol. 58, no. 6, pp. 2835–2848, Jul. 2009.
- D. Nguyen, L.-N. Tran, P. Pirinen, and M. Latva-aho, "Precoding for full duplex multiuser MIMO systems: Spectral and energy efficiency maximization," IEEE Transactions on Signal Processing, vol. 61, no. 16, pp. 4038 – 4050, Aug 2013.

User-centric EE Model

- **Game theoretic approach** $\mathcal{G} \triangleq \{\mathcal{K}, \{\mathcal{P}_k(\mathbf{p}_{-k})\}_k, \{\mathrm{EE}_k(p_k, \mathbf{p}_{-k})\}_k\}$
- **Best response** of user *k*

$$\max_{\mathbf{p}_k \in \mathcal{P}_k} \quad \mathrm{EE}_k = \max_{\mathbf{p}_k \in \mathcal{P}_k} \quad \frac{\sum_{n=1}^{N} B \log_2(1+\gamma_{k,n})}{p_{c,k} + \mathbf{1}^T \mathbf{p}_k} \quad \forall k.$$

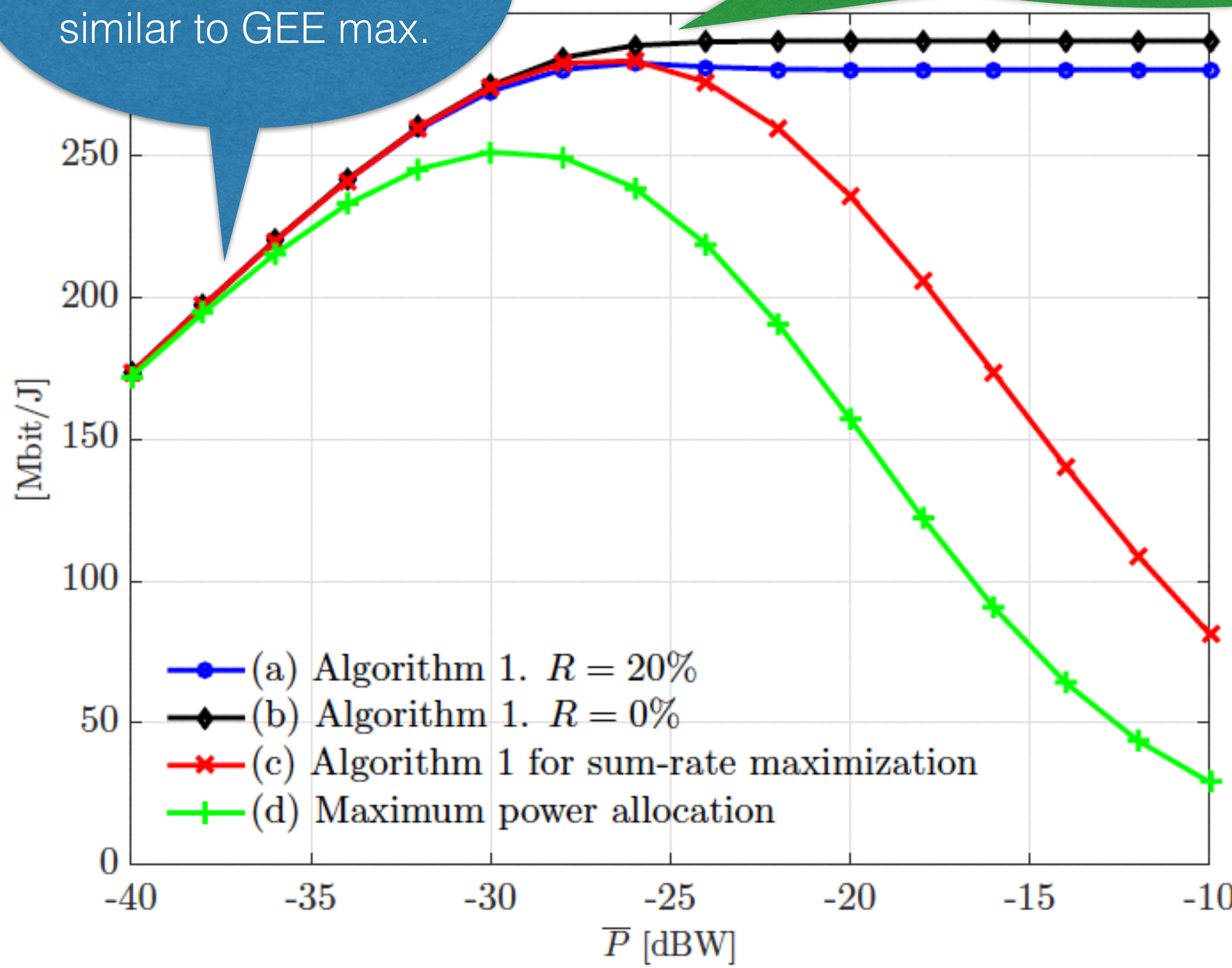
1. *The game has non-empty set of of GNE points.*
2. *The game G admits a **unique GNE point**, which can be obtained by starting from any feasible power playing the BRD.*
3. *The BRD can be **implemented** in **distributed** way exploiting the Dinkelbach algorithm from fractional programming.*

Numerical C… GEE

…e MIMO v…

Low SNR:
sum-rate maximization
similar to GEE max.

High SNR: (a) uses some power to satisfy rate constraints, (c) sum rate maximization uses too much power and becomes energy inefficient.



$K = 5, M = 50, \tau = 10^{-2}$
$B = 1\text{MHz}$

Average achieved GEE versus power constraint

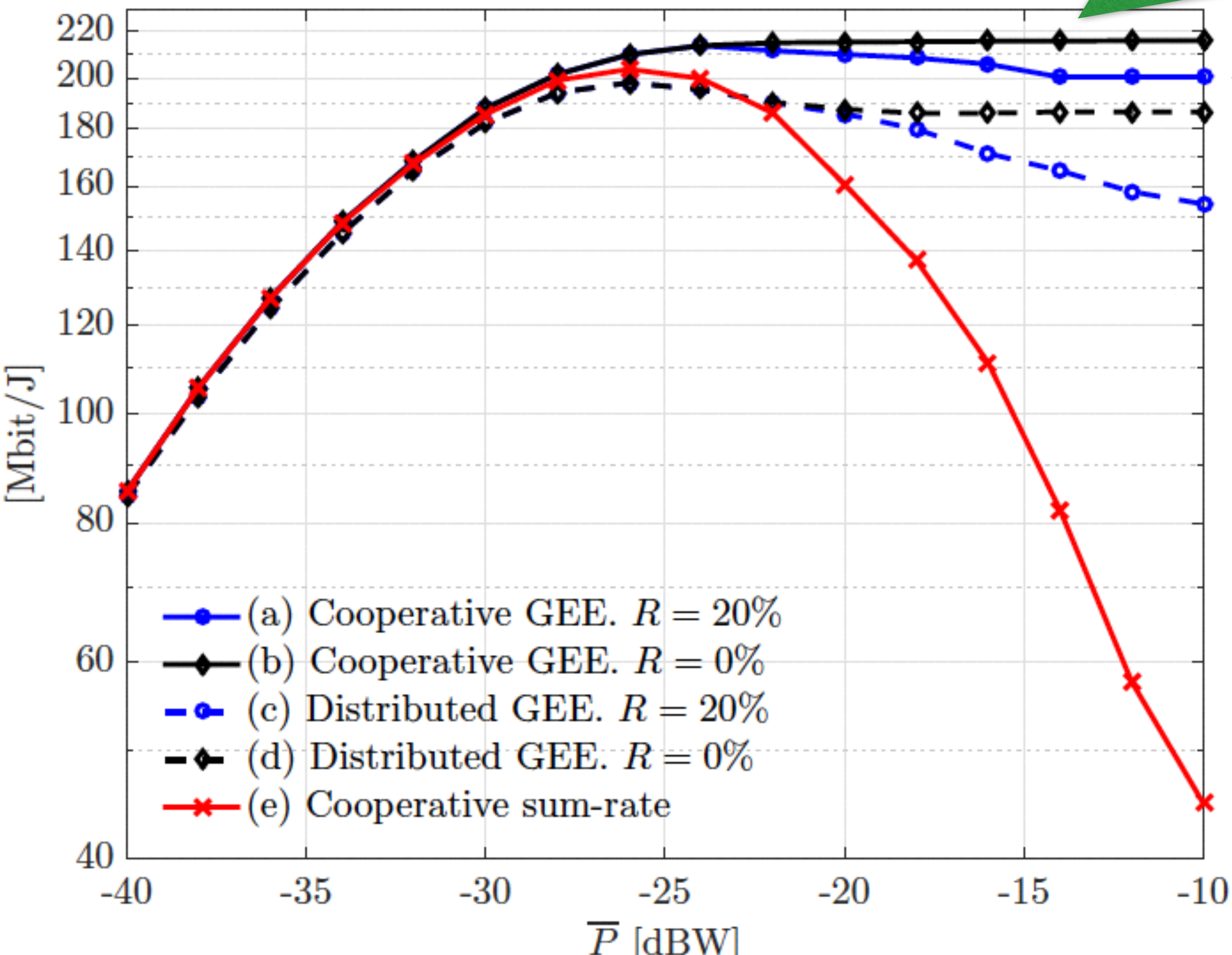
Algorithm 1 is centralized optimizing GEE

Numerical Distributed EE

Relay-assisted OFDMA int

Low Price of Anarchy because of many resources and few users

$S = 3, N = 16, K = 3, M = 3,$
$B = 180\text{kHz}, \text{dist} = [100, 300]\text{m}$



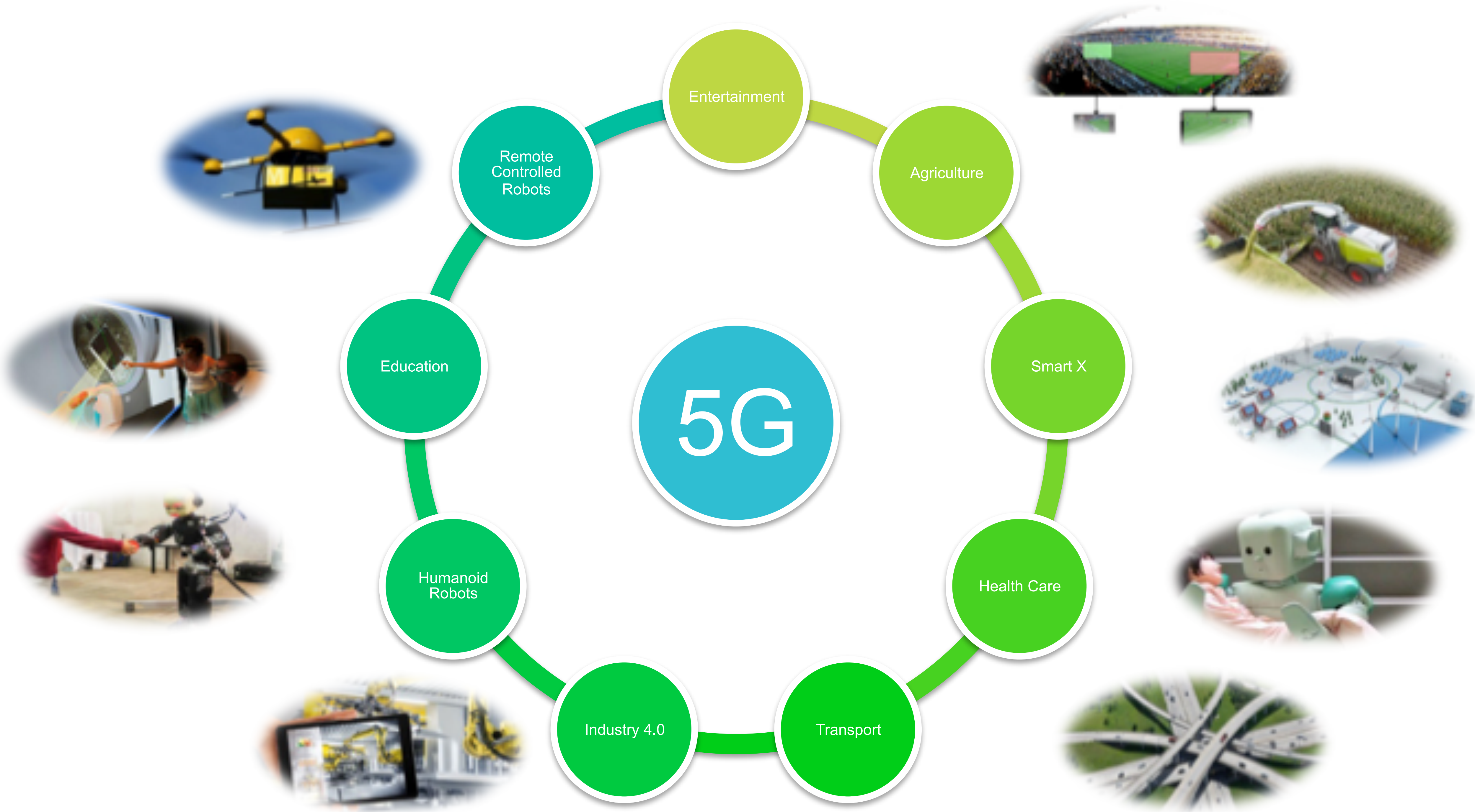
Average achieved GEE versus power constraint

Users' minimum rate:

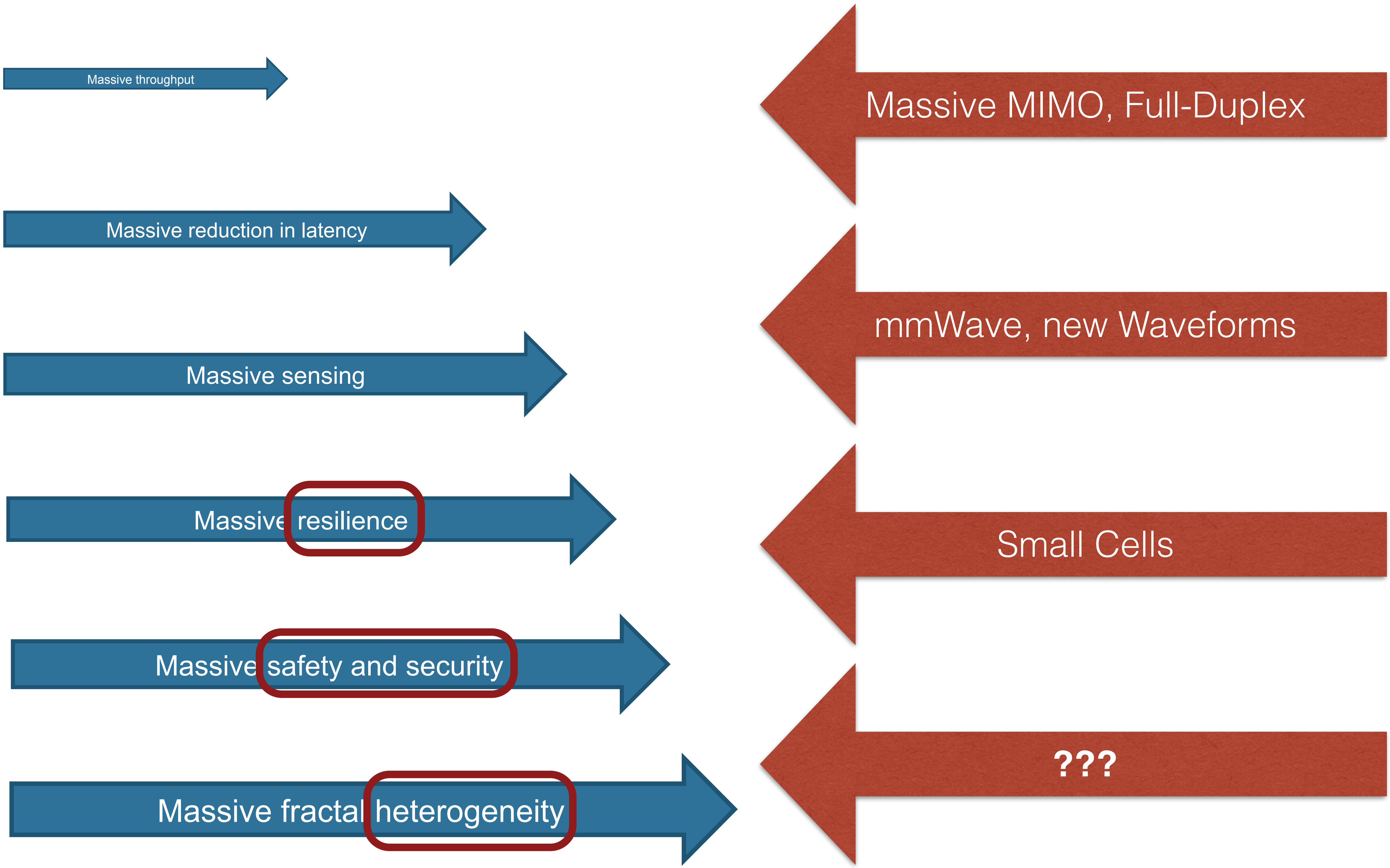
$3.8[\text{bit/s/Hz/user}]$

$7.16[\text{bit/s/Hz/user}]$

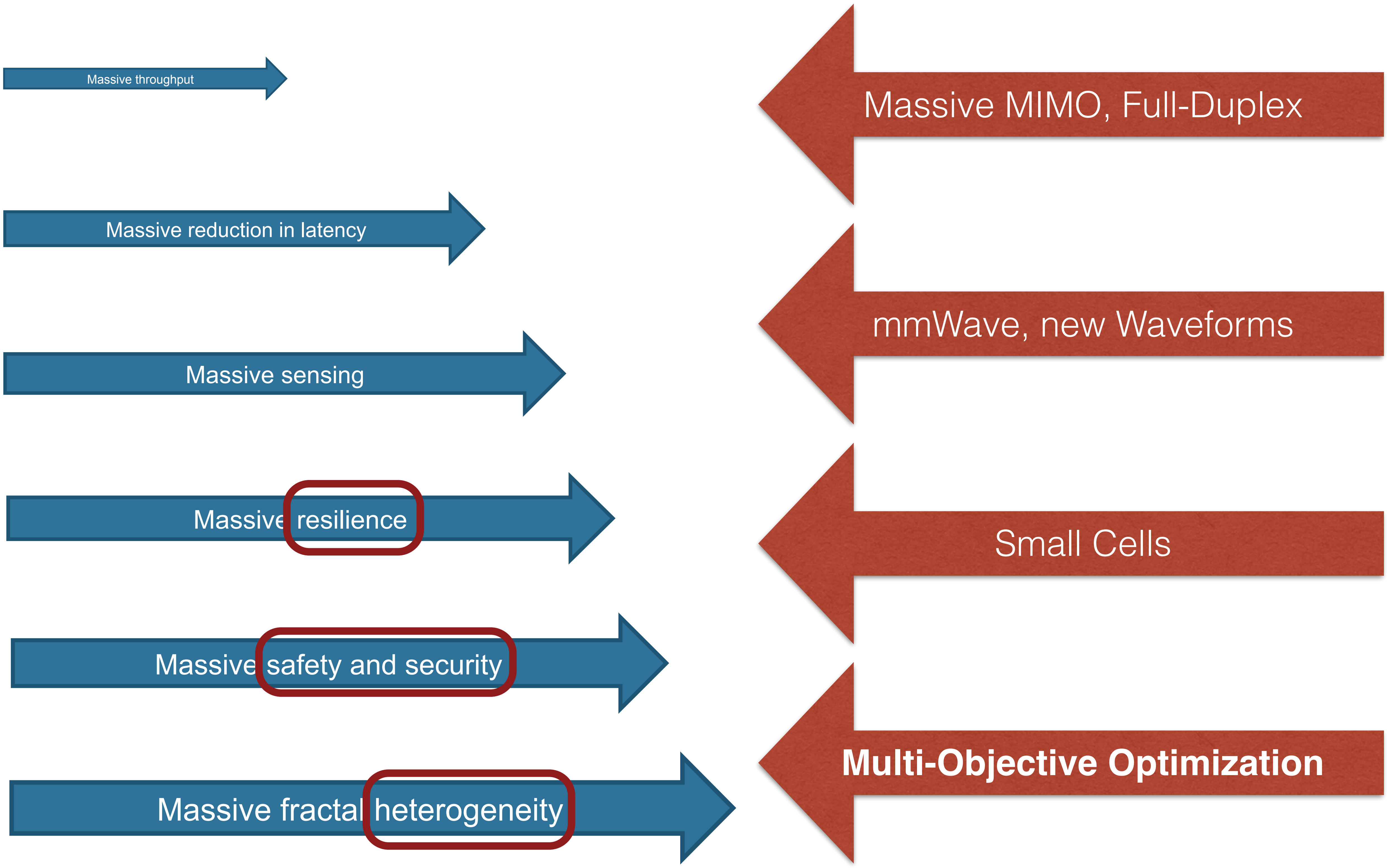
Conclusions



Challenges - Solutions



Challenges - Solutions



Conclusions

- The fifth and subsequent generations of mobile communications introduce a number of **massive requirements** in terms of *throughput* and *efficiency* improvement, reduction in *latency*, *scaling* with large number of devices, *robustness* and *resilience*, *safety* and *security*, as well as *heterogeneity*.

- Some of the goals (e.g. the throughput improvement) will be achieved by **new technologies**, e.g., massive MIMO, full duplex, mmWave, new waveforms, adaptive flexible spectrum management.

- Other important requirements as heterogeneity, efficiency, security are to be achieved by new systematic solution concepts (**e.g. multi-objective optimization, fractional programming**).

References

- A. Zappone and E. Jorswieck, "Energy Efficiency in Wireless Networks via Fractional Programming Theory". **Foundations and Trends in Communications and Information Theory**, vol. 11, no. 3-4, June 2015, pp. 185-396.
- A. Zappone, F. Di Stasio, S. Buzzi, E. Jorswieck, "Sequential Fractional Programming for Energy-Efficient Resource Allocation in 5G Networks: General Theory and a Case Study based on Device-to-Device Underlay", **John Wiley & Sons**, to appear 2015.
- A. Zappone, L. Sanguinetti, G. Bacci, E. Jorswieck, M. Debbah, "Energy-Efficient Power Control: A Look at 5G Wireless Technologies", **IEEE Trans. on Signal Processing**, will appear 2016.
- E. Björnson, E. Jorswieck, M. Debbah, B. Ottersten, "Multi-Objective Signal Processing Optimization: The Way to Balance Conflicting Metrics in 5G Systems", **IEEE Signal Processing Magazine**, vol. 31, no. 6, pp. 14-23, Nov. 2014.

Thank you for your attention!

5G Lab GERMANY

Backup Slides

Computational Complexity

Table II

$K = 5; M = 50; \tau = 10^{-2}$. AVERAGE NUMBER OF REQUIRED ITERATIONS TO REACH CONVERGENCE VERSUS P_{max} FOR: (A) ALGORITHM 1 FOR GEE MAXIMIZATION WITH $R = 20\%$; (B) ALGORITHM 1 FOR GEE MAXIMIZATION WITH $R = 0\%$; (C) ALGORITHM 2 FOR DISTRIBUTED RESOURCE ALLOCATION WITH $R = 20\%$; (D) ALGORITHM 2 FOR DISTRIBUTED RESOURCE ALLOCATION WITH $R = 0\%$.

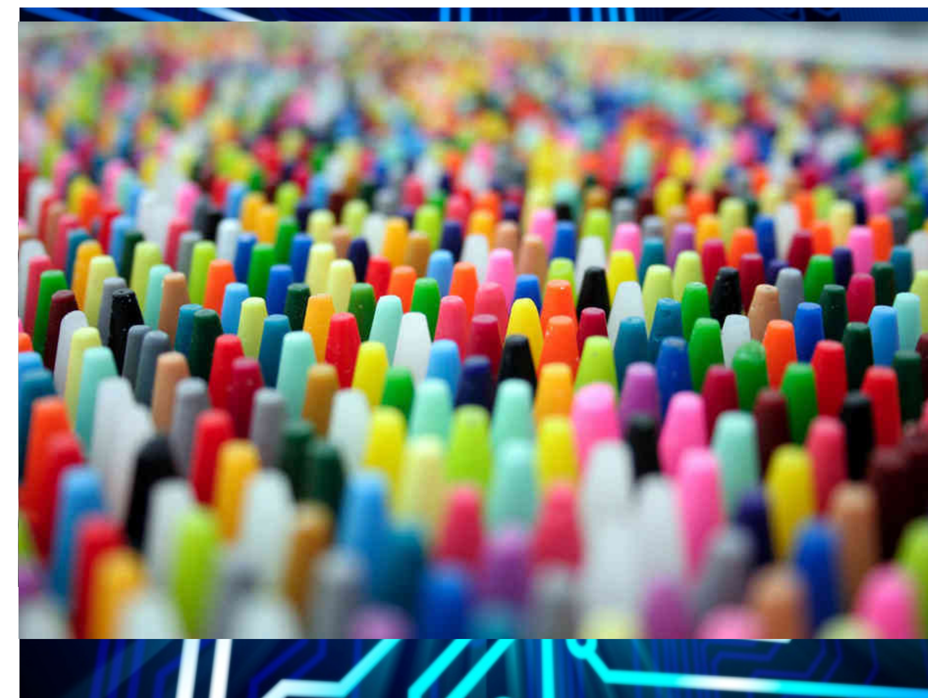
	Maximum power $\overline{P}$ [dBW]							
	$\overline{P} = -38$	$\overline{P} = -34$	$\overline{P} = -30$	$\overline{P} = -26$	$\overline{P} = -22$	$\overline{P} = -18$	$\overline{P} = -14$	$\overline{P} = -10$
Algorithm 1. $R = 0\%$	2.63	3.69	4.68	6.30	6.53	6.49	6.50	6.51
Algorithm 1. $R = 20\%$	2.63	3.67	4.87	6.68	6.70	6.76	6.76	6.77
Algorithm 2. $R = 0\%$	1	1.01	1.07	1.42	2.54	3.66	4.12	4.50
Algorithm 2. $R = 20\%$	1	1.01	1.07	1.42	2.54	3.67	4.19	6.71

- Centralized Algorithm has polynomial complexity (in K and N).
- Decentralized Algorithm has polynomial complexity, too. (in N, scales linearly with K)

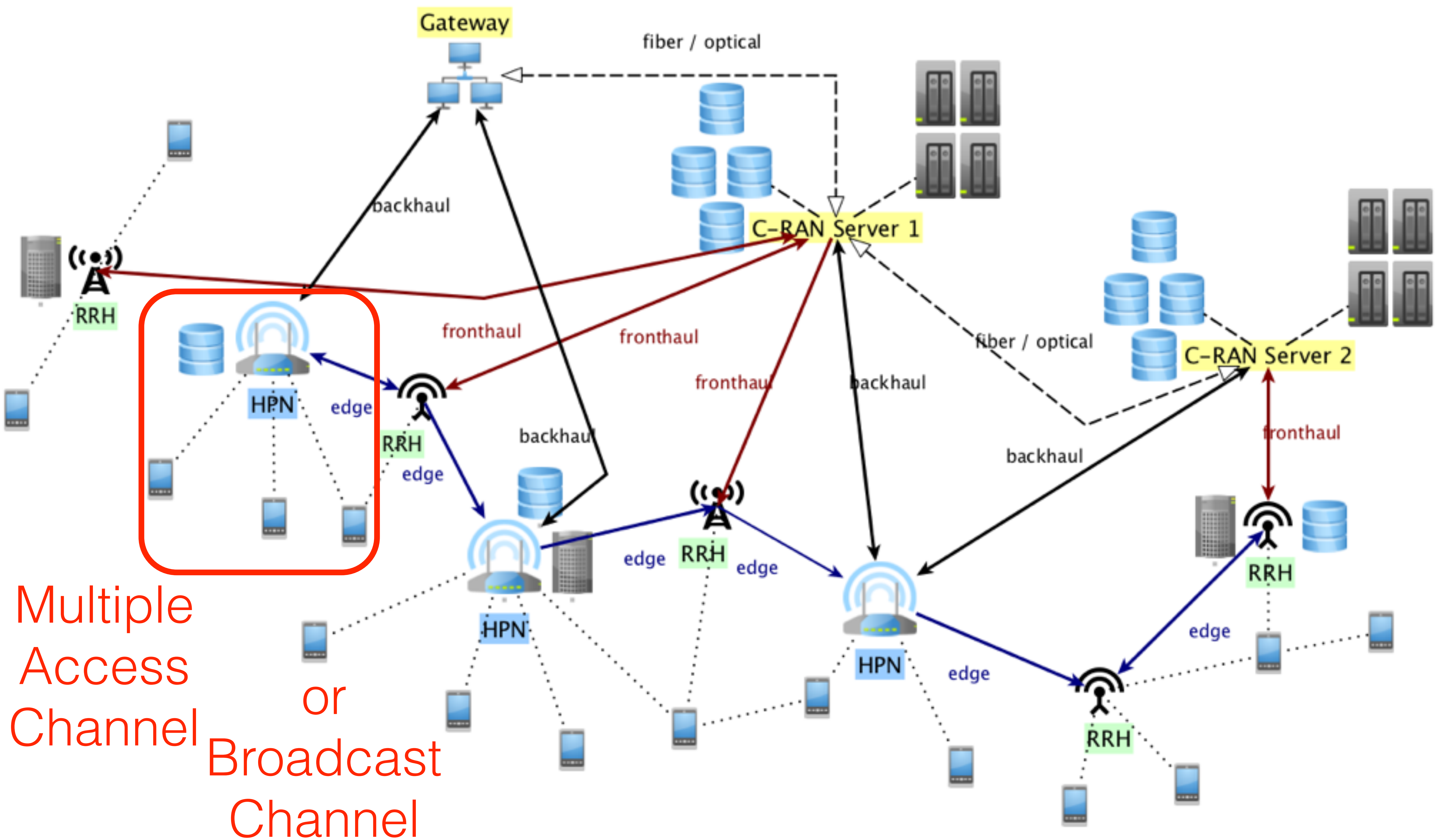
5G - Massive Requirements

State of the art

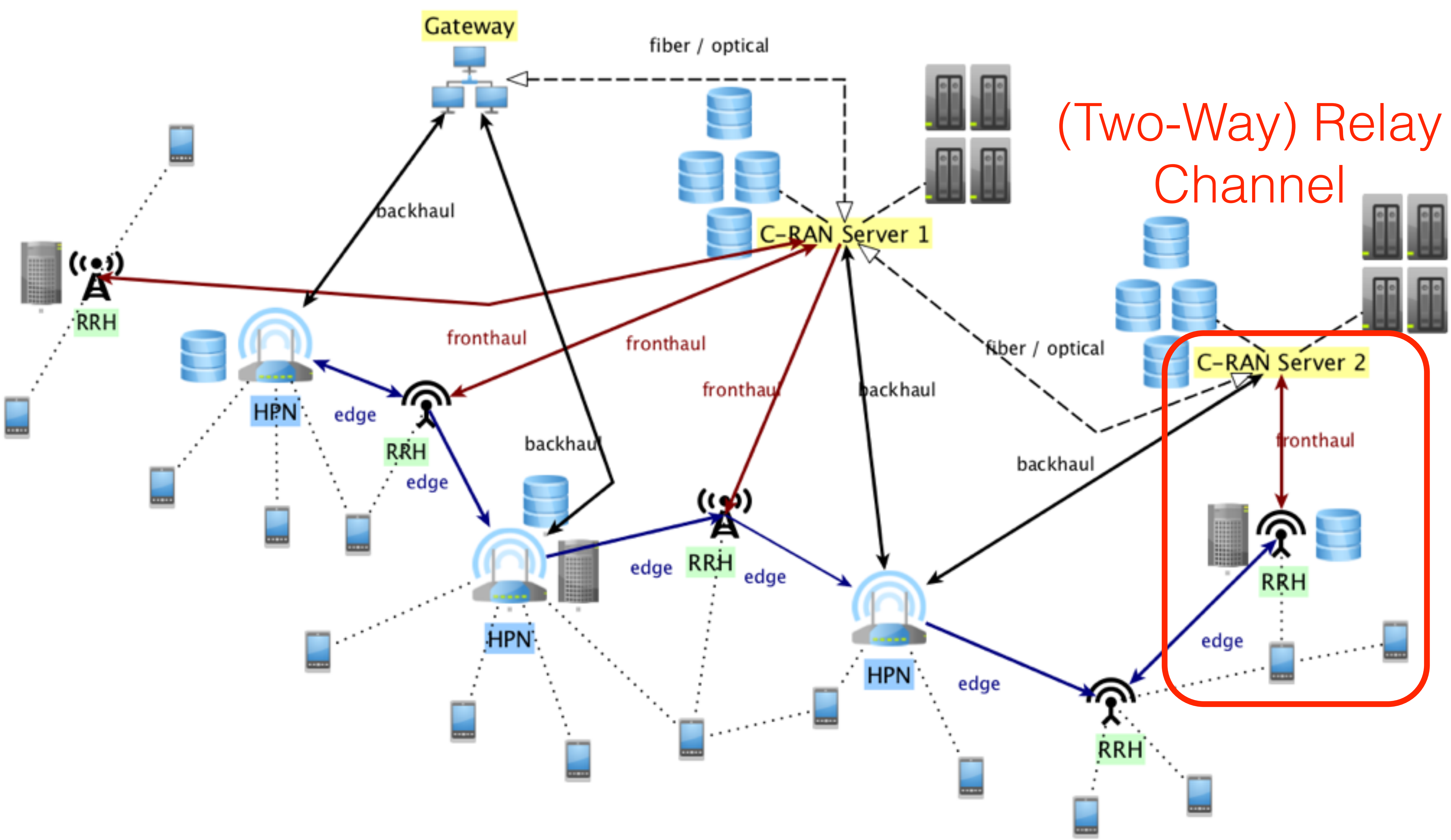
- Massive throughput
- Massive reduction in latency
- Massive sensing
- Massive resilience
- Massive safety and security
- Massive fractal heterogeneity



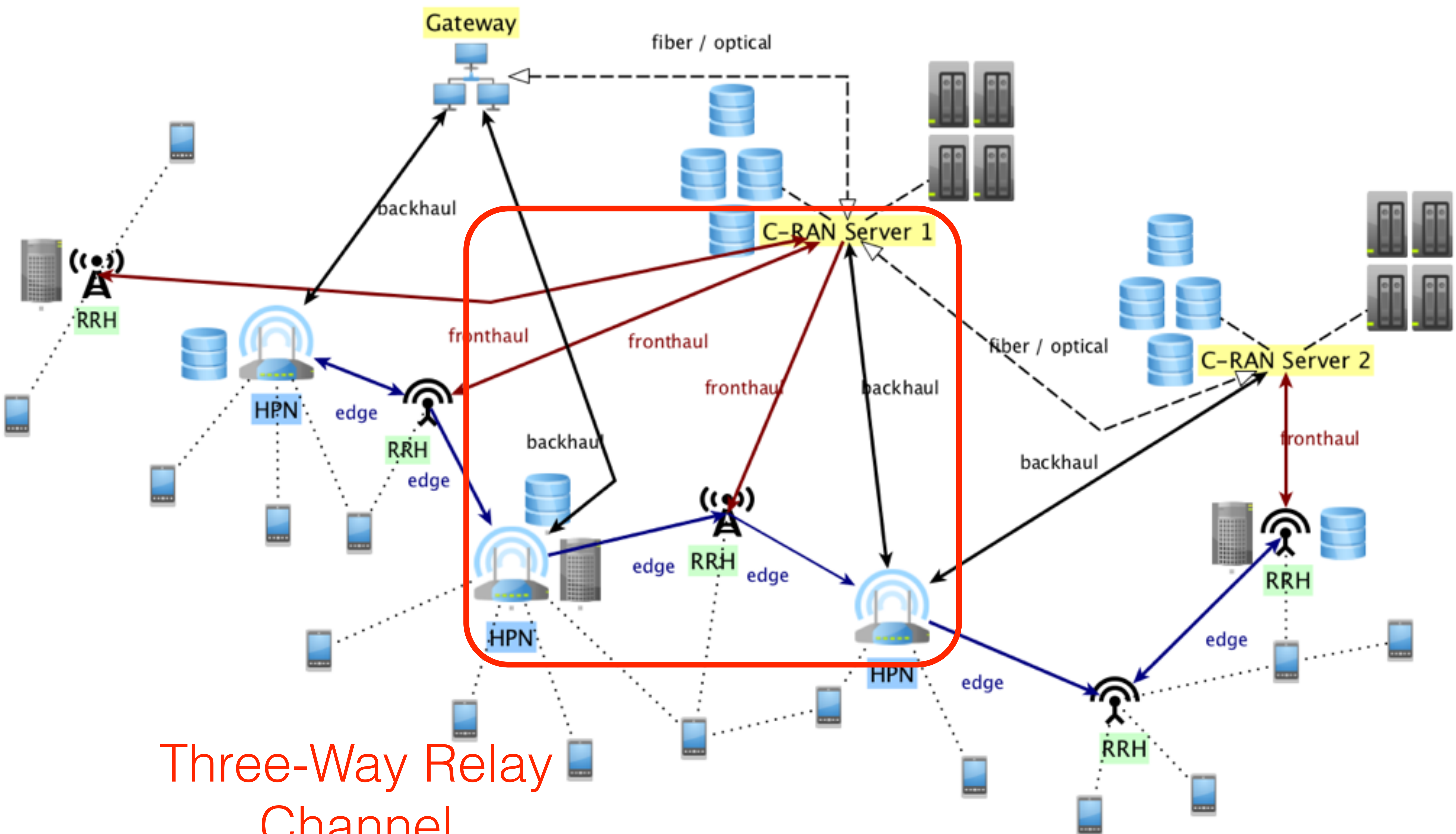
Heterogenous Networks



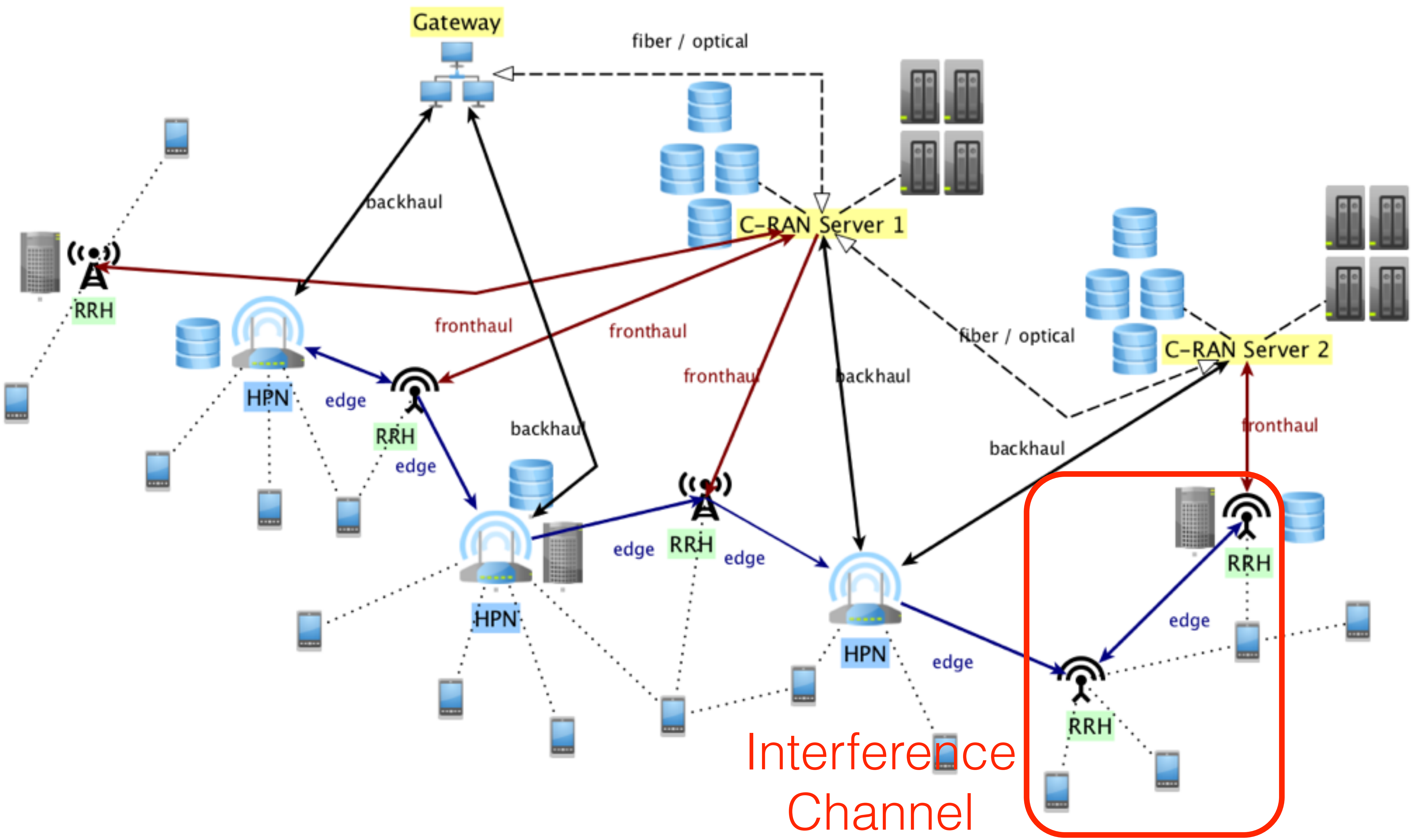
Heterogenous Networks



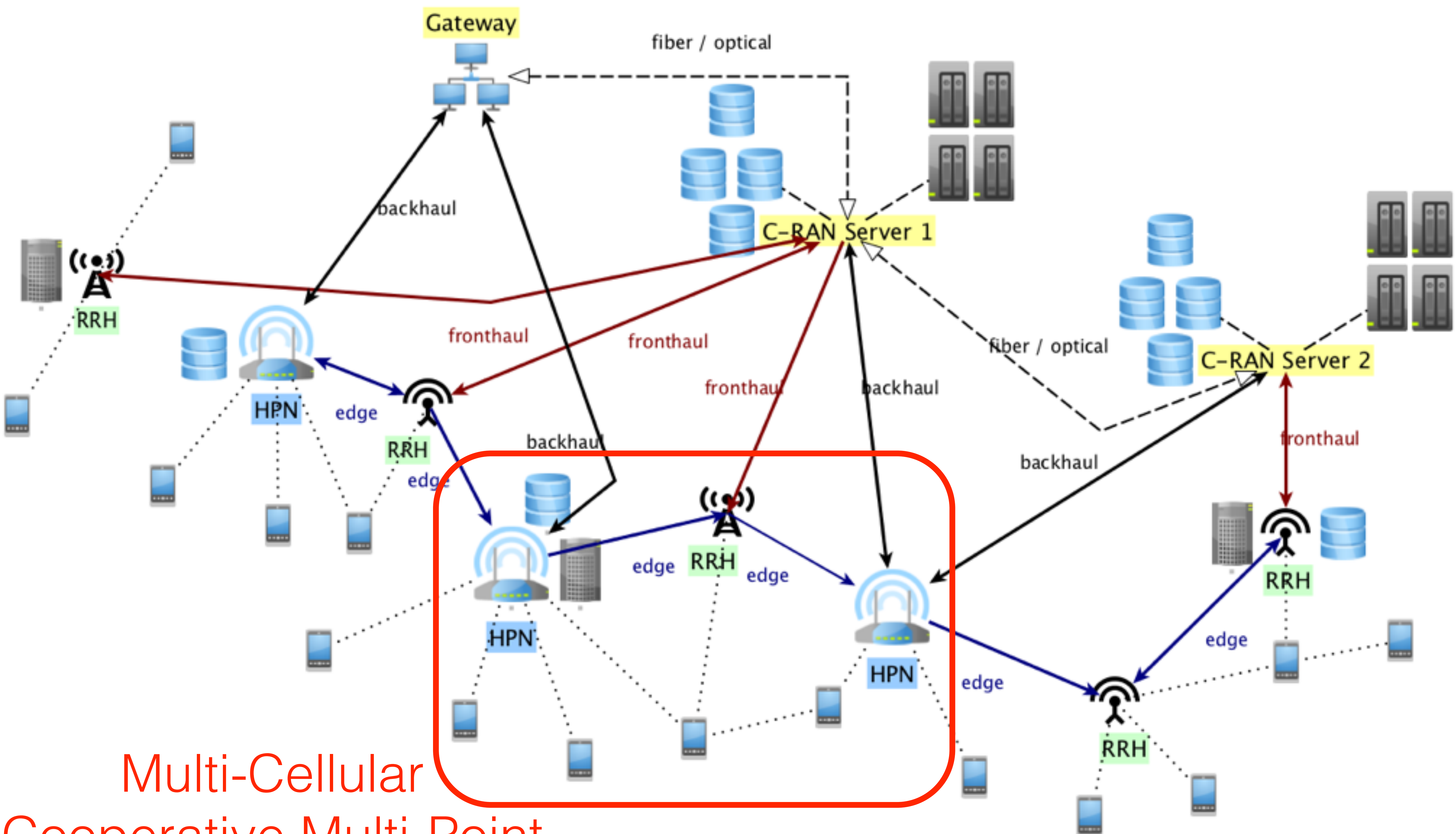
Heterogenous Networks



Heterogenous Networks

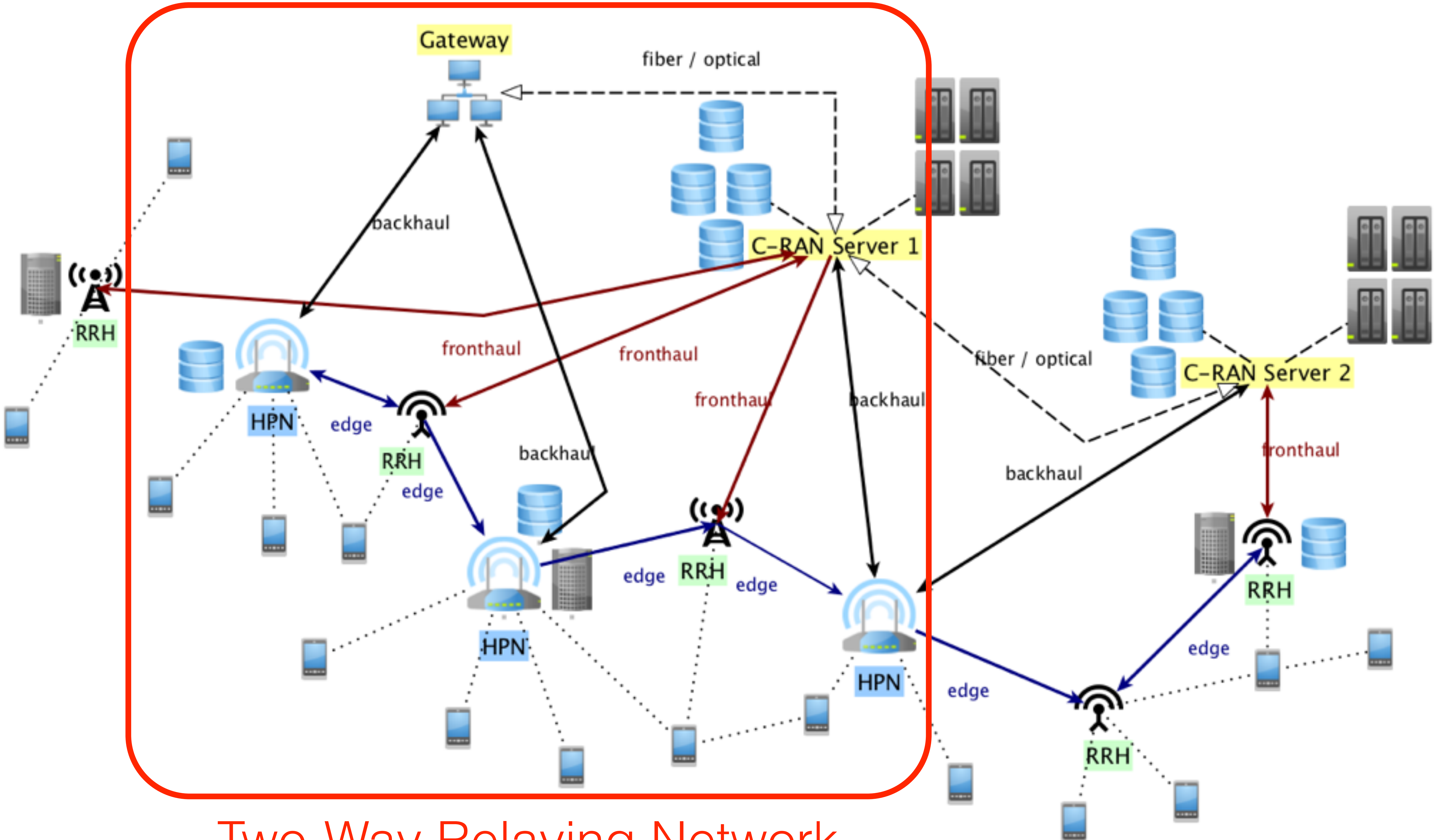


Heterogenous Networks



Multi-Cellular
Cooperative Multi-Point

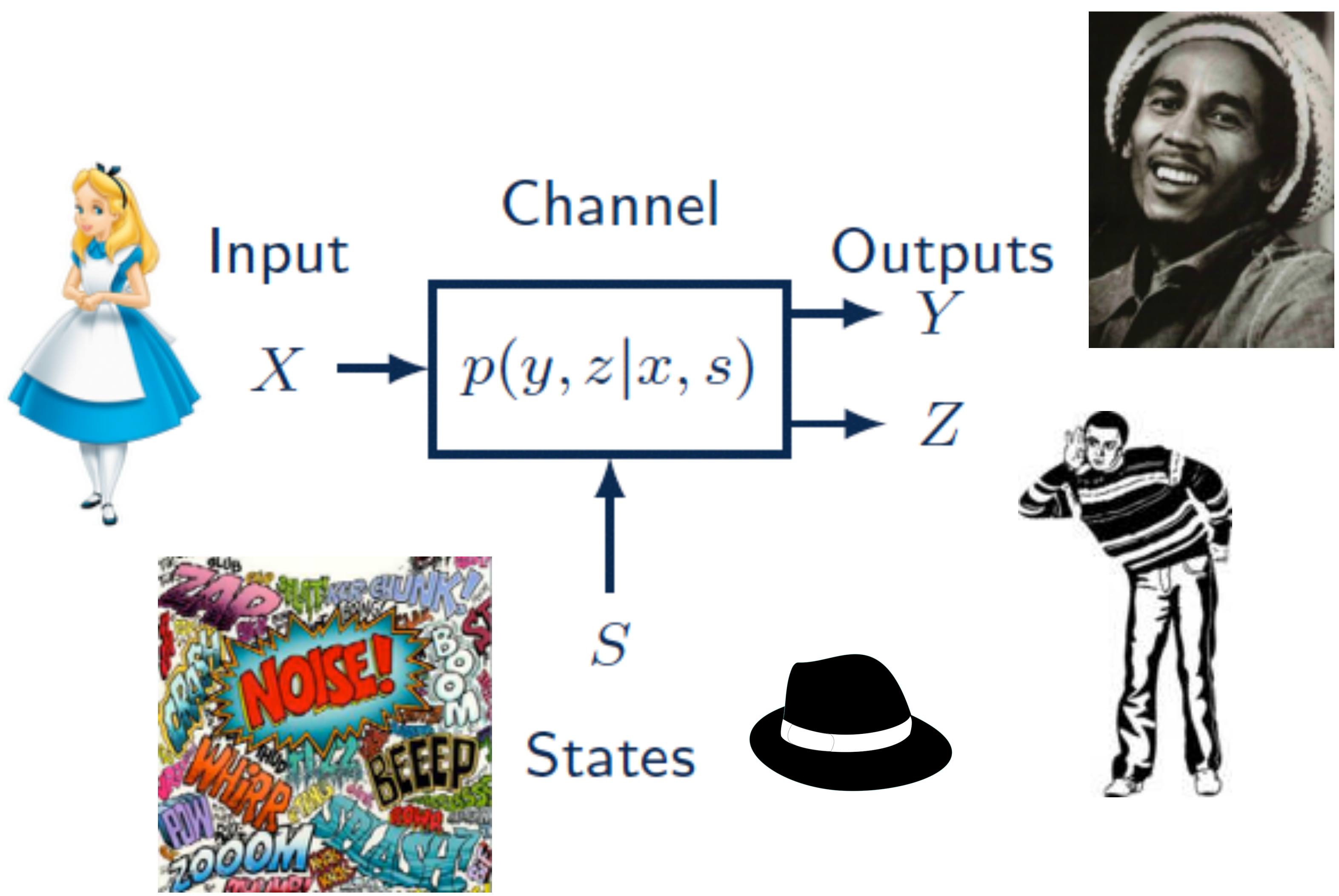
Heterogenous Networks



Two-Way Relaying Network

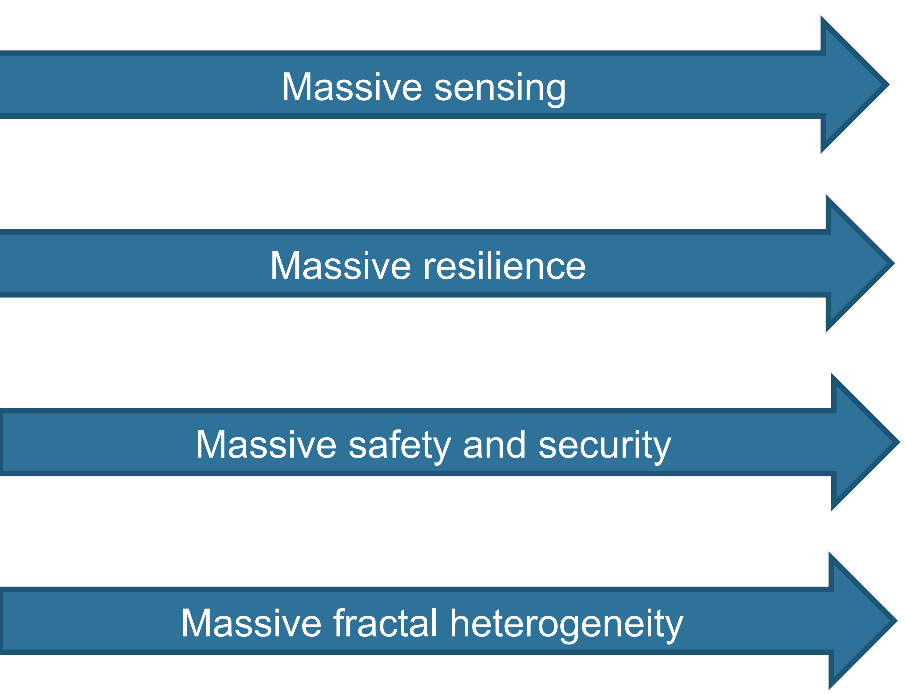
Applications 2

Physical Layer Security



Motivation for Physical Layer Security

- **Large number** of connected **devices**.
- **Cryptographic** solutions to confidentiality or authentication **do not scale**
- Physical layer security provides **unconditional security** (information theoretic security)



- Secure communications
- Secret key generation
- Wireless authentication

E. Jorswieck, S. Tomasin, A. Sezgin, "Broadcasting into the Uncertainty: Authentication and Confidentiality by Physical Layer Processing", Proceedings of IEEE, vol. 103, no. 10, pp. 1702-1724, Oct. 2015.

Confidentiality Measures

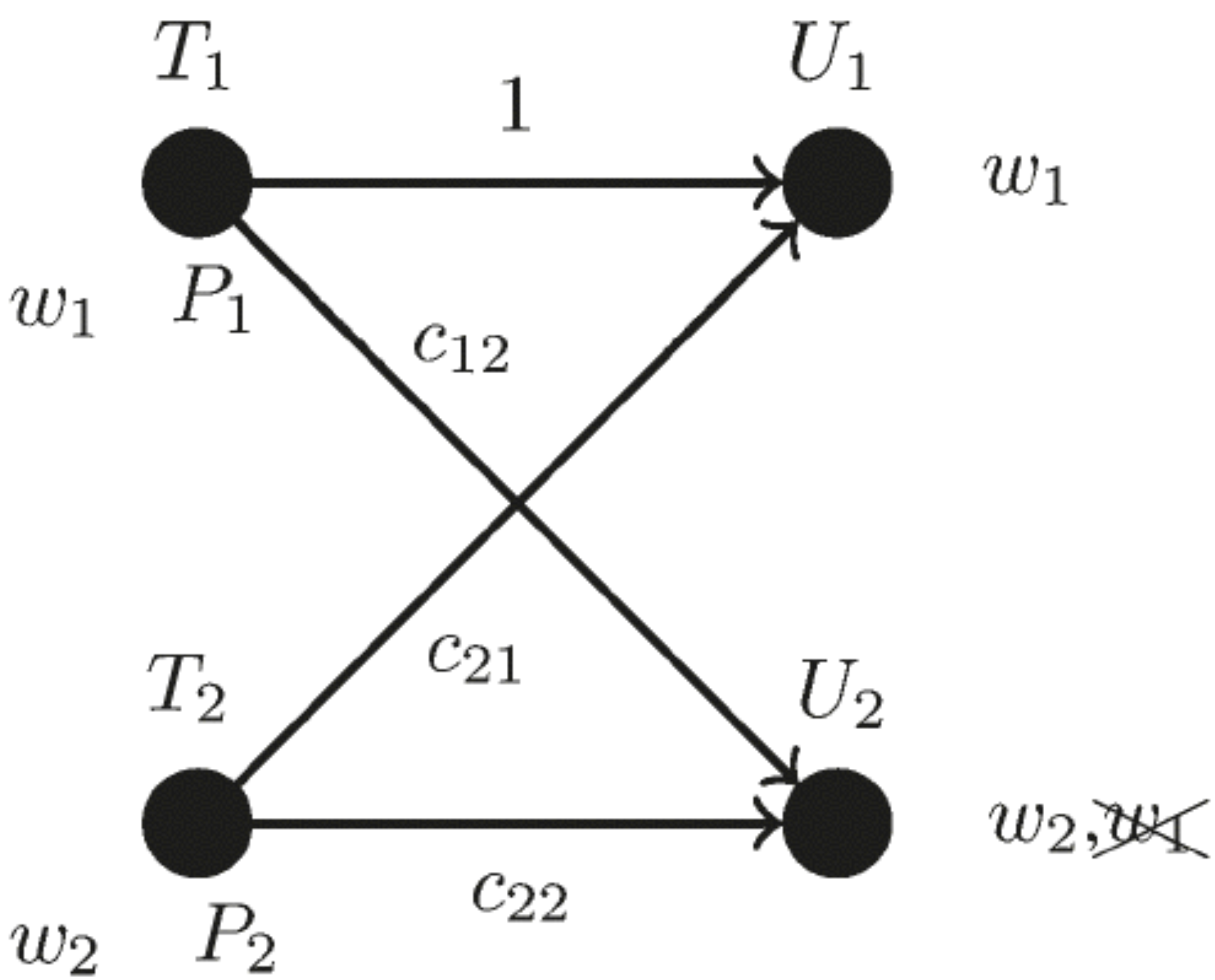
- *Whatever the adversary overhears, it should not contain any information about the message.*

- Information Theoretic **Confidentiality Measures**

New Objective Function or Additional Constraints in MOP

- Instantaneous $I(M; z) \leq \epsilon$
- Sequence (weak) $\frac{1}{n} I(M; \mathbf{z}^n) \leq \epsilon$
- Sequence (strong) $I(M; \mathbf{z}^n) \leq \epsilon$
- Variation distance $\max_{m,m'} \mathbb{V}(p_{\mathbf{z}^n|M=m}, p_{\mathbf{z}^n|M=m'}) < \epsilon$

Interference Channel with Secrecy Constraints



- Primary (legacy) link with **confidential** message
- Secondary (adaptive) link with two goals

1. **Protect** the primary message
2. **Maximize energy-efficiency** of its own transmission

F. Gabry, A. Zappone, R. Thobaben, E. Jorswieck, M. Skoglund, "Energy Efficiency Analysis of Cooperative Jamming in Cognitive Radio Networks with Secrecy Constraints", IEEE Wireless Communications Letters, vol. 4, no. 4, pp. 437-440, Aug. 2015.

Preliminaries & Problem Statement

- **Achievable rate region** under cooperative jamming:

$$R_1 < \left(\mathcal{C}\left(\frac{P_1}{1+c_{21}P_2}\right) - \mathcal{C}\left(\frac{c_{12}P_1}{1+c_{22}\rho P_2}\right)\right)^+,$$

$$R_2 < \mathcal{C}\left(\frac{c_{22}(1-\rho)P_2}{1+c_{12}P_1+c_{22}P_2\rho}\right).$$

- Maximize secondary user **energy-efficiency** under primary user **secrecy constraints**

$$\max_{\rho, P_2} \frac{R_2}{\mu P_2 + P_C}$$

$$\text{s.t.} \quad R_1 \geq R_1^{WT} \text{ and } P_2 \leq P_2^{max}$$

F. Gabry et al., "On the optimization of the secondary transmitter's strategy in cognitive radio channels with secrecy," IEEE J. Sel. Areas Commun., vol. 32, no. 3, pp. 451–463, Mar. 2014.

Characterization of Solution

- The programming problem admits a unique solution if and only if the **following condition** is satisfied:

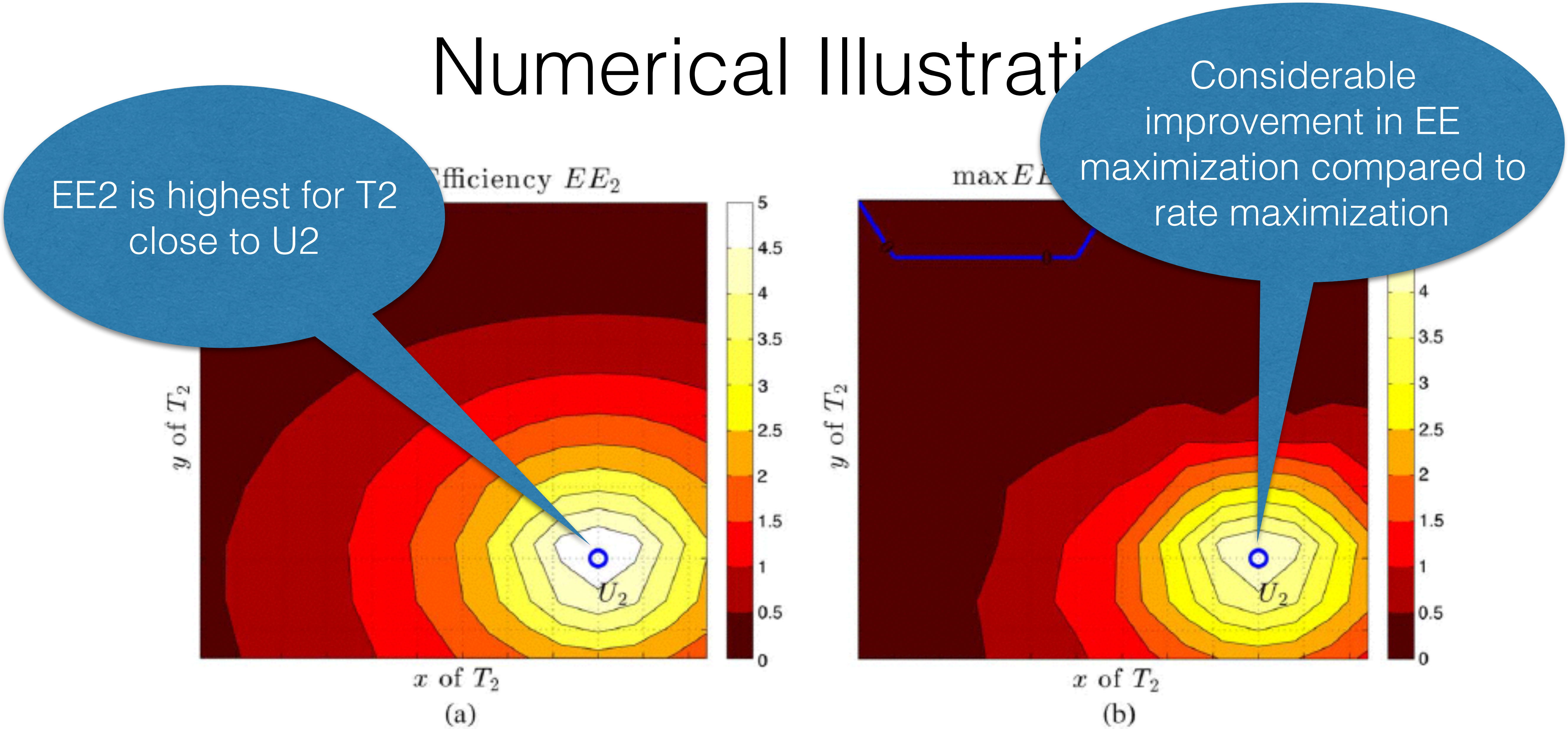
$$\frac{c_{21}(1 + c_{12}P_1)}{c_{22}c_{12}(1 + P_1)} < 1$$

- For large transmit power this converges to

$$\frac{c_{21}}{c_{22}} < 1$$

- **Intuition**: Only if the channel to eavesdropper is better than to legitimate receiver, jamming is successful.

Numerical Illustrati



Energy efficiency analysis: (a) Secondary energy efficiency depending on the position of T2.
(b) Comparison of the energy efficiency obtained from optimixation (EE2) and max R2.