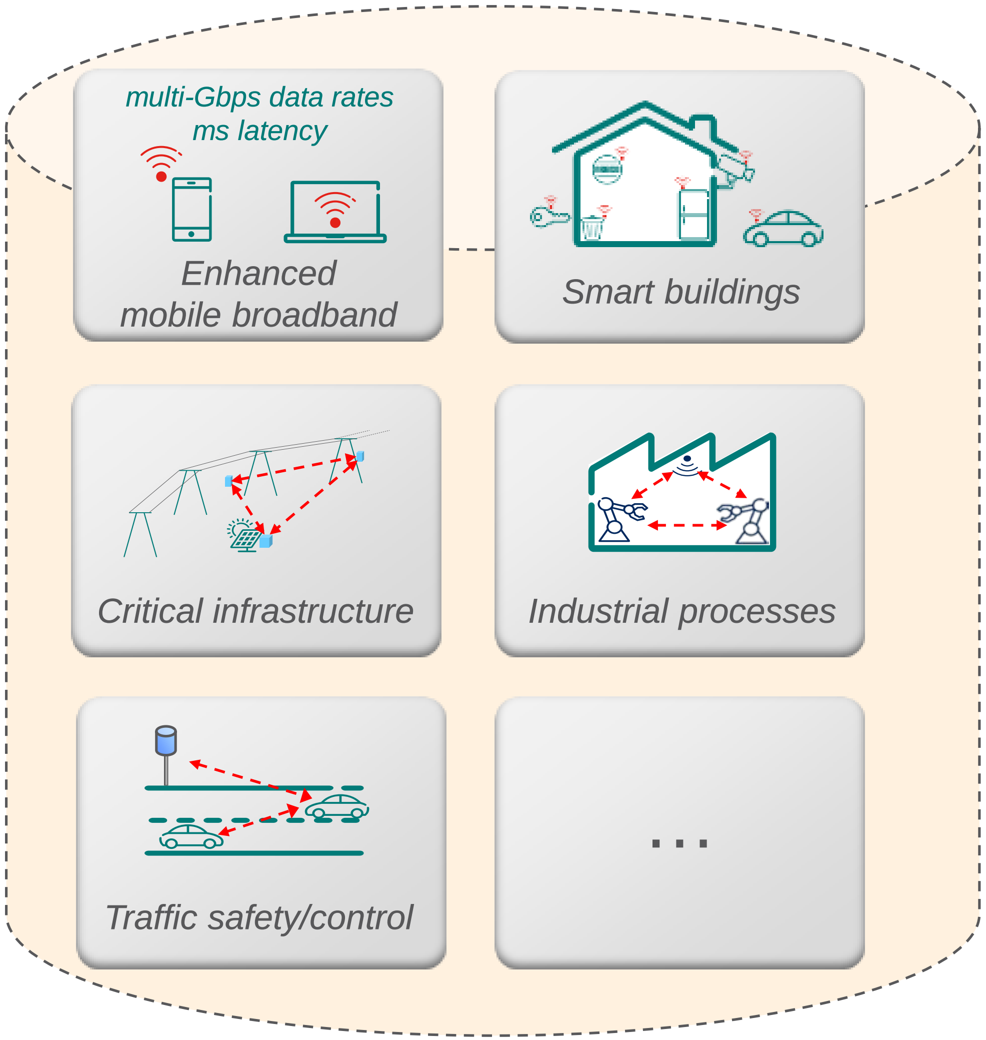
TUNING THE RECEIVER STRUCTURE AND THE PILOT-TO-DATA POWER RATIO IN MULTIPLE INPUT MULTIPLE OUTPUT SYSTEMS

GABOR FODOR

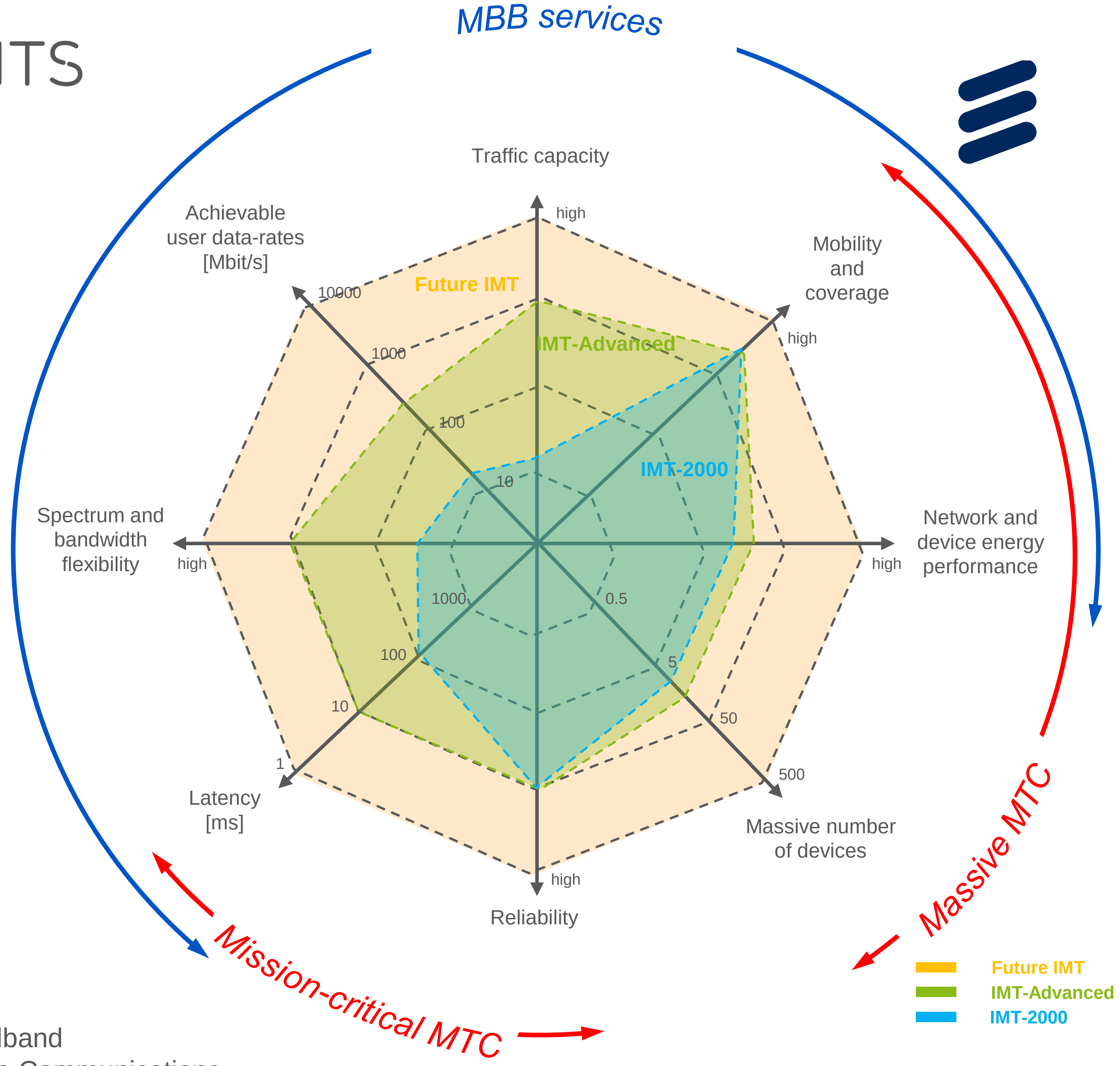
ERICSSON RESEARCH

ROYAL INSTITUTE OF TECHNOLOGY

5G: SCENARIOS & REQUIREMENTS



5G network



MBB: Mobile Broadband
MTC: Machine Type Communications
IMT: International Mobile Telecommunications

R. Baldemair, E. Dahlman, G. Fodor, G. Mildh, S. Parkvall, Y. Selén, "Evolving Wireless Communications: Addressing the Challenges and Expectations of the Future", IEEE Vehicular Technology Magazine, Vol. 8, No. 1, pp. 24-30, Mar. 2013

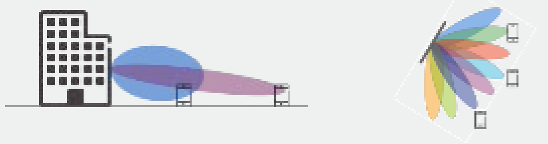
5G TECHNOLOGY COMPONENTS

ACCESS Linnaeus Centre

Multi-antenna Technologies

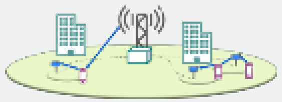
For higher as well as lower frequencies

Beam-forming for coverage | **Multi-user MIMO for capacity**



Multi-site Coordination

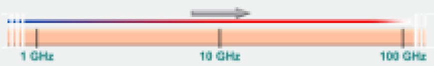
Multi-site transmission/reception



Multi-layer connectivity

Extension to Higher Frequencies

Complementing lower frequencies for extreme capacity and data rates in dense areas



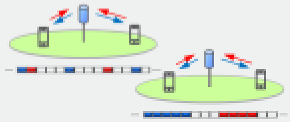
Spectrum Flexibility

Spectrum sharing

- ***Unlicensed***
- ***Shared licensed***

Complementing dedicated licensed spectrum

(Full) Duplex Flexibility



Ultra-lean Design

Minimize transmissions not related to user data

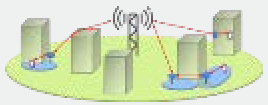
Separate delivery of user data and system information

Higher data rates and enhanced energy efficiency

Access/backhaul Integration

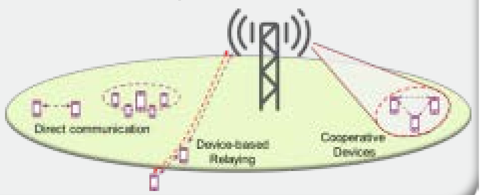
Same technology for access and backhaul

Same spectrum for access and backhaul



Device-to-Device Communication

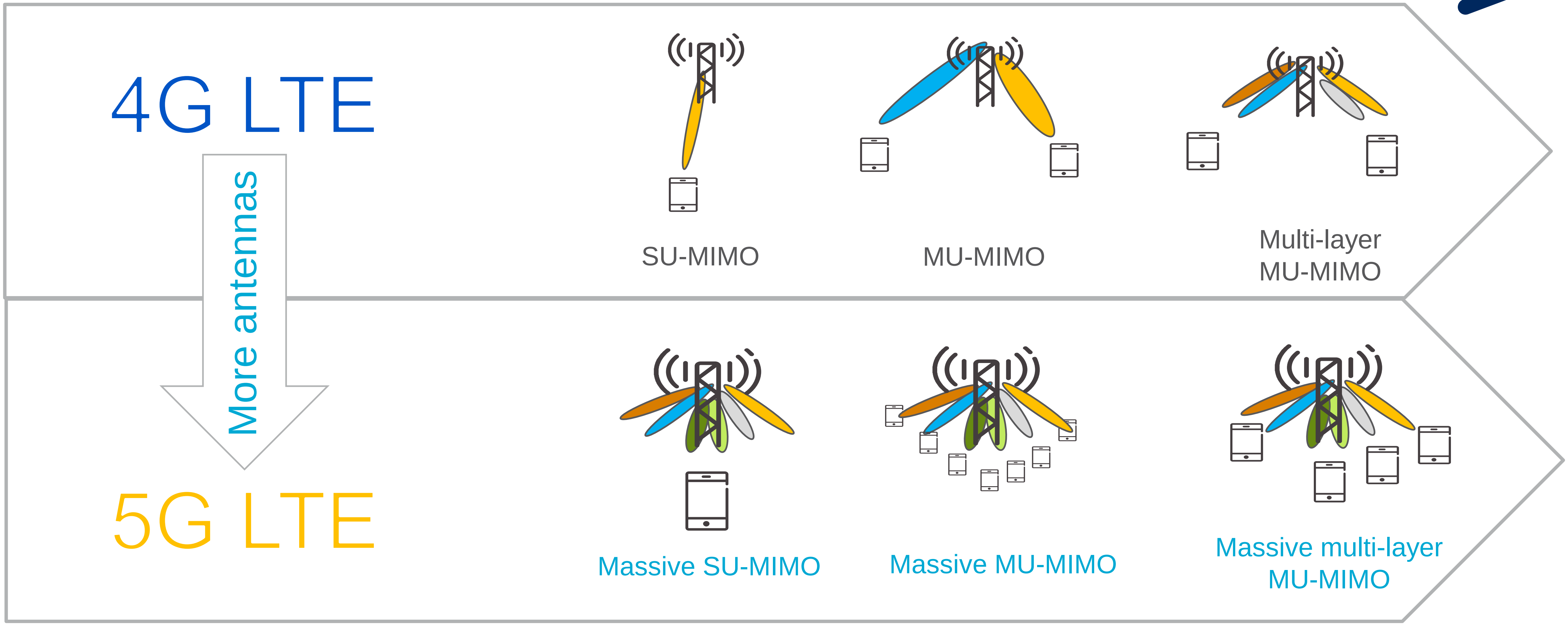
Direct communication
Device-based relaying
Cooperative devices
⋮



H. Shokri-Ghadikolaei, F. Boccardi, C. Fischione, G. Fodor and M. Zorzi, "Spectrum Sharing in mmWave Cellular Networks via Cell Association, Coordination, and Beamforming", IEEE J. on Selected Areas in Communications, Vol. 34, Issue 11, pp. 2902-2917, 2016

D. Astely, E. Dahlman, G. Fodor, S. Parkvall and J. Sachs, "LTE Release 12 and Beyond", IEEE Comm. Mag., Vol. 51, No. 7, pp. 154-160, July 2013.

MIMO EVOLUTION



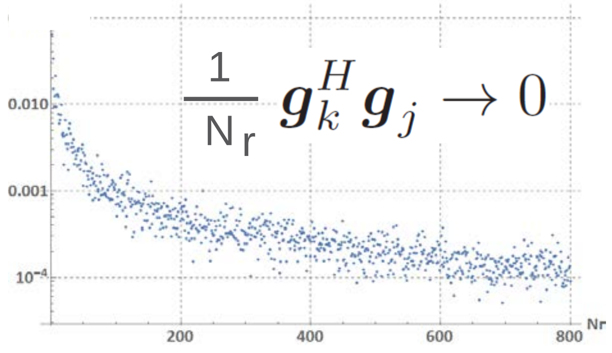
LTE: Long Term Evolution
SU MIMO: Single User Multiple Input Multiple Output
MU MIMO: Multiuser Multiple Input Multiple Output

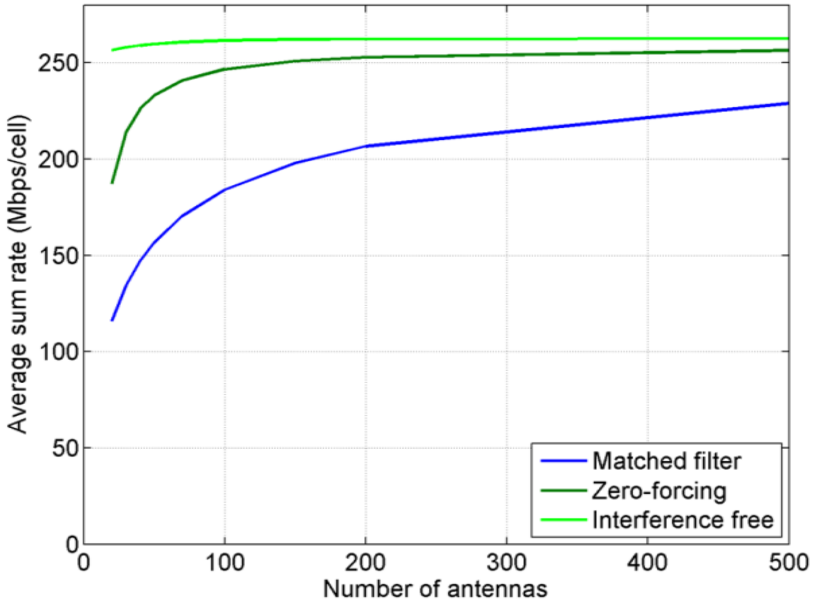
G. Fodor, N. Rajatheva, W. Zirwas, L. Thiele, M. Kurras, K. Guo, A. Tolli, J. H. Sorensen, E. de Carvalho, "An Overview of Massive MIMO Technology Components in METIS", IEEE Communications Magazine, Vol. 55, Issue 6, pp. 155-161, June 2017.

WHY FULL DIMENSION MIMO ?

- The vector channel to a desired user becomes orthogonal to the vector channel of a random interfering user;
- Rejecting interference becomes possible simply by aligning the BF vector with the desired channel; CSI is important !
- Ultimate limitation is CSI error

$$\frac{1}{N_r} \boldsymbol{g}_k^H \boldsymbol{g}_j \to 0$$





- Uniform Linear Array
- 10 users
- **Perfect CSI**

- The capacity performance of conjugate BF and ZF become asymptotically identical. [Yang, Marzetta, *IEEE JSAC* 2013]

BS: Base Station
CSI: Channel State Information
ZF: Zero Forcing
BF: Beam Forming

V. Saxena, G. Fodor, E. Karipidis, "Mitigating Pilot Contamination by Pilot Reuse and Power Control Schemes for Massive MIMO Systems", IEEE VTC Spring, Glasgow, Scotland, May 2015.

ACCESS Linnaeus Centre

UL MU MIMO RECEIVER DESIGN QUESTIONS

ACCESS Linnaeus Centre

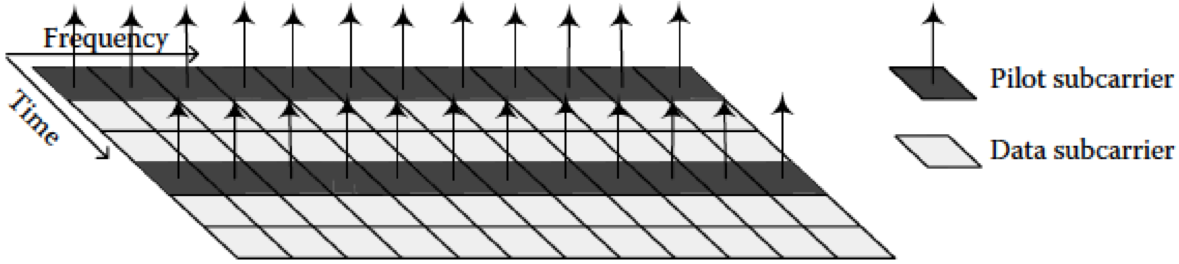
- How can we improve the performance of the MMSE receiver in the presence of CSI errors in terms of:
  - Mean squared error of the received data symbols;
  - Spectral efficiency
- What are the gains of CSI error aware receivers over naïve receivers ?
- Do such gains increase/decrease as the number of antennas grows large ?
- What is the impact of correlated antennas ?

UL: Uplink
MU MIMO: Multiuser Multiple Input Multiple Output
MMSE: Minimum Mean Squared Error
CSI: Channel State Information

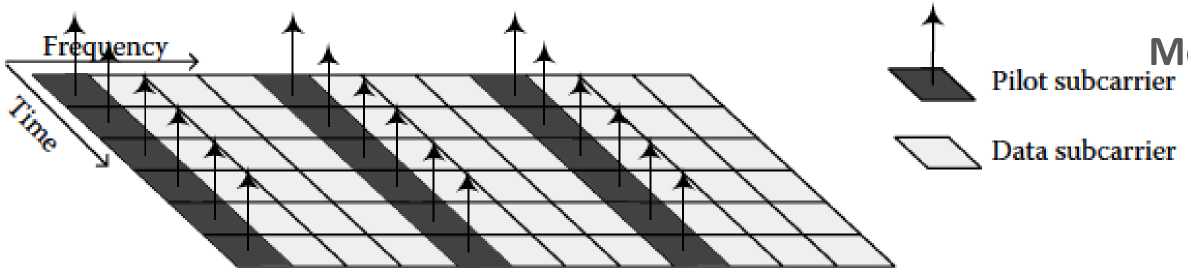
N. Rajatheva, S. Suyama, W. Zirwas, L. Thiele, G. Fodor, A.Tölli, E. Carvalho, J. H. Sorensen, "Massive Multiple Input Multiple Output (MIMO) Systems", Chapter 8 in: A. Osseiran, J. F. Monserrat, P. Marsch, "5G Mobile and Wireless Communications Technology", Cambridge University Press, 2016.

L. S. Muppirisetty, T. Charalambous, J. Karout, G. Fodor, H. Wymeersch, "Location-Aided Pilot Contamination Avoidance for Massive MIMO Systems", IEEE Trans. Wireless Comm, April 2018.

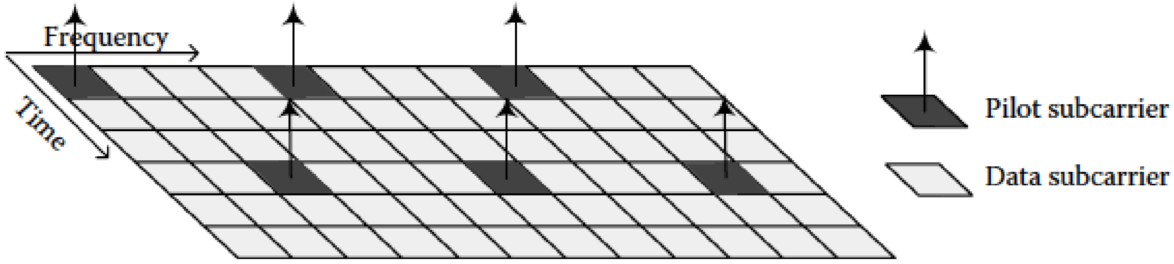
PILOT-BASED CHANNEL ESTIMATION



(a) Frequency continuous–time spaced pilot allocation (Block type)



(b) Time continuous–frequency spaced pilot allocation (Comb type)



(c) Time spaced–frequency spaced pilot allocation

Trade-offs:

More pilot symbols
- → Better channel estimate
  Less aggressive pilot reuse
  More users for MU multiplexing
- → Less data symbols

Higher pilot power
- → Better channel estimate
- → SNR degradation for data
  + increased pilot contamination

MU: Multi user
SNR: Signal-to-Noise-Ratio

G. Fodor, P. D. Marco, M. Telek, "Performance Analysis of Block and Comb Type Channel Estimation for Massive MIMO Systems", 1st International Conference on 5G for Ubiquitous Connectivity, Levi, Finland, Nov. 2014.

K. Guo, Y. Guo, G. Fodor and G. Ascheid, "Uplink Power Control with MMSE Receiver in Multicell Multi-User Massive MIMO Systems", IEEE International Conference on Communications (ICC), Sydney, Australia, June 2014.

FULL DIMENSION IN 3GPP

- Full Dimension MIMO (FD-MIMO)
  - Greater number of antenna ports
  - Efficient MU MIMO Spatial Multiplexing
  - Robustness against CSI Impairments (e.g. intercell interference)

- 3GPP Technical Report: Study on Elevation Beamforming and FD-MIMO for LTE
  - See also:
    - 36.873 Study on 3D Channel Model for LTE
    - 37.105 Active Antenna System BS Radio Transmission and Reception

3GPP TSG RAN Meeting #71 RP-160623
Göteborg, Sweden, March 7 - 10, 2016

Source:	Samsung
Title:	New WID Proposal: Enhancements on Full-Dimension (FD) MIMO for LTE
Document for:	Approval
Agenda Item:	10.1.1

3GPP™ Work Item Description

For guidance, see 3GPP Working Procedures, article 39; and 3GPP TR 21.900.
Comprehensive instructions can be found at http://www.3gpp.org/Work-Items

Title: Enhancements on Full-Dimension (FD) MIMO for LTE

Acronym: LTE_eFDMIMO

Unique identifier:

NOTE: If this is a RAN WID including Core and Perf. Part, then Title, Acronym and Unique identifier refer to the feature WI. Please tick (X) the applicable box(es) in the table below:

This WID includes a Core part	X
This WID includes a Performance part	X

1 3GPP Work Area

X	Radio Access
	Core Network
	Services

3GPP TR 36.897 V13.0.0 (2015-06)

Technical Report

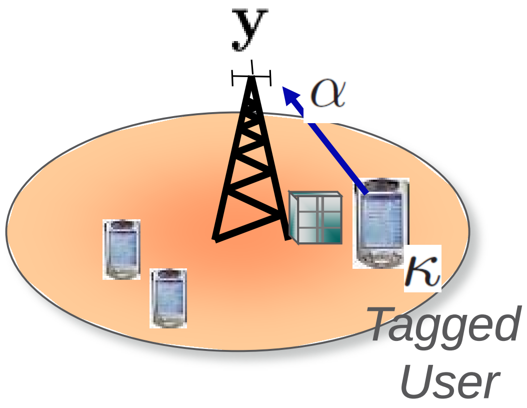
**3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Study on elevation beamforming / Full-Dimension (FD) Multiple Input Multiple Output (MIMO) for LTE
(Release 13)**

3GPP TS 37.105 V1.0.0 (2016-03)

Technical Specification

**3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Active Antenna System (AAS) Base Station (BS) radio transmission and reception
(Release 13)**

MU MIMO UPLINK SIGNAL MODEL



Data signal model:

$$\mathbf{y} = \underbrace{\alpha_\kappa \mathbf{h}_\kappa \sqrt{P_\kappa} x_\kappa}_{\text{User-}\kappa} + \underbrace{\sum_{k \neq \kappa}^{K} \alpha_k \mathbf{h}_k \sqrt{P_k} x_k}_{\text{Other users}} + \mathbf{n}_d$$

$$\mathbf{G}^{\text{naïve}} = \mathbf{G}^{\text{naïve}}(\hat{\mathbf{h}}) = \frac{\alpha \sqrt{P} \hat{\mathbf{h}}^H}{\alpha^2 P ||\hat{\mathbf{h}}||^2 + \sigma^2}$$

The naïve G minimizes the MSE of the received data symbols when perfect channel estimation is available at the receiver.

G. Fodor, P. Di Marco and M.Telek, "On the Impact of Antenna Correlation on the Pilot-Data Balance in Multiple Antenna Systems" IEEE International Conference on Communications (ICC), London, UK, June 2015.

RELATED WORKS ON MMSE RECEIVERS/ESTIMATORS

M. R. McKay, I. B. Collings, and A. M. Tulino, "Achievable sum rate of MIMO MMSE receivers: A general analytic framework," *IEEE Trans. Inf. Theory*, vol. 56, no. 1, pp. 396 – 410, January 2010.

Y. Jiang, M. K. Varanasi, and J. Li, "Performance analysis of ZF and MMSE equalizers for MIMO systems: An in-depth study of the high SNR regime," *IEEE Trans. on Info. Theory*, vol. 57, no. 4, pp. 2008–2026, March 2011.

A. H. Mehana and A. Nosratinia, "Diversity of MMSE MIMO receivers," *IEEE Transactions on Information Theory*, vol. 58, no. 11, pp. 6788–6805, November 2012.

——, "Diversity of MMSE receivers in MIMO multiple access channels," *IEEE W. Comm. Letters*, vol. 2, no. 3, pp. 275–278, June 2013.

CSI Errors
are not considered

T.-M. Ma, Y.-S. Shi, and Y.-G. Wang, "A low complexity MMSE for OFDM systems over frequency-selective fading channels," *IEEE Commun. Lett.*, vol. 16, no. 3, Mar. 2012.

Focuses on
channel estimation only

E. Eraslan, B. Daneshrad, and C.-Y. Lou, "Performance indicator for MIMO MMSE receivers in the presence of channel estimation error," *IEEE W. Comm. Letters*, vol. 2, no. 2, pp. 211–214, April 2013.

Uses the naïve receiver

PRELIMINARIES I

ACCESS Linnaeus Centre

Pilot signal model: $\mathbf{Y}^p = \alpha\sqrt{P_p}\mathbf{h}\mathbf{s}^T + \mathbf{N}$ $\quad \mathbf{h} \in \mathbb{C}^{N_r \times 1}$

Estimated channel: $\hat{\mathbf{h}} = \mathbf{h} + \mathbf{w} = \frac{1}{\alpha\sqrt{P_p}}\mathbf{Y}^p\mathbf{s}^*(\mathbf{s}^T\mathbf{s}^*)^{-1} = \mathbf{h} + \frac{1}{\alpha\sqrt{P_p\tau_p}}\mathbf{N}\,\mathbf{s}^*$

Conditional channel distribution: $(\mathbf{h} \mid \hat{\mathbf{h}}) \sim \mathbf{D}\hat{\mathbf{h}} + \underbrace{\mathcal{CN}\big(\mathbf{0}, \mathbf{Q}\big)}_{\text{“channel estimation noise”}}$

$\mathbf{D} \triangleq \mathbf{C}\mathbf{R}^{-1}$

$\mathbf{Q} \triangleq \mathbf{C} - \mathbf{C}\mathbf{R}^{-1}\mathbf{C}$

Covariance of the estimated channel: $\mathbf{R} \triangleq \mathbb{E}\{\hat{\mathbf{h}}\hat{\mathbf{h}}^H\} = \mathbf{C} + \frac{\sigma_p^2}{\alpha^2 P_p \tau_p}\mathbf{I}_{N_r}$

G. Fodor, M. Telek, “On the Pilot-Data Trade Off in Single Input Multiple Output Systems”, European Wireless ’14, pp. 485-492, Barcelona, May 2014.

PRELIMINARIES II

Data signal model:

$$\mathbf{y} = \underbrace{\alpha_\kappa \mathbf{h}_\kappa \sqrt{P_\kappa} x_\kappa}_{\text{User-}\kappa} + \underbrace{\sum_{k \neq \kappa}^{K} \alpha_k \mathbf{h}_k \sqrt{P_k} x_k}_{\text{Other users}} + \mathbf{n}_d$$

MU MIMO Receiver at the BS:

$$\mathbf{G}_\kappa^\star \triangleq \arg\min_{\mathbf{G}} \mathbb{E}\{\text{MSE}\} = \arg\min_{\mathbf{G}} \mathbb{E}\{|\mathbf{G}\mathbf{y} - x_\kappa|^2\}$$

N. Rajatheva, S. Suyama, W. Zirwas, L. Thiele, G. Fodor, A.Tölli, E. Carvalho, J. H. Sorensen, "Massive Multiple Input Multiple Output (MIMO) Systems", Chapter 8 in: A. Osseiran, J. F. Monserrat, P. Marsch, "5G Mobile and Wireless Communications Technology", Cambridge University Press, June 2016. ISBN: 9781107130098

HOW TO FIND THE (TRUE) MMSE RECEIVER ? -- APPROACH 1

$$\text{MSE}\left(\mathbf{G}_\kappa, \mathbf{h}_1, \ldots, \mathbf{h}_K\right) = \mathbb{E}_{x,\mathbf{n}_d}\{|\mathbf{G}_\kappa \mathbf{y} - x_\kappa|^2\}$$

$$\mathbb{E}_{\mathbf{h}_1,\ldots,\mathbf{h}_{\kappa-1},\mathbf{h}_{\kappa+1},\ldots,\mathbf{h}_K}$$

- Determine the MSE of a tagged User κ as a function of G_κ and the actual channel

$$\text{MSE}\left(\mathbf{G}_\kappa, \mathbf{h}_\kappa\right)$$

$$(\mathbf{h} \mid \hat{\mathbf{h}}) \sim \mathbf{D}\hat{\mathbf{h}} + \mathcal{CN}\left(\mathbf{0}, \mathbf{Q}\right)$$

- Determine the MSE of a tagged User κ as a function of G_κ and the estimated channel

$$\text{MSE}\left(\mathbf{G}_\kappa, \hat{\mathbf{h}}_\kappa\right) = \mathbb{E}_{\mathbf{h}_\kappa|\hat{\mathbf{h}}_\kappa} \text{MSE}\left(\mathbf{G}_\kappa, \mathbf{h}_\kappa\right)$$

$$\mathbf{G}_\kappa \triangleq \arg\min_{\mathbf{G}} \mathbb{E}\{\text{MSE}\} = \arg\min_{\mathbf{G}} \mathbb{E}\{|\mathbf{G}\mathbf{y} - x_\kappa|^2\}$$

HOW TO FIND THE (TRUE) MMSE RECEIVER ? -- APPROACH 2

$$\mathrm{MSE}\left(\mathbf{G}_\kappa, \mathbf{h}_1, \ldots, \mathbf{h}_K\right) = \mathbb{E}_{x,\mathbf{n}_d}\{|\mathbf{G}_\kappa \mathbf{y} - x_\kappa|^2\}$$

~~$\mathbb{E}_{\mathbf{h}_1,\ldots,\mathbf{h}_{\kappa-1},\mathbf{h}_{\kappa+1},\ldots,\mathbf{h}_K}$~~

- Determine the MSE of a tagged User κ as a function of G_κ and the actual channel of all users

$$\mathrm{MSE}\left(\mathbf{G}_\kappa, \hat{\mathbf{H}}\right) = \mathbb{E}_{\mathbf{H}|\hat{\mathbf{H}}}\mathrm{MSE}\left(\mathbf{G}_\kappa, \mathbf{H}\right)$$

$$(\mathbf{h} \mid \hat{\mathbf{h}}) \sim \mathbf{D}\hat{\mathbf{h}} + \mathcal{CN}\left(\mathbf{0}, \mathbf{Q}\right)$$

- Determine the MSE of a tagged User κ as a function of G_κ and the estimated channel of all users

$$\mathrm{MSE}\left(\mathbf{G}_\kappa, \hat{\mathbf{h}}_\kappa\right) = \mathbb{E}_{\mathbf{h}_\kappa|\hat{\mathbf{h}}_\kappa}\mathrm{MSE}\left(\mathbf{G}_\kappa, \mathbf{h}_\kappa\right)$$

$$\mathbf{G}_\kappa \triangleq \arg\min_{\mathbf{G}} \mathbb{E}\{\mathrm{MSE}\} = \arg\min_{\mathbf{G}} \mathbb{E}\{|\mathbf{G}\mathbf{y} - x_\kappa|^2\}$$

RESULTS

- Closed form expression for the MMSE receiver in the presence of CSI errors
- Closed form expression for the MSE when using the naïve and the MMSE receiver
- Closed form expressions for the optimum pilot-to-data power ratio when using the MMSE receiver

HOW TO FIND THE (TRUE) MMSE RECEIVER ?

Proposition *The optimal* $\mathbf{G}_\kappa^\star$ *can be derived as:*

$$\mathbf{G}_\kappa^\star = \alpha_\kappa \sqrt{P_\kappa} \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa{}^H \left(\alpha_\kappa^2 P_\kappa \underbrace{\left(\mathbf{D}_\kappa \hat{\mathbf{h}}_\kappa \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa{}^H + \mathbf{Q}_\kappa \right)}_{\text{CSI error compensation by 2nd order statistics (D and Q)}} + \underbrace{\sum_{k \neq \kappa}^{K} \alpha_k^2 P_k \mathbf{C}_k}_{\text{MU-MIMO Interference}} + \sigma_d^2 \mathbf{I} \right)^{-1}$$

CSI error compensation by 2^{nd} order statistics (D and Q)

MU-MIMO Interference

Elements of proof:

$$\mathrm{MSE}\left(\mathbf{G}_\kappa, \hat{\mathbf{h}}_\kappa\right) = -\underbrace{\mathbf{G}_\kappa}_{\mathbf{x}} \underbrace{\alpha_\kappa \sqrt{P_\kappa} \mathbf{D}_\kappa \hat{\mathbf{h}}_\kappa}_{\mathbf{B}} - \alpha_\kappa \sqrt{P_\kappa} \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa^H \mathbf{G}_\kappa^H + 1 +$$

$$+ \mathbf{G}_\kappa \underbrace{\left(\alpha_\kappa^2 P_\kappa \left(\mathbf{D}_\kappa \hat{\mathbf{h}}_\kappa \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa{}^H + \mathbf{Q}_\kappa \right) + \sum_{k \neq \kappa}^{K} \alpha_k^2 P_k \mathbf{C}_k + \sigma_d^2 \mathbf{I} \right)}_{\mathbf{A}} \mathbf{G}_\kappa^H$$

Quadratic Form:

$$\left(\mathbf{x} \mathbf{A} \mathbf{x}^H - \mathbf{x} \mathbf{B} - \mathbf{B}^H \mathbf{x}^H + 1 \right)$$

$$\mathbf{x}^\star = \mathbf{B}^H \mathbf{A}^{-1}$$

G. Fodor, P. Di Marco, M. Telek "On Minimizing the MSE in Multiple Antenna Systems in the Presence of Channel State Information Errors", IEEE Communications Letters, Vol. 19, No. 9, pp. 1604-1607, September 2015.

HOW TO FIND THE (TRUE) MMSE RECEIVER ?

Proposition *The optimal* $\mathbf{G}_\kappa^\star$ *can be derived as:*

$$\mathbf{G}_\kappa^\star = \alpha_\kappa \sqrt{P_\kappa} \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa{}^H \left(\alpha_\kappa^2 P_\kappa \underbrace{\left(\mathbf{D}_\kappa \hat{\mathbf{h}}_\kappa \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa{}^H + \mathbf{Q}_\kappa \right)}_{\text{CSI error compensation by 2nd order statistics (D and Q)}} + \underbrace{\sum_{k \neq \kappa}^{K} \alpha_k^2 P_k \mathbf{C}_k}_{\text{MU-MIMO Interference}} + \sigma_d^2 \mathbf{I} \right)^{-1}$$

CSI error compensation by 2nd order statistics (D and Q)

MU-MIMO Interference

"Perfect"

Approach 2:

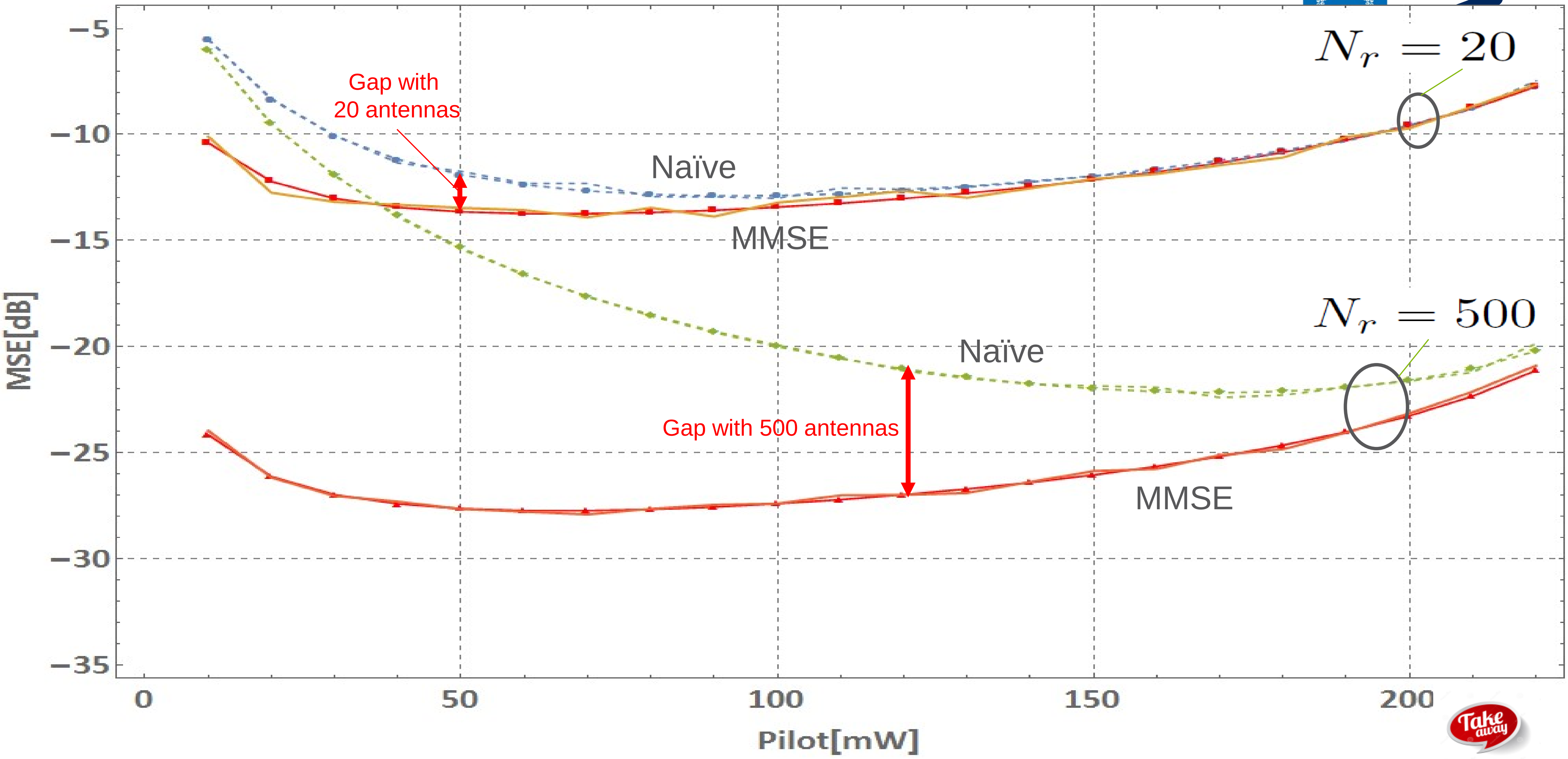
$$\mathbf{G}_\kappa^* = \alpha_\kappa \sqrt{P_\kappa} \hat{\mathbf{h}}_\kappa^H \mathbf{D}_\kappa^H \left(\sum_{k=1}^{K} \alpha_k^2 P_k \left(\mathbf{D}_k \underbrace{\hat{\mathbf{h}}_k \hat{\mathbf{h}}_k^H}_{\text{"Estimate"}} \mathbf{D}_k^H + \mathbf{Q}_k \right) + \sigma_d^2 \mathbf{I} \right)^{-1}$$

"Estimate"

COMPARING ANALYTICAL AND SIMULATION RESULTS

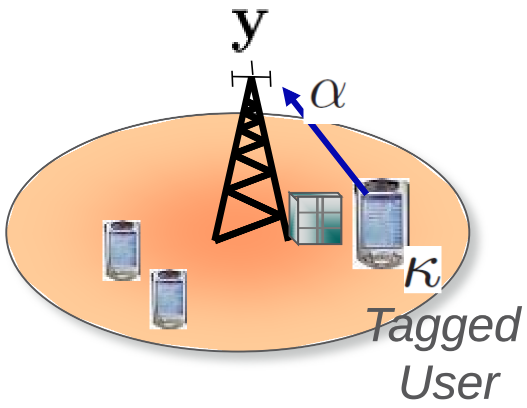
ACCESS Linnaeus Centre

COMPARING SIMULATION AND ANALYTICAL RESULTS



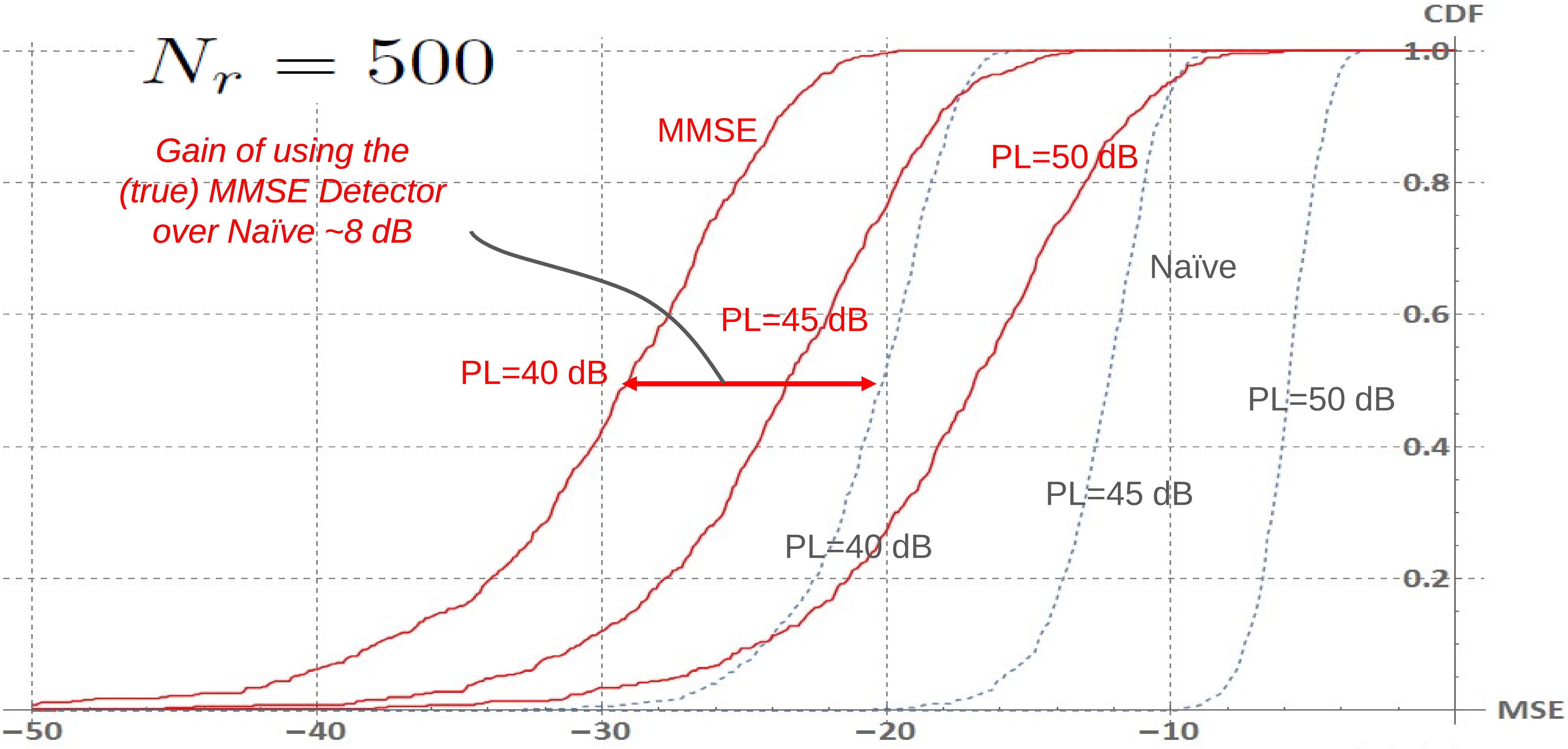
The gain of the (true) MMSE receiver over the naïve receiver increases when the number of antennas increases.

SIMULATION SETUP



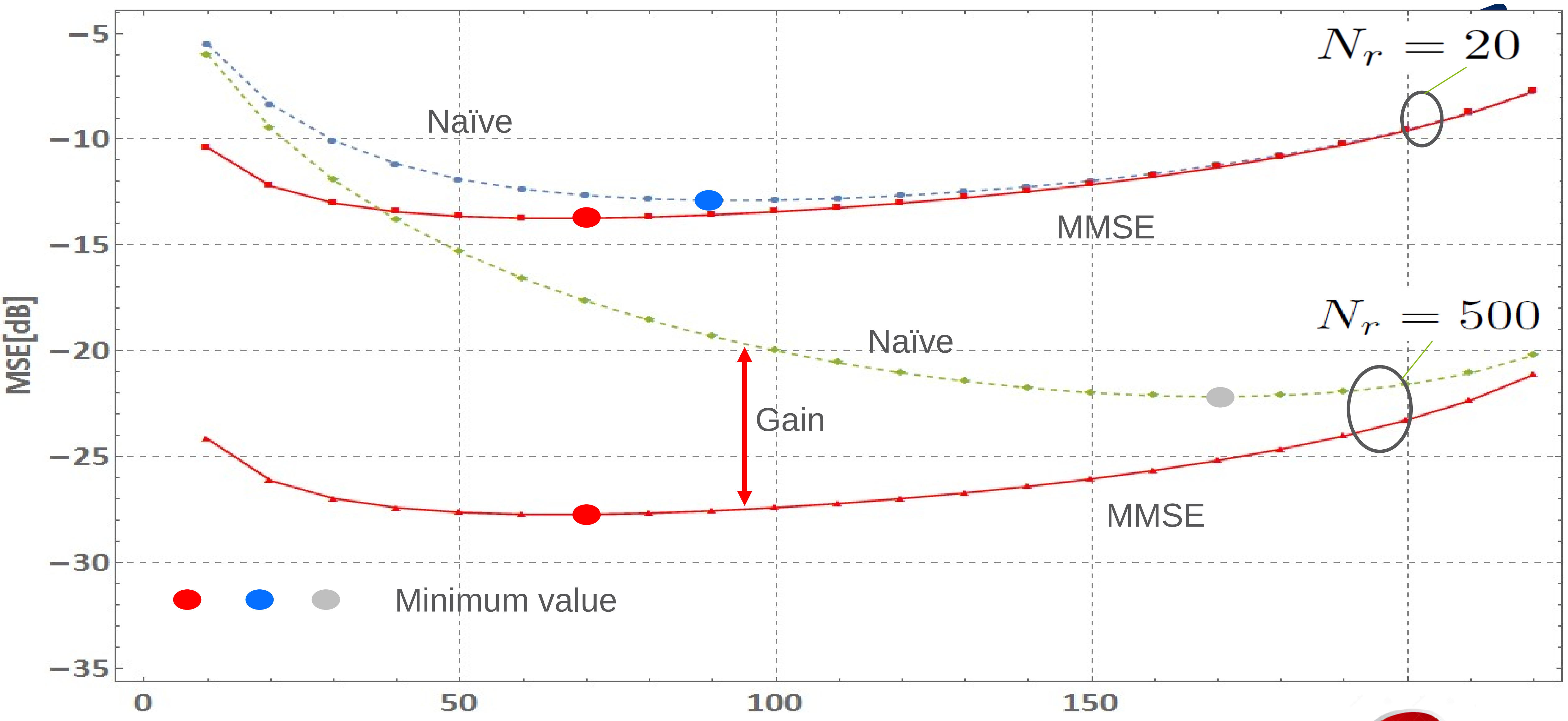
- Single user system, that is no MU MIMO interference

Parameter	Value
Number of antennas	$N_r = 2, 4, 8, 10, 20, 50, 100, 500$
Path Loss of tagged User-κ	$\alpha = 40, 45, 50$ dB
Number of pilot and data symbols	$\tau_p = 1; \ \tau_d = 11$
Power budget	$\tau_p P_p + \tau_d P = P_{tot}$ =250 mW.



The optimal receiver yields significant gains over the whole CDF, including the 10 and 90 percentiles and for various levels of the path loss.

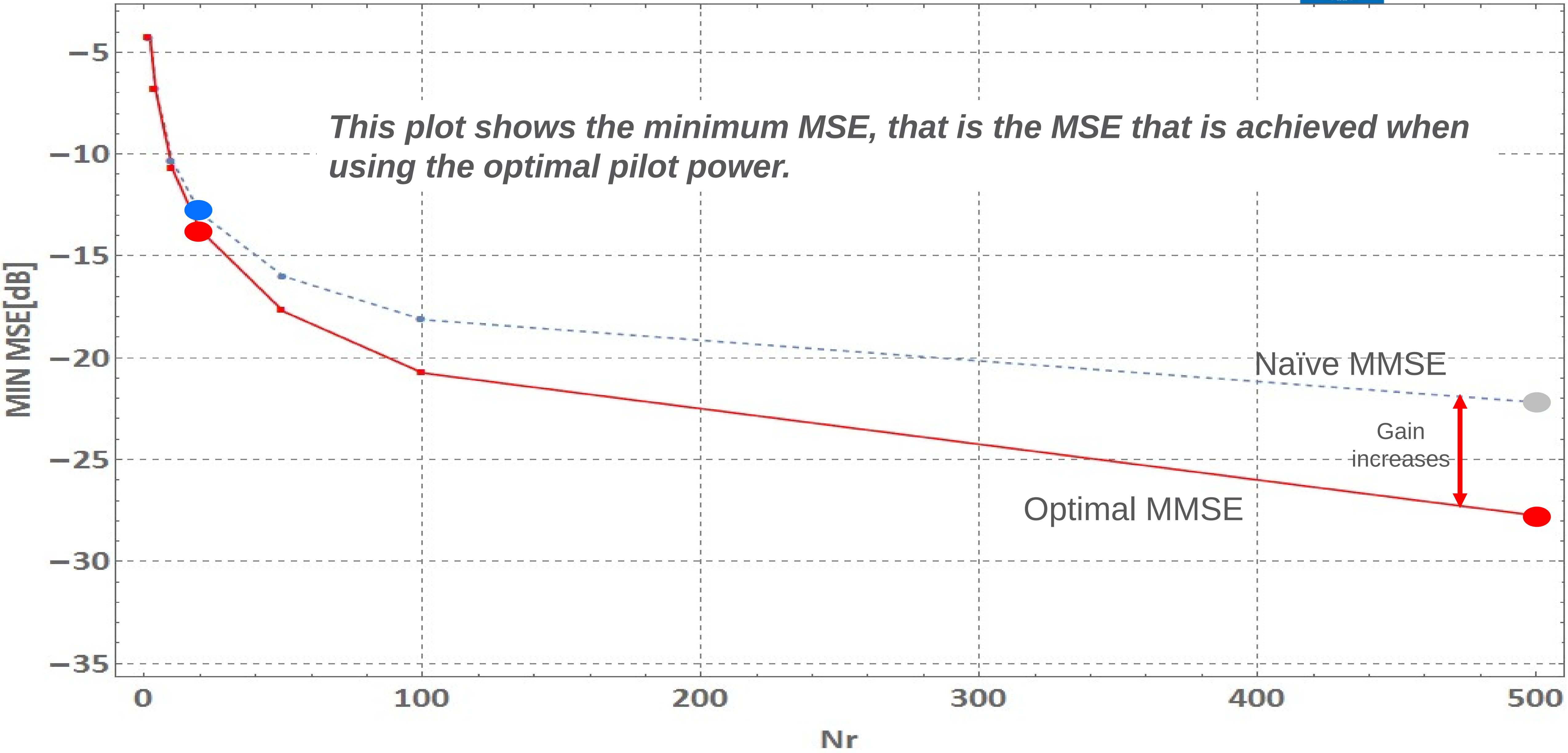
OPTIMUM PILOT POWER SETTING



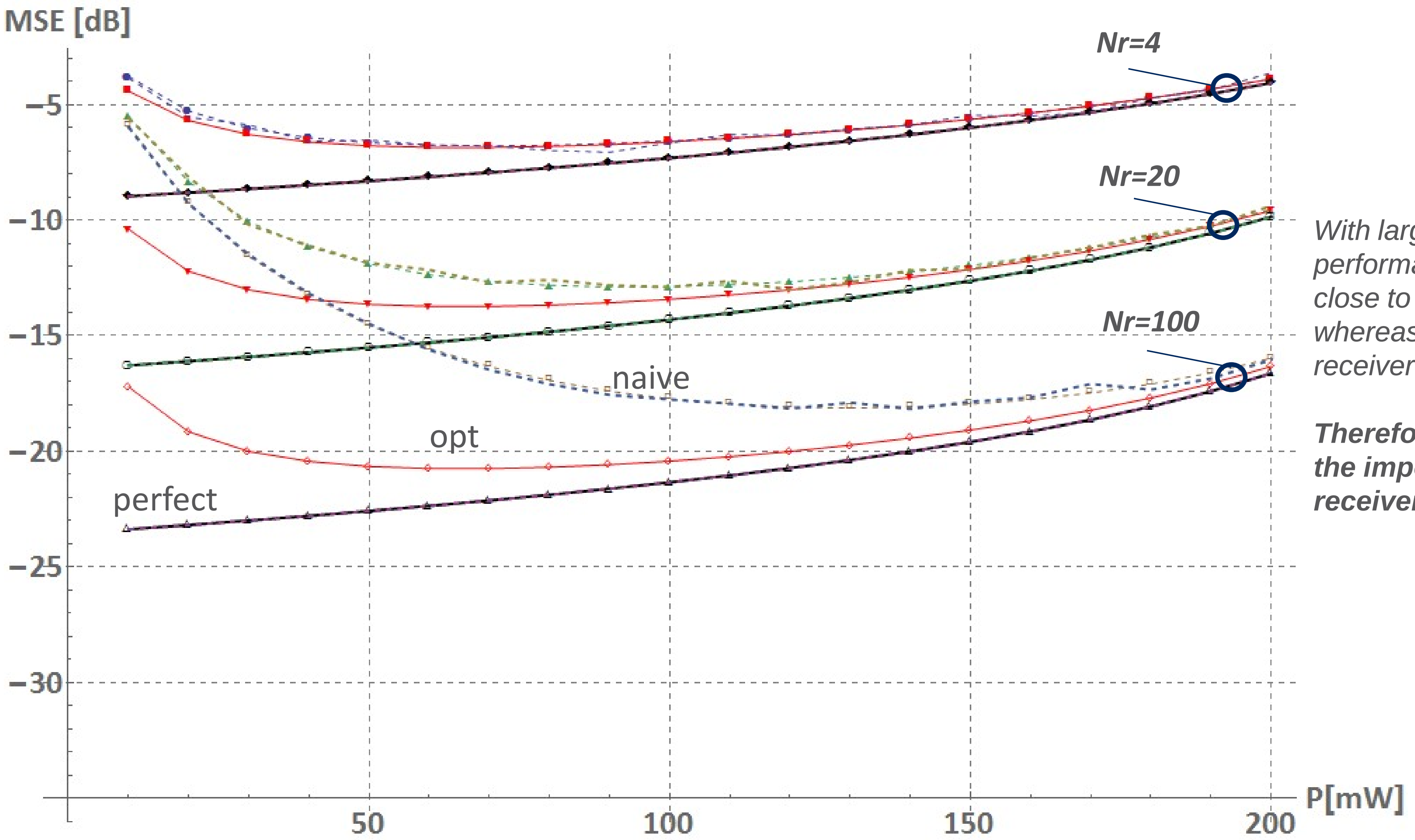
The gain of the optimal receiver increases with increasing number of antennas.

With the true MMSE, the transmit power that minimizes the MSE, does not depend on the number of receive antennas.

HOW DOES THE GAIN DEPEND ON THE NUMBER OF ANTENNAS ?



COMPARISON WITH PERFECT CSI



Data transmit power decreases

With large number of antennas, the MSE performance of the optimal receiver remains close to the perfect CSI performance, whereas the performance of the naïve receiver is far from the perfect CSI case.

Therefore, with larger number of antennas, the importance of applying the optimal receiver increases.

TAKE AWAY

ACCESS Linnaeus Centre

- The gain of the optimal receiver increases with increasing number of antennas. In the massive MIMO domain, this gain can be up to 8-10 dB in terms of MSE;

- The true MMSE receiver well approximates the perfect channel estimation case, independently of the number of antennas (as opposed to the naïve receiver);

- With the true MMSE, the transmit power that minimizes the MSE, does not depend on the number of receive antennas (as opposed to the naïve receiver);

TUNING THE PILOT-TO-DATA POWER RATIO

KEY TAKE-AWAY

Multiuser MIMO Pilot Setting

Fixed pilot resources

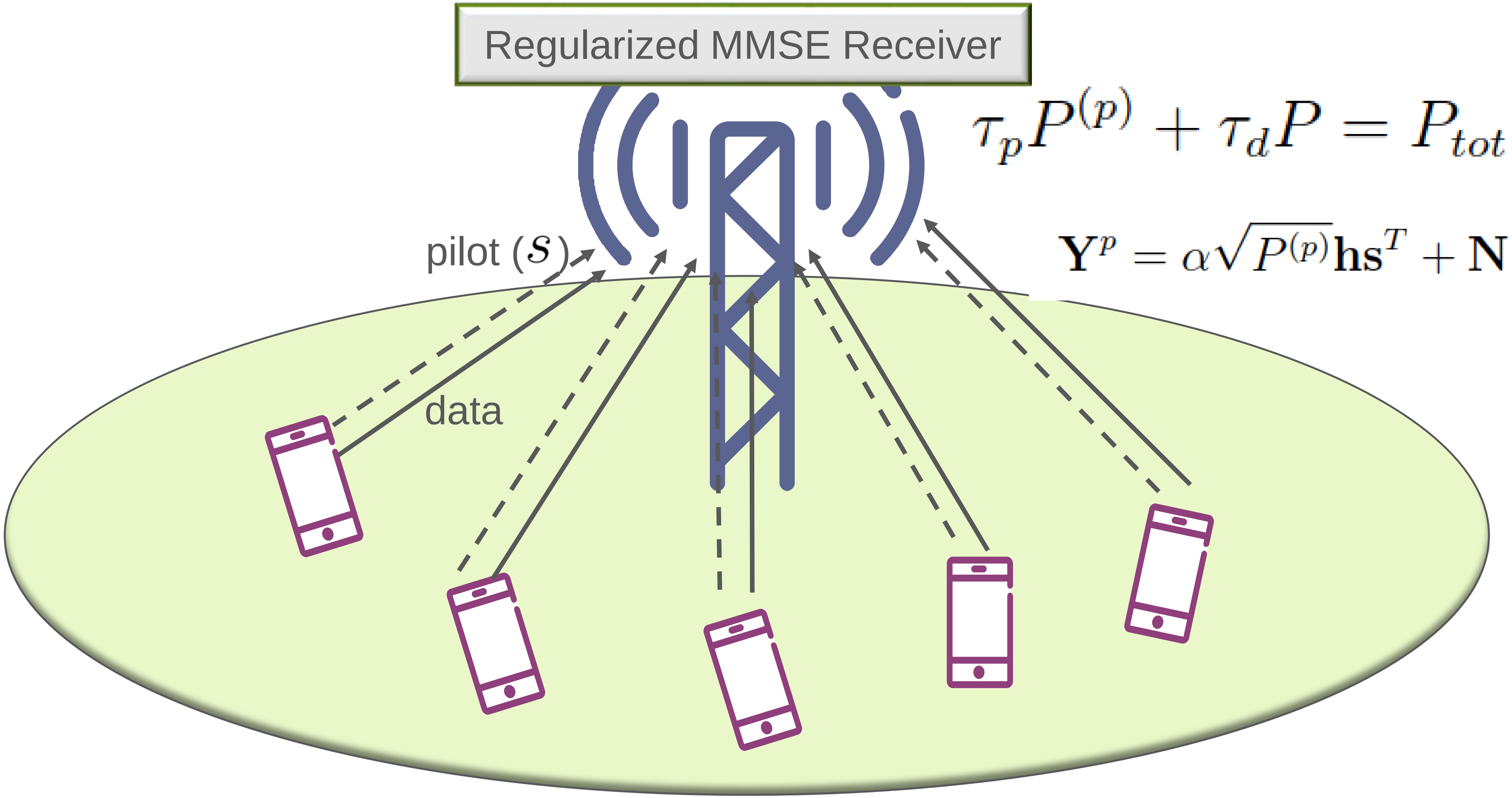
e.g. LTE Demodulation Reference Signals

Adaptive pilot resources

Centralized Algorithms

Decentralized/Hybrid Algorithms

SINGLE CELL MU MIMO MODEL

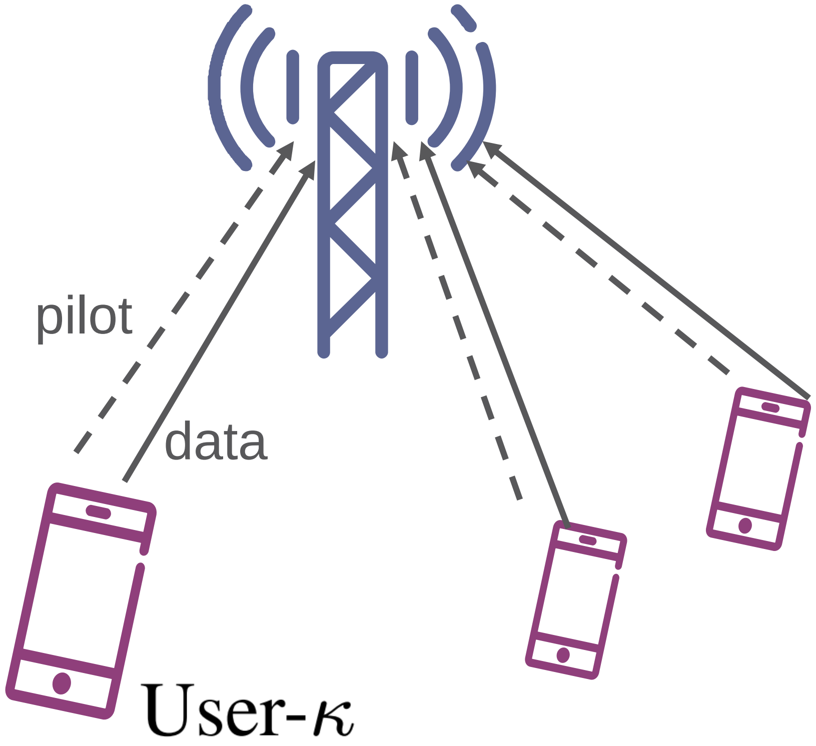


$$\tau_p P^{(p)} + \tau_d P = P_{tot}$$

$$\mathbf{Y}^p = \alpha\sqrt{P^{(p)}}\mathbf{h}\mathbf{s}^T + \mathbf{N}$$

P. Zhao, G. Fodor, G. Dan, and M. Telek, "A Game Theoretic Approach to Setting the Pilot Power Ratio in Multi-User MIMO Systems", IEEE Transactions on Communications, Vol. 66, Issue 3, March 2018.

MU MIMO GAME



Each user tunes his PPR to minimize the own MSE.

Best Response Power Allocation:

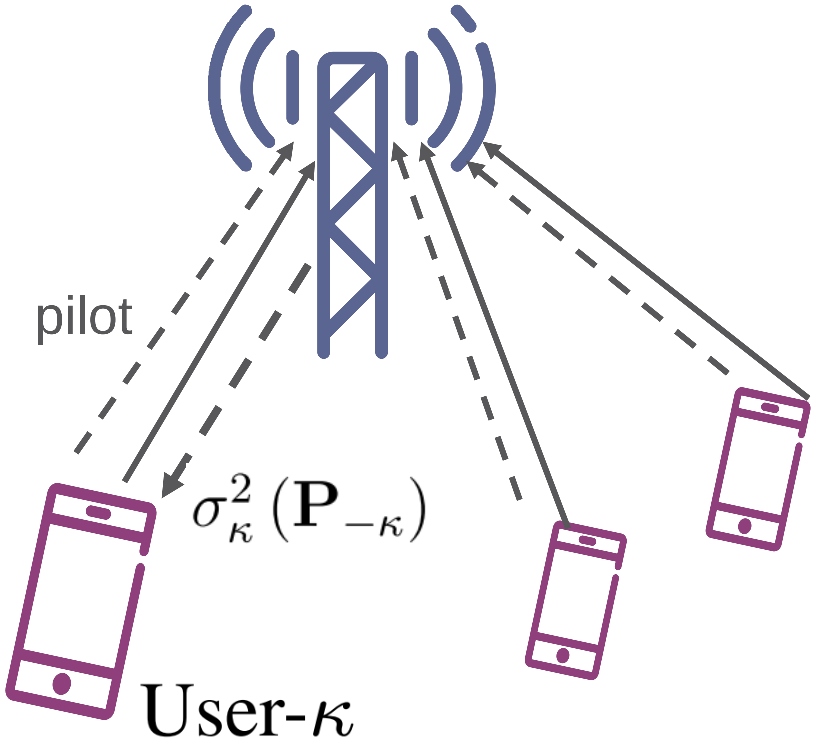
$$\mathrm{MSE}_\kappa(P_\kappa^\star, \mathbf{P}_{-\kappa}) \leq \mathrm{MSE}_\kappa(P_\kappa, \mathbf{P}_{-\kappa})$$

transmit power of all other players

$$\mathbf{P} \triangleq \{P_1, \ldots, P_K\} \in \mathbb{R}^{1\times K}$$

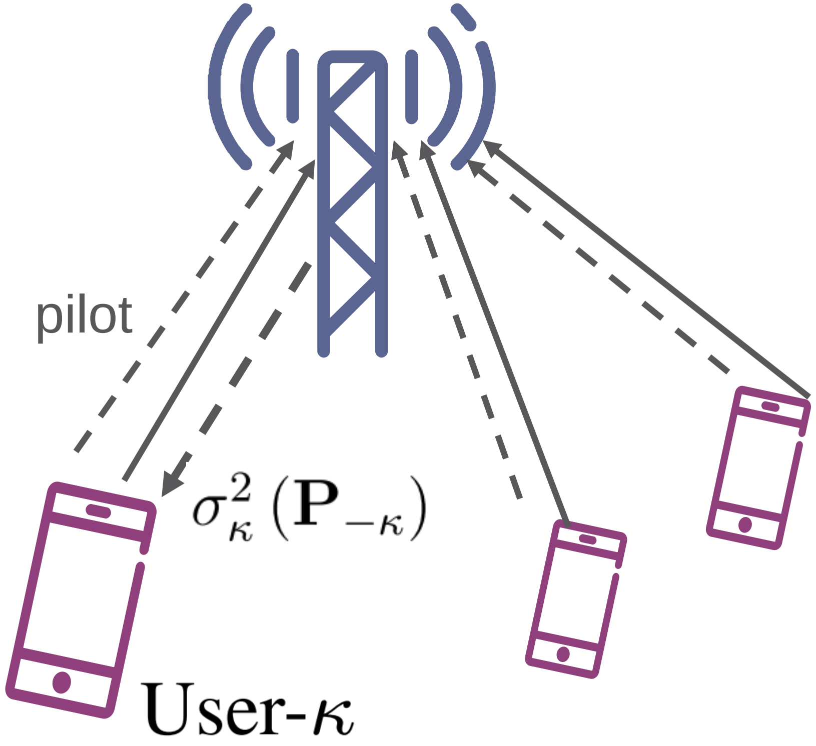
P. Zhao, G. Fodor, G. Dan, and M. Telek, "A Game Theoretic Approach to Setting the Pilot Power Ratio in Multi-User MIMO Systems", IEEE Transactions on Communications, December 2017.

BEST PILOT-DATA POWER RATIO ALGORITHM



- Each user minimizes the own MSE by setting the PPR
- BPA converges to a pure strategy Nash equilibrium
  - BS can help User-κ by signaling $\sigma_\kappa^2(\mathbf{P}_{-\kappa})$ to User-κ

BEST PILOT-DATA POWER RATIO ALGORITHM (BPA)



Non-cooperative Game:

$$\mathcal{G} \triangleq < \mathcal{K}, (\mathcal{P}_d), (\text{MSE}_{\kappa}(\mathbf{P})) >$$

$P_{\kappa}^{\star}(\mathbf{P}_{-\kappa})$: Best response power allocation of the tagged MS, as a function of the currently used transmit power of all other MSs.

Mapping from $\mathbf{P}$ to $\mathbf{P}^{\star}$:

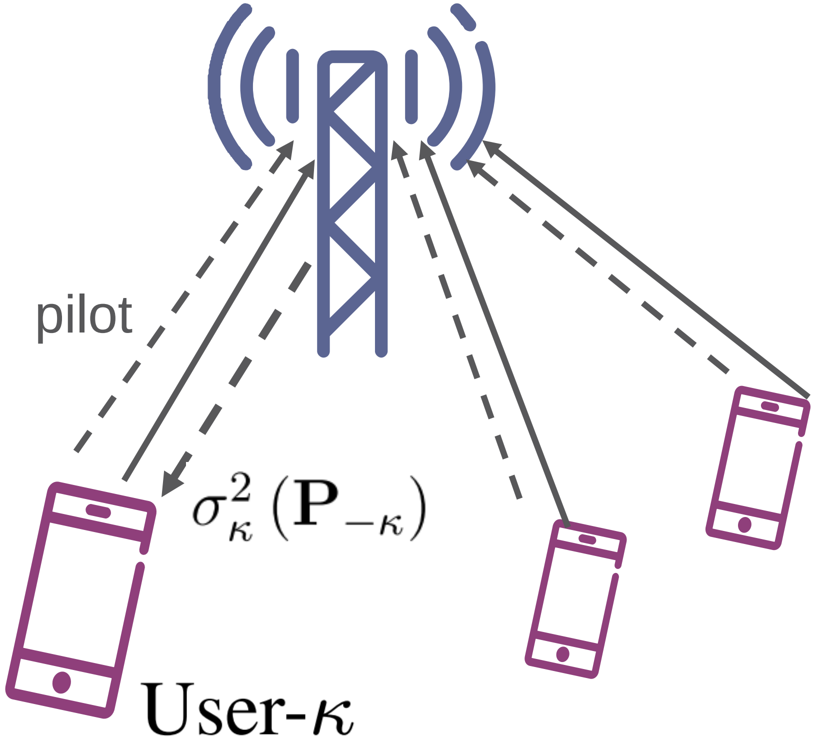
$$\mathbf{f}(\mathbf{P}) \triangleq [P_1^{\star}(P_1, \mathbf{P}_{-1}), \ldots, P_K^{\star}(P_K, \mathbf{P}_{-K})]$$

$$f_j(\mathbf{P}) = P_j^{\star}(\mathbf{P}_{-j})$$

$$\mathbf{F}(\mathbf{P})_{ij} \triangleq \frac{\partial}{\partial P_i} f_j(\mathbf{P}) = \frac{\partial}{\partial P_i} P_j^{\star}(\mathbf{P})$$

BEST PILOT-DATA POWER RATIO ALGORITHM (BPA)

$P^{\star}_{\kappa}(\mathbf{P}_{-\kappa})$ Best response power allocation of the tagged MS, as a function of the currently used transmit power of all other MSs.



Algorithm 1: Best PPR Algorithm (BPA)

Input: MSE improvement threshold ϵ,
Mode $\in \{\mathrm{MIN}, \mathrm{MAX}\}$

if *Mode* == MIN **then**
  Initial data power $P^{(0)}_{\kappa} = P^{\star}_{\kappa}(\mathbf{0})$, $\forall \kappa \in \mathcal{K}$
else
  Initial data power $P^{(0)}_{\kappa} = P^{\star}_{\kappa}\left(\frac{P_{tot}}{\tau_d}\,\mathbf{e}\right)$, $\forall \kappa \in \mathcal{K}$
end
$i = 0$
repeat
  BS sends σ^2_p and $\sigma^2_{\kappa}\left(\mathbf{P}^{(i-1)}_{-\kappa}\right)$ to MS-κ, $\kappa \in \mathcal{K}$
  for $\kappa \in \mathcal{K}$ **do**
    if **then**
      $P^{(i)}_{\kappa} = P^{\star}_{\kappa}\left(\mathbf{P}^{(i-1)}_{-\kappa}\right)$
    else
      $P^{(i)}_{\kappa} = P^{(i-1)}_{\kappa}$
    end
  end
  $i = i + 1$
until $P^{(i)}_{\kappa} == P^{(i-1)}_{\kappa}$, $\forall \kappa \in \mathcal{K}$;
Output: Data power allocation $\mathbf{P}$.

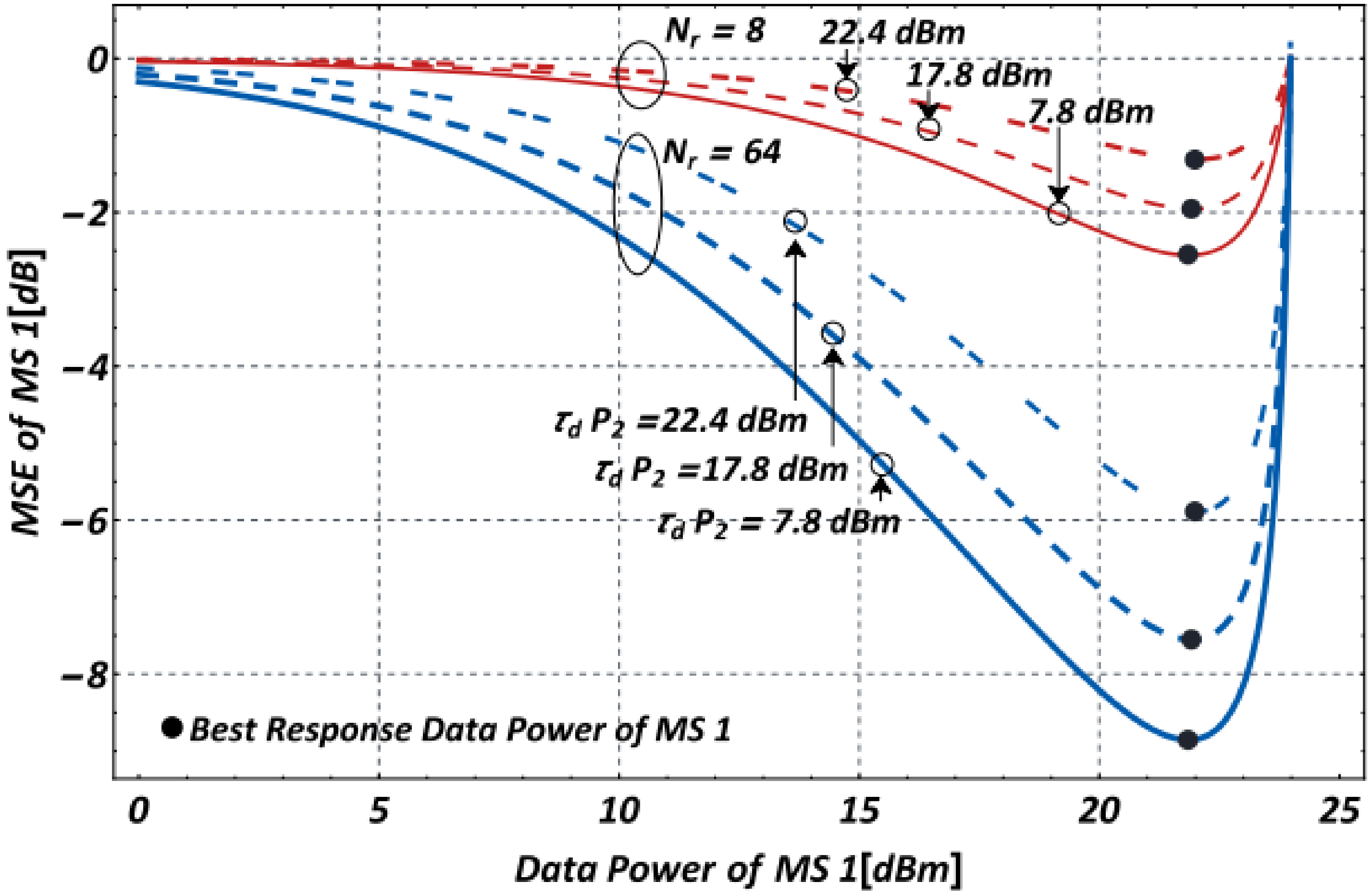
OUTLINE

- What is the Pilot-to-Data Power Ratio ?
- MU MIMO Game
- Numerical Results
- Conclusions

SINGLE CELL PARAMETER SETTING

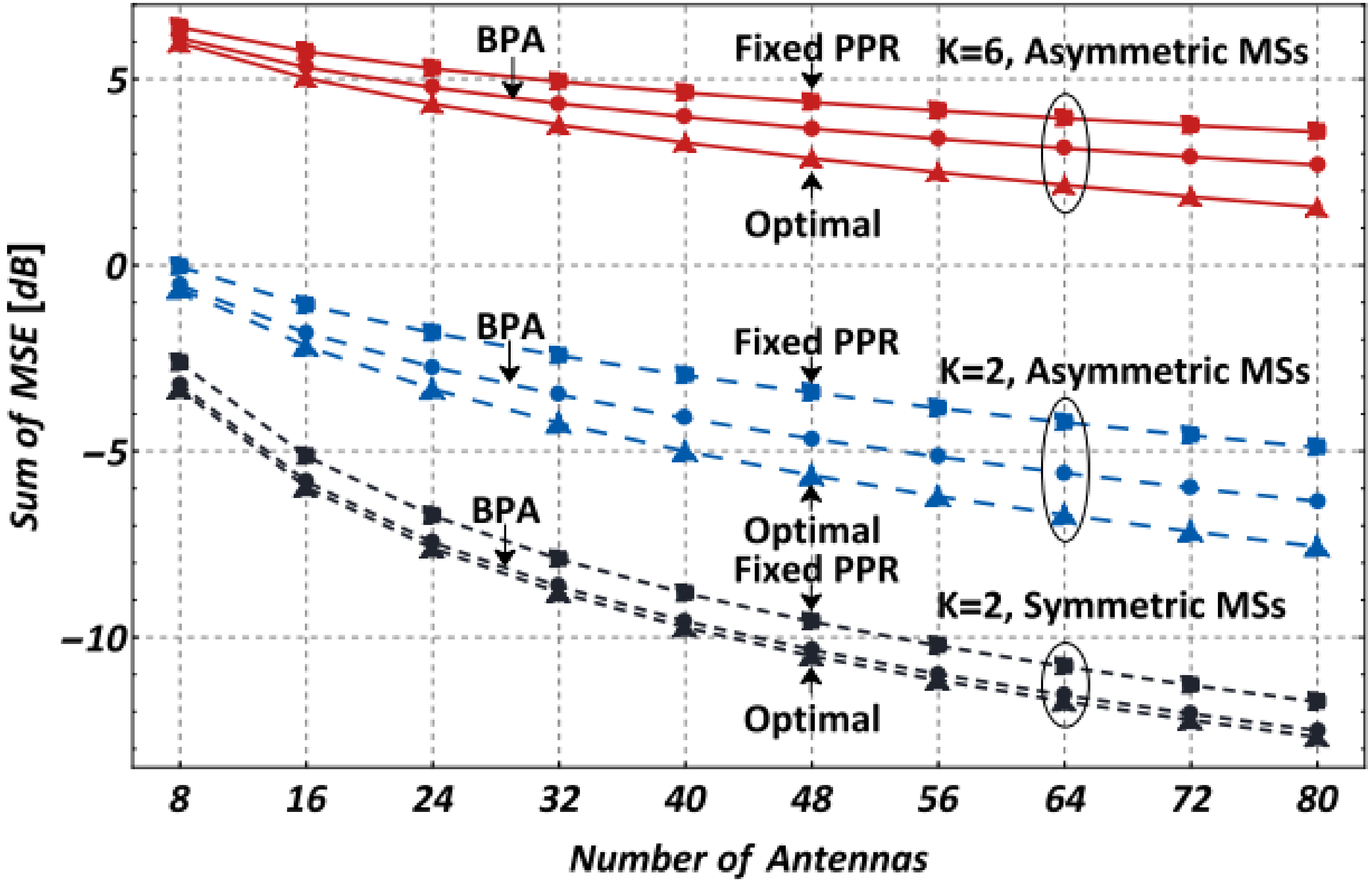
Parameter	**Value**
Number of antennas at the BS	$N_r = 8, \ldots, 80$
Number of MSs	$K = 2, 6$
Total number of symbols (per time slot)	$F = 12$
Number of data symbols (per time slot)	$\tau_d = 6$
Number of pilot symbols (per time slot)	$F - \tau_d$
Power budget	$P_{tot} = 24$ dBm
Thermal noise per MHz	-114 dBm

2-PLAYER GAME



- 2-3 iterations are needed to converge to the Nash equilibrium
- MSE of MS 1 is hit by the data power of MS 2 ($\tau_d P_2$)
- Large gain of increasing the number of antennas

2 AND 6-PLAYER GAME



- Adaptive PPR is superior to fixed PPR
- BPA is close to the optimal PPR

CONCLUSIONS

- Adaptive rather than fixed PPR is beneficial for reducing the MSE
- A game theoretic, decentralized PPR setting algorithm quickly converges to a near optimal setting

KEY TAKE-AWAY

Multiuser MIMO Pilot Setting

Fixed pilot resources

e.g. LTE Demodulation Reference Signals

Adaptive pilot resources

Centralized Algorithms

Decentralized/Hybrid Algorithms