Massive MIMO Systems: Signal Processing Challenges and Research Trends

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Introduction (1/2)

- Wireless networks are experiencing a huge increase in the delivered amount of data due to emerging applications: M2M, video, etc.

- Key problems: High data rates require extra spectrum and energy which are very scarce, scalability of devices and signal processing algorithms.

- Future networks will require techniques that can substantially increase the capacity (bits/Hz) whilst not requiring extra spectrum or extra energy.

- Massive MIMO is a potential solution to these problems:
  - Very large arrays with an order of magnitude higher number of sensors.
  - Deployment of devices (access points, mobile phones and tables) with a large number of antenna elements.
  - Huge multiplexing gains allowing an order of magnitude higher data rates.

T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

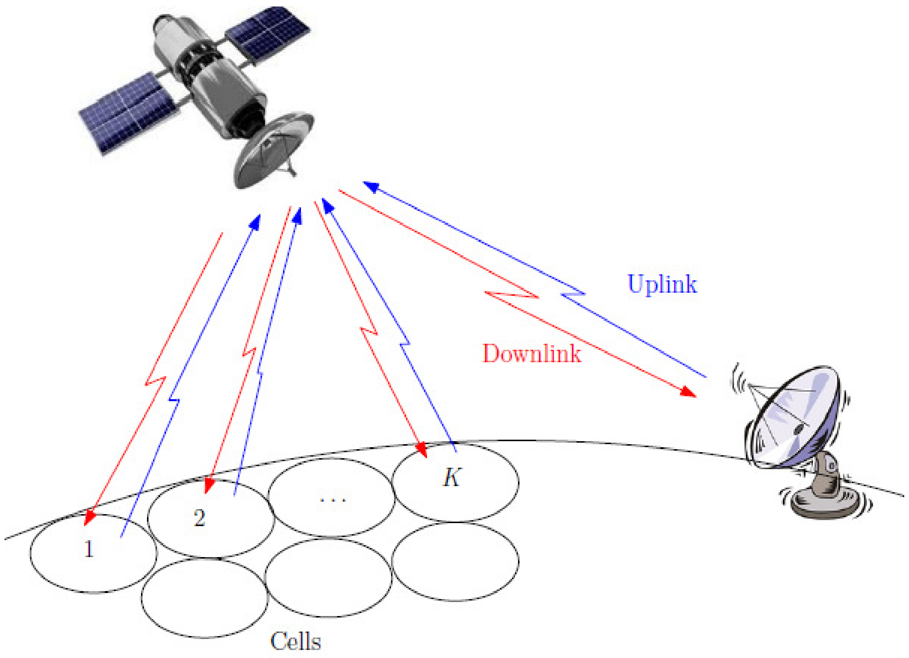
Introduction (2/2)

Massive MIMO networks will be structure around the following elements:

- Antennas:
  - Reduction of RF chains and costs,
  - Compact antennas and mitigation of coupling effects.
- Electronic components:
  - Low-cost components such as power amplifiers and RF components.
  - Flexibility for different air interfaces and replacement of coaxial cables.
- Network architectures:
  - Heterogeneous networks, small cells and network MIMO,
  - Cloud radio access networks to help different devices.
- Protocols:
  - Scheduling and medium-access protocols for numerous heterogeneous users.
- Signal processing:
  - Transmit and receive processing,
  - Scalability and hardware implementation,
  - Integration between signal processing and RF devices to deal with impairments.

Application Scenarios: Satellite Networks

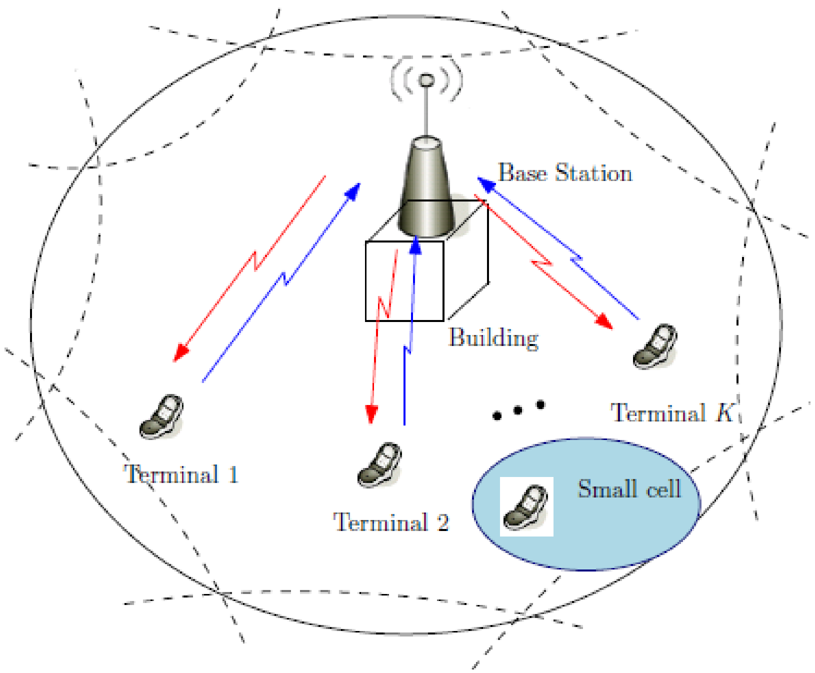
- Multi-beam satellite systems:
  - Clear and well-defined scenario for massive MIMO.
  - Coverage region is served by multiple spot beams intended for the users .
  - Beams are shaped by the antenna feeds forming part of the payload.
- Research problem:
  - interference caused by multiple adjacent spot beams that share the same frequency band.
- Interference mitigation:
  - Precoding for the forward link that needs CSI.
  - Detection algorithms for the reverse link.



J. Arnau, B. Devillers, C. Mosquera, A. Prez-Neira, "Performance study of multiuser interference mitigation schemes for hybrid broadband multibeam satellite architectures", EURASIP Journal on Wireless Communications and Networking, 2012:132 (5 April 2012).

Application Scenarios: Mobile Cellular Networks

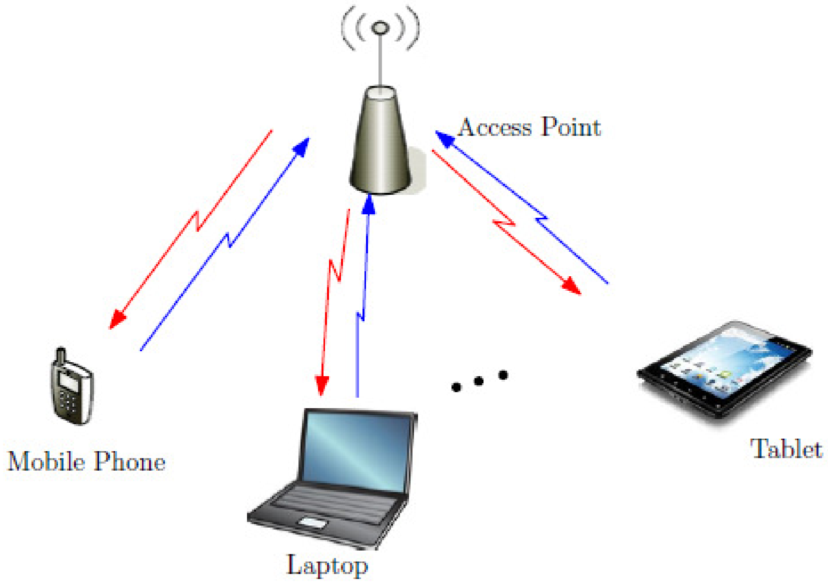
- 5G mobile cellular networks:
  - Base stations: very large arrays placed on rooftops and façades.
  - User terminals: phones, tablets with a significant number of antenna elements.
  - Compact antennas: mutual coupling
  - Coordination between cells.
  - Operation in TDD Mode.
- Research problems:
  - Uplink channel estimation: use of non-orthogonal pilots, the existence of adjacent cells and the coherence time of the channel require the system to reuse the pilots.
  - Pilot contamination: occurs when the CSI at the base station in one cell is affected by users from other cells.
- Topics for investigation:
  - Design of channel estimation strategies that avoid pilot contamination.
  - Design of precoding and detection algorithms for Network MIMO with large arrays.



J. Jose, A. Ashikhmin, T. L. Marzetta, S. Vishwanath, "Pilot Contamination and Precoding in Multi-Cell TDD Systems," *IEEE Transactions on Wireless Communications*, vol.10, no.8, pp. 2640-2651, August 2011.

Application Scenarios: Local Area Networks

- Future wireless local area networks:
  - Tremendous increase in the last years with the proliferation of access points (APs) in hot spots and home users.
  - IEEE 802.11ac: MIMO-OFDM with 20 or 40 MHz, up to 8 antennas at APs, 64 subcarriers which are not all used.
  - Massive MIMO: compact antennas, planar array geometries, etc.
- Research problems:
  - Coupling effects and I/Q imbalances.
  - Physical dimensions of APs and user devices.
- Topics for investigation:
  - Coupling must be mitigated by DSP or smart RF solutions.
  - Design of efficient precoding and detection algorithms.
  - Design of decoding algorithms with reduced delay.



Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Very High Throughput for Operation in Bands Below 6GHz, IEEE P802.11ac/D1.0 Stdandard., Jan. 2011

Signal Models: Downlink Case

- Multiuser massive MIMO system:
  - N_A antennas at the transmitter (satellite gateway, base station or WLAN AP).
  - K users and each is equipped with N_U antennas.
- Fundamental massive MIMO scenarios:
  - When $N_A >> KN_U$ -> excess degrees of freedom leverages array gain
  - When $N_A \sim KN_U$ -> absence of extra degrees of freedom
- Precoded data:
  - KN_U x 1 data vector $\mathbf{s}[i] = [\mathbf{s}_1^T[i] \ldots \mathbf{s}_k^T[i] \ldots \mathbf{s}_K^T[i]]^T$
  - N_A x 1 precoded data $\mathbf{x}_k[i] = P(\mathbf{s}_k[i])$,

where each symbol $s_i \in A = \{a_1, \ldots, a_N\}$, has zero mean and variance σ_s^2.

- Received data:
  - N_U x 1 received vector

$$r_k[i] = \sum_{k=1}^{K} \boldsymbol{H}_k x_k[i] + n_k[i]$$

where $\mathbf{H}_k$ is the N_U x N_A channel matrix and $\mathbf{n}_k$ is the N_U x 1 noise vector.

Signal Models: Uplink Case

- Multiuser massive MIMO system:
  - N_A antennas at the receiver (satellite gateway, base station or WLAN AP).
  - K users and each is equipped with N_U antennas.
- Fundamental massive MIMO scenarios:
  - When $N_A >> KN_U$ -> excess degrees of freedom leverages array gain
  - When $N_A \sim KN_U$ -> absence of extra degrees of freedom
- Received data with sufficient statistics:
  - N_A x 1 received vector

$$\boldsymbol{r}[i] = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{s}_k[i] + \boldsymbol{n}[i]$$

where $\mathbf{H}_k$ is the N_A x N_U channel matrix and $\mathbf{n}$ is the N_A x 1 noise vector.

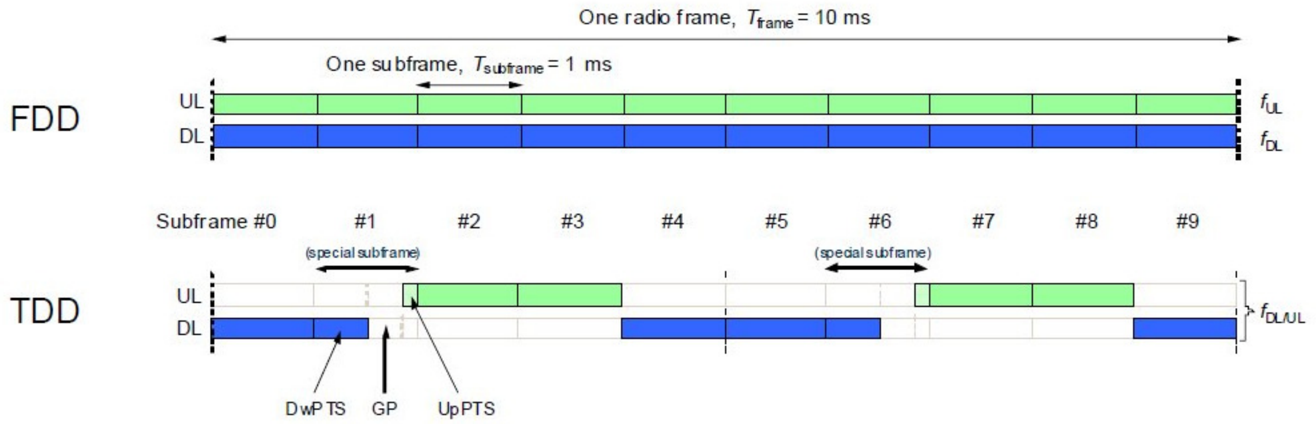
Transmit Processing

- Optimal transmit strategy:
  - Requires CSI, obtained either by feedback channels or reciprocity.
  - Dirty paper coding.
  - Implicit scheduling and power allocation.
  - Very costly and impractical.
- Practical strategies:
  - TDD mode.
  - Pilot contamination.
  - Resource allocation.
  - Precoding techniques.

G. Caire and S. Shamai (Shitz), "On the achievable throughput of a multiantenna Gaussian broadcast channel," IEEE Trans. Inform. Theory, vol. 49, no. 7, pp. 1691–1706, July 2003.

A. Ashikhmin and T. L. Marzetta, "Pilot contamination precoding in multi-cell large scale antenna systems," in IEEE International Symposium on Information Theory (ISIT), Cambridge, MA, Jul. 2012.

Operation in TDD Mode

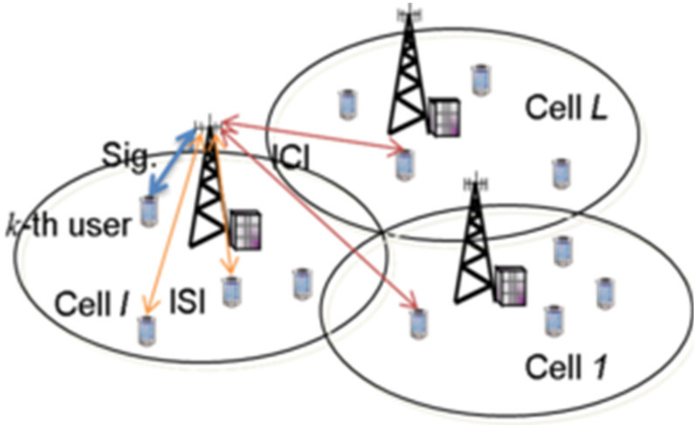


- Does not require feedback channels to acquire CSI
- Rely on reciprocity to obtain CSI at the either the Tx or the Rx.
  - In Massive MIMO CSI is obtained at the base station or AP.
  - Problem with the amplifiers and filters that are different.
- Independent from the number of antennas N_A at the base station or AP.
  - In FDD the CSI feedback requirements are proportional to the number of antennas.
  - In Massive MIMO it is more likely the use of TDD to eliminate the need for CSI feedback.
- Research problems:
  - Calibration and measurement techniques.

X. Gao, F. Tufvesson, O. Edfors, and F. Rusek, "Measured propagation characteristics for very-large MIMO at 2.6 GHz," in Proc. of the 46th Annual Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, California, USA, Nov. 2012.

Pilot Contamination

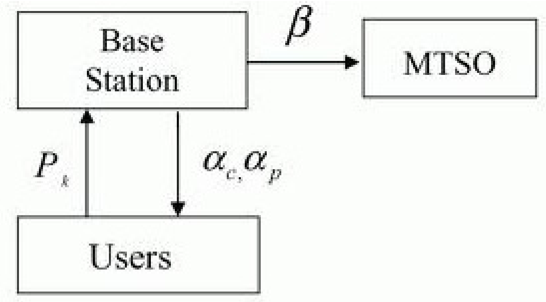
- Adoption of TDD, network MIMO and uplink training -> phenomenon called Pilot Contamination.
- In multi-cell scenarios, it is difficult to employ orthogonal pilot sequences because their duration depends on the number of cells.
- The duration of the sequences is limited by the channel coherence time.
- Therefore, non-orthogonal pilot sequences are likely to be employed and this affects the CSI accuracy employed at the transmitter.
- Specifically, CSI is contaminated by a linear combination of channels of other users that share the same pilot.
- Consequently, the precoders and resource allocation will be highly affected by the contaminated CSI.
- Research problems:
  - Design of innovative training schemes
  - Design of precoders and resource allocation algorithms that can deal with pilot contamination.



A. Ashikhmin and T. L. Marzetta, "Pilot contamination precoding in multi-cell large scale antenna systems," in IEEE International Symposium on Information Theory (ISIT), Cambridge, MA, Jul. 2012.

Resource Allocation

- Key resources such as antennas, users and power: must be allocated based on the instantaneous CSI of users and a metric.
- In massive MIMO systems, the spatial signatures of the users to be scheduled play a fundamental role -> they are quasi orthogonal.
- The multiuser diversity along with high array gains might be exploited by resource allocation algorithms along with timely CSI.
- Problem of user selection: scheduling is a combinatorial problem equivalent to the combination of *K* choosing *Q*.
- When *K* in the system is reasonably large: we need cost-effective user selection algorithms.
- Research problems:
  - Strategies based on greedy, low-cost and discrete optimization methods.
  - Chunk strategies : aggregate certain parameters per groups of users to reduce cost.



N. Dao and Y. Sun, "User-selection algorithms for multiuser precoding," IEEE Trans. Veh. Technol., vol. 59, no. 7, Sep. 2010.

Precoding and Related Techniques (1/2)

- Main goals:
  - Mitigation of the multiuser interference.
  - Increase in the achievable sum-rates.
- Transmit matched filter:

$$\boldsymbol{x}[i] = \boldsymbol{H}^H \boldsymbol{s}[i]$$

the N_A x K N_U matrix **H** contains the parameters of all the channels and the N_A x 1 vector **x**[i] represents the data processed.

- Linear precoding:

$$\boldsymbol{x}[i] = \boldsymbol{W}_k \boldsymbol{s}_k[i] + \sum_{l=1, l \neq k}^{K} \boldsymbol{W}_l \boldsymbol{s}_l[i],$$

where the N_A x NU precoding matrix $\mathbf{W}_k$ is a function of the channels.

- Block diagonalization precoding:
  - Improved BER and sum-rate performance over linear MMSE or ZF precoding.
  - Computational complexity of original BD is high for large systems.

K. Zu, R. C. de Lamare and M. Haardt, "Generalized design of low- complexity block diagonalization type precoding algorithms for multiuser MIMO systems", IEEE Trans. Communications, 2013.

Precoding and Related Techniques (2/2)

- Tomlinson-Harashima precoding:

$$\boldsymbol{x}[i] = \boldsymbol{F}\tilde{\boldsymbol{x}}[i]$$

where **F** is the N_A x K N_U feedforward matrix obtained by an LQ decomposition of the channel matrix **H** and the input is computed element-by-element by

$$\tilde{x}_l[i] = \mathrm{mod}\{s_l[i] - \sum_{q=1}^{l-1} b_{lq} x_q[i]\}, \quad l = 1, \ldots, KN_U$$

where b_{lq} are the elements of the K N_U x K N_U lower triangular matrix **B** that can also be obtained by an LQ decomposition.

- Vector perturbation precoding:

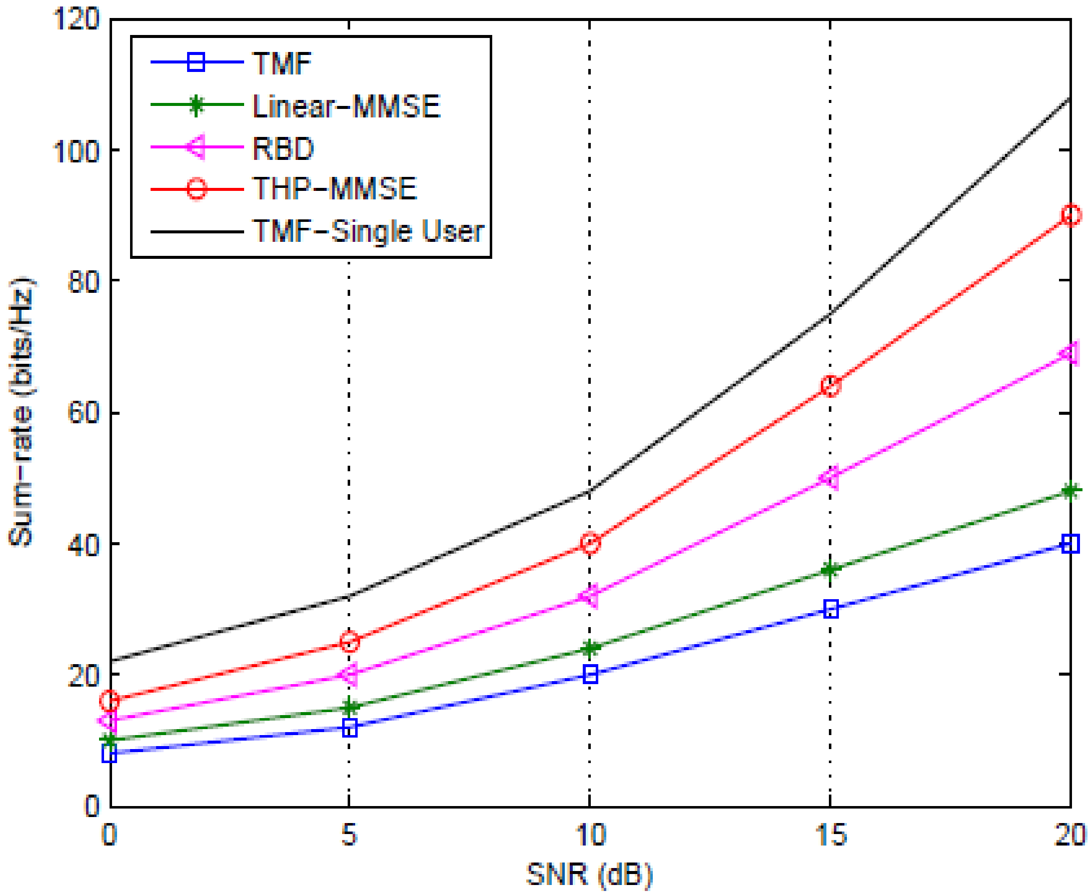
$$\boldsymbol{p}[i] = \arg \min_{\boldsymbol{p}'[i] \in ACZ^K} ||\boldsymbol{W}(\boldsymbol{s}[i] + \boldsymbol{p}'[i]||^2$$

where **W** is a precoder such that Tr($\mathbf{W}^H\mathbf{W}$) ≤ P, the scalar A depends on the constellation size and CZK is the K-dimensional complex lattice

K. Zu, R. C. de Lamare and M. Haardt , “Multi-Branch Tomlinson-Harashima Precoding Design for MU-MIMO Systems: Theory and Algorithm”, IEEE Trans. Communications, 2014 (to appear).

Simulation Results

- Sum-rate performance against SNR of precoding algorithms
- Scenario: N_A = 128, K = 8 users and N_U = 8 antenna elements



Receive Processing

- Parameter estimation techniques:
  - Channel estimation.
  - Estimation of receive filter parameters.
- Detection strategies:
  - ML detection.
  - Suboptimal detection.
- Error control coding:
  - Channel codes.
  - Iterative detection and decoding.
- Mitigation of RF impairments
  - I/Q imbalances in the RF chains of large arrays.
  - Mutual coupling between antenna elements in compact arrays

Parameter Estimation Techniques

- Channel estimation:
  - Semi-blind techniques to deal with pilot contamination.
  - Superimposed training techniques.

- Receive filter parameter estimation:
  - Reduced-rank techniques.
  - Sparsity-aware algorithms.
  - Low-complexity adaptive techniques for estimating and tracking parameters in the presence of mobility.

H. Qian and S. N. Batalama, “Data-record-based criteria for the selection of an auxiliary vector estimator of the MMSE/MVDR filter,” IEEE Trans. Commun., vol. 51, no. 10, pp. 1700–1708, Oct. 2003.
Y. Sun, V. Tripathi, and M. L. Honig, “Adaptive, iterative, reduced-rank (turbo) equalization,” IEEE Trans. Wireless Commun., vol. 4, no. 6, pp. 2789–2800, Nov. 2005.
R. C. de Lamare and R. Sampaio-Neto, “Adaptive reduced-rank processing based on joint and iterative interpolation, decimation, and filtering,” IEEE Trans. Signal Process., vol. 57, no. 7, July 2009, pp. 2503-2514.
R.C. de Lamare and R. Sampaio-Neto, “Adaptive reduced-rank equalization algorithms based on alternating optimization design techniques for MIMO systems,” IEEE Trans. Veh. Technol., vol. 60, no. 6, pp. 2482-2494, July 2011.

Detection Techniques (1/2)

- Main goal: to separate the data streams of the users at the receiver
- Optimal ML detector:

$$\hat{s}_{\mathrm{ML}}[i] = \arg\min_{\boldsymbol{s}[i]} ||\boldsymbol{r}[i] - \boldsymbol{H}\boldsymbol{s}[i]||^2$$

where the KN_U x 1 data vector **s**[i] contains the symbols of all users.

- The complexity of the ML detector grows exponentially with the constellation size and KN_U.
- Sphere decoders are appealing in MIMO systems with small dimensions but are unlikely to be used in massive MIMO systems.

M. O. Damen, H. E. Gamal, and G. Caire, "On maximum likelihood detection and the search for the closest lattice point," *IEEE Trans. Inform. Theory*, vol. 49, pp. 2389–2402, Oct. 2003.

Detection Techniques (2/2)

- Linear detectors:

$$\hat{s}[i] = Q\big(\boldsymbol{W}^H \boldsymbol{r}[i]\big)$$

where **W** is the N_A x KN_U matrix receive filter applied to the received data

- Decision feedback detectors:

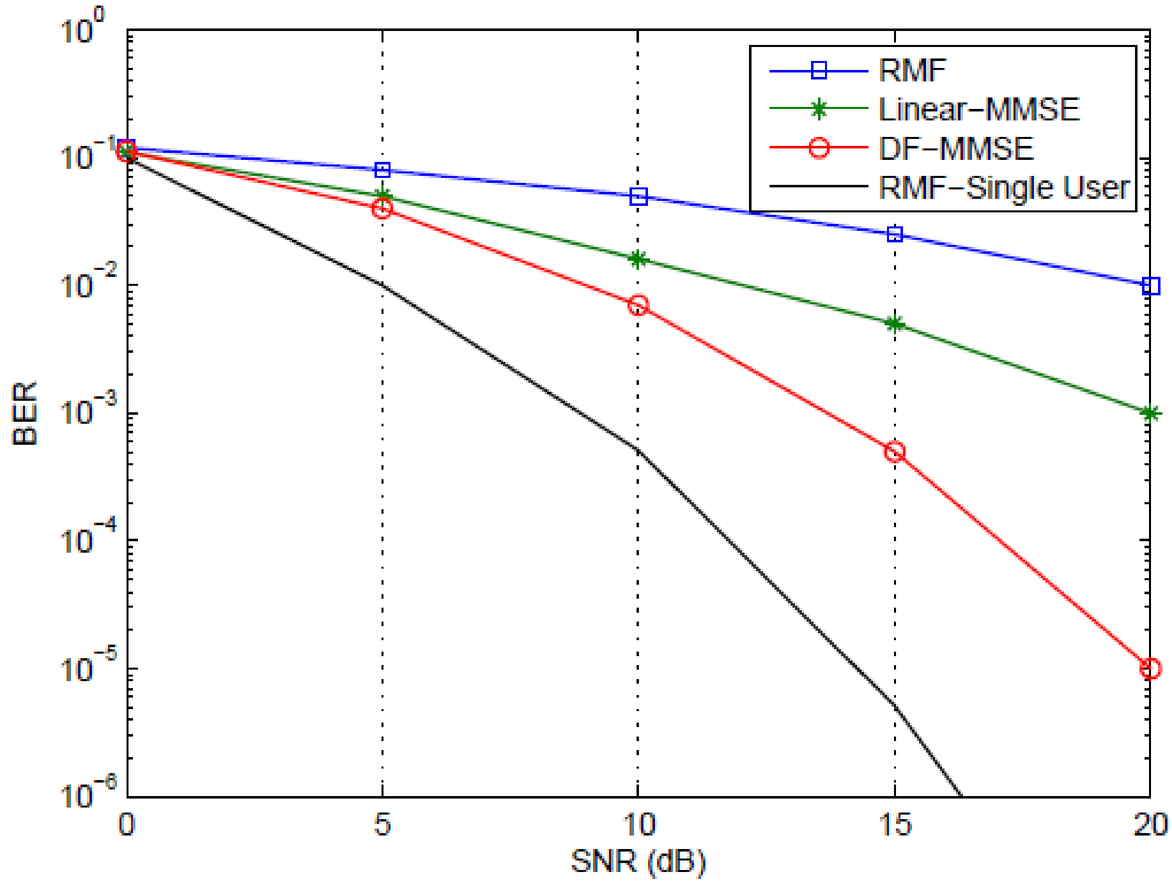
$$\hat{s} = Q\big(\boldsymbol{W}^H \boldsymbol{r}[i] - \boldsymbol{F}^H \hat{s}_o[i]\big)$$

where the receive filters **W** and **F** can be computed using various design criteria and optimization algorithms.

J. H. Choi, H. Y. Yu, Y. H. Lee, "Adaptive MIMO decision feedback equalization for receivers with time-varying channels", *IEEE Trans. Signal Proc.*, 2005, 53, no. 11, pp. 4295-4303.
P. Li, R. C. de Lamare and R. Fa, "Multiple Feedback Successive Interference Cancellation Detection for Multiuser MIMO Systems," *IEEE Transactions on Wireless Communications*, vol. 10, no. 8, pp. 2434 - 2439, August 2011.
P. Li and R. C. de Lamare, "Adaptive Decision-Feedback Detection With Constellation Constraints for MIMO Systems", *IEEE Transactions on Vehicular Technology*, vol. 61, no. 2, 853-859, 2012.

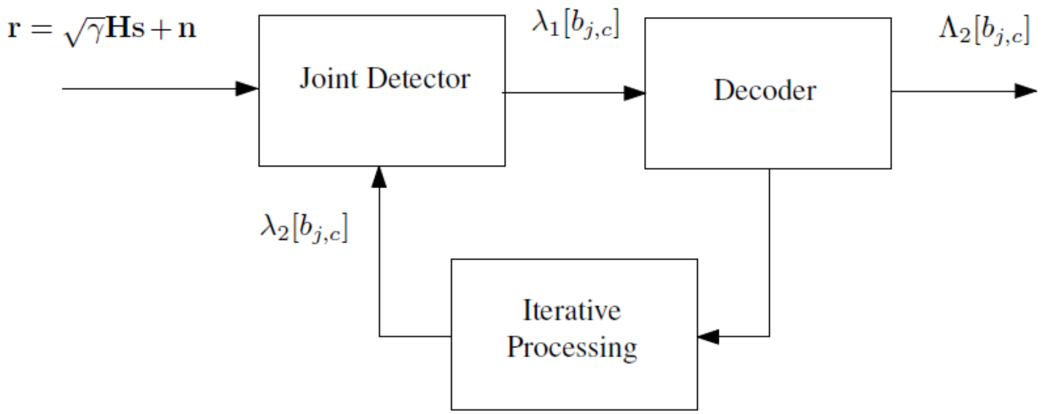
Simulation Results

- BER performance against SNR of detection algorithms
- Scenario: N_A = 128, K = 8 users and N_U = 8 antenna elements



Error Control Coding

- Choice of channel coding
  - Convolutional codes.
  - Turbo codes.
  - LDPC codes.
- Iterative detection and decoding
  - Helps with interference mitigation.



- Research problems
  - Reducing the number of iterations.
  - Improving the exchange of soft information.

H. Wymeersch, F. Penna and V. Savic, "Uniformly Reweighted Belief Propagation for Estimation and Detection in Wireless Networks," IEEE Trans. Wireless Communications, vol. PP, No. 99, pp. 1-9, Feb. 2012.

Mitigation of RF Impairments

- Coupling effects:
  - Reduction of the physical size of antennas induces coupling.
  - Coupling reduces the multiplexing gain and the degrades the performance.
- I/Q imbalances:
  - Phase offsets degrade the performance.
  - Originate non-circular data.
- Failures of antenna elements:
  - Cheaper components may lead to more frequent failures.
  - Reduction of the degrees of freedom.
  - Signal processing algorithms should be able to cope with them.

T. Adali, P. J. Schreier and L. L. Scharf, "Complex-valued signal processing: the proper way to deal with impropriety", IEEE Trans. Signal Processing, vol. 59, no. 11, pp. 5101–5125 , November 2011.
N. Song, R. C. de Lamare, M. Haardt, and M. Wolf, "Adaptive Widely Linear Reduced-Rank Interference Suppression based on the Multi-Stage Wiener Filter," IEEE Transactions on Signal Processing, vol. 60, no. 8, 2012.

Future Trends and Emerging Topics

- Transmit processing
  - Cost-effective scheduling techniques: greedy techniques and discrete optimisation tools.
  - Calibration techniques.
  - Precoders with scalability in terms of complexity: use of transmit matched filters as the front-end.

- Receive processing
  - Cost-effective detection algorithms: use of the receive matched filter as the front-end.
  - Reduced-delay decoding algorithms and IDD schemes.
  - Mitigation of impairments: use of widely-linear processing.

Concluding Remarks

- A tutorial on massive MIMO systems focusing on signal processing challenges and future trends in this exciting research topic has been given.
- Key application scenarios which include multibeam satellite, cellular and local area networks have been examined along with several operational requirements of massive MIMO networks.
- Transmit and receive processing tasks have been discussed and signal processing needs for future massive MIMO networks have been identified.
- Numerical results have illustrated some of the discussions on transmit and receive processing functions and future trends have been highlighted.
- Massive MIMO technology is likely to be incorporated into applications on a gradual basis by the increase in the number of antenna elements.