Rate-Splitting Multiple Access for 6G: Principles, Applications, and Opportunities

Bruno Clerckx

Communications and Signal Processing Group
Department of Electrical and Electronic Engineering

Imperial College London

Thanks to my PhD students, postdocs and many collaborators at TU Eindhoven, University Erlangen-Nuremberg, Ruhr University Bochum, TU Braunschweig, University of Bremen, TU Darmstadt, Princeton, HKU, Xidian, NUDT, TU Berlin, Eurecom, UCL, KCL, Edinburgh, Surrey, York, PUC-Rio, Pusan, Southeast, Samsung, Huawei,...

WTC online seminar 2020
Outline

1. Principles
2. Applications
3. Opportunities
Outline

1. Principles
2. Applications
3. Opportunities
The Building Block: MISO Broadcast Channel

- Number of transmit antenna: \( N_t \)
- Number of user: \( K \)
- Perfect CSIR: \( \mathbf{H} = [\mathbf{h}_1, \ldots, \mathbf{h}_K] \)
- Imperfect CSIT: channel estimates \( \hat{\mathbf{H}} = [\hat{\mathbf{h}}_1, \ldots, \hat{\mathbf{h}}_K] \) are obtained from feedback (in FDD) or UL training (in TDD).

![Diagram of K-user MISO system with CSIT acquisition]

**Optimal Strategy:**
- Perfect CSIT: DPC
- Imperfect CSIT: Unknown

**Figure:** \( K \)-user MISO system with CSIT acquisition.
Conventional Architecture (4G and 5G)

Multi-User Linear Precoding (MU–LP):

From $K$ messages, we create $K$ streams.

Significant loss if multi-user interference is not within noise level.
Non-Orthogonal Multiple Access (NOMA):

One user fully decodes the messages of other users.

From $K$ messages, we create $K$ streams.

Careful of the inefficient use of multi-antenna and SIC receivers!
Split message $W_k$ into two parts: common $W_{c,k}$ and private $W_{p,k}$.

Rate of user-$k$ has been split: rate of $s_k$ + part of the rate of $s_c$

Users decode parts of the messages of other users and treat other parts as noise.

Adjust power allocated to $s_c$ such that multi-user interference is within noise level.
Degrees-of-Freedom (DoF) - Multiplexing Gains

DoF (multiplexing gain): slope of rate vs SNR

The larger the DoF, the faster the rate increases with SNR

\[ K = N_t = 4 \]

\[ K = N_t = 2 \]

\[
\text{Rate: sum-rate } \sum_k R_k, \text{ weighted sum-rate } \sum_k u_k R_k, \text{ min rate } \min_k R_k, \ldots
\]
Multiplexing Gain vs Number of SIC Layers

\( K = 6, N_t = 4 \) for perfect CSIT (left) and imperfect CSIT (right)

- **Sum multiplexing gain** \( d_s: \sum_k R_k \approx d_s \log_2(P) + \text{const.} \)
- **MMF multiplexing gain** \( d_{\text{mmf}}: \min_k R_k \approx d_{\text{mmf}} \log_2(P) + \text{const.} \)

1-layer RS achieves larger sum/MMF multiplexing gains than MU-LP and NOMA with a single layer of SIC!
Sum-rate: $N_t = K = 2$, $N_t = K = 4$, imperfect CSIT ($\sigma_e^2 = P^{-0.5}$)

Slope increases $\rightarrow$ Rate increases! Cannot reach any better slope!
Rate Fairness Enhancement

MMF rate: $K = 6, N_t = 4$, perfect CSIT (left) and imperfect CSIT (right)

Huge gains with 1-layer RS: rate, fairness and robustness enhancements with only 1 SIC!
Ergodic rate regions: $N_t = K = 2$, imperfect CSIT ($\sigma_e^2 = P^{-0.6}$)

RS schemes outperform MU-LP, NOMA and DPC!
Information Theoretic Optimality

Information theoretic channel (e.g. MISO BC)

Information theoretic limits (Capacity region)

Communication scheme (e.g. DPC)

Signal processing (Precoder optimization)

Imperfect CSIT (Robust optimization)

\[ x = \sum_{k=1}^{K} p_k s_k \]

4G/5G approach
BUT perfect CSIT to start with!

Information theoretic channel (e.g. MISO BC with Imperfect CSIT)

Information theoretic limits (Capacity region - unknown)

Alternative information theoretic limits (DoF region)

Communication scheme (Based on Rate-Splitting)

Signal processing (Precoder optimization)

\[ x = p_c s_c + \sum_{k=1}^{K} p_k s_k \]

Rate-Splitting approach
Optimal in a DoF (region) sense!

Bruno Clerckx (ICL EEE)
partially decode interference and partially treat interference as noise
Two-user MU-LP and NOMA: subsets of RSMA

SDMA based on MU–LP

- Simply allocate no power to $s_c$ and treat multi-user interference as noise $x = p_1 s_1 + p_2 s_2$

NOMA based on SC–SIC

- Forcing user-1 to fully decode the message of user-2
- Allocate no power to $s_2$, encode $W_1$ into $s_1$ and encode $W_2$ into $s_c$
  $x = p_c s_c + p_1 s_1$
Mapping of Messages to Streams in RS

General framework: RS \supset SDMA/OMA/NOMA/Multicast.
Rate-Splitting Example

User-1
- \( W_1 = (a_1 \ a_2 \ a_3 \ a_4) \in \mathcal{W}_1 = \{0000, 0001, 0010, \ldots, 1111\} \), \(|\mathcal{W}_1| = 16\)

User-2
- \( W_2 = (b_1 \ b_2 \ b_3) \in \mathcal{W}_2 = \{000, 001, 010, \ldots, 111\} \), \(|\mathcal{W}_2| = 8\)

Message split for User-1
- \( W_{c,1} = (a_1 \ a_2) \), \( W_{p,1} = (a_3 \ a_4) \)

Message split for User-2
- \( W_{c,2} = (b_1) \), \( W_{p,2} = (b_2 \ b_3) \)

Common message
- \( W_c = (W_{c,1} \ W_{c,2}) = (a_1 \ a_2 \ b_1) \)
**PHY layer design**: message split, channel coding (polar codes) for common and private streams, interleaver, finite constellation modulation (4-QAM, 16-QAM, 64-QAM and 256-QAM), precoder optimization, adaptive modulation and coding, decoder and SIC receiver (incorporating error propagation)
Link-level Simulations

Throughput: \( K = 2, N_t = 2, \) imperfect CSIT \( (\sigma_e^2 = P^{-0.6}) \)

RSMA more robust and significantly outperforms SDMA and NOMA
Beyond 1-layer RS: combination of RS and DPC into DPC-RS

DPC-RS boils down to DPC if CSIT is perfect. Is DPC-RS capacity achieving in imperfect CSIT?
Other RSMA schemes: Multi-Layer RS

Beyond 1-layer RS: multiple splits of messages and layers of SIC

1-layer RS, SDMA/MU-LP and NOMA sub-schemes of RSMA.
Outline

1. Principles
2. Applications
3. Opportunities
RS Applications

Interference Channel
[Carleial78], [Han and Kobayashi81]

MU-MISO with Partial CSIT
[Yang et al.13], [Hao et al.15] ... etc.

Multi-Cell MISO with partial CSIT
[Hao and Clerckx16]

Massive MIMO with partial CSIT
[Dai et al.16]

Robust Cache Aided Interference Management
[Piovano et al.2017]

Multigroup Multicasting
[Joudeh and Clerckx17]

Joint unicast and multicast
[Mao et al.2018]

Coordinated Multipoint Joint Transmission
[Mao et al.2018]

Simultaneous Wireless Information and Power Transfer (SWIPT)
[Mao et al.2019]

mmWave with limited feedback
[Dai and Clerckx17]

Rate Splitting and its applications
Overloaded/Massive Access

Weighted sum rate with QoS constraints: $N_t = 2$, $K = 10$, perfect CSIT

Huge gains with RS (1 SIC layer) vs NOMA (9 SIC layers!)

General framework: higher rate, QoS, robustness and lower complexity
Mobility in TDD Massive MIMO

Throughput: $N_t = 32, K = 8$, 10ms CSI feedback delay

RSMA maintains multiuser connectivity in mobility conditions!
Data compression

For a given fronthaul capacity constraint, RSMA schemes are more spectrally and energy efficient than SDMA and NOMA.
Cooperative Transmission with User Relaying

**Cooperative Rate-Splitting**: one user forwards its decoded common message to another user.

Adjust split and power to common message depending on propagation conditions.
Max-min fair rate performance of multibeam satellite system versus per-feed available power. 7 beams and 14 users (2 users per beam).

Superiority of RS: manage inter-beam interference, CSIT uncertainty, practical per-feed constraints and overloaded regime.
Joint Sensing and Communication

How to make the best **use of the spectrum** for the dual purpose of **sensing** and **communication**?
Find the strategy that achieves the best tradeoff between WSR and MSE.

**Superiority of RS**: efficiently manage radar-communication interference, lead to larger WSR-MSE region.
Outline

1. Principles
2. Applications
3. Opportunities
General Observations of RS/RSMA

- Partially decode interference, partially treat interference as noise
- Robust interference management strategy
- Flexible non-orthogonal transmission strategy
- Powerful enabler of unified multiple access
- Fundamental changes to PHY and MAC layers
Opportunities

Performance benefits

- Spectral and energy efficiency gains,
- QoS and fairness enhancements,
- Robust to imperfect CSIT,
- Reduce feedback overhead,
- Robust to hardware impairments (phase noise),
- Cope with any user distribution (disparity of channel directions and strengths) and network load (underloaded, overloaded),
- Complexity reduction (compared to NOMA)
A gold mine of research problems for academia and industry:
Opportunities

Pathways to 3GPP B5G/6G

- RS can leverage 5G study/work items
- Missing piece: message split at the transmitter
- Applications to 6G in enhanced eMBB, URLLC, mMTC, and new services (joint sensing/radar and communications, wireless information and power transfer, integrated cellular and satellite communications, ...)

Bruno Clerckx (ICL EEE)
Two upcoming RSMA Workshops

- IEEE WCNC 2021 Workshop on Rate-Splitting (Multiple Access) for Beyond 5G
  
  https://wcnc2021.ieee-wcnc.org
  
  (29 March - 1 April 2021 // Nanjing, China)

- IEEE ICC 2021 Workshop on Rate-Splitting (Multiple Access) for 6G
  
  https://icc2021.ieee-icc.org
  
  (14 - 18 June 2021 // Montreal, Canada)
A Non-Exhaustive List of References


A Non-Exhaustive List of References


**RS rate analysis and unifying various multiple access**: B. Clerckx, Y. Mao, R. Schober, and H. V. Poor, *Rate-Splitting Unifying SDMA, OMA, NOMA, and Multicasting in MISO Broadcast Channel: A Simple Two-User Rate Analysis*, accepted to IEEE Wireless Communications Letters

A Non-Exhaustive List of References


A Non-Exhaustive List of References


