Radio Resource Management in Massive MIMO Communication Systems

Final Report of the CENIIT Project 15.01

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The project has focused on algorithmic development and analysis of Massive MIMO (multiple-input multiple-output) systems, which in layman terms means that the base stations in cellular networks utilize arrays of many active antennas instead of a single passive antenna. This enables the network to transmit with adaptive directivity, thereby enabling many users to access simultaneously on the same frequency. When the project started, the academic research on Massive MIMO had mainly focused on physical-layer aspects, while the resource management that takes place in the media access control (MAC) layer had received little attention. This left the door open for major research contributions, because the large gains in area throughput offered by the Massive MIMO physical layer need to be canalized by novel resource management schemes (e.g., scheduling, pilot and power allocation, etc.) that exploit the unique system characteristics. The project has delivered such schemes.

Most important scientific results

Many notable research contributions have been made throughout this project and these have been disseminated in 45 publications: one textbook, one book chapter, four survey articles, 21 journal articles, and 24 conference papers. The survey article "Massive MIMO: Ten Myths and One Critical Question" from 2016 has received 900+ citations and received the 2019 IEEE Communications Society Fred W. Ellersick Prize. The textbook has become the standard reference in the field and received 650+ citations.

The project consisted of three work packages (WPs). The most important scientific results in each WP will be summarized below.

WP1 (Interference- and Distortion-Aware Pilot Allocation): The project has popularized an analytically tractable model of how transceiver hardware distortion affects communication performance, particularly in Massive MIMO systems. This model has been used in numerous papers, within the project, and also by many other authors. It has also been criticized in a few papers for not being sufficiently accurate and defended by new publications within this project that further motivate the models and validate their accuracy in Massive MIMO systems, while explaining in which non-Massive-MIMO scenarios the model is less accurate and how to deal with that. A positive side-effect of this scientific debate is that new distortion-aware processing schemes were developed.

A large number of algorithms for pilot allocation and power allocation have been developed within the project, considering different optimization objectives, network architectures, and types of hardware distortion. There is now comprehensive know-how of how to deal with such design problems and these can also be adapted to solve new related problems and predict the conclusions based on the existing results.

WP2 (Coordinated Beamforming and Load Balancing): The project developed a new beamforming scheme called "multi-cell MMSE" to enable multi-cell coordination

at the physical layer without the need for explicit signaling between base stations. This scheme turned out to solve a long-standing research challenge: how to mitigate the upper performance limit created by pilot contamination. The asymptotic upper limit exists for all the conventional beamforming schemes but not the new scheme. Another important conclusion is that multi-cell cooperation requires coherent joint transmission to be effective: if non-coherent transmission is assumed, then the optimal load balancing will assign each user to only one of the base stations. Coherent joint transmission is the key building block within the new field of cell-free massive MIMO, which was also studied within the project.

WP3 (Proactive and Traffic-Aware Scheduling): The first framework for traffic-aware scheduling and power control in cellular and cell-free Massive MIMO systems was developed within the project, which is closer to practical implementations than prior work. The project also pioneered the modeling of intermittent user activity in massive MIMO systems, both in the random access phase and for grant-free data transmission. This has opened up two new lines of research. The project has also proved that many conventional radio resource allocation tasks are vastly simplified in the massive MIMO setting. For example, time-frequency scheduling is seldom needed since it is more efficient to spatially multiplex more users than the system was dimensioned to handle than using scheduling.

People funded by the project

The project has provided partial funding for the doctoral students Daniel Verenzuela, Trinh Van Chien, and Özgecan Özdogan. The project leader was/is the main supervisor of these students. The project has also provided partial funding for the postdoc Zheng Chen. The project leader's involvement in the project has mainly been financed by other sources.

Degrees, awards, and promotions

The project leader was a research fellow at LiU when the project started. He has since been promoted twice: to senior lecturer (lektor) in January 2016 and to associate professor (bitr. professor) in December 2017. He also received a visiting full professorship at KTH in 2020.

The project leader has received the prestigious grants Future Researcher Leader and Wallenberg Academy Fellow. Moreover, the project leader has received four career awards in recent years: the 2019 EURASIP Early Career Award, the 2020 Pierre-Simon Laplace Early Career Technical Achievement Award, the 2020 CTTC Early Achievement Award, and the 2021 IEEE ComSoc RCC Early Achievement Award.

Trinh Van Chien received the doctoral degree in January 2020 and his thesis was entitled "Spatial Resource Allocation in Massive MIMO Communications: From Cellular to Cell-Free". Daniel Verenzuela received the doctoral degree in February 2020 and his thesis was entitled "Exploring Alternative Massive MIMO Designs: Superimposed Pilots and Mixed-ADCs". They had previously also received licentiate degrees. Özgecan Özdogan received her licentiate degree in March 2020 and the doctoral defense is planned for 2022.

Zheng Chen was a postdoc within the project leader's research group between 2017 and 2019. She was then promoted to a researcher position within the division.

Consolidation of the research group

The project has been essential in expanding and consolidating the project leader's research group and attracting new funding to support it. The research results developed within the project has been utilized as prior work when securing several major research grants:

- Project grant from the Swedish Research Council (VR) on the topic "Optimized Design of Wireless Networks with Multiple Performance Metrics", 2016–2019.

- Project grant from the Swedish Research Council (VR) on the topic "The Next Leap in Wireless Spectral Efficiency: Exploiting Spatial Correlation and Distributed Antenna Surfaces", 2020–2023.
- Future Researcher Leader Grant from the Swedish Foundation for Strategic Research (SSF) on the topic "Intelligent wireless networks with innovative MIMO topology", 2020-2025.
- Wallenberg Academy Fellow Grant from KAW on the topic "Impairment-aware Signal Detection (ISIDE)".

Over the past five years, the project leader has been the main supervisor of 4 doctoral students, the co-supervisor of 5 doctoral students, and the advisor of 7 postdocs.

Industrial connections within the project

The project was focused on technologies that became key components of the 5G wireless standard. Time-wise, the 5G standardization was carried out in parallel to the project. The project leader has collaborated actively with the research team in Linköping that is currently headed by Nicklas Johansson and formerly headed by Gunnar Bark. One essential part of the collaboration was bimonthly meetings where new results from the CENIIT project were disseminated and future research directions were discussed. Another important part of the collaboration was joint innovation. The project leader and employees at Ericsson Research in Linköping are the co-inventors of 25 patent applications that were filed in 2015–2020. Most of these inventions are directly related to the Massive MIMO technology and 8 of them as thus far been approved in the USA.

The project has contributed to establishing the project leader as a world-leading expert on Massive MIMO and spatial radio resource management. He currently has an h-index of 57 and more than 14000 citations listed in Google Scholar. He has been offered several consulting jobs as an expert on future wireless network technology, for example, in a court case in the Federal Court of Australia and by several investment banks.

Master's theses within the scope of the project

One Master's thesis has been carried out within the scope of the project: "Simulating and Evaluating 5G Massive MIMO Under Practical Conditions" by Ali Waqi, from 2020 to 2021.

Connections to other CENIIT projects

There have not been any collaborations with other CENIIT projects. The only related CENIIT project was terminated in 2015 since the project leader left the university.

Dissemination beyond publications

The project leader has experimented with new ways of disseminating research results and insights. The YouTube channel "Wireless Future" was built up during the project and now has 14000+ subscribers. The video "Basics of Antennas and Beamforming" has more than 170,000 views. Moreover, the "Wireless Future" blog (http://ma-mimo.ellintech.se) has become a well-known place to learn about Massive MIMO technology and ask questions. There are more than 100 posts and more than 1000 comments.

Appendix: List of publications

Books and book chapters:

B2 Emil Björnson, Jakob Hoydis, Luca Sanguinetti, "Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency," Foundations and Trends in Signal Processing: vol. 11, no. 3-4, pp. 154–655, 2017.

B1 Trinh van Chien, Emil Björnson, "Massive MIMO Communications," in 5G Mobile Communications, W. Xiang et al. (eds.), pp. 77-116, Springer, 2017.

Survey articles:

S4 Emil Björnson, Luca Sanguinetti, Henk Wymeersch, Jakob Hoydis, Thomas L. Marzetta, "Massive MIMO is a Reality—What is Next? Five Promising Research Directions for Antenna Arrays," Digital Signal Processing, vol. 94, pp. 3-20, November 2019.

S3 Emil Björnson, Liesbet Van der Perre, Stefano Buzzi, Erik G. Larsson, "Massive MIMO in Sub-6 GHz and mmWave: Physical, Practical, and Use-Case Differences," IEEE Wireless Communications, vol. 26, no. 2, pp. 100-108, April 2019.

S2 Elisabeth de Carvalho, Emil Björnson, Jesper H. Sorensen, Petar Popovski, Erik G. Larsson, "Random Access Protocols for Massive MIMO," IEEE Communications Magazine, vol. 55, no. 5, pp. 216-222, May 2017.

S1 Emil Björnson, Erik G. Larsson, Thomas L. Marzetta, "Massive MIMO: Ten Myths and One Critical Question," IEEE Communications Magazine, vol. 54, no. 2, pp. 114-123, February 2016.

Journal articles:

J21 Zheng Chen, Nikolaos Pappas, Emil Björnson, Erik G. Larsson, "Optimizing Information Freshness in a Multiple Access Channel with Heterogeneous Devices," IEEE Open Journal of the Communications Society, vol. 2, pp. 456-470, 2021.

J20 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Joint Power Allocation and Load Balancing Optimization for Energy-Efficient Cell-Free Massive MIMO Networks," IEEE Transactions on Wireless Communications, vol. 19, no. 10, pp. 6798-6812, October 2020.

J19 Trinh Van Chien, Thuong Nguyen Canh, Emil Björnson, Erik G. Larsson, "Power Control in Cellular Massive MIMO with Varying User Activity: A Deep Learning Solution," IEEE Transactions on Wireless Communications, vol. 19, no. 9, pp. 5732-5748, September 2020.

J18 Zheng Chen, Emil Björnson, Erik G. Larsson, "Dynamic Resource Allocation in Co-Located and Cell-Free Massive MIMO," IEEE Transactions on Green Communications and Networking, vol. 4, no. 1, pp. 209-220, March 2020.

J17 Trinh Van Chien, Christopher Mollén, Emil Björnson, "Large-Scale-Fading Decoding in Cellular Massive MIMO Systems with Spatially Correlated Channels," IEEE Transactions on Communications, vol. 67, no. 4, pp. 2746-2762, April 2019.

J16 Emil Björnson, Luca Sanguinetti, Jakob Hoydis, "Hardware Distortion Correlation Has Negligible Impact on UL Massive MIMO Spectral Efficiency," IEEE Transactions on Communications, vol. 67, no. 2, pp. 1085-1098, February 2019.

J15 Zheng Chen, Emil Björnson, "Channel Hardening and Favorable Propagation in Cell-Free Massive MIMO with Stochastic Geometry," IEEE Transactions on Communications, vol. 17, no. 11, pp. 5205-5219, November 2018.

J14 Zheng Chen, Emil Björnson, Erik G. Larsson, "When is the Achievable Rate Region Convex in Two-User Massive MIMO Systems?," IEEE Wireless Communications Letters, vol. 7, no. 5, pp. 796-799, October 2018.

J13 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Joint Pilot Design and Uplink Power Allocation in Multi-Cell Massive MIMO Systems," IEEE Transactions on Wireless Communications, vol. 17, no. 3, pp. 2000-2015, March 2018.

J12 Jiayi Zhang, Xipeng Xue, Emil Björnson, Bo Ai, Shi Jin, "Spectral Efficiency of Multipair Massive MIMO Two-Way Relaying with Hardware Impairments," IEEE Wireless Communications Letters, vol. 7, no. 1, pp. 14-17, February 2018.

J11 Hei Victor Cheng, Emil Björnson, Erik G. Larsson, "Performance Analysis of NOMA in Training Based Multiuser MIMO Systems," IEEE Transactions on Wireless Communications, vol. 17, no. 1, pp. 372-385, January 2018.

J10 Elisabeth de Carvalho, Emil Björnson, Jesper H. Sorensen, Erik G. Larsson, Petar Popovski, "Random Pilot and Data Access in Massive MIMO for Machine-type Communications," IEEE Transactions on Wireless Communications, vol. 16, no. 12, pp. 7703-7717, December 2017.

J9 Tan Tai Do, Emil Björnson, Erik G. Larsson, "Jamming-Resistant Receivers for the Massive MIMO Uplink," IEEE Transactions on Information Forensics & Security, vol. 13, no. 1, pp. 210-223, January 2018.

J8 Xueru Li, Emil Björnson, Erik G. Larsson, Shidong Zhou, Jing Wang, "Massive MIMO with Multi-cell MMSE Processing: Exploiting All Pilots for Interference Suppression," EURASIP Journal on Wireless Communications and Networking, 2017:117, June 2017.

J7 Hei Victor Cheng, Emil Björnson, Erik G. Larsson, "Optimal Pilot and Payload Power Control in Single-Cell Massive MIMO Systems," IEEE Transactions on Signal Processing, vol. 65, no. 9, pp. 2363-2378, May 2017.

J6 Emil Björnson, Elisabeth de Carvalho, Jesper H. Sorensen, Erik G. Larsson, Petar Popovski, "A Random Access Protocol for Pilot Allocation in Crowded Massive MIMO Systems," IEEE Transactions on Wireless Communications, vol. 16, no. 4, pp. 2220-2234, April 2017.

J5 Jiayi Zhang, Linglong Dai, Xinling Zhang, Emil Björnson, Zhaocheng Wang, "Achievable Rate of Rician Large-Scale MIMO Channels with Transceiver Hardware Impairments," IEEE Transactions on Vehicular Technology, vol. 65, no. 10, pp. 8800-8806, October 2016.

J4 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Joint Power Allocation and User Association Optimization for Massive MIMO Systems," IEEE Transactions on Wireless Communications, vol. 15, no. 9, pp. 6384-6399, September 2016.

J3 Rami Mochaourab, Emil Björnson, Mats Bengtsson, "Adaptive Pilot Clustering in Heterogeneous Massive MIMO Networks," IEEE Transactions on Wireless Communications, vol. 15, no. 8, pp. 5555-5568, August 2016.

J2 Xueru Li, Emil Björnson, Erik G. Larsson, Shidong Zhou, Jing Wang, "Massive MIMO with Multi-cell MMSE Processing: Exploiting All Pilots for Interference Suppression," EURASIP Journal on Wireless Communications and Networking, To appear.

J1 Xinlin Zhang, Michail Matthaiou, Emil Björnson, Mikael Coldrey, "Impact of residual transmit RF impairments on training-based MIMO systems," IEEE Transactions on Communications, vol. 63, no. 8, pp. 2899-2911, August 2015.

Conference papers:

C24 Trinh Van Chien, Emil Björnson, Hien Quoc Ngo, "Uplink Power Control in Cellular Massive MIMO Systems: Coping With the Congestion Issue," IEEE International Conference on Communications (ICC), Workshop on Scalable Massive MIMO Technologies for Beyond 5G, Virtual conference, June 2020.

C23 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Optimal Design of Energy-Efficient Cell-Free Massive MIMO: Joint Power Allocation and Load Balancing," Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Virtual conference, May 2020.

C22 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Sum Spectral Efficiency Maximization in Massive MIMO Systems: Benefits from Deep Learning," Proceedings of IEEE International Conference on Communications (ICC), Shanghai, China, May 2019.

C21 Trinh Van Chien, Christopher Mollén, Emil Björnson, "Two-Layer Decoding in Cellular Massive MIMO Systems with Spatial Channel Correlation," Proceedings of IEEE International Conference on Communications (ICC), Shanghai, China, May 2019.

C20 Zheng Chen, Emil Björnson, Erik G. Larsson, "Dynamic Scheduling and Power Control in Uplink Massive MIMO with Random Data Arrivals," Proceedings of IEEE International Conference on Communications (ICC), Shanghai, China, May 2019.

C19 Zheng Chen, Nikolaos Pappas, Emil Björnson, Erik G. Larsson, "Age of Information in a Multiple Access Channel with Heterogeneous Traffic and an Energy Harvesting Node," Proceedings of 2nd Age of Information Workshop, International Conference on Computer Communications (INFOCOM), Paris, France, May 2019.

C18 Emil Björnson, Luca Sanguinetti, Jakob Hoydis, "Can Hardware Distortion Correlation be Neglected When Analyzing Uplink SE in Massive MIMO?," Proceedings of IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Kalamata, Greece, July 2018.

C17 Hei Victor Cheng, Emil Björnson, Erik G. Larsson, "Semi-Closed Form Solution For Sum Rate Maximization in Downlink Multiuser MIMO via Large-System Analysis" Proceedings of IEEE Conference on Acoustics, Speech, and Signal Processing (ICASSP), Calgary, Canada, April 2018.

C16 Trinh Van Chien, Emil Björnson, Erik G. Larsson, Tuan Anh Le, "Distributed Power Control in Downlink Cellular Massive MIMO Systems," Proceedings of ITG Workshop on Smart Antennas (WSA), Bochum, Germany, March 2018.

C15 Zheng Chen, Emil Björnson, "Can We Rely on Channel Hardening in Cell-Free Massive MIMO?," Proceedings of IEEE Global Communications Conference (GLOBECOM), International Workshop on Large-Scale Antenna Systems in Licensed and Unlicensed Bands, Singapore, December 2017.

C14 Hei Victor Cheng, Emil Björnson, Erik G. Larsson, "NOMA in Multiuser MIMO Systems with Imperfect CSI," Proceedings of IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Sapporo, Japan, July 2017.

C13 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Joint Pilot Sequence Design and Power Control for Max-Min Fairness in Uplink Massive MIMO," IEEE International Conference on Communications (ICC), Paris, France, May 2017.

C12 Emil Björnson, Luca Sanguinetti, Merouane Debbah, "Massive MIMO with Imperfect Channel Covariance Information," Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, USA, November 2016.

C11 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Multi-Cell Massive MIMO Performance with Double Scattering Channels," IEEE International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD), Toronto, Canada, October 2016.

C10 Emil Björnson, Elisabeth de Carvalho, Erik G. Larsson, Petar Popovski, "Random Access Protocol for Massive MIMO: Strongest-User Collision Resolution (SUCR)," IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, May 2016.

C9 Daniel Verenzuela, Emil Björnson, Luca Sanguinetti, "Optimal Design of Wireless Networks for Broadband Access with Minimum Power Consumption," IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, May 2016.

C8 Trinh Van Chien, Emil Björnson, Erik G. Larsson, "Downlink Power Control for Massive MIMO Cellular Systems with Optimal User Association," IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, May 2016.

C7 Elisabeth de Carvalho, Emil Björnson, Erik G. Larsson, Petar Popovski, "Random Access for Massive MIMO Systems with Intra-Cell Pilot Contamination," Proceedings of IEEE Conference on Acoustics, Speech, and Signal Processing (ICASSP), Shanghai, China, March 2016.

C6 Emil Björnson, Erik G. Larsson, "Three Practical Aspects of Massive MIMO: Intermittent User Activity, Pilot Synchronism, and Asymmetric Deployment," Proceedings of IEEE Global Communications Conference (GLOBECOM), Workshop on Massive MIMO: From theory to practice, San Diego, California, USA, December 2015.

C5 Xueru Li, Emil Björnson, Erik G. Larsson, Shidong Zhou, Jing Wang, "A Multi-cell MMSE Detector for Massive MIMO Systems and New Large System Analysis," Proceedings of IEEE Global Communications Conference (GLOBECOM), San Diego, California, USA, December 2015.

C4 Xueru Li, Emil Björnson, Erik G. Larsson, Shidong Zhou, Jing Wang, "A Multi-cell MMSE Precoder for Massive MIMO Systems and New Large System Analysis," Proceedings of IEEE Global Communications Conference (GLOBECOM), San Diego, California, USA, December 2015.

C3 Emil Björnson, Michail Matthaiou, Antonios Pitarokoilis, Erik G. Larsson, "Distributed Massive MIMO in Cellular Networks: Impact of Imperfect Hardware and Number of Oscillators," Proceedings of the 23rd European Signal Processing Conference (EUSIPCO-2015), Nice, France, September 2015.

C2 Hei Victor Cheng, Emil Björnson, Erik G. Larsson, "Uplink Pilot and Data Power Control for Single Cell Massive MIMO Systems with MRC," Proceedings of International Symposium on Wireless Communication Systems (ISWCS), Brussels, Belgium, August 2015.

C1 Rami Mochaourab, Emil Björnson, Mats Bengtsson, "Pilot Clustering in Asymmetric Massive MIMO Networks," Proceedings of IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Stockholm, Sweden, July 2015.