Signal processing and Communications Group

ROUTE56 - Newsletter June 2023

Radio technologies for ubiquitous communications in the evolution from 5G to 6G

Project Overview

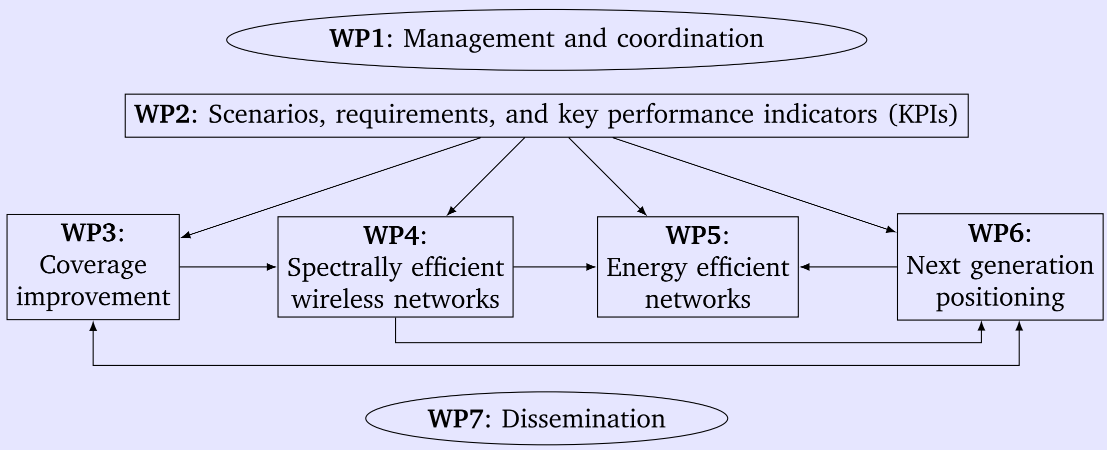
The ROUTE56 project proposes to make sensible progress in several promising technical approaches that might contribute to defining the next generation of mobile communication systems:

- Blocking and statistical coverage analysis
- Spectrally efficiency boosting with advanced technologies
- Energy-efficient networks
- Artificial intelligence and reinforcement learning (RL) strategies
- Next-generation positioning

The project will also promote results in international forums, like 5GPPP, 6G Flagship Initiative, 5GBarcelona, and world-class conferences, and will position the research team in a competitive place towards the forthcoming EU work programme.

Work Plan Structure

The structure of the project is illustrated below and its core (**WP3-WP6**) focuses on the three following key areas:



- **WP3:** Design of new tools to model and predict the coverage at very high frequencies (by better fitting reality), and new strategies to manage in an optimal way hybrid communication technologies.
- **WP4:** Improvement of spectral efficiency will significantly increase the number of users that can be served simultaneously and the rates that can be achieved. This will translate into more efficient use of resources and the provision of a better quality of service to users.
- **WP5:** Reduction of energy consumption, which will imply a reduction of the CO2 footprint and an increase in the lifetimes of the batteries.
- **WP6:** Development of new advanced positioning strategies that will give support to location-aware user applications and contribute to enhancing location-aided communication technologies.

Third Year Work

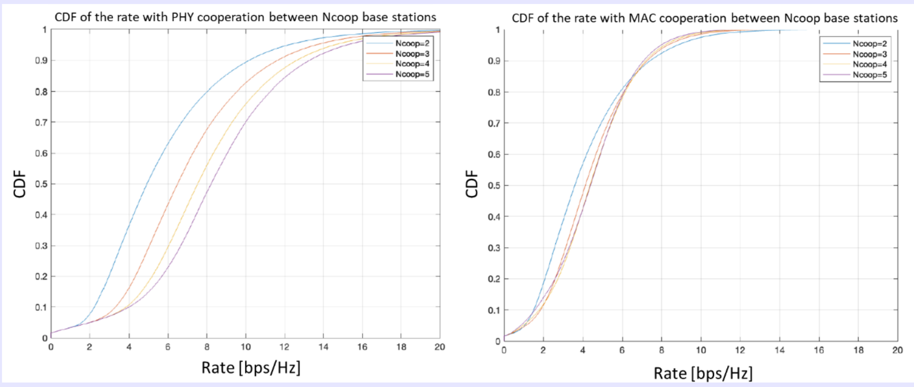
Task 3.2: Techniques for blocking mitigation in mmWave networks

During the third year, we finished the evaluation of several macro-diversity schemes to mitigate the blocking effects in millimeter wave (mmWave) transmission. The main characteristic of mmWave transmission is that any building or object in the scenario can block the reception of the signal whenever there is no line of sight between the transmitter and the receiver. Almost all the analysis was carried out during the second year; in the last year, we developed final concluding remarks.

Basically, these concluding remarks were based on the fact that the blocking effects in mmWave transmission affect not only the desired signal but also the interfering ones. We have performed analysis using two different macro-diversity schemes:

- Cooperation at the signal level (PHY): the cooperating base stations (BSs) send the signals to the intended user to be combined constructively at the user terminal.
- Cooperation at the access level (MAC): the cooperating BSs access the channel in an orthogonal way so that the signals do not interfere among them.

In both cooperation schemes, the BSs that do not cooperate can generate interference over the intended user terminal if any building or object in the scenario does not block such interference. Some statistical results were obtained to evaluate these techniques using a scenario modeled by means of stochastic geometry and random shape theory. In the following, an example is illustrated where we present the cumulative density function (CDF) of the rate achieved by an intended user in a scenario with a density of $2 \cdot 10^{-4}$ buildings/m^2 and different numbers of cooperating BSs.

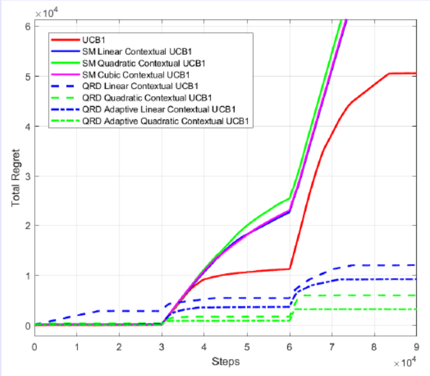


The main conclusion is that increasing the number of cooperating BSs provides significant gains in the case of PHY cooperation and that PHY cooperation is better than MAC cooperation, although its implementation is quite more complex.

Task 3.3: Coverage boosting through hybrid cooperation in heterogeneous communication networks

As the number of wireless technologies (4G, 5G, 802.11ax, and others) has been rapidly increasing, so has the number of wireless networks concurrently deployed in a given coverage area. As a result, the judicious selection of the network that maximizes the quality perceived by a user terminal has become a significantly relevant problem. Contextual multi-armed bandits (CMAB) are viable models to approach the problem. While multiple CMAB algorithms have been designed, most of them are only suited for stationary environments. Our work thus proposes a new set of network selection algorithms that relate the traffic type (used as contextual information) to the perceived quality of the available networks for non-stationary scenarios. Results have shown significantly improved performance when compared to non-adaptive approaches.

The following figure illustrates the evolution of the total regret for different CMAB methods in a non-stationary scenario where 5 networks and 3 traffic types are present.

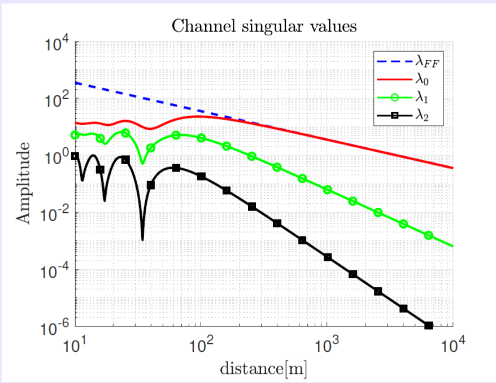


Task 4.1: Channel model for the near-field propagation conditions

A channel model based on the near-field propagation characteristics has been obtained from several papers in the literature and has been used in other tasks in this project to evaluate transmission and localization schemes based on intelligent reflecting surfaces (IRSs) and extremely large antenna arrays (ELAAs).

In particular, we have focused attention on the characteristics of near-field propagation, which differs substantially from what a far-field assumption may predict. These differences between the near-field and far-field are especially important when exploiting IRSs and ELAAs since the far-field region at mmWave frequencies can achieve ranges of kilometers.

Under the far-field assumption, the multi-antenna channel matrix has rank 1, so, it substantially limits the number of information streams that can be transmitted simultaneously. On the other hand, when considering the realistic near-field assumption, the channel rank is higher, which translates into a richer set of spatial modes. The following figure illustrates the eigenvalues of the channel (that is, the gains of the spatial modes) depending on the distance under near-field conditions. The conclusion is that the distance has to be high enough so that the assumption of having only one active spatial mode is realistic.



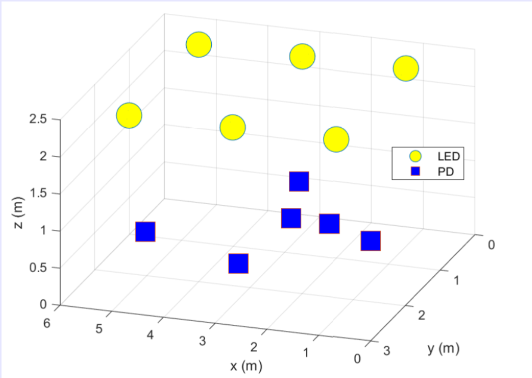
Task 4.2: Cell-free implementation of LIS/ELAAs in wireless systems

We have been working on schemes for multi-user scenarios.

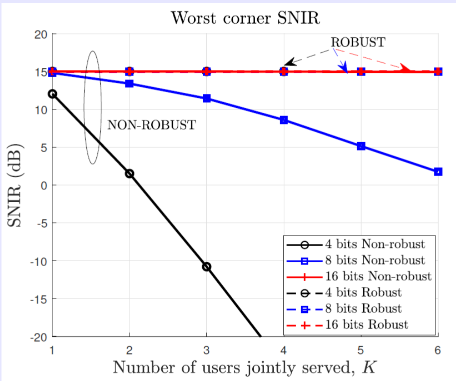
On the one hand, we have developed a novel transmission scheme for visible light communications (VLC), which is considered a possible access method in 5G. In this case, we assumed that there are no BSs, that is, no cell scheme, but there are several light-emitting diodes (LEDs) that cooperate among themselves to send different signals to different users in the same region (for example, in a train wagon) at the same time.

In this case, the interference among users is avoided thanks to the available channel knowledge when designing the transmission precoders. This channel knowledge is often imperfect, which may increase interference. The imperfection of the channel information is usually due to the quantization and the use of finite codebooks to send this information to the transmitting LEDs through a feedback channel. Such an increase in interference can be controlled by using robust designs that take into account explicitly the presence of errors in the available channel information when designing the precoders.

In the following, we illustrate a possible scenario with several LEDs and several receivers (photodiodes – PDs).



The performance of a robust VLC design versus a non-robust design is illustrated next, where it is concluded that the robust design can assure a worst-case signal-to-noise-plus-interference ratio (SNIR) much higher than what can be assured by a non-robust design even for a high number of users being served simultaneously.

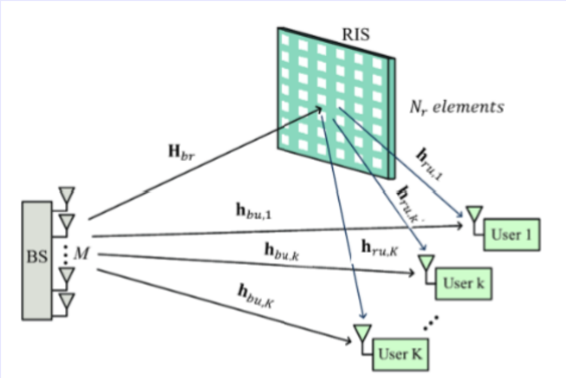


In this period we have also launched an activity on the evaluation of multi-user downlink (DL) transmissions for very large arrays at the BS and the RIS, with terminals located in the near-field of the array. On these locations, matrix channel rank is not deficient even in line-of-sight propagation, and the non-planar propagation wave implies a maximum of received power on small-size areas rather than on a line. The use of large RIS has the potential of extending further this area to positions in the cell that are in the far field from the BS.

Task 4.3: IRS versus active antennas and conventional relays

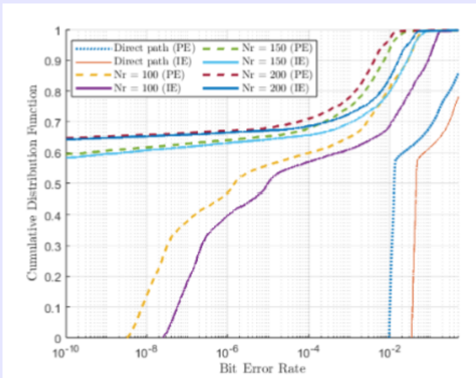
In this task, we have proposed a reconfigurable intelligent surface (RIS) transmission based on zero-forcing (ZF) precoding for a DL multi-user multiple-input single-output (MU-MISO) system in mmWave bands. ZF precoding is a linear precoding method that enables complete spatial multiplexing and multi-user diversity in high signal-to-noise ratio (SNR) regimes since it can completely cancel out multi-user interference, but its use is cumbersome in mmWave bands due to the lack of propagation scattering which entails rank deficiency in the channel matrix. In MU transmissions, the equivalent MU channel matrix may also become rank deficient if users have strongly different channel gains, or if they are aligned with respect to (w.r.t.) the position of the BS. Hence the use of RIS to assist the communication between terminals is an affordable and effective way to enhance the channel matrix rank. Additionally, RIS can also cope with shadowing situations and the higher path losses associated with mmWave bands. The contribution of this research is a joint design for the RIS elements phases that maximize the received SNR based on perfect channel knowledge.

The following figure illustrates the scenario under evaluation for multi-user RIS-aided transmission in the DL.



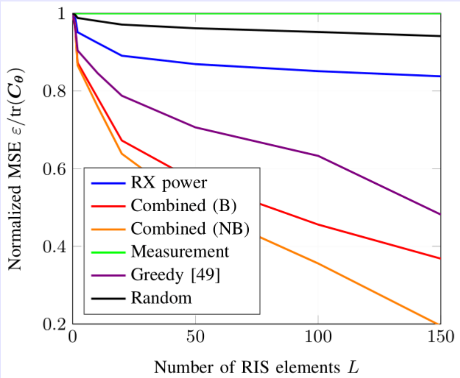
We have demonstrated that the proposed RIS-aided ZF MU-MISO communication is more than a viable solution for better coverage and availability. While each RIS may focus on nearby terminals, it also opens the possibility of exhibiting performance resilience to user grouping. We have as well investigated the impact of channel estimation on spectral efficiency and analyzed the impact of imperfect channel state knowledge at the transmitter side.

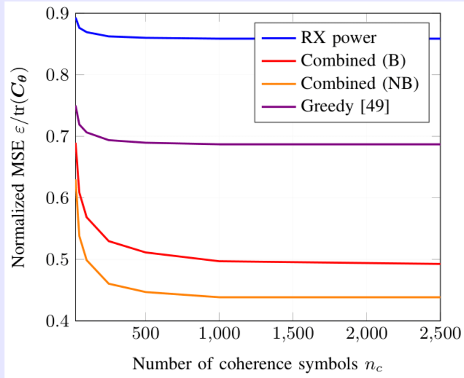
The following figure illustrates the CDF of the bit error rate (BER) for ZF-based precoding towards two users, using 4-QAM transmissions and 4 antennas at the BS, with perfect estimation (PE) and imperfect estimation (IE). Different numbers of elements at the RIS (Nr) have been tested.



On the other hand, we have also completed the design of the RIS for parameter estimation in mMTC environments. Considering a network where numerous single-antenna sensors transmit spatially correlated measurements to a multi-antenna collector node using non-orthogonal multiple access, we derived a parameter estimation scheme based on the minimum mean square error (MMSE) criterion. To mitigate communication failures in noisy and interference-prone channels, successive interference cancellation (SIC) was incorporated at the receiver. Various methodologies for acquiring channel state information (CSI) at the CN were also explored. The RIS configuration and SIC decoding order were then optimized to minimize parameter estimation errors, accounting for channel temporal variations and the effects of communication and imperfect CSI errors. Simulation experiments demonstrated the benefits of large reflecting surfaces and the importance of selecting an appropriate decoding order for accurate and high-performance parameter estimation.

The following figures illustrate the normalized MSE (NMSE) versus the size of the RIS and the number of coherence symbols, respectively. Each of the curves corresponds to a different decoding order.



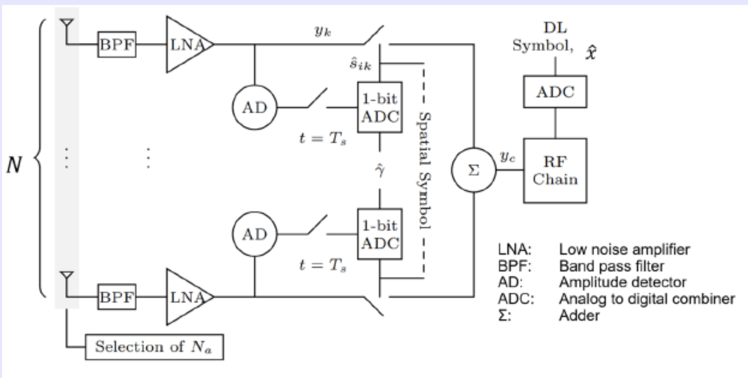


Task 5.1: Spatial modulation

Receive spatial modulation (RSM) has been proposed as an effective transmission technology for next-generation wireless communications systems because of its reduced complexity and low energy consumption at the receiver end. Compared to conventional multiple-input multiple-output (MIMO) transceivers, which require one radio-frequency (RF) chain and analog-to-digital converter per receive antenna, RSM can be implemented with one amplitude detector per antenna and a single RF chain, with mild performance degradation in terms of spectral efficiency. However, its implementation using ZF or MMSE precoders is cumbersome in mmWave channels due to the lack of propagation scattering and, hence, rank deficiency in the channel matrix.

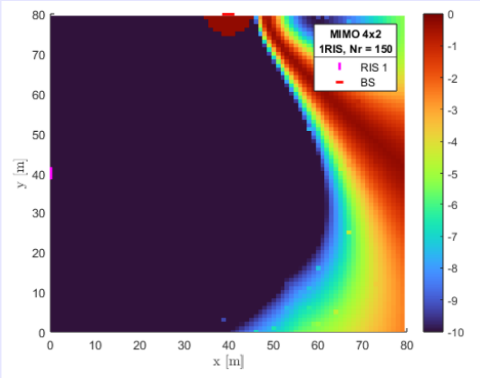
This has been only partially solved in the past using receiver antenna selection, which requires additional receive antennas. In that sense, using RISs, which can effectively create scatter and enhance the channel matrix rank, is an affordable solution that can also cope with shadowing situations and the higher path losses associated with mmWave bands. During this third year, we have proposed using a RIS in a single-user MIMO communication with RSM to improve the DL transmission.

The following figure illustrates a single RF multi-antenna receiver for an RSM transmission scheme.



Our work shows that RIS-assisted RSM communication is more than a good option in mmWave channels in terms of BER due to the multipath induced in the channel and the link budget boosting.

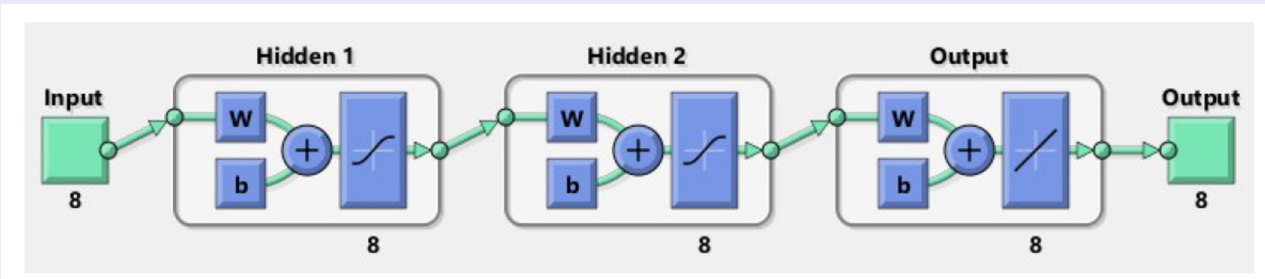
The following figure illustrates the bit error probability for an RSM transmission scheme in log scale on a coverage area with 1 RIS and 150 reflective elements in a dominant LOS propagation channel in the 30 GHz band.



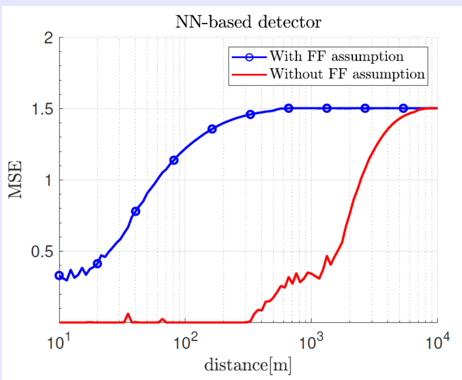
On the other hand, we have also developed a transmission strategy based on a BS endowed with a RIS composed of several elements. Each individual element of the RIS can act as a transmitting antenna or as a reflector whose reflection characteristics can be changed by the BS in real-time during the transmission depending on the symbols to be transmitted.

The main point in the developed strategy is that the number of elements at the RIS can be very high, which allows sending several information symbols simultaneously exploiting different spatial modulation (SM) schemes. The problem is that if the number of receive antennas at the user equipment is low, traditional schemes based on linear receivers cannot detect the transmitted symbols even if the channel is full-rank thanks for being in the near-field. A possible solution consists in using non-linear detectors based on neural networks (NNs) schemes that can achieve a performance close to the optimum one corresponding to a maximum likelihood detector but with a substantially lower computational load.

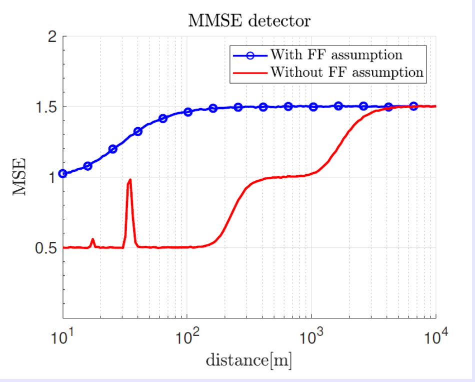
The following figure illustrates a possible receiver scheme based on a NN with 8 input and 8 output variables and 3 layers.



The following figure illustrates the performance in terms of the MSE of the estimated symbols using the proposed NN receiver assuming incorrectly the far-field condition and under the correct near-field assumption. The main conclusion is that the performance in the near-field is much better than when assuming the far-field condition incorrectly.



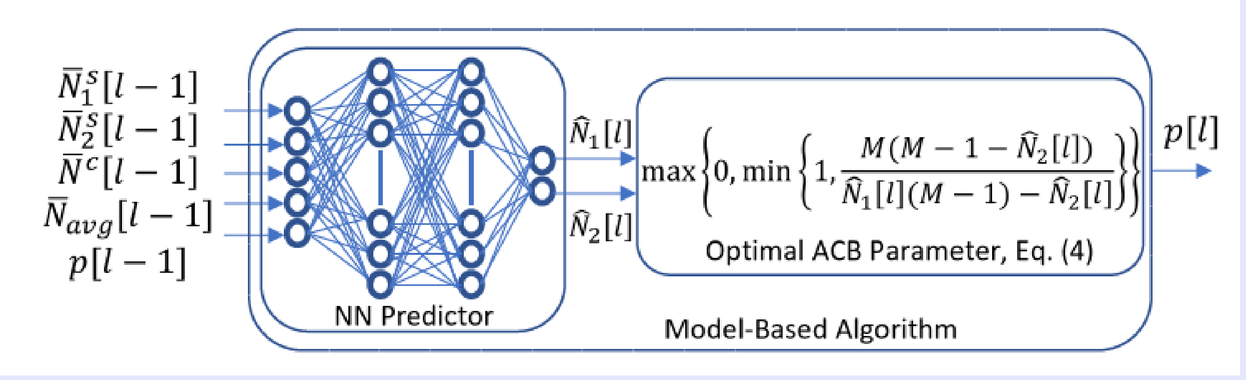
The following figure illustrates equivalent results when using a classical linear receiver. The conclusion is that a linear receiver performs quite worse than a NN detector.



Task 5.3: Energy-efficient multiple access strategies in multi-user/MTC communications

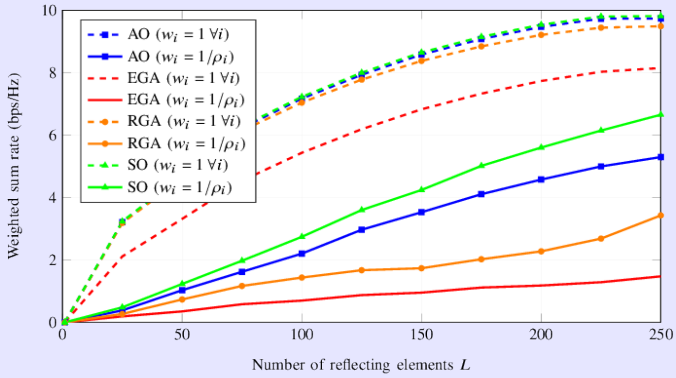
During this third year, we have assessed through simulation results the goodness of our proposed NN-based approach for access class barring (ACB) parameter estimation, which closely follows the analytical bound. It achieves the same number of successfully connected MTC devices and keeps a stable number of collisions during the peak of access demand, just like under optimal conditions. We have also shown that our NN-based approach outperforms model-free Deep Q-learning agents operating under the same conditions.

The following figure illustrates a graphic schematic of our proposed two-step, NN-based approach to estimate the optimal ACB parameter.

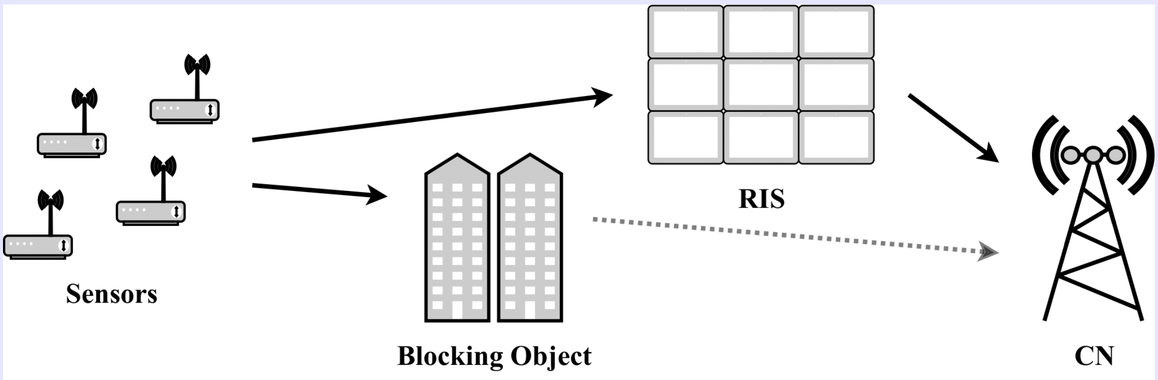


On the other hand, we have also been working on the design of a RIS to support the non-orthogonal transmission from a group of sensors to a collector node in mMTC. Given the short length of the data packets, the focus has been the maximization of the weighted sum and minimum rates in the finite blocklength regime. The optimizations have been formulated as non-convex problems, and two suboptimal solutions based on gradient ascent (GA) and sequential optimization (SO) with semi-definite relaxation have been proposed. Numerical results demonstrate that SO outperforms GA and that traditional Shannon capacity optimization may not be suitable for mMTC networks.

The following figure illustrates the sum rate obtained through alternating optimization (AO), Euclidean GA (EGA), Riemannian GA (RGA), and SO w.r.t. the number of reflecting elements and for different weight criteria.



Additionally, significant progress has been made in extending the previous derivations to the case of imperfect CSI and multi-antenna collector nodes. The following figure illustrates the scenario under evaluation.



Task 6.1: Multipath-assisted localization

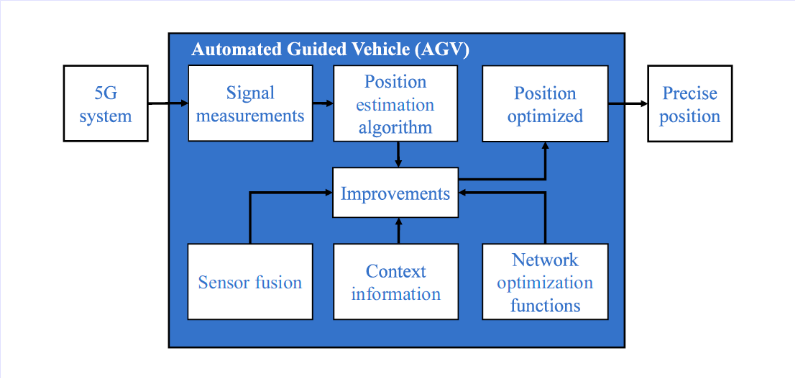
Localization considering RIS is proposed with a recursive two stages approach. First, the parameters needed for position estimation are obtained using compressed sensing, in particular, orthogonal matching pursuit is considered for estimating the angles of arrival and departure as well as the distances between user equipment (UE) and RIS. Once the UE position is obtained from the estimated parameters, the phases of the RIS are optimized minimizing the Cramer-Rao lower bound (CRLB) in this position to maximize the location accuracy. Multi-layer perceptron has been proposed for this second stage to efficiently obtain the RIS phases optimizing the CRLB. These two stages are repeated until convergence to the solution of minimum positioning error.

Task 6.2: Location-aided communication

To achieve maximum efficiency in Industry 4.0 (I4.0), strong advances in indoor positioning as well as in wireless communications are needed. In this task, we propose enhanced techniques that have the potential to improve the accuracy of 5G-based positioning for the use case of AGV in a controlled industrial environment.

The proposed positioning architecture is illustrated below and includes:

- Sensor fusion, which integrates multi-modal sensors data (acceleration, angular velocity, distances) with 5G measurements data reducing the positioning error.
- Context information available in the form of industrial processes that will improve the position prediction.
- Network optimization enhancing positioning accuracy, efficiency, and radio network management.



Task 7.1: Dissemination through scientific publications, newsletters and reports to interested companies

The team has organized the "Ph.D. Symposium on Next Generation Networks: AI, Architectures, Interfaces, and Implementations", on 13 June 2023, at the Universitat Politècnica de Catalunya, Campus Nord, Barcelona, Spain. Co-located with IEEE-IFIP 2023, the goal of this symposium has been a forum for discussion among Ph.D. students and senior researchers. The format of participation is a one-page abstract plus a poster presentation, for original works on the general topic of Next Generation Networks.

In terms of participation, there were 35 submissions of 7 different projects representing 17 institutions and 12 countries.

Other aspects can be found on the symposium website: https://networking.ifip.org/2023/index.php/phd-symposium

Task 7.3: Participation in international initiatives

The group is active in the following projects:

- 5GSmartFact, of the MSCA-ITN EID programme (https://5gsmartfact.upc.edu/)
- Predict-6G of the SNS-JU of HE (https://predict-6g.eu/)
- TIMING of NextGenerationEU - UNICO

and has participated in infrastructure proposals of the programme UNICO sectorial 5G.

Publications

Journals

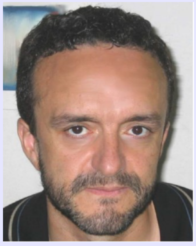
- Olga Muñoz Medina, Antonio Pascual Iserte, and Guillermo San Arranz, “Robust Precoding for Multi-User Visible Light Communications with Quantized Channel Information”, in *Sensors (special issue: 5G Wireless Communication Systems and IoT Based on Artificial Intelligence)*, vol. 22, no. 23, 9238, pp. 1-12, ISSN 1424-8220, November 2022. DOI: 10.3390/s22239238.
- Sergi Liesegang Maria, Alessio Zappone, Olga Muñoz Medina, and Antonio Pascual Iserte, “Rate Optimization for RIS-Aided mMTC Networks in the Finite Blocklength Regime,” in *IEEE Communications Letters*, vol. 27, no. 3, pp. 921-925, March 2023, DOI: 10.1109/LCOMM.2022.3231717.
- Martí Llobet Turró, Margarita Cabrera Bean, Josep Vidal Manzano, and Adrian Agustín de Dios, “Optimizing Access Demand for mMTC Traffic Using Neural Networks”, accepted for publication in *IEEE Transactions on Vehicular Technology*, July 2023.
- Sergi Liesegang Maria, Antonio Pascual Iserte, and Olga Muñoz Medina, “Robust Design of Reconfigurable Intelligent Surfaces for Parameter Estimation in mMTC”, submitted to *IEEE Transactions on Wireless Communications*, May 2023.
- Sergi Liesegang Maria, Antonio Pascual Iserte, Olga Muñoz Medina, and Alessio Zappone, “Design of RIS-aided mMTC Networks for Rate Maximization under the Finite Blocklength Regime with Imperfect Channel Knowledge”, in preparation.

Conference Proceedings

- Karthik Muthineni, Alexander Artemenko, Josep Vidal, and Montse Nájar, “A Survey of 5G-Based Positioning for Industry 4.0: State of the Art and Enhanced Techniques”, paper presented at *2023 European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, June 2023.
- David Campoy García, Olga Muñoz Medina, and Antonio Pascual Iserte, “Linear and Non-Linear Receivers for RIS-Aided Communication Systems in Near-Field Conditions”, poster presented at *Ph.D. Symposium on Next-Generation Networks: AI, Architectures, Interfaces, and Implementations*. Barcelona (Spain), pp. 30, June 2023.
- Ainna Yue Moreno-Locubiche, Josep Vidal Manzano, Antonio Pascual Iserte, and Olga Muñoz Medina, “Reconfigurable Intelligent Surfaces for Receive Spatial Modulation in Rank-Deficient Channels”, submitted to *2023 IEEE Global Communications Conference (GLOBECOM)*, Kuala Lumpur (Malaysia), December 2023.
- Lluís Martínez Casanovas, Josep Vidal Manzano, and Margarita Cabrera Bean, “Contextual Multi-Armed Bandits for Non-Stationary Wireless Network Selection”, submitted to *2023 IEEE Global Communications Conference (GLOBECOM)*, Kuala Lumpur (Malaysia), December 2023.
- Ainna Yue Moreno-Locubiche, Josep Vidal Manzano, Antonio Pascual Iserte, and Olga Muñoz Medina, “Reconfigurable Intelligent Surfaces for Multiuser MISO Downlink Transmission”, submitted to *2023 IEEE Global Communications Conference (GLOBECOM)*, Kuala Lumpur (Malaysia), December 2023.

Participants

Antonio Pascual Iserte (IP1) (Senior Member, IEEE) was born in Barcelona, Spain, in 1977. He received the degree in electrical engineering and the Ph.D. degree from Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 2000 and 2005, respectively. From September 1998 to June 1999, he was a Teaching Assistant in the field of microprocessor programming with the Department of Electronic Engineering, UPC. From June 1999 to December 2000, he was with Retevision R&D, working on the implantation of the DVB-T and T-DAB networks in Spain. In January 2001, he joined the Department of Signal Theory and Communications, UPC, where he was a Research Assistant until September 2003. He received a predoctoral grant from the Catalan Government for his Ph.D. studies during this period. He became Assistant Professor in September 2003 and since April 2008 he is Associate Professor. He currently teaches undergraduate courses on signal theory and communications. He also teaches postgraduate courses on advanced signal processing with the Department of Signal Theory and Communications. He has been involved in several research projects funded by the Spanish Government and the European Commission. He was the author or coauthor of several papers in international and national conference proceedings and journals. His research interests include array processing, robust designs, orthogonal frequency-division multiplexing, multiple-input multiple-output channels, multi-user access, optimization theory, energy-efficient networks, massive machine-type communications, and stochastic geometry.



Josep Vidal Manzano (IP2) (Senior Member, IEEE) received the Ph.D. degree in telecommunication engineering from the Universitat Politècnica de Catalunya (UPC) in 1993. He is currently a Professor in the Signal Theory and Communications Department. His research interests are in statistical signal processing, information and communication theory, and machine learning, areas in which he has authored more than 200 journals and conference papers. Since 2002, he has coordinated collaborative EC-funded projects ROMANTIK, ROCKET, FREEDOM, TROPIC, TUCAN3G, and 5GSmartFact belonging to the FP5, FP6, FP7, and H2020 programmes, in different areas of MIMO relay communications, self-organization, cooperative transmission, and heterogeneous networks. He has held research appointments with EPF Lausanne, INP Toulouse, and the University of Hawaii. He has organized several international workshops. He has served as an Associate Editor of the IEEE TRANSACTIONS ON SIGNAL PROCESSING and as reviewer of several national and international research agencies. He belongs to the IEEE ComSoc Signal Processing for Communications and Electronics Technical Committee.

Olga Muñoz Medina (Member, IEEE) received M.S. and Ph.D. degrees in electrical engineering from the Universitat Politècnica de Catalunya (UPC), Spain, in 1993 and 1998, respectively. In 1994, she joined the Department of Signal Theory and Communications, UPC, where she teaches graduate and undergraduate signal processing and communications courses. She has been a Visiting Associate Professor at Stanford University from September–November 2014 and January–June 2015, respectively. She has served as a Reviewer for the Spanish Research Council. Besides, she has also served as a Reviewer in numerous journals and conferences. She accumulates substantial experience in relaying and cooperative upgraded networks backed by her work on European Commission projects ROMANTIK (5thFP), FIREWORKS (6thFP), and ROCKET (7thFP). She also has experience in heterogeneous and femtocell-based networks backed by her work in the project FREEDOM (7thFP) and the Spanish Government funded project MOSAIC (call 2010). She has participated in TROPIC (7thFP), pushing the idea of merging cloud computing with femtocell networking, and in TUCAN3G (7thFP), focused on providing connectivity to rural areas through new wireless technologies for the access network and WiLD (WiFi for Long Distances)-WiMAXVSAT heterogeneous backhauling. More recently, she has been designing, analyzing, and evaluating radio technologies in ultra-dense networks to meet the capacity and quality of service requirements, distributed intelligence, and flexibility needed for the 5G and beyond. She has published over 70 papers in books, international conferences, and journals in the areas of signal processing and communications.

Margarita Cabrera Bean received the MSc degree and the Ph.D. degree in Electronic Engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1986 and 1991, respectively and the MSc degree in Mathematics from the Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain in 2013. Currently, she is a Tenured Associate Professor at the Department of Signal Theory and Communications at UPC, where she teaches in the areas of Analog and Digital Communications and Signal Processing. Her research interests are in Signal Processing and include Mobile Communication Systems and Machine Learning techniques applied to medical applications where she has published around 60 papers in books, international conferences, and journals. She has been serving as Vice-Dean at the School of Telecommunications Engineering of Barcelona at the UPC (2009-2015) and as expert in the Evaluation committees in verification program (Bachelor's and Master's) of the Andalucian Agency of Knowledge, Spain (2016-).

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