Signal processing and Communications Group

# ROUTE56 - Newsletter February 2024

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

**In this issue ...**



## Project Overview

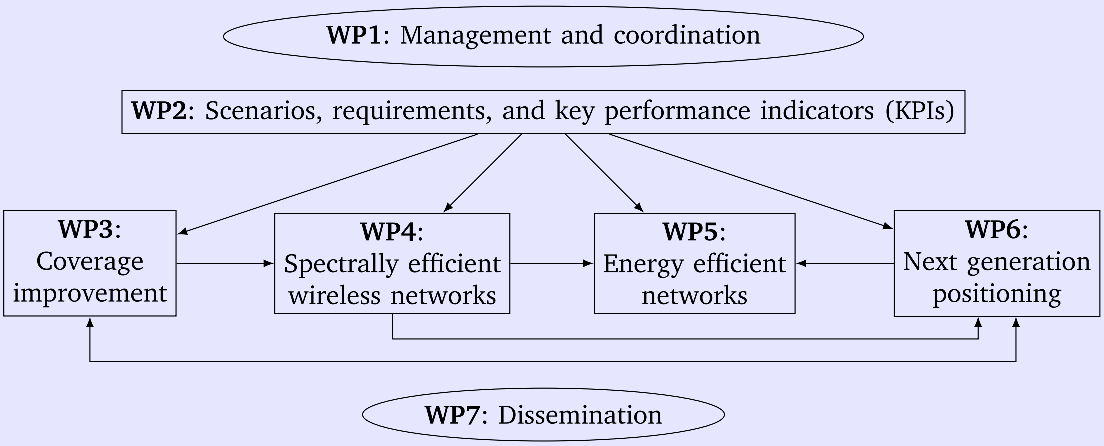
The ROUTE56 project proposes to make sensible progress in several promising technical approaches that might contribute to defining the next generation of mobile communication systems:

- 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:

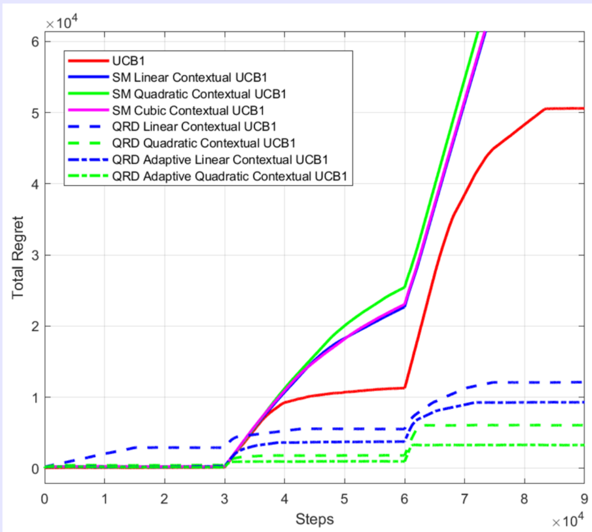



- **WP3:** Design of new tools to model and predict the coverage at very high frequencies (by better fitting reality), and new strategies to manage in an optimal way hybrid communication technologies.
- **WP4:** Improvement of spectral efficiency will significantly increase the number of users that can 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.

# Fourth Year Work

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

As the number of wireless technologies (4G, 5G, 802.11ax and other) have been rapidly increasing, so have the number of wireless networks concurrently deployed on 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. In this task we have proposed 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. The classic contextual LinUCB1 algorithm has been improved by introducing a polynomial model for the context. Moreover, it has been demonstrated that all algorithms perform poorly in non-stationary environments. To this end, a forgetting factor has been introduced in the iterative solution using QR decomposition which does not present the instability problems of other matrix decomposition algorithms, allowing adaptation to model drifting in the scenario. A further improvement has been proposed by introducing an adaptive mechanism that detects non-stationarity and controls the memory of the algorithm by changing the value of the forgetting factor. Finally, all algorithms have been tested in realistic models-based environments where the agent must select the best wireless network with changing traffic types and non-stationary network parameters. An excellent performance has been confirmed for the adaptive algorithms, as can be observed in the figure below, where the regret (or losses due to bad selection of networks) of the proposed techniques is well below those achieved for non-contextual and for contextual-non-adaptive MAB.




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

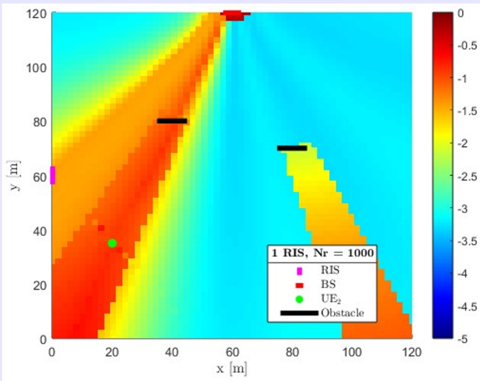
During the last year, final results have been obtained concerning how LIS can focus the energy towards a given area in a region under near-field propagation conditions. That is related with the fact that in the near-field, the radiation pattern is distance-dependent and allows to schedule users even when they are aligned with the BS equipped with a LIS or an ELAA.

In addition, some results have been obtained in this task in combination with Task 6.1 related with localization, where several IRSs are considered, each one paired with an antenna array collecting the reflections from the corresponding IRS. All the signals from all the arrays are sent to a central processor, following a cell-free approach, to process them and locate the positions of the sources with a high accuracy.

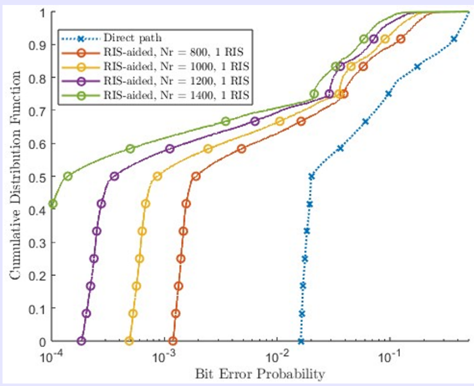
**Task 4.3: IRS versus active antennas and conventional relays**

In this task, we propose the use of an IRS in a multiuser multiple-input single-output (MU-MISO) transmission system utilizing zero-forcing (ZF) precoding for the downlink (DL) in millimeter-wave (mmWave) bands, where propagation primarily occurs in line-of-sight (LOS) conditions. ZF precoding facilitates complete spatial multiplexing and multiuser diversity in a high signal-to-noise ratio (SNR) environment by eliminating multiuser interference under perfect channel state knowledge. In MIMO transmission, some care is required in LOS propagation due to the absence of scattering, which may result in rank deficiency. In the MU-MISO channel matrix, rank deficiency may also arise if users exhibit significantly different channel gains or if they are aligned with the position of the base station (BS). Introducing one or several IRSs can shape the radio environment by introducing artificial scattering, address matrix rank deficiency situations, and partially compensate for the higher path losses associated with mmWave bands. The key contribution of this research is the joint design of the phases of the reflecting elements of one or several IRSs to maximize the received SNR when using a ZF precoder. We explore scenarios with both perfect channel knowledge and imperfect channel estimation, assessing the impact on spectral efficiency (SE) and bit error rate (BER). This evaluation shows the advantages of IRS-aided ZF MU-MISO communication. While each IRS may focus on nearby terminals, it also opens the possibility of exhibiting performance resilience to user grouping.

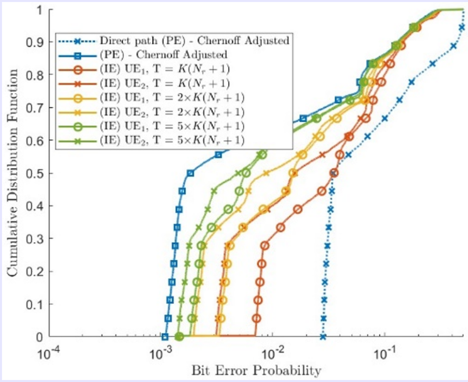
In our simulations, we have taken into account the presence of obstacles, which are common in real-world deployment scenarios, to ensure the realism and practicality of our evaluations. The following figure illustrates the BER of the 2-users in a dominant LOS propagation channel in the 30 GHz band MISO 4-QAM IRS-assisted transmission in the DL, assuming perfect channel estimation, in log scale on a coverage area with 1 IRS and 1000 reflective elements. One of the users is placed in the green dot position at coordinates (20 m, 40 m). The other user is placed in every other position in the 120 m x 120 m area. Note that the ZF precoder determines that SNR (and hence BER) is the same for both users.




The following figure illustrates the CDF of the BER for the previous scenario and different number of IRS elements, Nr. Note that for each IRS configuration there are two prominent slopes at different values. The leftmost steep slope is due to areas not shadowed by obstacles: for higher Nr, the BER is significantly reduced specially when compared to the scenario without IRS (blue line). The rightmost steep slope is due to shadowed areas, and the central BER value is very similar for all the configurations, but again we observe a reduction in BER compared to the scenario without IRS.

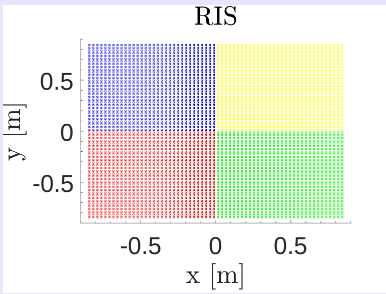


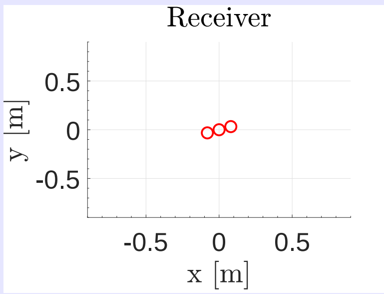
We have investigated the impact of channel estimation on spectral efficiency and analyzed the impact of imperfect channel state knowledge at the transmitter side as well. The following figure provides the CDF of the BER for the previous configuration and 1000 reflective elements, with perfect estimation (PE) and imperfect estimation (IE) with different values of pilots sent (T). It can be checked that the effect of errors increases with Nr, and it also shows that this BER increase can be combated with the use of more pilot symbols T at the expense, however, of reducing the spectral efficiency.



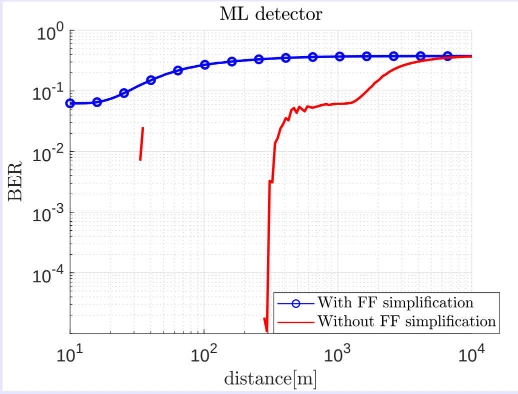

**Task 5.1: Spatial modulation**

During the last year, the work developed in this task has focused on generalizing some of the notation and results obtained during the third year in relation with spatial modulation schemes. In particular, we have assumed that the transmitter consists of a single-carrier high-frequency emitter and an IRS located close to such an emitter. The unmodulated RF carrier impinges on the all the reflecting elements of the IRS and are then reflected. The value of the reflection coefficients can be changed in real time through a convenient setup. In the proposed modulation scheme, the reflection coefficients of the IRS elements depend on the transmitted symbols, which implies that they change along time. In the following example, we show an IRS composed by 64x64 elements, where they are grouped in 4 groups, each of them with 32x32 elements, so that all the reflection coefficients of the elements in the same group are equal and changed according to one common information symbol. That means that in this example, 4 information symbols are transmitted per channel use.




The notation generalized during the last year includes the channel responses between the single-carrier high-frequency emitter and all the reflection elements of the IRS. We have also compared the performance of a neural-network (NN)-based receiver and a linear minimum mean-squared-error (MMSE) (already presented in the previous newsletter) with the optimum maximum likelihood (ML) detector, whose performance is shown next comparing the results from simulations corresponding to the unrealistic simplification of a 3-antenna receiver being in the far-field (FF) of the IRS and the correct assumption without this simplification. The transmitter sends 4 symbol streams in parallel.




The ML detector shows lower BER than the NN and the MMSE receivers, although its computational complexity is much higher (roughly 50 times). In that sense, we can state that the NN proposed detector (already explained in the previous newsletter) has the best tradeoff between complexity and performance. Note that thanks to the fact of being in the near-field (NF) and considering that in the simulations correctly, the system is able to detect the symbols with a very low BER even when the number of transmitted streams is higher than the number of receiver antennas, which is not true when assuming incorrectly to be in the FF. This happens since the channel matrix in the NF has a rank higher than one even in LOS conditions, which is not true in the FF. Accordingly to this, the transmitter should adapt the transmission rate and the number of streams according to the position of the receiver.

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

Work has been completed to verify the impact of using our analytically derived optimal Access Class Barring (ACB) parameter, as standardized by 3GPP, in Machine-type communications. These communications often exhibit unique spatial and temporal correlation properties, leading to bursty access demand profiles. The goal is to improve the average number of served Machine Type Communication Devices (MTCDs) and minimize the number of collisions. To achieve this, we employ Neural Networks (NNs) to predict the type and number of accessing devices based on measurements acquired by the Base Station (BS). Using these estimates, we effectively implement the optimal barring scheme, achieving performance results close to the theoretical bound.

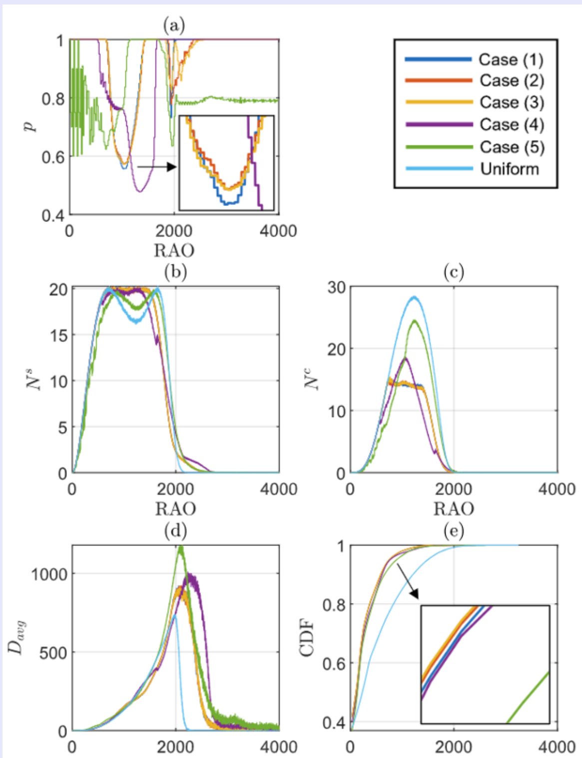


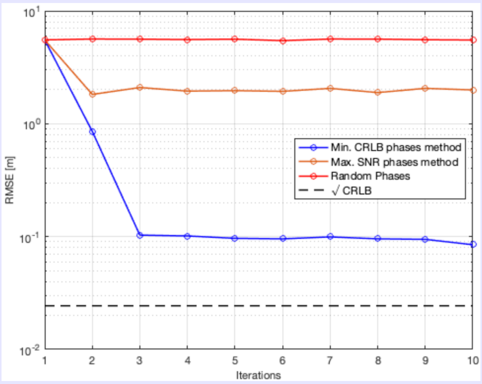
Figure shows some KPIs (optimized ACB parameter $p$ in a), Number of served MTCDs $N_s$ in b), Number of collisions $N_c$ in c and average delay $D_{avg}(d, e)$ of the served MTCDs in terms of time. Results have been averaged over 1000 simulation runs.

Case 1 represents the use of the optimal parameter, unknown at the base station, which is used in simulations for comparative benchmarking purposes. Cases 2 and 3 correspond to two variants of our proposed algorithm (ACB-NN), while cases 4 and 5 use state-of-the-art reinforcement learning-based algorithms (QL and DQN). The ACB-NN algorithm exhibits the highest number of served MTCDs, the lowest number of collisions, and the lowest delay times.

**Task 6.1: Multipath-assisted localization**

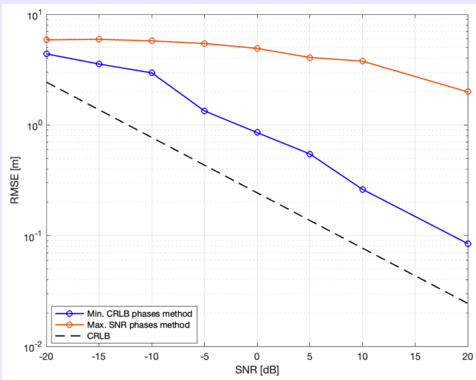
This work addresses near-field localization using Reconfigurable Intelligent Surfaces (RIS) in 5G systems, where Line-of-Sight (LOS) between the base station and the user is obstructed. We propose a RIS phase optimization method based on the minimization of the Cramér-Rao Lower Bound (CRLB) for position estimation. The proposed method has shown an improvement with respect to our baseline (i.e. phase optimization through SNR maximization), in terms of positioning accuracy.

The figure below depicts a comparative analysis of the evolution of the RMSE given a fixed number of RIS elements. As expected, the use of non-optimized phases results in a high positioning error (on the order of almost 5 meters), coupled with a non-convergent behavior. In contrast, phases optimized maximizing the SNR show higher convergence, achieving in this case an error magnitude of 2 meters approximately. However, the proposed optimization method (Min. CRLB phases method) has shown a clear efficacy improvement, with a rapid convergence as well and a substantially higher positioning accuracy comparable to the theoretical CRLB.

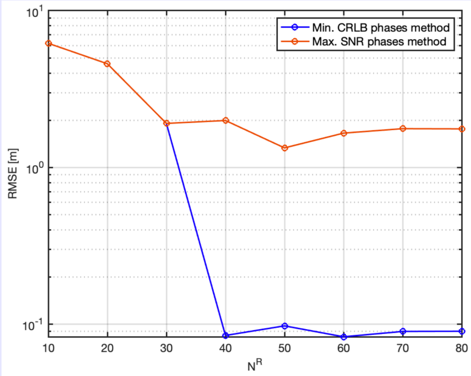



This outperformance has proven to be robust to the variation of some key system parameters (RIS size and transmission SNR). In addition, we have achieved positioning accuracy values comparable to the theoretical CRLB.

In the next figure, the influence of SNR on RMSE is presented for the two distinct methods. Notably, employing the proposed method yields a substantial reduction in RMSE as SNR increases, converging towards the theoretical bound. In contrast, utilizing the maximization of the SNR method, results in a difference of one order of magnitude between RMSE and the CRLB even for high SNR.



Theoretically, an increase on the number of reflecting elements in the RIS contributes to enhancing the resolution and, consequently, the positioning accuracy. The figure below illustrates how increasing the number of RIS elements results in a lower theoretical CRLB, throughout different SNR values.




This relation between RIS elements and RMSE can be empirically validated, for both iterative methods, as shown in the figure. However, this behavior persists only until Nris=40, beyond which the RMSE stabilizes. Moreover, the previous plot leads to a further result. In comparison to Max. SNR phases method, obtaining RIS phases through the proposed method is particularly more efficient when the number of RIS elements is increased, showing a significantly lower RMSE value. However, the difference stabilizes after the aforementioned Nris=40.

In order to reduce the computational cost of the CRLB minimization, we have developed an ML-based framework to replicate the computation of the optimal RIS phases according to the CRLB minimization, for 5G systems in a near-field scenario with remarkable computational savings and positioning performance. The proposed methods show a huge computational gain with respect to our baseline method (i.e., phase optimization through direct CRLB minimization), without excessively compromising the positioning error (same order of magnitude errors).

Two types of phase pre-processing methods have been proposed in order to enhance the MLP training for our task, showing a slight improvement in both training and positioning errors.

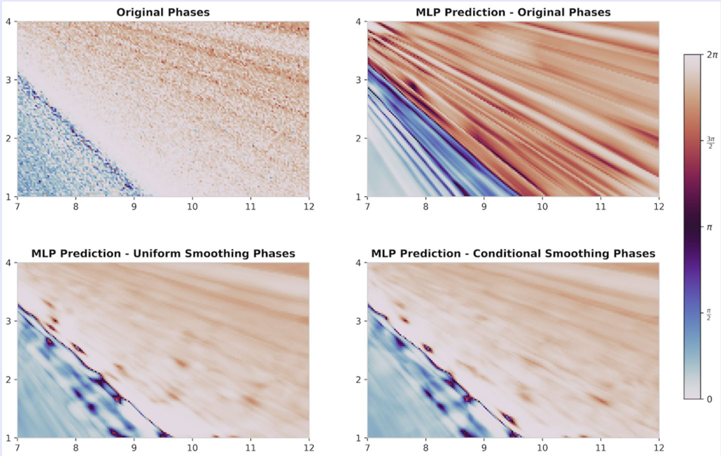
- *Uniform smoothing:* application of a median filter with a squared kernel over the distribution of each individual phase when taken as a grid according to their associated positions.
- *Conditional smoothing:* Similar to the previous process, apply a median filter over the distribution of phases. However, in this case, the resulting filtered phase value will only be taken for those positions in which the resulting value differs from more than a threshold k with respect to its original value. The idea is to correct only the values that are clear outliers and preserve the details of the original phase distribution.

The quantitative comparison of the training results for each kind of data is summarized in the following table.

| Preprocessing | MAE (rad) | RMSE (rad) |
|---|---|---|
| No smooth. | 0.643 | 0.978 |
| Uniform smooth. | 0.505 | 0.765 |
| Conditional smooth. | 0.508 | 0.769 |

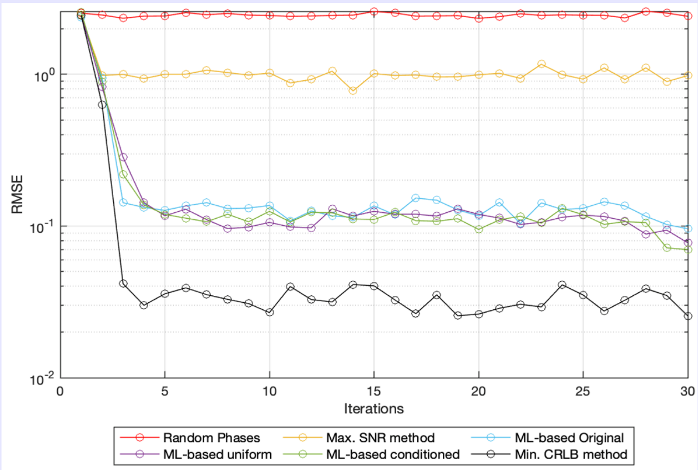
Notice that, no matter whether the phases have been previously preprocessed, to evaluate the prediction accuracy of each framework we will always compare the predicted phases with the original non-processed ones (given that these are theoretically the ones we aim to resemble).

In terms of qualitative analysis, next figure shows how discontinuities in the original phase distribution worsen the MLP predictions (MLP Prediction - Original Phases). For close positions in the grid, we appear to have hard-to-generalize phase changes (i.e. outliers) and so the MLP proves to be unable to track these changes during training. The result is an averaged prediction as shown in the figure. Such a result backs our original hypothesis motivating the use of preprocessed phases for the training.




Next figure provides a quantitative analysis of the position estimation accuracy, focusing on the comparison between methods and their respective associated computational costs. We will distinguish six different frameworks based on the RIS phases optimization method used:

- Random phases: non-optimized (random) phases.
- Max. SNR method: phases optimized maximizing the SNR.
- Min. CRLB method: phases optimized minimizing the CRLB.
- MLP Original Phases: ML-based optimization using the raw phases.
- MLP Uniform Smoothing: ML-based optimization using uniform smoothing on the phases.
- MLP Conditional Smoothing: ML-based optimization using conditional smoothing on the phases.

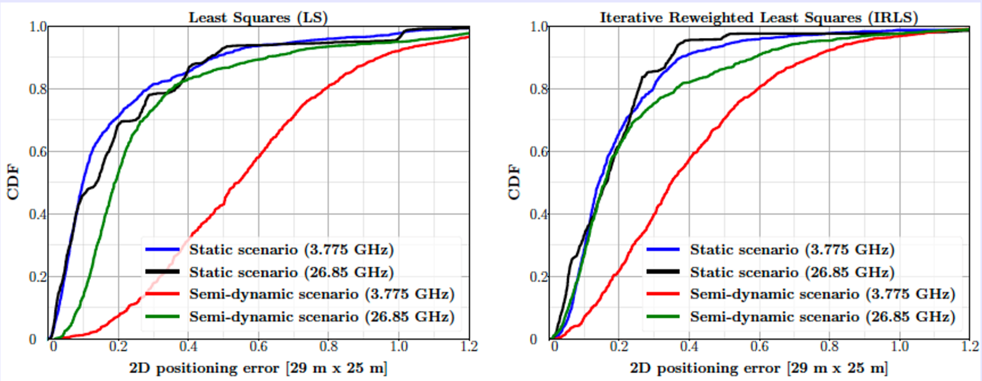



| Minimization method | Time (s) |
|---|---|
| Min. CRLB method | 3227 |
| ML-based methods | 49 |

**Task 6.2: Location-aided communication**

The radio channel conditions existing inside industrial buildings will have a higher influence on the achievable indoor positioning accuracy. The presence of heavy metallic objects, concrete walls, and a dynamic environment in the form of moving forklifts creates the Non-Line-of-Sight (NLoS) condition between the base station and the User Equipment (UE), which gives rise to Multi-Path Components (MPCs). The Time-of-Arrival (ToA), Time Difference of Arrival (TDoA), and Angle-of-Arrival (AoA) estimation under a heavy MPCs dominant scenario lead to errors. To overcome the above limitations we implement the Iteratively Reweighted Least Squares (IRLS) positioning technique, which is robust to the outliers. Instead of using a fixed base station as a reference in TDoA measurements, the IRLS positioning uses every base station as a reference once to obtain distinct possible position estimations. After that, a weighting criterion is employed to give less weight or reject the outlier measurements and assign more weight to those with higher confidence, resulting in a weighted average position estimate with higher accuracy.

The performance of the IRLS positioning technique has been evaluated in a dense-clutter Ray-Tracing enabled industrial scenario. The results show the improvement in the positioning accuracy, with the applied IRLS under both static as well as semi-dynamic scenarios. Specifically, when compared with the state-of-the-art LS technique, we are able to avoid larger positioning errors at the higher percentiles.




**Tasks 7.1 and 7.2: Dissemination through scientific publications, newsletters and reports to interested companies, and open-access code through online platforms**

All the scientific publications and newsletters generated by the project can be found in the following websites:

- Project website (https://spcom.upc.edu/en/projects/radio-technologies-for-ubiquitous-communications-in-the-evolution-from-5g-to-6g)
- Publications portal (https://futur.upc.edu/28926919)
- GitHub portal (https://github.com/route56repository)

**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 (https://timing.upc.edu/)

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

# Publications

## Journals

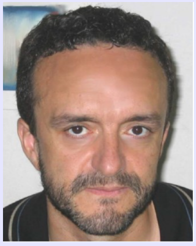
- Martí Llobet Turró, Margarita Cabrera-Bean, Josep Vidal Manzano, Adrián Agustín de Dios,"Optimizing Access Demand for mMTC Traffic Using Neural Networks", in *IEEE Transactions on Vehicular Technology*, vol. 72, no. 12, pp. 16834-16838, December 2023, doi: 10.1109/TVT.2023.3294724.
- Sergi Liesegang Maria, Antonio Pascual Iserte, Olga Muñoz Medina, "Robust Design of Reconfigurable Intelligent Surfaces for Parameter Estimation in mMTC", submitted to *IEEE Transactions on Communications*, February 2024.
- Ainna Yue Moreno-Locubiche, Josep Vidal Manzano, Antonio Pascual-Iserte, Olga Muñoz Medina, "RIS-assisted Multiuser MISO Downlink Transmission under Imperfect Channel Estimation", submitted to *IEEE Transactions on Signal Processsing*, April 2024.
- Sergi Liesegang Maria, Antonio Pascual Iserte, Olga Muñoz Medina, Alessio Zappone, "Design of RIS-aided mMTC Networks for Rate Maximization under the Finite Blocklength Regime with Imperfect Channel Knowledge", in preparation.

## Conference Proceedings

- Lluís Martínez Casanovas, Josep Vidal Manzano, Margarita Cabrera-Bean, "Contextual Multi-Armed Bandits for Non-Stationary Wireless Network Selection". Proceedings IEEE Global Communications Conference (GLOBECOM 2023), pp. 285-290, Kuala Lumpur (Malaysia), December 2023, doi: 10.1109/GLOBECOM54140.2023.10437363
- Ainna Yue Moreno-Locubiche, Josep Vidal Manzano, Antonio Pascual-Iserte, Olga Muñoz Medina, "Reconfigurable Intelligent Surfaces for Receive Spatial Modulation in Rank-Deficient Channels". Proceedings IEEE Global Communications Conference (GLOBECOM 2023), pp. 5720-5726, Kuala Lumpur (Malaysia), December 2023, doi: 10.1109/GLOBECOM54140.2023.10437329
- Karthik Muthineni, Alexander Artemenko, Josep Vidal Manzano, Montse Nájar Martón, "Outlier Rejection for 5G-Based Indoor Positioning in Ray-Tracing-Enabled Industrial Scenario". Accepted to be published at Proceedings IEEE International Conference on Communications (ICC 2024), Denver (USA), June 2024.
- Carla Macías López, Arnau Saumell, Montse Nájar Martón, Pau Closas, "RIS Phase Optimization for Near-Field 5G Positioning: ML-enhanced CRLB Minimization". Submitted to 32th European Signal Processing Conference (EUSIPCO 2024), Lyon (France), August 2024.
- David Campoy García, Olga Muñoz Medina, Antonio Pascual Iserte, "Impact of Near-Field Conditions on the Performance of RIS-aided mmWave Communication Strategies". Submitted to IEEE Vehicular Technology Conference Fall (VTC Fall 2024), Washington D.C. (USA), October 2024.
- Adrián Pastor Redondo, Antonio Pascual Iserte, Olga Muñoz Medina, "RIS-aided Location Estimation Based on MVDR in Near-Field Conditions". Submitted to IEEE Vehicular Technology Conference Fall (VTC Fall 2024), Washington D.C. (USA), October 2024.

# 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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