Document Number: ICT-317669-METIS/D3.1

Project Name:
Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS)

# Deliverable D3.1

# Positioning of multi-node/multi-antenna technologies



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| Date of delivery: | 31-07-13 | Version | 1 |
| Start date of Project: | 01-11-12 | End date of Project | 30-04-15 |

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| **Document Number:** | ICT-317669-METIS/D3.1 |
| **Document Title:** | Positioning of multi-node/multi-antenna technologies |
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| **Dissemination Level:** | Public |
| **Contractual Date of Delivery:** | 31/07/2013 |
| **Status:** | Final |
| **Version:** | 1 |
| **File Name:** | METIS_D3.1_v1.docx |

**Revision History:**

| Revision | Date | Issued by | Description |
|---|---|---|---|
| 1 | July 31, 2013 | METIS | D3.1 release v1 |

**Abstract:**

This document describes the research activity in multi-node/multi-antenna technologies within METIS and positions it with respect to the state-of-the-art in the academic literature and in the standardization bodies. Based on the state-of-the-art and as well as on the METIS objectives, we set the research objectives and we group the different activities (or technology components) into research clusters with similar research objectives. The technology components and the research objectives have been set to achieve an ambidextrous purpose. On one side we aim at providing the METIS system with those technological components that are a natural but non-trivial evolution of 4G. On the other side, we aim at seeking for disruptive technologies that could radically change 5G with respect to 4G. Moreover, we mapped the different technology components to METIS' other activities and to the overall goals of the project.

**Keywords:**

Multi-antenna, Massive-MIMO, inter-node coordination, relay, multi-hop communication, wireless network coding

# Executive summary

This document describes the research activity in METIS multi-node/multi-antenna work package (WP3) and positions it with respect to the state-of-the-art in the academic literature and in the standardization bodies. WP3 is divided in three tasks: Multi-antenna/Massive-MIMO (T3.1), Advanced inter-node coordination (T3.2) and Multi-hop communications/wireless network coding (T3.3). We divide each task in research clusters (i.e. research activities with the same macro-scope) in a way that each research cluster provides one or more technology components (i.e. technical solutions targeting a specific problem). In each task we set the objectives with a twofold purpose. The first purpose is to provide sustaining technology components, in a way to foster a natural evolution from 4G to 5G systems. The second purpose is to seek disruptive solutions, in a way to radically change the design of future 5G systems with respect to current ones. That is, we set WP3's organization and scope to provide both evolutionary and revolutionary components to the METIS system by taking the best from previous systems and at the same time by introducing radical and disruptive changes. To steer the research towards METIS' objectives, we map each technology component to one or more of METIS Test Cases and to one or more METIS Horizontal Topics. We note that, in order to allow both for system evolution and revolution through disruptive innovation, we keep a rather loose connection among the technology components aiming at long-term research. On the contrary, we require a tighter connection for technology components aiming at medium-term research.

Concerning the activity in T3.1, we steer the research on Massive-MIMO towards two main directions: assessment of real-world impairments on a system-level perspective and further exploration of the theoretical foundations at both traditional and millimeter-wave frequencies.

Concerning T3.2, we slightly defocus the activity from "classical" Coordinated Multi-Point techniques, like joint processing and coordinated scheduling. We focus the research on novel concepts of coordination that can arise as a consequence of the evolution in the network access techniques or improvements or new enablers available in future user equipments.

Concerning T3.3, we aim at providing enablers for network densification based on the use of infrastructure-deployed relays and techniques for wireless backhauling, exploiting ideas like wireless network coding and buffer-aided relaying. Moreover, we also target a second set of solutions, based on moving relays and D2D communications.

# Contents

# List of Tables

# List of Abbreviations, Acronyms, and Definitions

| | |
|---|---|
| **3GPP** | 3rd Generation Partnership Project |
| **4G** | 4th Generation |
| **5G** | 5th Generation |
| **ABS** | Almost Blank Subframe |
| **AF** | Amplify and Forward |
| **BC** | Broadcast Channel |
| **BF** | Beamforming |
| **BS** | Base Station |
| **BVDM** | Building Vector Data Map |
| **CA** | Candidate Antenna |
| **CAPEX** | Capital Expenditure |
| **CDMA** | Code Division Multiple Access |
| **CoMP** | Coordinated Multi -Point |
| **CQI** | Channel Quality Indicator |
| **CR** | Cognitive Radio |
| **CRS** | Common Reference Signals |
| **CSI** | Channel State Information |
| **CSMA** | Carrier Sense Multiple Access |
| **CSIT** | CSI at the Transmitter |
| **C2X** | Car-to-Anything |
| **D2D** | Device-to-Device |
| **DF** | Decode and Forward |
| **DL** | Downlink |
| **DPB** | Dynamic Point Blanking |
| **DNF** | De-Noise and Forward |
| **DPS** | Dynamic Point Selection |
| **DoA** | Direction of Arrival |
| **DoD** | Direction of Departure |
| **DoF** | Degree of Freedom |
| **D2D** | Device-to-Device |
| **EHF** | Extremely High Frequency |
| **eNB** | evolved Node B |
| **EMF** | Electro Magnetic Field |
| **E2E** | End-to-End |
| **FD** | Full Duplex |
| **FDD** | Frequency Division Duplex |
| **FRA** | Future Radio Access |
| **GPRS** | General Packet Radio Service |
| **GSM** | Global System for Mobile communications |
| **GSM-R** | Global System for Mobile communications - Railway |
| **HD** | Half Duplex |
| **HO** | Hand Over |
| **HT** | Horizontal Topics |
| **HTD** | Horizontal Topic Driver |
| **IA** | Interference Alignment |
| **ICI** | Inter-Channel Interference |
| **IC** | Interference Cancellation |
| **ICT** | Information and Communications Technology |
| **IA** | Interference Alignment |
| **IDMA** | Interleave Division Multiple Access |

| | |
|---|---|
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **IMAC** | Interfering Multiple Access Channel |
| **IMF** | Interference Mitigation Framework |
| **IMT** | International Mobile Communications |
| **IS** | Interference Suppression |
| **ITU** | International Telecommunication Union |
| **ITU-R** | International Telecommunication Union-Radio |
| **JT CoMP** | Joint Transmission CoMP |
| **KPI** | Key Performance Indicator |
| **L2** | Layer 2 |
| **L3** | Layer 3 |
| **LAN** | Local Area Network |
| **LOS** | Line-Of-Sight |
| **LSAS** | Large Scale Antenna System |
| **LTE** | Long Term Evolution |
| **LTE-A** | Long Term Evolution-Advanced |
| **M2M** | Machine-to-Machine |
| **MA** | Multiple Access |
| **MAC** | Medium-Access Control |
| **MAMRC** | Multiple-Access Multiple Relay Channel |
| **MARC** | Multiple-Access Relay |
| **MBCP** | Model Based Channel Prediction |
| **MIMO** | Multiple-Input Multiple-Output |
| **MISO** | Multiple-Input Single-Output |
| **MMC** | Massive Machine Communication |
| **MMSE** | Minimum Mean Square Error |
| **MMW** | Millimetre Waves |
| **MN** | Mobile Network |
| **MRN** | Moving Relay Node |
| **MUE** | Mobile UE |
| **MU-MIMO** | Multi-User MIMO |
| **NC** | Network Coding |
| **NOMA** | Non-Orthogonal Multiple Access |
| **OFDM** | Orthogonal Frequency Division Multiplexing |
| **OFDMA** | Orthogonal Frequency Division Multiple Access |
| **OPEX** | Operational Expenditure |
| **PA** | Predictor Antenna |
| **PBCH** | Physical Broadcast Channel |
| **PC** | Project Coordinator |
| **PDCCH** | Physical Downlink Control Channel |
| **PHY** | Physical layer |
| **PLNC** | Physical Layer NC |

| | |
|---|---|
| **ProSe** | Proximity Services |
| **PSS** | Primary Synchronization Signal |
| **PTDPR** | Pilot-To-Data Power Ratio |
| **PUCCH** | Physical Uplink Control Channel |
| **QAM** | Quadrature Amplitude Modulation |
| **QoE** | Quality of Experience |
| **QoS** | Quality of Service |
| **RAN** | Radio Access Network |
| **RAT** | Radio Access Technology |
| **RC** | Research Cluster |
| **RF** | Radio Frequency |
| **R&D** | Research and Development |
| **RRH** | Remote Radio-Head |
| **R&TTE** | Radio and Telecommunications Terminal Equipment |
| **RRH** | Remote Radio Head |
| **RRM** | Radio Resource Management |
| **RS** | Reference Signal |
| **Rx** | Receiver |
| **SC** | Small Cells |
| **SCA** | SC Access Point |
| **SCM** | Spatial Channel Model |
| **SDF** | Selective Decode and Forward |
| **SDMA** | Space-Division Multiple Access |
| **SDR** | Software Defined Radio |
| **SHF** | Super High Frequency |
| **SI** | Study Item |
| **SINR** | Signal -to -Interference -plus -Noise Ratio |
| **SOS** | Switch Off Scheme |
| **SRTA** | Separate Receive and Training |

| | |
|---|---|
| | Antennas |
| **SSS** | Secondary Synchronization Signal |
| **SUE** | Small cell UE |
| **SU-MIMO** | Single-User MIMO |
| **T** | Task |
| **TC** | Test Case |
| **TDD** | Time Division Duplex |
| **TDMA** | Time Division Multiple Access |
| **TeC** | Technology Component |
| **Tx** | Transmitter |
| **UDN** | Ultra Dense Networks |
| **UE** | User Equipment |
| **UHF** | Ultra High Frequency |
| **UL** | Uplink |
| **UMTS** | Universal Mobile Telecommunications System |
| **URN** | Ultra Reliable Networks |
| **USRP** | Universal Software Radio Peripheral |
| **V2V** | Vehicle-to-Vehicle |
| **V2X** | Vehicle-to-Anything |
| **WCDMA** | Wideband Code Division Multiple Access |
| **WFC** | Wireless Flow Coupling |
| **WI** | Work Item |
| **WiFi** | WLAN |
| **WLAN** | Wireless Local Area Network |
| **WNC** | Wireless Network Coding |
| **WP** | Work Package |
| **WRC** | World Radiocommunication Conference |

# 1 Introduction

This document has several objectives. First, we review the WP3-related state-of-the-art in the academic literature and in the standardization bodies, in particular 3GPP and to a lower extent IEEE. This is done with the aim of differentiating the work in WP3 with respect to previous and on-going works, as well as impacting both the standardization works and the academic community on a medium- and on a long-term time scale. Second, based on the partners' core competencies, on the above state-of-the-art analysis and on the METIS overall objectives, we set the research objectives in each task and we group the different research activities (also referred as Technology Components (TeCs)) with similar objectives and scope into the same Research Cluster (RC). In other words, each task is divided in RCs (i.e. research activities with the same macro-scope) and each RC provides one or more TeCs (i.e. technical solutions targeting a specific problem). TeCs and corresponding research objectives are set with a twofold goal. On one side, we aim at providing sustaining technology components in a way to foster a natural evolution from 4G to 5G systems. On the other side, we aim at seeking disruptive solutions, in a way to radically change the design [GER+03] of future 5G systems with respect to current ones. That is, WP3's organization and scope have been defined to provide both evolutionary and revolutionary components to the METIS system by taking the best from previous systems and at the same time by introducing radical and disruptive changes. We note that sustaining and disruptive components [CHR+97] are both important for the definitions of 5G systems, and the research activity in WP3 has been defined in order to find the right balance between the two.

Finally, we map each TeC to one or more WP1 TCs and to or more HTs, in a way to steer the research towards the directions that have a maximum impact on the definition of the METIS system. We emphasize that we use a different approach for the different TeCs. A TeC that has a higher disruptive potential has consequences that reach broader than the TC. On the other hand, some TeCs are seen as evolution of designs that are currently dominant, such that the innovation shifts towards the way in which the TeC is applied to a TC. The document is structured according to the three tasks that constitute WP3, such that sections 2, 3, and 4 are focused on the activities within tasks T3.1, T3.2, and T3.3, respectively.

In Section 2 we analyze the research activities undergoing in T3.1. The state-of-the-art assessment shows that, due to the fact that Massive-MIMO gained a significant attention only in the recent years, works available in literature only partially assessed the impact of real-world impairments on a system-level perspective. These real-world challenges include, for example, channel estimation and pilot design, antenna calibration, link adaptation, antenna design, propagation effects. On the other hand, because of its "youth", Massive-MIMO also needs some further investigations to allow a better understanding of its theoretical foundations and its interplay with other technologies. Moreover Massive-MIMO is an important enabler for MMW communications, due to the need of maximizing the array gain in order to reach a sufficient link budget. We believe that T3.1 is very well positioned, both to provide the right components to evolve current 4G MIMO techniques into solutions with a larger number of antennas, and to introduce potentially disruptive solutions, using high-frequency communications or novel array solutions.

In Section 3 we analyze the research activities undergoing in T3.2. The state-of-the-art analysis shows that advanced inter-node coordination has been the subject of several studies in particular for "classical" CoMP techniques, like joint processing and coordinated scheduling. We note that the gains of these classical CoMP techniques are still object of debates in the research community, and they are mainly limited by the effects of clustering, channel estimation/feedback and backhaul throughput and latency. While T3.2 is further studying classical CoMP techniques, the major focus has been moved towards novel concepts of coordination that can arise as a consequence of the evolution in the network access techniques or improvements or new enablers available in future UEs. In particular, we believe that future UEs should be “radio-smarter”, and should implement solutions like advanced interference-rejection, D2D or other forms of local coordination. Changing the paradigm from centralized coordinated solutions to distributed coordinated solutions could lead to a disruptive architectural change in future systems.

In Section 4 we analyze the research activities from T3.3. The state-of-the-art analysis shows that in current systems, wireless relaying and multi-hop communications have been considered as an additional feature to the core wireless infrastructure, with very limited applications beside hole-coverage and range-extension. However, the trends of network densification, reliability and support of moving networks, call for new technical solutions for which relays could become fundamental enabling components. In particular T3.3 tackles the problem of network densification through the use of infrastructure-deployed relays and techniques for wireless backhauling. Specifically, the use of ideas of wireless network coding, buffer-aided relaying, and joint processing of interfering flows brings high promises to make wireless a viable option for efficient in-band backhauling. Moreover, T3.3 also targets a second set of solutions, based on moving relays and D2D communication. These techniques could have a strong impact on the design of future 5G systems, both at a component level and at an architectural level.

This document is structured as follows. As mentioned above, Sections 2, 3 and 4 are dedicated to the description of the activity within each task. In each of these sections, we first give an overview of the state-of-art, considering both academic and industrial research. Then, we discuss the different technology components, in particular emphasizing the contribution for advancing the state-of-art. Finally, we connect each technology component to the TCs, to the HTs, and to the activity in the other WPs. We conclude the document in Section 5.

# 2 Multi-antenna/Massive-MIMO

The research activities from Task 3.1, “Multi-antenna/Massive-MIMO”, are elaborated in this chapter. A general overview of this new area, Massive-MIMO, is given first along with potential issues to be resolved for practical implementations. The current state of the art is discussed next along with activities related to standards.

The two research clusters, effect of real world impairments and related enablers and further studies on Massive-MIMO precoding schemes under ideal assumptions, around which the research effort is coordinated, are detailed afterwards. In each cluster for different TeCs, the main idea, the test cases defined in [MET+13D11] which can have a direct impact and potential benefits are summarized. Finally, we provide the expected impact of research in T3.1 on test cases, horizontal topics and other work packages in METIS, followed by the conclusion. A concise description of the test cases and horizontal topics is provided in the annex (section 7 and 8).

## 2.1 General overview

After Marzetta’s pioneering work [MAR 10], Massive-MIMO setups gained a significant attention, in both the academic and the industrial community. The concept of Massive-MIMO has been introduced for cellular networks where BS equipped with a very large number of antennas serves simultaneously multiple UEs. A Massive-MIMO network exploits the additional spatial DoF to multiplex messages for several terminals on the same time-frequency resource, to maximize the beamforming gain by focusing the radiated energy towards the intended receivers and to minimize the intracell and intercell interference. The main defining feature of Massive-MIMO is the large number of antennas at the BS, which can lead to a drastic reduction of the transmit energy and, consequently, a significant interference reduction. This helps reducing the signalling overhead required for coordinating the interference in the system.

On one hand, Massive-MIMO is still a recent concept and further theoretical works are needed to better understand its fundamentals. On the other hand, practical applications require a better assessment of the impact of real-world impairments on a system-level perspective and the design of the right enablers, such as pilot signals and CSI feedback. Moreover, how to effectively design Massive-MIMO solutions for high frequencies, still requires more investigations.

One of these real-world challenges is given by the need of an accurate CSI at the BS side. In principle, the CSI may be obtained through transmission of orthogonal reference signals from each transmit antenna element, and then feeding back the observed spatial channel from the user to the BS. This approach has the drawback that the reference signal overhead in terms of required CSI grows linearly with the number of transmit antennas. Another option for obtaining the CSI is to utilize channel reciprocity, in particular under the assumption of TDD. The cost in utilizing reciprocity is that it requires array calibration in order to take the differences in the transmit/receive RF chains of the different antenna elements into account. If the channel is time varying, the delay between training and data transmission also represents an effect that should be further studied: for example channel prediction techniques could be used to mitigate this effect.

Another challenge is to understand the impact of Massive-MIMO in a multi-cell multi-tier network. One of the problems is the impact of pilot contamination [JAM+11]. Another problem is how to exploit Massive-MIMO in a network with an ultra dense deployment of small cells due to size of the antenna array. One approach is to deploy Massive-MIMO at the macro side, and to exploit the spatial DoF to lower the interference between the macro and the small cells. Another approach is to study possible Massive-MIMO deployments at the small cell side, in particular in high-frequency systems, where the small antenna dimensions allow the deployment of large-scale antenna arrays with a realistic footprint (coverage).

The linear multi-antenna transmitter-receiver design in multi-user (multi-cell) setting has received considerable attention in the literature; see for example [DY+10], [JAM+11], [VPW+10], [SRL+11], [TPK+11], [TPW+11], [THT+12], [WWX+12], [KTJ+13]. In general, (near) optimal design to maximize a certain optimization objective often leads to an iterative solution where each sub-problem is presented as an optimization problem, and at each iteration some information needs to be exchanged between adjacent cells. In a Massive-MIMO setting, the coordinated transceiver design methods can be potentially simplified, as compared to state-of-the-art iterative optimization based schemes. As the imbalance between the number of independently fading antennas $N$ at the serving node and the number of users $K$ in the cell becomes large, i.e., $N >> K$, a simple zero-forcing based design is close to optimal. However, given practical non-idealities such as non-zero correlation between antennas and physical limitation of antenna array sizes, coordinated designs with some limited coordination between adjacent cells can be still beneficial.

The objective of the research work in this task of the METIS project is two-fold, with scenario-specific and general objectives, respectively. The research work aims to answer more general questions related to the use of Massive-MIMO in wireless networks, such as the following:

1. What is the impact of real-world impairments into Massive-MIMO performance?
2. What is the benefit of Massive-MIMO at a system-level, in particular with different tiers of cells and assuming a massive deployment of small cells?
3. What are the main enablers (e.g. methods for pilot coordination to avoid pilot pollution) that should be discussed for the standardization of a 2020 system as well as for non-standardized features?
4. What are the best approaches of designing precoding and combining weights to exploit the degrees-of-freedom given by the massive number of antennas?
5. What are the most effective ways of designing Massive-MIMO solutions for high frequencies?

On the other hand, regarding the scenario-specific objectives, it will produce technologies relying on Massive-MIMO that appear as solutions to a particular problem posed within a METIS scenario or a test case.

## 2.2 State of the art and benchmarks

### 2.2.1 Literature review

The idea of increasing the number of antennas deployed at each site to form a Massive-MIMO network was firstly proposed in [MAR+10]. As we mentioned above, a Massive-MIMO network exploits the additional spatial DoF to multiplex messages for several terminals on the same time-frequency resource, to maximize the beamforming gain by focusing the radiated energy towards the intended receivers and to minimize the intracell and intercell interference. We refer to reference [RPL+12] for a good overview.

One of the intuitions in [MAR+10] is that the need for the fast exchange of CSI among terminals and BS transmitter (CSIT), can be alleviated by increasing the number of antennas at the transmitter. This is because, under certain assumptions, as the number of antennas grows large, the channel between a given terminal and its serving BS tends to become orthogonal to the channel of a randomly selected interfering terminal. This result is promising, but it relies on the assumption of perfect channel estimation at the BS side, which stresses the importance of channel estimation procedures and pilot design for very large MIMO systems.

Many works in the literature have been studying mechanisms that enable accurate CSI at the transmitter side. This approach has the drawback that the reference signal overhead grows linearly with the number of transmit antennas, and is furthermore impacted by the feedback overhead due to the high dimensionality of the channel. Another option for obtaining the CSI is to utilize channel reciprocity. The propagation channel between the BS and the user is reciprocal when TDD is used. In case of FDD, the channel is not reciprocal due to the difference of UL and DL carrier frequency. However, the underlying characteristics of the channel are still reciprocal in the sense that the UL DoA and DL DoD are highly correlated [HKL+02]. Reference [ANA+12] showed that the downlink channel training and feedback in FDD systems constrains the number of BS antennas. As a matter of fact, many research works have been focusing on TDD rather than FDD, due to the fact that the time for pilots in a TDD system is proportional to the number of terminal antennas served and is independent of the number of BS antennas. Also exploitation of increased degree of freedoms (DoFs) is possible with the TDD without being constrained by limited frequency resources for pilots in FDD.

The channel estimation and pilot resource allocation problem becomes particularly complex in multicell systems, in which the pilot signals may cause significant interference (pilot pollution) to one another. This is due to the reuse of non-orthogonal pilot sequences across neighbouring cells which limits the interference rejection performance of large MIMO systems [JAM+11] [HTD+11]. Solutions for the mitigation of the pilot contamination effect have been considered in several works, including [MAR+10], [MUL+12], [AM+12]. For example, a less aggressive frequency reuse factor has been shown to improve the cell edge performance at the expense of reduced average throughput [MAR+10]. Pilot contamination precoding has been proposed in [AM+12], where cooperative transmission over a multiplicity of cells is considered to nullify the directed interference that results from pilot contamination.

As mentioned above, channel reciprocity is an important enabler for Massive-MIMO. The problem in utilizing reciprocity is that it requires array calibration in order to take the differences in the Tx/Rx RF chains of the different antenna elements into account. The calibration may be achieved through relative array calibration [GSK+05], [KHG+10] where occasional transmission of orthogonal reference signals from the BS facilitates full channel estimation corresponding to all antennas carried out at the users. Once the BS has estimates of the UL and DL channels, it may use these to obtain calibration matrices that enable utilizing the UL channel estimates in DL precoder selection. Further studies on calibrations are e.g. [HYK+08], [PWK+10], [KGZ+11] and [KGD+12].

The desirable features described above are based on several crucial but optimistic assumptions about the propagation conditions, hardware implementations, and the number of antennas which can be deployed in practice. Therefore, recent papers study Massive-MIMO under more realistic assumptions, e.g., a physical channel model with a finite number of DoF [NLM+11] or constant-envelope transmissions with per-antenna power constraints [ML+11]. Also first channel measurements with large antenna arrays were reported in [GER+11], [PT+12], [HHW+12].

One important aspect for the evaluation of Massive-MIMO systems is the channel model. For example, in [RPL+12], the channel transfer function is described by a Kronecker model [KSP+02]. However, this model does not support some important characteristics such as polarization, antenna field patterns or broadband channels. All of those have the potential to significantly impact the performance of Massive-MIMO systems. As an alternative, geometric channel models such as the WINNER channel model [KMH+07],[HMK+10] or the COST 2100 channel model [OCD+12] can be used. Those models try to establish a model for the physical propagation environment that leads to specific channel transfer function instead of modeling the transfer function itself. Hence, more accurate results can be obtained.

However, an issue arises from the modeling of the wave-front. The WINNER model always uses a plane-wave approximation [WIN2D112]. This restricts the antenna arrays sizes to a few wavelengths. When the arrays get larger, as it is the case for many Massive-MIMO systems, the errors in the phase of the multipath components grow too large. This imposes a higher correlation and thus lowers the capacity. As an alternative, the COST 2100 model assumes spherical wave propagation. It characterizes the channel on the level of individual clusters and thus, it intrinsically includes the correct correlation between links [CO+08]. However, despite the effort that has been made to parameterize the model [PHL+11, ZTE+12], it still lacks sufficient parameters for many interesting scenarios.

While the discussion above focuses on the use of Massive-MIMO in traditional cellular frequencies (up to 3 GHz), we emphasize that Massive-MIMO could have a large impact also at MMW frequencies. As a matter of fact, on one side the reduced antenna footprint at high frequencies allows the deployment of arrays with a large number of antenna elements also in small cells. On the other side, the use of highly directive beams is essential for achieving the required link budget, and therefore Massive-MIMO is a fundamental enabling component for MMW systems. Nevertheless, the implementation of Massive-MIMO at high frequencies is still challenging with today's technology. In particular, the cost of RF antenna chains at high frequencies imposes a design tradeoff between number of RF chains and degrees-of-freedom.

### 2.2.2 Standards

The 3rd Generation Partnership Project (3GPP) standard for the LTE was one of the first wireless standards designed with MIMO in mind from the beginning. LTE adopts various MIMO technologies [BCG+12].

In Rel. 8, LTE downlink transmission supports up to 4 antennas at the BS. It allows transmit diversity, codebook-based beamforming and spatial multiplexing with up to 4 layers per user, and moreover codebook-based MU-MIMO. In addition, user-specific beamforming is supported for any number of antennas at the BS, relying on channel reciprocity. For uplink transmissions, only 1 antenna is supported for transmission from the user terminal. However, there is an option for performing antenna switching with up to two transmit antennas. MU-MIMO is also supported in uplink.

In Rel. 9, two new user-specific reference signals are introduced in order to enable non-codebook based dual-layer MU-MIMO beamforming.

Rel. 10 (also known as LTE-Advanced or LTE-A) introduces enhanced MIMO technologies. For the downlink new reference signals (user-specific reference signals (RS)) are adopted to enable the use of so-called non-codebook based, for example, zero-forcing (ZF), MIMO transmissions. As a matter of fact, user-specific RS allow the estimation of an equivalent channel including the precoding weights between BS and user. A new codebook and feedback design are introduced to support spatial multiplexing with up to 8 independent spatial streams and enhanced MU-MIMO transmissions. Dynamic switching between SU-MIMO and MU-MIMO is also supported. In uplink, SU-MIMO has been introduced with up to 4 transmit antennas at the user side and transmit diversity is supported for the control channel.

Rel. 11 did not introduce any major enhancement for MIMO, focusing rather on CoMP.

Current works on Rel. 12 are focusing on 3D-channel modeling [3GPP+RP122015], with the goal of studying new channel models supporting both vertical and horizontal dimensions. Some Study Items on vertical-beamforming and MIMO with more than 8 antennas have been proposed but not yet approved [3GPP12+RP121994], [3GPP12+RP122015].

From the assessment above, we conclude that T3.1 is very well positioned with the respect to the works in 3GPP as the topics treated herein will not be tackled in 3GPP before the activities for Rel. 13 will start.

Concerning MMW technologies, they are fundamental components of IEEE 802.15.3c and IEEE 802.11ad. These standards carry out typical data rates ranged from 800 Mbps to 6600 Mbps over the 60 GHz band. They use both single carrier and OFDM combined with beam steering and multi-user MIMO RF schemes. Usual transmitted radiated power level may exceed 55 dBm (ensuring large radio coverage in indoor LOS/OLOS situations). The IEEE802.11ad PHY layer is directly derived from the IEEE802.15.3c standard with similar usage models and OFDM parameter sets [IEEE 802.11ad], [IEEE+P802.15.3c]. These two standards utilize channels adjusted to 2160 MHz and a single FFT size to perform several Gbps.

## 2.3 Research clusters

The research activity in T3.1 is structured along two main directions. The first research direction is devoted to better assessing the impact of real-world impairments from a system-level perspective and to designing the right enablers (e.g. pilot signals and CSI feedback). The second research direction is aimed at further studying the theoretical foundations of Massive-MIMO. These research directions are mapped to the following research clusters:

- Cluster 1: effect of real world impairments and related enablers.
- Cluster 2: further studies on Massive-MIMO precoding schemes under ideal assumptions.

### 2.3.1 Research Cluster 1 and related technology components: effect of real world impairments and related enablers

This research cluster has two objectives. The first is to gain a clear understanding of the impact of real-world impairments, such as pilot contamination, imperfect array calibration, imperfect CSI, channel aging and propagation effects. The second goal is to provide enabling techniques to cope with these effects, such as pilot coordination between different cells, methods for enabling an effective array calibration, channel predictors, and low complexity precoders designed under the assumption of imperfect CSI.

In such a context, one of the most important enablers is the accurate channel prediction in combination with a reporting scheme with very low overhead. Assuming the availability of a perfect building vector data map (BVDM) model of the eNB surrounding several channel components could be reported with few kbit/s per UE. The main challenge, which is rather generally valid for channel prediction, is the high sensitivity to model errors.

On the issue of channel models, most existing ones in the context of system level simulations are still based on the plane-wave assumption. Considering Massive-MIMO systems this effect obviously worsens because of the larger array dimensions. Spherical propagation model is therefore considered with large scale antenna system (LSAS) BSs. In addition the large aperture of the BS antenna can be used to discriminate the users.

In the high mobility environments standard precoding fails as channel is considerably different due to movement. A scheme is proposed where the vehicle roof is equipped with one predictor antenna (PA) at the front and several “Candidate Antennas” (CAs) aligned behind the PA to account for this problem.

The technology components contained in research cluster 1 are outlined in the tables below.

**Table 2-1. T3.1 Technology Component 1.**

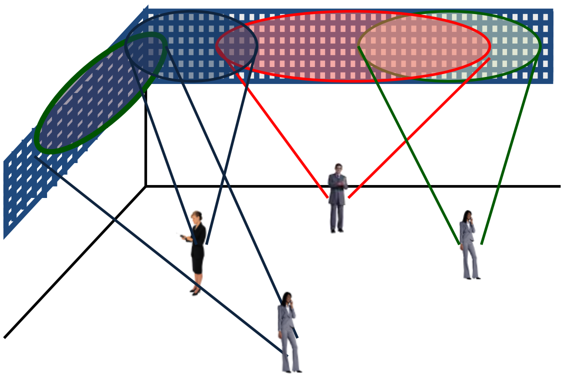
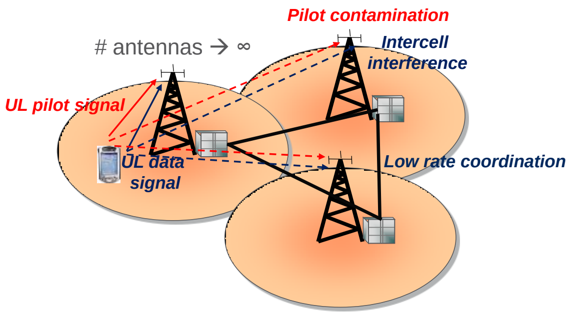
| **T3.1 Technology component 1**<br>**Communicating in the near field of a large aperture massive array** | |
|---|---|
| **System Model**<br><br>2D or 3D large aperture massive arrays deployed in a hop spot. Multiple users equipped with MIMO communicate simultaneously in the near-field of the array. A line-of sight and scattering environment is considered. | **Main Idea**<br>The main idea is to deploy massive arrays of **large aperture** to serve as access points in new infrastructures, such as airport halls, shopping malls, stadium, concert stages, etc. In such a hot spot, communication happens in the near-field where the phase and amplitude of the channel varies across the array.<br>The general objective is the development of low-complexity and energy-efficient multi-antenna transceiver techniques in a multi-user communication framework where a 2D or 3D large array serves multiple users simultaneously. The large aperture of the array allow for a specific discrimination among the users where they occupy sections of the array, possibly overlapping. |
| **Test Cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival | **Main Benefits**<br>• High spectral efficiency<br>• Access for high device density |

Table 2-2. T3.1 Technology Component 2.

<table>
<tr><td colspan="2">T3.1 Technology component 2<br><br>Low rate and simple coordination techniques for pilots</td></tr>
<tr><td>

**System Model**




Multicell pilot coordination. The pilot resources within a cell are orthogonal, but pilot signals suffer from inter-cell interference.

</td><td>

**Main Idea**

The issue of balancing the pilot-to-data power ratio (PTDPR) in the uplink of multicell systems is investigated, in which cooperation between multiple cells is feasible. Multiple cells employ a coordinated approach to channel estimation as well as allocating transmit power both to the pilot and the data channels.

A model that takes into account the impact of interfering pilot power on the quality of channel estimation, the impact of intercell interference on the data channels and the tradeoff between the pilot and data power is proposed to be used for the simultaneous transmission of pilot and data signals.

</td></tr>
<tr><td>

**Test Cases**

- TC2: Dense Urban Information Society
- TC3: Shopping mall
- TC4: Stadium
- TC9: Open air festival

</td><td>

**Main Benefits**

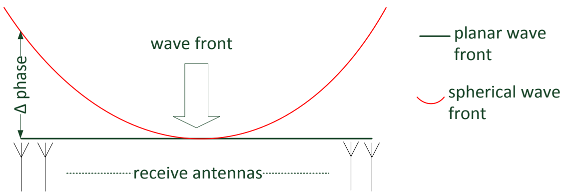
- High spectral efficiency
- Access for high device density

</td></tr>
</table>

Table 2-3. T3.1 Technology Component 3.

<table>
<tr><td colspan="2">T3.1 Technology component 3<br><br>Modelling with spherical waves, Linear precoding</td></tr>
<tr><td>

**System Model**




Spherical wave modelling. The common assumption of plane wave front is corrected for near field communication

</td><td>

**Main Idea**

The influence on spectral efficiency caused by spherical instead of planar waves is considered in the channel model. The spherical model is necessary due to the increased aperture size, which is linked with the large number of antennas when assuming fixed antenna spacing.

</td></tr>
<tr><td>

**Test Cases**

- TC9: Open air festival

</td><td>

**Main Benefits**

Quantification of the error made with current channel models in the presence of a large scale antenna system where users are not located in the antenna far field.

</td></tr>
</table>

**Table 2-4. T3.1 Technology Component 4.**

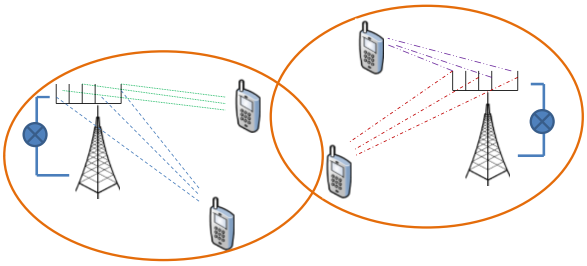
<table>
<tr><th colspan="2">T3.1 Technology component 4<br>Multicell MU-MIMO in real world scenarios-antenna calibration</th></tr>
<tr><td>System Model<br><br>Multicell MU-MIMO. Imperfect antenna calibration. Calibration is done at the BS.</td><td>Main Idea<br>The calibration of the BS array is assumed to be carried out e.g. through UE assistance while the calibration error is modelled to study the impact of imperfections. Different types of reference signals are assumed for purposes of data demodulation, CQI measurement, UL sounding, and array calibration. Precoding schemes related to zero-forcing are applied at the BSs. The variability of interference power is taken into account in scheduling, link adaptation and interference measurement in CQI feedback schemes. The study focuses on DL of TDD systems, while also FDD may be considered (reciprocity in angular domain).</td></tr>
<tr><td>Test Cases<br>• TC4: Stadium</td><td>Main Benefits<br>• Higher cell capacity</td></tr>
</table>

**Table 2-5. T3.1 Technology Component 5.**

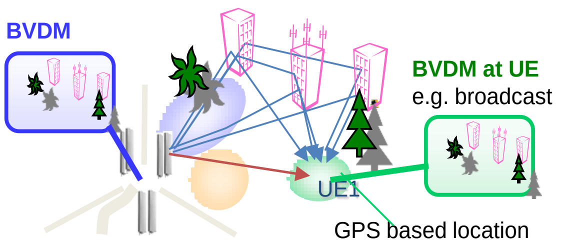
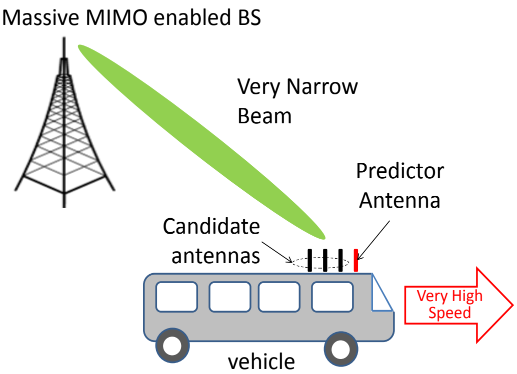
<table>
<tr><th colspan="2">T3.1 Technology component 5<br>Model based channel prediction</th></tr>
<tr><td>System Model<br><br><br>Basic concept of model based channel prediction, low rate feedback model based channel prediction is considered and is an enabler.</td><td>Main Idea<br>This is a partially theoretical study on limitations of model based channel prediction (MBCP). It investigates novel algorithms for extraction of as much as possible of relevant information out of coarse building vector data maps (BVDM) for channel prediction. MBCP is thereby seen as one of the most important enablers for future advanced radio algorithms like JT CoMP or Massive-MIMO.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society</td><td>Main Benefits<br>• High spectral efficiency<br>• High throughput</td></tr>
</table>

**Table 2-6. T3.1 Technology Component 6.**

<table>
<tr><th colspan="2">T3.1 Technology component 6<br>Robust and energy efficient wireless backhaul for very fast moving relays</th></tr>
<tr><td>

**System Model**




Vehicle with very high speed served by a massive-MIMO enabled BS using very narrow beams. The vehicle is equipped with one predictor antenna and a set of candidate antennas. All the antennas are aligned.

</td><td>

**Main Idea**

A new scheme called Separate Receive and Training Antennas (SRTA) with antenna Switch Off Scheme (SOS) is proposed specifically for large MISO downlink beamforming in TDD. The objective is to achieve high energy efficient wireless backhaul for fast moving vehicular relays. The vehicle roof is equipped with one predictor antenna (PA) at the front and several “Candidate Antennas” aligned behind the predictor antenna. Among the CAs, one Receive Antenna (RA) is selected dynamically to compensate BF mispointing due to speed. SOS dynamically reduces the BS array aperture and hence the beam width to cope with residual BF mispointing.

</td></tr>
<tr><td>

**Test Cases**

- TC8: Real-time remote computing for mobile terminals

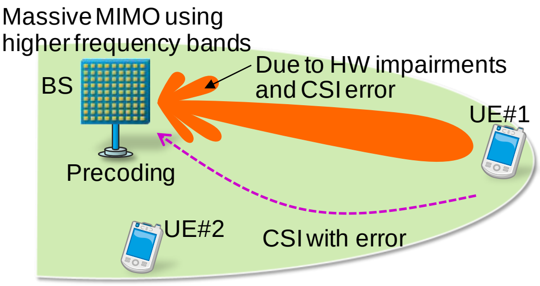
</td><td>

**Main Benefits**

- High reliability in high mobility, high energy efficiency

</td></tr>
</table>

**Table 2-7. T3.1 Technology Component 7.**

| **T3.1 Technology component 7**<br><br>**Massive MIMO Transmission Using Higher Frequency Bands Based on Measured Channels with CSI Error and Hardware Impairments** | |
|---|---|
| **System Model**<br><br><br>Massive-MIMO transmission using higher frequency bands based on measured channels with CSI error and hardware impairments. | **Main Idea**<br>Performance evaluation of Massive-MIMO transmission using higher frequency bands based on the measured channels is performed by computer simulations, and requirements of both CSI error and hardware impairments are clarified. Computer simulations in Massive-MIMO eigenmode transmission are conducted by using some appropriate channel models and exploiting CSI that the Massive-MIMO channel sounder measured in field experiments. In order to clarify the requirements, the influence of the CSI error and the hardware impairments on the throughput performance are evaluated. From these investigations, novel precoding and compensation methods will be proposed so as to satisfy the requirements for Massive-MIMO using higher frequency bands. |
| **Test Cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival | **Main Benefits**<br>• High spectral efficiency<br>• High bit rate |

### 2.3.2 Research Cluster 2 and related technology components: further studies on Massive-MIMO precoding schemes under ideal assumptions

This research cluster is focused on further study of the theoretical foundations of Massive MIMO. The common assumption in the different contributions is the use of TDD as duplexing scheme and a perfect CSIT. The studies herein target low-complexity precoding/beamforming solutions, interference rejection techniques and asymptotic analysis.

First distributed precoding for a two tier network is considered. A TDD-based network architecture with the aim of integrating a Massive-MIMO macro network with a dense layer of Small Cells (SCs) is studied. Due to the large number of SCs, the focus is on a distributed, uncoordinated framework, where interference is tackled locally.

The uplink performance of multi-cell MMSE based detection in interference-dominated MU-MIMO systems will be analysed. As the exact analysis of MMSE receivers is a challenging mathematical problem in a multi-cell MU-MIMO setup, the lower bound on the ergodic achievable rate is expected to be obtained.

The next study focuses on fast converging methods that require fewer over-the-air signaling cycles, without losing in terms of the performance after convergence. The optimization problem is generalized from BS-specific sum power constraints to allowing antenna-specific transmit power constraints.

Finally precoding methods for downlink are considered where the number of UE is equal to the number of transmit antennas at large scale antenna system (LSAS) BSs, to exploit massive SDMA. In most of the other works the number of UE is much smaller than the number of transmit antennas and there is no user grouping. Therefore, an investigation is carried out in order to see whether user grouping is required in the regime when the number of UE approximates the number of transmit antennas.

The technology components related to research cluster 2 are summarized in the tables below.

**Table 2-8. T3.1 Technology Component 8.**

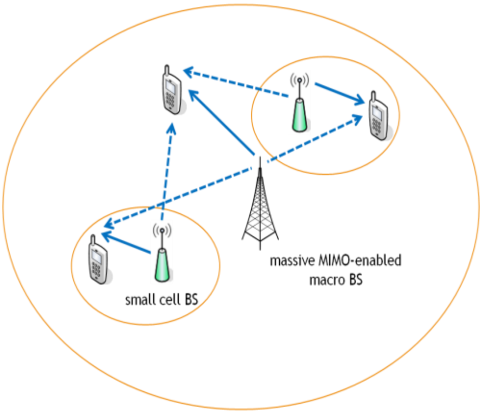
| **T3.1 Technology component 8**<br>**Integrating a Massive-MIMO macro network with a dense layer of small cells (SCs) – two tier deployment** | |
|---|---|
| **System Model**<br><br>Two tier deployments - TDD-based network architecture with the aim of integrating a Massive-MIMO macro network with a dense layer of SCs. | **Main Idea**<br>A network where a macro tier is augmented with low range SCs. Each BS employs N antennas to serve its K associated single-antenna MUEs. Each SC has F antennas and devotes its available resources to its pre-scheduled small-cell user equipment (SUE). We assume that transmissions across the tiers are perfectly synchronized. Both tiers share the available bandwidth with universal frequency reuse. All transmissions are assumed to take place over flat fading channels. The main idea is to exploit channel reciprocity not only for estimation of large-dimensional channels at the BSs but also for interference aware precoding with the goal of reducing intra- and intertier interference. The proposed scheme relies only on locally available information and does not require any data exchange between the nodes. It is hence fully distributed and scalable. |
| **Test Cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival | **Main Benefits**<br>• High spectral efficiency<br>• Access for high device density |

**Table 2-9. T3.1 Technology Component 9.**

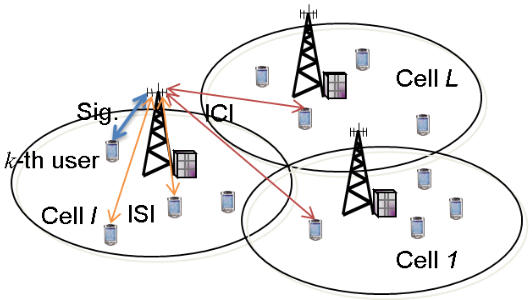
| **T3.1 Technology component 9**<br>**Multi-cell MU MIMO maximizing weighted sum rate** | |
|---|---|
| **System Model**<br><br>Multicell multi-user MIMO. BSs are equipped with a very large number of antennas and users with a single antenna. Interference comprises inter-cell interference and inter-stream interference. | **Main Idea**<br>The asymptotic performance of multi-cell MMSE based detection and precoding in interference dominated multi-user MIMO systems is analysed in a scenario with multiple BSs equipped with large number of antennas and multiple single antenna users. Since the exact analysis of MMSE precoders/receivers is a challenging mathematical problem in a multi-cell MU-MIMO setup, instead the lower bound on the ergodic achievable rate by using results of the random matrix theory will be derived. |
| **Test Cases**<br>• TC2: Dense Urban Information Society | **Main Benefits**<br>• High throughput, traffic volume |



**Table 2-10. T3.1 Technology Component 10.**

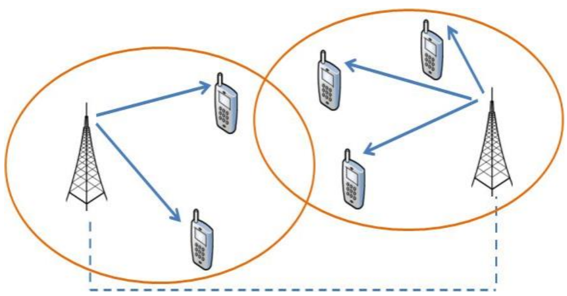
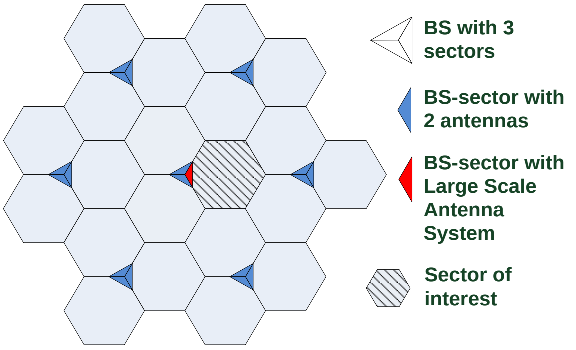
| **T3.1 Technology component 10**<br>**Multi-cell MU MIMO, decentralized transceiver design** | |
|---|---|
| **System Model**<br><br>Multicell multi-user MIMO. Each BS has a much larger number of antennas compared to those at user terminals. A decentralized beam forming algorithm is considered with some backhaul signalling among BS. | **Main Idea**<br>MIMO interfering broadcast channel (IBC) and interfering multiple access channel (IMAC) are considered. Each BS serves its own set of user terminals and co-channel transmissions from each BS cause interference to the user terminals of other cells. It is expected to investigate how and if the coordinated transceiver design methods can be simplified when the imbalance between the number of antennas at the serving node and the number of users in the cell is large. The performance loss of simplified multiuser transmitter and receiver designs is compared to (near) optimal schemes in different deployment scenarios. |
| **Test Cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival | **Main Benefits**<br>• High throughput<br>• Access for high device density |

**Table 2-11. T3.1 Technology Component 11.**

<table>
<tr><td colspan="2">T3.1 Technology component 11<br>Heterogeneous Multi-cell, MU Massive-MIMO, massive SDMA</td></tr>
<tr><td>System Model<br>




Homogeneous network with 3 sectors per BS and a large scale antenna system at a single sector in the center of the cellular deployment.</td>
<td>Main Idea<br>Given a hexagonal cellular deployment each base station (BS) has 3 sectors and 2 antennas per sector. In the center of the deployment a single BS with a large-scale antenna system (LSAS) at one sector is assumed. The idea is to use the LSAS for massive spatial division multiple access (SDMA) in the downlink of a time division duplex system. Massive means that the number of served mobile stations (MSs) in the spatial domain is increased up to the number of transmit antennas. As we assume channel state information at the BS to all connected MSs and based on this linear precoding, users have to be grouped carefully with respect to the selected precoding method. Investigations target codebook and non-codebook-based precoding methods, as well as sum-rate and fair user grouping schemes.<br><br>Performance is evaluated by multi-cell simulations using the Quadriga channel model.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival</td>
<td>Main Benefits<br>• High spectral efficiency<br>• Energy efficiency</td></tr>
</table>

## 2.4 Summary of mapping between technology components and test cases

In this section we give an overview of the TeCs investigated in T3.1 and their impact on the METIS Test cases defined in [MET+13D11]. Multi antenna/Massive-MIMO is seen as having a significant contribution in the scenarios of “Great service in a crowd” and “Amazingly fast”. The main factor here is very high bit rates needed for these cases. Test case 2 (Dense urban information society), 3 (Shopping mall), 4 (Stadium) and 9 (Open air festival) are the major cases of interest. The Test case 8, Real-time remote computing for mobile terminals is also expected to have some impact due to work on high speed relays.

**Table 2-12. Summary of mapping between technology components and test cases for T3.1.**

| | Technology component | Test case number | | | | | | | | | | | | Expected benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Communicating in the near field of a large aperture massive array | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High throughput, access for high device density, low energy consumption |
| Research cluster 1 | **TeC2**: Low rate and simple coordination techniques for pilots | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High throughput, access for high device density |
| Research cluster 1 | **TeC3**: Modeling with spherical waves | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | Quantification of channel model error |
| Research cluster 1 | **TeC4**: Multicell MU-MIMO in real world scenarios-antenna calibration | 1 | 2 | 3 | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Higher cell capacity |
| Research cluster 1 | **TeC5**: Model based channel prediction – low feedback rates | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High spectral efficiency, throughput |
| Research cluster 1 | **TeC6**: Selective receive and transmit antennas (SRTA) with predictor antennas and switch off scheme (SOS) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | **8** | 9 | 10 | 11 | 12 | High reliability in high mobility, high energy efficiency |
| Research cluster 1 | **TeC7**: MIMO-OFDM transmission based on measured channels with CSI error and hardware impairments | 1 | **2** | **3** | **4** | 5 | 6 | 7 | | **9** | 10 | 11 | 12 | High spectral efficiency, high bit rate |
| Research cluster 2 | **TeC8**: Integrating a Massive-MIMO macro network with a dense layer of small cells (SCs) – two tier deployment | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High throughput, access for high device density |
| Research cluster 2 | **TeC9**: Multi-cell MU MIMO maximizing weighted sum rate | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High throughput, traffic volume |
| Research cluster 2 | **TeC10**: Multi-cell MU MIMO , decentralized transceiver design | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High throughput, access for high device density |
| Research cluster 2 | **TeC11:** HetNet Multi-cell, MU Massive-MIMO, massive SDMA | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High spectral efficiency, energy efficiency |
| | Number of technology components per test case | **0** | **8** | **6** | **7** | **0** | **0** | **0** | **1** | **7** | **0** | **0** | **0** | |

## 2.5 Summary of mapping between technology components and horizontal topics

Herein we summarize the relevance of the research effort in Task 3.1 with respect to METIS HTs. The HT of highest concentration is Ultra-dense networks. With TeC6 the case of moving relays are addressed which then can have an effect on the horizontal topic of moving networks.

**Table 2-13. Summary of mapping between technology components and horizontal topics for T3.1.**

| | Technology component | Horizontal topic | | | | |
|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Communicating in the near field of a large aperture massive array | D2D | MMC | **UDN** | MN | URC |
| | **TeC2**: Low rate and simple coordination techniques for pilots | D2D | MMC | **UDN** | MN | URC |
| | **TeC3**: Modeling with spherical waves | D2D | MMC | **UDN** | MN | URC |
| | **TeC4**: Multicell MU-MIMO in real world scenarios-antenna calibration | D2D | MMC | **UDN** | MN | URC |
| | **TeC5**: Model based channel prediction – low feedback rates | D2D | MMC | **UDN** | MN | URC |
| | **TeC6**: Robust and energy efficient wireless backhaul for very fast moving relays | D2D | MMC | UDN | **MN** | URC |
| | **TeC7**: Massive-MIMO Transmission Based on Measured Channels with CSI Error and Hardware Impairments | D2D | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC8**: Integrating a Massive-MIMO macro network with a dense layer of small cells (SCs) – two tier deployment | D2D | MMC | **UDN** | MN | URC |
| | **TeC9**: Multi-cell MU MIMO maximizing weighted sum rate | D2D | MMC | **UDN** | MN | URC |
| | **TeC10**: Multi-cell MU MIMO , decentralized transceiver design | D2D | MMC | **UDN** | MN | URC |
| | **TeC11:** HetNet Multi-cell, MU Massive-MIMO, massive SDMA | D2D | MMC | **UDN** | MN | URC |
| | Number of technology components per test case | **0** | **0** | **10** | **1** | **0** |

## 2.6 Mapping between T3.1 and the other METIS WPs

In this section we summarize the mapping between the activity in T3.1 and the other METIS WPs, by emphasizing the most relevant connections.

**Table 2-14. Mapping between the activity in T3.1 and the other METIS WPs.**

| | |
|---|---|
| **WP1** | • Implications of new channel measurements, in particular at high-frequencies. |
| **WP2** | • Implications of flexible air-interface design (for both traditional and MMW frequencies);<br>• effect of new waveforms and modulation on the design of MIMO schemes;<br>• performance and design of novel multiple access approaches, in particular at MMW frequencies. |
| **WP4** | • Implications of new approaches for smart device/service to RAT mapping and smart signaling for mobility, in particular for MMW frequencies;<br>• implications of novel architectural concepts (e.g. phantom cell);<br>• implications of novel Massive-MIMO schemes for WP4 studies. |
| **WP5** | • Prioritization of MMW frequency: the selected frequencies have an impact on the transceiver design. |
| **WP6** | • Architectural implications at both traditional and MMW frequencies. |

# 3 Advanced inter-node coordination

This chapter illustrates the main research directions investigated in Task 3.2 "Advanced inter-node coordination". The first two subsections provide a general overview on the broad field of multi-point transmission coordination, highlighting the main research questions that still need to be clarified and providing a comprehensive description of the state of the art, including both existing studies in literature and references to standardization efforts carried out in the main standardization bodies.

The second part describes the structure of the research work in Task 3.2, introducing the three main Research Clusters that have been identified, namely: further improvements to classical coordination techniques, studies on Interference Alignment, and coordination with enhanced network and UE capabilities.

For each cluster a description of the Technology Components (TeC) investigated in the cluster is provided, highlighting the main benefits that can be obtained, the impact that is expected on METIS Test Cases defined in [MET+13D11] and their connection to other work packages in METIS. A concise description of the test cases and horizontal topics is provided in the annex (section 7 and 8).

In the end, the expected impact of the overall research work in Task 3.2 on Test Cases and Horizontal Topic is summarized and discussed, highlighting the potential of coordination techniques as valuable tools to address the "Great service in a crowd" and "Amazingly fast" scenarios [MET+13D11] targeted by the METIS system.

## 3.1 General overview

Coordinated multi-point (CoMP) transmission has attracted a lot of attention during the past few years due to its great potential to boost capacity of radio networks and quality-of-service for UEs in an interference limited scenario. CoMP entails that a number of transmission points share information and jointly act to mitigate inter-cell interference, allowing transmissions coming from different nodes to cooperate in delivering services to users rather than interfere with each other. Depending on whether the user data is shared among the transmission points or not, downlink CoMP transmission schemes can be divided into two main categories: joint processing and coordinated scheduling/beamforming [3GPP11+36819]. In joint processing, data is available at each point in the cooperating set and transmission occurs from one or multiple transmission points. In coordinated scheduling/beamforming, data is only available at the serving cell but user scheduling/beamforming decisions are made using coordination among cells.

Studies on upper bound of CoMP have shown significant potentiality, however, these studies mostly assume perfect CSI knowledge for all the transmitters and fully centralized coordination of a network, which is impossible to accomplish in practical cellular systems.

One way to alleviate these requirements and reduce the complexity incurred in coordinating the whole network, is to limit CoMP techniques to a number of cells within a "cluster". In that way CoMP transmission can actively reduce the interference inside the cluster; however the design of efficient clustering solution is challenging and in any case practical systems will still suffer from intra-cluster interference. There is a variety of reasons which destroy the inter-user orthogonality inside the cluster. Several CoMP techniques rely on the CSI being fed back through the feedback links and require information exchange between BSs through backhaul links. This information can be CSI, user scheduling decisions, and transition decisions. However in practical systems, the quality of feedback and backhaul links in terms of capacity, latency and reliability cannot be granted. For example, there is always a delay between the channel estimation at the mobile terminal, the feedback towards the BS and the time instant when this estimate is used for composing the following downlink transmission. Moreover, channel estimation and quantization, channel aging effects and synchronization errors between multiple BS, can significantly impair the effectiveness of most CoMP techniques. At present, commercial deployment of some of the most promising techniques is still considered to be very challenging for this sensitivity to impairments and the constraints posed by the backhauling. Further studies are needed in order to overcome these limits and reach all the potential promised by CoMP.

In the broad field of coordination, in the last years IA emerged as a new technique to lower intra-cell interference; this technique implies processing the signal at several transmitters so that the interference it creates at the receiver can be easily suppressed. Although the feasibility of this approach has been demonstrated in theory, unfortunately up to now IA has been studied only with a limited number of cells and no practical scheme has been identified so far. Further work is therefore needed to investigate how the theoretically promising IA concept can provide benefits in a real network.

In general, the design of practical and efficient schemes to control interference in the network is expected to become even more important in a future environment, where a high number of nodes, deployed very densely in space, are used to tackle the increasing demand of traffic expected for the future. In fact, in order to fully exploit the additional capacity offered by all these nodes a mechanism to efficiently coordinate their transmissions will be needed. At present however, the investigation in the literature is rather focused on homogeneous networks. With the densification of networks, and the introduction of pico- and femtocells, new clustering and coordination schemes will be needed to deal with different and numerous sources of co-channel interference. However, network densification with the deployment of coordinated small cells might not be sufficient to satisfy the exponential increase in the volume of mobile traffic that is expected for the network of the future. To satisfy these demanding traffic requirements, a combination of multiple approaches could be necessary, and the introduction of new technologies that can boost overall spectrum efficiency should be expected. In that sense, new non-orthogonal multiple access schemes, device-to-device communications, receiver architectures equipped with interference suppression algorithm are just examples of possible evolutions that can change the way interference is created and treated inside the network, and that can pose new opportunities and challenges when considered in coordination schemes, which still need to be investigated.

The objective of the research work in this task of the METIS project is two-fold, with scenario-specific and general objectives, respectively. Regarding the scenario-specific objectives, it will produce technologies based on advanced inter-node coordination that appear as solutions to a particular problem posed within a METIS scenario or a test case. On the other hand, research work aims to answer more general questions related to the feasibility of advanced inter-node coordination in wireless networks and its evolution, such as the following:

1. Is it possible to overcome the impact of real-world impairments into inter-node coordination?
2. What are the enablers that could be used to alleviate/simplify the clustering and coordination problem?
3. How can advanced coordination techniques be used to manage interference in an ultra-dense network?
4. How can IA techniques be implemented in a realistic framework?
5. How can novel UE capabilities be exploited by advanced coordination techniques?

## 3.2 State of the art and benchmarks

### 3.2.1 Literature review

CoMP transmission/reception has been the subject of several studies, aiming to improve the coverage of high data rates, increase cell-edge throughput and provide higher system capacity in both high and low load scenarios.

The work carried out in European projects such as WINNER+ [WIN+09-D14][WIN+09-D18][WIN+10-D19] or ARTIST4G [ART10+D12][ART11+D13], together with several academic studies and test demonstrations [IDM+11] paved the way and then pushed the introduction of this technique in 3GPP, making it one of the techniques considered for LTE Advanced.

A general classification is to distinguish between the techniques involving only CSI exchange (interference coordination) and the multi-cell processing schemes that require both CSI and users data exchange.

The first class of techniques, i.e. **interference coordination strategies**, exploit the availability of the CSI at the BSs to define a cooperative strategy that adapts with respect to the state of the channel in order to reduce the mutual interference created by each of the transmitting points on the signals of others. These techniques involve only CSI exchange, and require a fine BS synchronization. Interference coordination strategies include:

- **Coordinated beamforming/coordinated scheduling** – here the overall performance can be improved using the additional spatial dimensions allowed by the multiple antennas at the BSs. The optimization problem is formulated over all the cells in the network given a target signal-to-interference-plus-noise ratio (SINR). Beamforming is beneficial if the number of BS antennas exceeds the number of simultaneous single-antenna users served by the BS. The challenge to coordinated beamforming is to coordinate the BSs in a way to find the optimal solution jointly across all the BSs without excessive exchange of CSI. The transmit downlink beamforming problem is solved using convex optimization and uplink-downlink duality theory for the single-cell [BO+01] [SB+04] and multi-cell networks [BO+01] [DY+10].
- **Dynamic cell selection** - the data is transmitted by only one transmission point at a time. The choice of the serving BS is done regarding the channel quality between the receiving point and each of the transmission points. Dynamic Cell Selection schemes have a good trade-off between the transmission algorithm complexity, backhaul overhead, and system performance. The performance of such schemes is studied in e.g. [FSC+10] and [GLY+11]. Dynamic cell selection may be also applied together with DPB. In that approach the BSs leave certain sub-bands un-used in a coordinated fashion in order to reduce interference on the cell edge users.
- **Coordinated power control** - the resource allocation problem in the multi-cell setting has been studied extensively in the literature. In a general setting, where multiple users within each cell are separated in frequency domain (OFDMA), the joint power control and scheduling problem is that of deciding which user should be served and how much power should be used on each frequency tone. This is known to be a difficult problem, and no convex reformulation of this problem exists, even in the simpler case of fixed scheduling [VPW+09]. One approach to solve the power allocation problem is to let each cell independently optimize its own transmission power in a game theoretical model (e.g. [HJL+07]). Another technique is to encourage the interfering transmitter to lower its transmitting power whenever it causes too much interference to neighboring cells. In this technique, the BSs exchange measures on each other's interference (e.g. [SV+09], [YKS+10]).
- **Interference mitigation** - it is possible to further improve the strategies which treat inter-cell interference as noise by considering the possibility of detecting and then subtracting the interference. The largest known achievable rate region for the two-user

interference channel is the Han-Kobayashi region [HK+81]. For an interference channel with more than two transmitters, it is possible to specifically design transmit signals so that the interferences are always constrained at confined subspaces at each receiver allowing the receiver to efficiently rejecting the interference. This idea, known as **Interference Alignment (IA)** is one of the solutions emerged in the last few years to manage the interference efficiently by combining an "align" and "suppression" strategy. The fundamental idea of IA is developed in [CJ+08] [GJ+10] for the K-user interference channel. The linear scheme developed in [CJ+08] relies on globally available CSI at all nodes, while spatial IA schemes that only utilize local CSI feedback are considered in [GCS+08] [PH+11]. The IA concept is promising as it in general provides maximum DoF for 'K-User' interference channel, being a capacity-optimal scheme in high SNR regions. Further work is still needed in this field to build robust IA based algorithms and to understand operational regimes to which IA can be practically deployed.

Interference Coordination Strategies have been widely studied to control interference exchanging only CSI information between transmitting nodes. However further improvements in data rates are theoretically possible if the BSs are synchronized and the data streams for all the active users, or the received signals at all the antennas, are shared between the BSs via high-capacity backhaul links. This setting is considered in a second class of CoMP techniques, which involve **coding strategies for multi-cell processing networks**. Here the antennas from all the BSs are pooled together to form a big distributed antenna array. Many coding strategies have been proposed in the literature for this setting for both the uplink channel (e.g. [Ven+07]) and downlink channel (e.g. [HT+08]):

- **Uplink channel** The uplink channel can be viewed as a multiple-access channel with multiple transmitters and a single (or multiple) distributed multi-antenna receiver(s) with a centralized (or distributed) scheduler. Superposition coding and successive decoding is shown to achieve the capacity region [CT+91]. In order to achieve this capacity, the BSs need to share their information on CSI and data sequences which require a very high backhaul capacity and a very low backhaul latency. An alternative suboptimal strategy consists of making detection at each BS based on the received signal on this BS only, but BSs share the decoded bits for interference subtraction.

- **Downlink channel** The downlink channel can be viewed as broadcast channel with a single (or multiple) distributed multi-antenna transmitter(s) and multiple receivers. The dirty-paper coding strategy at the encoder achieves the capacity region on the downlink broadcast channel [WSS+06]. When the channel matrix associated with the interference network is diagonally dominant, the zero-forcing strategy is nearly optimal.

So far, studies on upper bound of different CoMP techniques have proved a great potential to improve the capacity of cellular systems [KFV+06a] [KFV+06b] [GHH+10]. However, these studies assume perfect CSI knowledge for all the transmitters and fully centralized coordination of a network, which is impossible to accomplish in practical cellular systems. Due to practical limitations, a realistic implementation of coordination should be performed in *clusters,* small sets of coordinated nodes. **Clustering** is one of the most challenging processes in CoMP transmission. Ideally it should take into account the channel state of all considered entities (the BSs and UEs), the traffic load distribution in the system and the backhaul availability. The simplest approach is to form clusters in a static way [MF+11a], specifying the coordination sets in the system planning process. However, such approach might be inefficient and lacks the flexibility that fully dynamic coordination offers. Therefore, dynamic clustering techniques gained a lot of interest recently [WIN+09-D18] [PGH+08] [GZN+11] [RCP+10] and should be further investigated.

As stated in the previous section, even if the overall complexity of CoMP can be somehow limited with a clustering approach, there are still several **realistic impairments** that should be overcome in order to reach the full gain promised from theoretical bounds. These are related to backhauling limitations in terms of bandwidth and latency, imperfection on the CSI used for coordination due to realistic estimation procedures, quantization effects, signalling delays or limitations, imperfect frequency/time synchronization, and so on. Some studies to assess these effects have been already produced [MF+11b], e.g. on backhauling latency [MLP+13][YKG+12], and delayed or quantized feedback [BH+11][RKH+12], but algorithms and enablers to efficiently overcome these limitations need still to be investigated.

New approaches in the field of cooperation will be possible as **novel capabilities** are introduced in the network of the future: the exploitation of Non-Orthogonal Multiple Access (NOMA) schemes [SKA+13], advanced receivers with interference suppression capabilities [ART11-D22], non-coherent transmission concepts [DS+90] [LSP+05] [SL+02] or receiver beaconing based distributed interference management schemes [HBH+06] [OHA+07] [JRK+11] [JRK+12] are example of new ideas that could be efficiently considered for a cooperation based approach. One important new feature in future cellular networks will also be integrated direct D2D communication, with network controlled operation in an underlay mode being supported, as well [DRW+09]. In such scenarios, interference coordination between the D2D links and the cellular network, transmission mode selection, and clustering of devices, present some of the major challenges. However, while managing resources for D2D communication on a longer time scale has already gained significant attention in the community, it remains to be understood how fast cooperation methods (e.g., on a frame level and below) could be efficiently utilized, having in mind the need for overhead reduction [FDM+12].

### 3.2.2 Standards

**CoMP** has been widely studied in 3GPP. The LTE-Advanced study [3GPP11+36819] showed different performance results, depending on several aspects:

- whether the serving cell is the only transmission point, as in Coordinated Scheduling/Beamforming, or multiple cells serve simultaneously as transmission points, as in Joint Transmission;
- whether cells involved in CoMP belong to the same eNodeB or different eNodeBs;
- assumptions relative to CSI-RS measurement, and the accuracy and nature of the CSI feedback for multiple cells participating in CoMP operation;
- assumptions on uplink sounding and channel reciprocity;
- assumptions about signalling and related delay for the information exchange between the cells.

Homogeneous macro networks have been studied, but also newer deployment types such as cells with distributed Remote Radio Heads (RRHs) in Heterogeneous Networks have been taken into account for performance evaluation.

The support of intra-cell and inter-cell downlink CoMP for homogenous and heterogeneous configurations in the framework of Rel-11 leads to focus on:

- Joint Transmission;
- Dynamic Point Selection, including dynamic point blanking;
- Coordinated Scheduling/Beamforming.

The standardization of downlink CoMP potentially includes enhancements and requirements on downlink reference signals, PDCCH extension and other enhancements on downlink control signalling, UE feedback scheme and related measurements, L2/L3 related protocols and procedures, X2 interface support, UE core and performance requirements.

The standardization of uplink CoMP potentially includes enhancements and requirements on uplink reference signals, enhancements to the uplink power control for open-loop and closed-loop operation, enhancements to PUCCH, enhancement for the uplink timing advance control to support efficient Joint Reception CoMP operation, L2/L3 related protocols and procedures, X2 interface support, UE core and performance requirements.

In [3GPP10+36814] four different scenarios have been selected to analyse the impact of CoMP in LTE-A network:

- in scenario 1 the multi-point coordination area is only among the BS belonging to the same tri-sectorial site;
- in scenario 2 the coordination area contains 9 cells of three adjacent sites;
- scenario 3 considers a heterogeneous network with low power RRHs within the macro cell coverage, where each low power RRH has a different cell ID which is also different from the macro cell IDs,
- in scenario 4 each low power RRH has the same cell ID of the macro cell where it is placed.

Scenarios 3 and 4 can support different configurations where low power nodes are distributed in the Macro-cells, and UEs are placed in the scenario. Details on these configurations are provided in [3GPP11+36819].

**Interference management for D2D communication** may be seen also as one case of interference management by coordination among multiple transmitters. In the case of a cellular system, the BSs may coordinate the communication resources that are used for D2D communication. On the other hand, in e.g. WiFi, D2D is supported more naturally. This is because the CSMA protocol may manage the D2D interference in the same way as for the communication in the infrastructure mode. The work in 3GPP on D2D standardization is conducted under the label Proximity Services (ProSe) with envisaged applications in commercial/social use, network offloading, public safety, assuming integration of current infrastructure services [3GPP12+22803]. The first phase in 3GPP activities towards Rel-12 focuses on proximity detection functionality, i.e., examining whether the devices are close enough to each other so that they can communicate, or not [3GPP12+23703]. Proximity Discovery is supposed to be an important enabler for the applications mentioned above and potentially new services of the operators. However, it is also of importance for the second phase of 3GPP activities which will investigate direct D2D communication. In this direction, interference management and scheduling in terms of basic resource configuration, that will enable the cellular network to setup and control D2D links (also one-to-many communications) are already being discussed in 3GPP [3GPP12+23703] [3GPP12+RP122009]. However, advanced cooperation methods, multi-antenna aspects, etc., still remain as open topics.

Different techniques for **inter-cell interference suppression and cancellation** have been studied in 3GPP. In a Rel-11 study [3GPP11+36829], the feasibility of interference mitigation receivers was analysed. More specifically, the performance of linear interference rejection combining MMSE receiver structures, exploiting estimated spatial covariance of the interference, was evaluated. These investigations assumed neither assistance to the UE processing from the network side nor network coordination between different cells.

In another Rel-11 work item on further enhanced inter-cell interference coordination [3GPP11+RP111369], the feasibility of non-linear interference cancellation techniques for a UE receiver was evaluated. More specifically, the performance of receiver structures performing non-linear explicit cancellation of dominant interference of different LTE physical channels and signals, including CRS, PSS/SSS, and PBCH, was analysed. In these investigations, the network-side inter-node interference coordination in terms of exchange of information over the X2 backhaul is assumed. Further, time-domain resource partitioning between the aggressor and the victim layers is performed by means of so-called almost blank subframes (ABSs).

From the assessment above it appears that, even if standardization is still very active in the field of inter-node cooperation, T3.2 has the opportunity to explore new approaches that can be more disruptive and exploit new paradigms (i.e. IA) or enhancement in UEs or network nodes in ways that go beyond the current standardization horizon.

## 3.3 Research clusters

The research activity in T3.2 is structured along three main directions. The first research direction is devoted to assess the impact of real-world impairments on classical coordination techniques, and to the definition of novel algorithm and enablers that can overcome these limitations. The second research direction is aimed at the development of the promising IA concept in a realistic framework. The third research direction considers novel approaches to coordination that can arise as a consequence of evolution in the network access technique or improvements or new enablers available in future UEs. These research directions are mapped to the following research:

- Cluster 1: Further improvements to classical coordination techniques
- Cluster 2: Studies on IA
- Cluster 3: Coordination with enhanced network and UE capabilities

### 3.3.1 Research Cluster 1 and related technology components: further improvements to classical coordination techniques.

Even if CoMP techniques have received a lot of attention in literature and in standardization works, solutions that can help to move forward from the various constraints that practical implementation imposes are still needed. The **overall research problem** consists in overcoming the impairments in terms of complexity and signaling that a realistic deployment of CoMP techniques has shown. The **overall research approach** consists in:

1. **defining efficient clustering** methods that can reduce the complexity and signaling overhead associated with the coordination of several transmission entities, while still ensuring significant coordination gains. In conjunction with the work carried out in Research Cluster 3, bounds in particular for clustered joint transmission will be provided and more in general a comparison of static and dynamic clustering will be given, delivering enablers and clustering algorithms than can cope with the increasing complexity associated with ultra dense networks envisaged in METIS.
2. studying techniques that can relax the requirements in terms of **backhauling, feedback and signaling**, analyzing the impact of feedback delays and backhauling latency and proposing techniques that optimize the feedback reporting period, reduce the requirement in term of signaling and allow the use of partial and delayed CSI at the transmitter with limited loss.

In the following tables are reported the technology components that belong to Research Cluster 1. Note that as previously mentioned, in their first stage also some technology components described in Research Custer 3 could provide inputs to this research cluster, in particular technology components 7, 10 and 14, as will be detailed in their descriptions hereafter.

**Table 3-1. T3.2 Technology Component 1.**

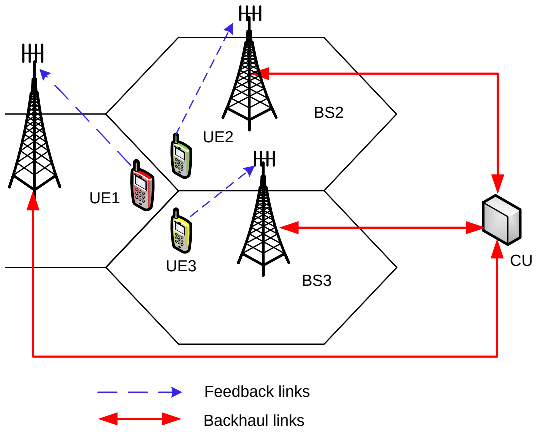
<table>
<tr><th colspan="2">T3.2 Technology component 1<br>Multi-Node Resource Allocation under Imperfect Feedback and Backhaul Channels</th></tr>
<tr><td>System Model<br><br><br>Multi-BS joint transmission in a centralized architecture. BSs are connected to a central unit that collects user CSI and designs the resource allocation and the transmission scheme. The work will be extended by considering also non-centralized network architectures.</td><td>Main Idea<br>The main focus is on backhaul load reduction strategies, by using MAC layer scheduling approaches, which provide a trade-off between sum rate and backhaul use.<br><br>The study takes the transmission latency, feedback and backhaul unreliability into account, and designs robust beamforming and power control schemes that achieve promising cooperation gain with low-complexity for densely deployed access points, heterogeneous in transmit power and activation probability.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society</td><td>Main Benefits<br>• Higher typical user throughput<br>• Increased active user density<br>• Minimum user required data rates<br>• Fast data transfer</td></tr>
</table>

Table 3-2. T3.2 Technology Component 2.

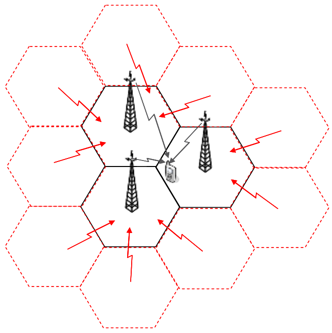
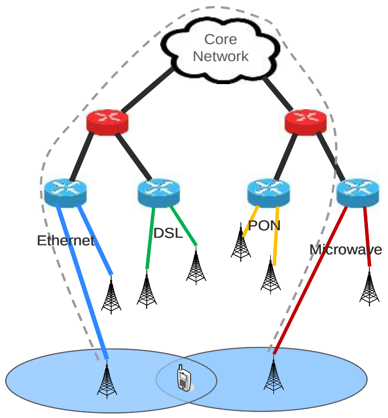
<table>
<tr><th colspan="2">T3.2 Technology component 2<br><br>CoMP feedback reduction and theoretical analysis of net DoF with delayed CSIT</th></tr>
<tr><td>System Model<br><br>Single user system with joint transmission. Assumptions include: inter-cell interference, single-antenna UE, first-order Gauss-Markov channel, quantized feedback.</td><td>Main Idea<br>The work proposes novel techniques to reduce the feedback in COMP schemes, determining the optimal feedback updating period based on channel correlation.<br><br>The work also includes a theoretical analysis to evaluate the DoF and net DoF of recent schemes for the MIMO interference channel and broadcast channel with delayed CSIT and finite coherence time.</td></tr>
<tr><td>Test Cases<ul><li>TC1: Virtual Reality Office</li><li>TC2: Dense Urban Information Society</li><li>TC6: Traffic Jam</li></ul></td><td>Main Benefits<ul><li>Higher typical user throughput</li><li>Fast data transfer</li></ul></td></tr>
</table>

**Table 3-3. T3.2 Technology Component 3.**

<table>
<tr><th colspan="2">T3.2 Technology component 3<br><br>Distributed Precoding in multicell multiantenna systems with data sharing</th></tr>
<tr><td>System Model<br><br>Complex backhaul structure (urban scenario) that might not guarantee the latency needed for joint transmission based CoMP. Assume applications with predictable behavior that enables data sharing (e.g. caching) among the BSs.</td>
<td>Main Idea<br>The main idea is to develop precoding strategies which utilize local CSI and exploit some form of data sharing among the BSs (e.g. the presence of caching mechanism in the BSs that stores frequently downloaded content) in order to mitigate the interference, relaxing backhauling requirements.</td></tr>
<tr><td>Test Cases<ul><li>TC2: Dense Urban Information Society</li><li>TC9: Open Air Festival</li></ul></td>
<td>Main Benefits<ul><li>Higher typical user throughput</li><li>Increased active user density</li><li>Minimum user required data rates</li><li>Fast data transfer</li><li>Low installation cost, scalability, reliability to changes of topology</li></ul></td></tr>
</table>

### 3.3.2 Research Cluster 2 and related technology components: studies on Interference Alignment.

In the last years IA emerged as a new technique to lower intra-cell interference, allowing a distributed or semi-distributed implementation.

Distributed algorithms for IA have been largely studied in the last few years as a primary technique that can approach the capacity limits in high SNR region for a network affected by complicated interference. However these algorithms rely on multiple rounds of ping-pong sharing of CSI, which results in long delay and overhead. Moreover, there is no clear understanding about how to operate these algorithms in a realistic network.

The **overall research problem** is to devise practical implementations of the IA concept. The **overall research approach** consists in:

1. developing robust IA algorithms that reduce the signaling overhead, while guaranteeing the convergence of the algorithm, and understand operational regimes to which the IA algorithms can be practically deployed.

2. investigate the trade-off between IA and useful signal maximization, through the introduction of a semi-distributed iterative algorithm that does not need CSI exchange on the backhaul and uses power control to limit the number of iterations.

The three technology components belonging to research cluster 2 are described below.

**Table 3-4. T3.2 Technology Component 4.**

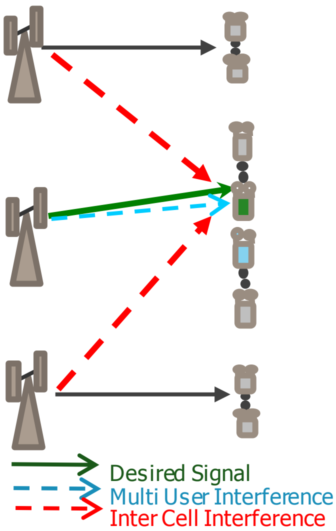
<table>
<tr><td colspan="2">T3.2 Technology component 4<br><br>Alignment of Intra Cell Multi User and Inter Cell Interference in a MU-MIMO Cellular Network</td></tr>
<tr><td>System Model<br>
<br>Multiuser MIMO cellular system with multi-antenna BS, serving multi-antenna UEs. Single stream transmission is assumed for each UE. A pair of UEs is selected simultaneously on the same time-frequency resource for transmission, so each of the UEs in the pair will cause MUI, and will also suffer from ICI due to the transmission in other cells.</td>
<td>Main Idea<br>The main idea is to find an algorithm for user selection that maximises the performance of multi user IA based transmit precoding, in order to maximise the system spectral efficiency.<br><br>The approach is to find a pair of users that can benefit most from the alignment technique that aims to align intra-cell and inter cell interference. Such a pair provides high system performance when IA is applied as transmission technique.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping Mall<br>• TC4: Stadium<br>• TC9: Open Air Festival</td>
<td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Low installation and operation cost</td></tr>
</table>

**Table 3-5. T3.2 Technology Component 5.**

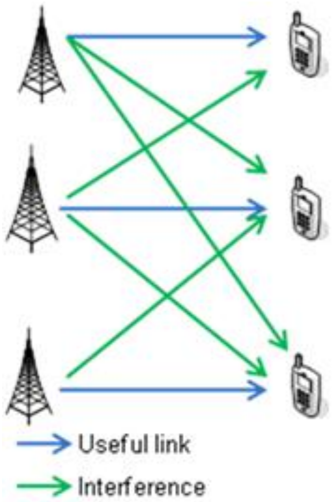
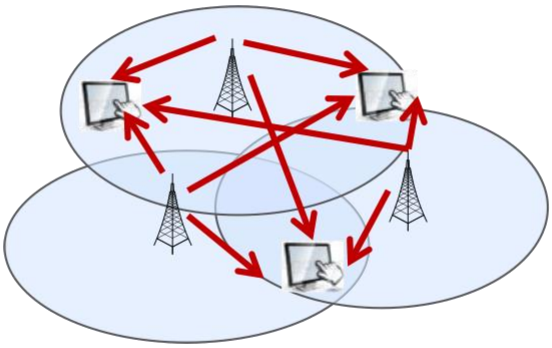
<table>
<tr><td colspan="2">T3.2 Technology component 5<br><br>Semi-distributed IA algorithm for MIMO-IC channel, with power control to speed up convergence</td></tr>
<tr><td>System Model<br><br>MIMO interference channel model. Each transmitter is paired with a single UE and interferes with all the other UEs. Local and perfect channel knowledge is assumed at each TX and RX node. Multiple antennas are assumed both for TX and RX nodes.</td><td>Main Idea<br>A semi-distributed algorithm is investigated to find the optimal filters at the BSs and UEs that achieve a target SINR at each UE. This algorithm is based on iterative computations that do not assume CSI exchange on the backhaul. To reduce the iteration number, the use of power control is considered. This power control permits at the beginning to check the existence of the optimal solution.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping Mall</td><td>Main Benefits<br>• High capacity /km2<br>• Higher typical user throughput</td></tr>
</table>

**Table 3-6. T3.2 Technology Component 6.**

<table>
<tr><td colspan="2">T3.2 Technology component 6<br>Robust decentralized scheme for IA with convergence control</td></tr>
<tr><td>System Model<br><br>Canonical K-user interference channel where each receiver wishes to decode the message of its desired transmitter, while suffering from interference generated by the remaining transmitters. The envisaged deployment environment is an indoor one.</td><td>Main Idea<br>The proposed scheme aims at developing a robust IA algorithm from a geometric perspective, in order to circumvent the inherent complications and overhead resulting from the so-called ping-pong filter updates, typically arising in distributed algorithms for IA.<br>The goal is to guarantee the convergence of the algorithm to a fixed tolerance within a fixed number of iterations, and to clearly understand operational regimes to which the IA algorithm can be practically deployed.</td></tr>
<tr><td>Test Cases<br>• TC1: Virtual Reality Office</td><td>Main Benefits<br>• High data volume / user<br>• Uniform experience across users<br>• Low installation and operation cost</td></tr>
</table>

### 3.3.3 Research Cluster 3 and related technology components: coordination with enhanced network and UE capabilities

The **overall research problem** deals with the study of coordination techniques that exploit enhanced capabilities offered by novel transmission techniques or enablers in the UE.

The **overall research approach** is based on the development of these enablers and the definition of algorithms that exploit the novel capabilities offered by UEs and future network, in order to provide advanced inter-node coordinate transmissions. Several approaches are considered:

1. **Network assisted advanced UEs exploitation;** the objective is to analyze, develop and evaluate techniques that allow to enhance the role of a UE receiver in future cellular system design. More specifically, it investigates the potential improvements that can be obtained when the network coordinates UEs with enhanced capabilities, e.g. with a high number of antennas, or when the network provides UEs with appropriate side information, regarding to precoder selections, reference signal ports, modulation and coding schemes, resource allocations etc., which can be used to enhance the UE receiver's ability to mitigate intra-cell inter-user interference and/or inter-cell interference. Technology components 7, 9, 10 and 12 described in the following tables mainly fall under this category.
2. **Enhanced network capabilities exploitation**; evaluates the potentiality of coordination in future networks, equipped with novel enablers that allows to save energy while still maintaining the CoMP gains in very dense network deployment, with active antennas capabilities that can be exploited to increase the CoMP potential, also

in a Massive-MIMO context, and addressing the potential gain available when the network coordinates transmission having the option to provide the service also with a two way transmission via Relay Nodes with physical layer network coding and considering the presence of clustered D2D communications. Technology components 13, 14 and 15 follow in general this approach.

3. **Use of alternative access scheme**; technology components that follow this approach evaluate the potential of cooperation schemes assuming future networks that are based on alternative access schemes. In particular:
    a. **Non-orthogonal multiple access (NOMA);** NOMA superposes multiple users in the power domain adopting a successive interference cancellation (SIC) receiver to allow multiple access. NOMA can be combined with MIMO to achieve higher capacity gain, and a multi-site extension of this novel approach will be investigated to offer further spectrum efficiency enhancement and to improve the user fairness. See technology component 8 hereafter.
    b. **Decentralized interference aware scheduling;** decentralized coordination schemes to control interference are a possible alternative to classical CoMP. It avoids the need for high performance backhauling communication links between the coordinating nodes, and is applicable to extremely dense deployments, D2D communications and the likes. A novel scheme will be considered where UEs send reverse beacons containing information that describes the received desired signal level, the received interference plus noise level, and the average throughput of the node, which can be used in a decentralized algorithm to coordinate transmitters schedulers based on these beacons. The proposed scheme will be adapted to suit the D2D communication scenario. This approach is described in technology component 11.
    c. **Non coherent communication techniques;** current cellular technologies are based on coherent demodulation, where pilot-based channel estimation techniques are used to demodulate the received information. However this approach involves a significant increase of both the receiver complexity and the pilot overhead when the system size rises due to the use of advanced techniques such as MIMO. Non-coherent detection mechanisms would potentially minimize the waste of resources due to the use of reference signals in cooperative systems, so different alternatives for non-coherent transmission will be brought into practical inter-node coordination systems to investigate the potentiality of these schemes. See technology component 16 hereafter.

**Table 3-7. T3.2 Technology Component 7.**

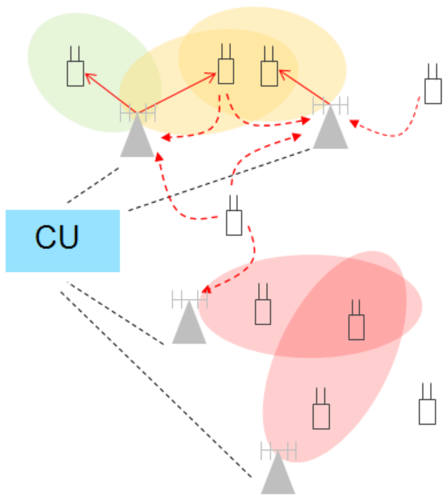
<table>
<tr><th colspan="2">T3.2 Technology component 7<br><br>Dynamic clustering with multiple receive antennas in downlink CoMP systems</th></tr>
<tr><td>System Model<br><br><br>Focus on downlink. BSs connected via optical fiber to a central unit in charge of layer 1 and layer 2 processing. Zero-latency backhaul links allow a sharing of CSI and data with no delay. Assume a maximum cluster size to serve the UEs. UEs equipped with multiple antennas.</td><td>Main Idea<br>The work considers a dynamic clustering and scheduling algorithm. The algorithms allow a dynamic optimization, in each time slot, of the set of non-overlapping clusters and the UEs scheduled within each cluster, maximizing the network weighted sum rate.<br><br>The approach is extended to the case where the UEs are equipped with multiple antennas and exploit them either to implement an interference rejection combining or to be served by multi-rank transmission.</td></tr>
<tr><td>Test Cases<br>• TC3: Shopping Mall<br>• TC4: Stadium</td><td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Low installation and operation cost</td></tr>
</table>

**Table 3-8. T3.2 Technology Component 8.**

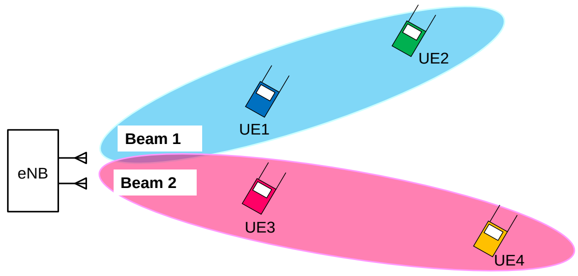
| **T3.2 Technology component 8**<br><br>**Non-orthogonal multiple access (NOMA) with multi-antenna nodes and multi-site extensions** | |
|---|---|
| **System Model**<br><br>Multi-user MIMO setting. BS and UEs have multiple antennas. Communications rely on a combination of multi-antenna transmission and non-orthogonal methods. Inter-site interference coordination is also considered. | **Main Idea**<br>The main idea is to combine non-orthogonal multiple access (NOMA) schemes with multi-antenna transmission schemes. One example is to use multiple antennas at the transmitter to form multiple beams and within each beam, multiple users are multiplexed using a non-orthogonal multiple access based technique.<br>This idea is extended to multi-site operations by introducing inter-site interference coordination (e.g., in frequency, space and/or power domains). |
| **Test Cases**<br>• TC2: Dense Urban Information Society | **Main Benefits**<br>• High capacity /km2<br>• Higher typical user throughput<br>• Increased active user density |

**Table 3-9. T3.2 Technology Component 9.**

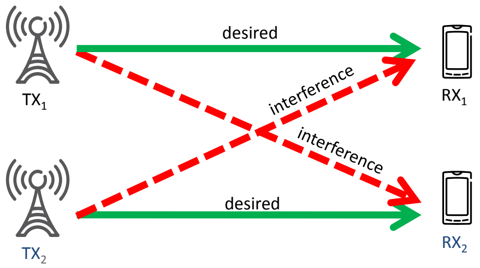
<table>
<tr><td colspan="2">T3.2 Technology component 9<br><br>Coordination scheme for medium range interference with message splitting to facilitate efficient SIC</td></tr>
<tr><td>System Model<br><br><br>The initial system is a two transmitter-receiver pair scenario with single antennas. The pairs interfere with each other. In later steps, possible extension to multiple antenna scenarios and more than two interfering users.</td><td>Main Idea<br>The work investigates a Han-Kobayashi like coordination scheme that pursues the generalized degree of freedom of the system by splitting each user message into two separate parts. One part is designed not to significantly interfere with the other message receiver, but rate adapted to the desired receiver, and another part is power-set and rate adapted to be decodable at the interfered receiver, to give a good likelihood of successful interference cancellation.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping Mall<br>• TC4: Stadium<br>• TC6: Traffic Jam</td><td>Main Benefits<br>• Experienced user throughput<br>• Traffic volume density</td></tr>
</table>

**Table 3-10. T3.2 Technology Component 10.**

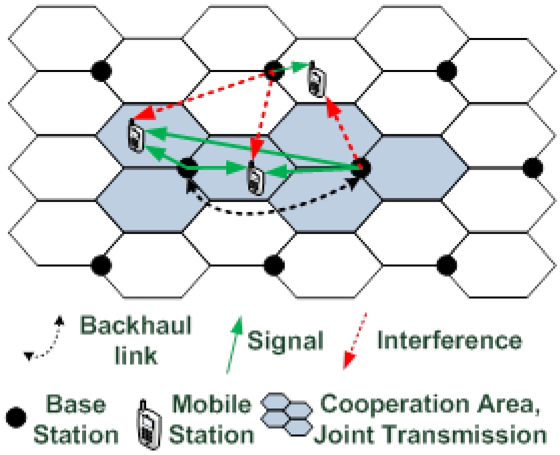
<table>
<tr><td colspan="2">T3.2 Technology component 10<br><br>Joint linear downlink CoMP with enhanced signal processing at the UEs and bounds for clustered JT</td></tr>
<tr><td>System Model<br><br><br>As a first step a homogeneous macro deployment is considered. In a second stage also heterogeneous scenarios are be investigated.</td><td>Main Idea<br>The work studies the effects of channel aging on CoMP joint transmission under zero-forcing precoding, assuming partial user data sharing.<br><br>It assumes all UEs to be equipped with multiple receive antennas and advanced signal processing capabilities. Therefore, UEs can exploit optimized spatial filters as well as adaptive filter-based channel prediction methods. These can efficiently reduce the amount of required feedback or mitigate the effects of user mobility.<br><br>Furthermore, the BC capacity for clustered joint transmission is theoretically obtained.</td></tr>
<tr><td>Test Cases<br>• TC2: Dense Urban Information Society<br>• TC9: Open Air Festival</td><td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Minimum user required data rates<br>• Low installation and operation cost</td></tr>
</table>

**Table 3-11. T3.2 Technology Component 11.**

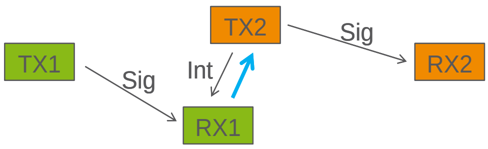
| **T3.2 Technology component 11**<br>**Decentralized interference aware scheduling** | |
|---|---|
| **System Model**<br><br>A TDD system is assumed. D2D links distributed on an area: uniform distribution of node locations and a certain distribution of link distance. Multi-antenna users are assumed.<br>Initially D2D communication on a separate frequency band from the one used for infrastructure communication is considered.<br>If the infrastructure communication is included (co-channel D2D and cellular mode communication), multi-antenna BSs serving different users are considered. | **Main Idea**<br>The work proposes a decentralized interference aware scheduling approach, based on the transmission of a reverse beacon. This beacon is broadcast from the destination node to surrounding sources, with information that describes e.g. the received desired signal level, the received interference+noise level and the average throughput of the node.<br>In particular, the work focuses on the implementation in the transmitters of schedulers that update the frame in which transmission is scheduled based on this observed reverse beacons. |
| **Test Cases**<br>• TC9: Open Air Festival | **Main Benefits**<br>• High capacity /km2<br>• Access for high device density<br>• Low installation and operation cost<br>• Scalable, reliable, easy to roll-out, and configure |

**Table 3-12. T3.2 Technology Component 12.**

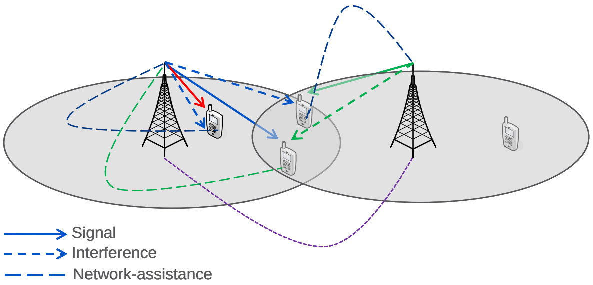
<table>
<tr><td colspan="2">T3.2 Technology component 12<br><br>Network-assisted interference suppressing/cancelling receivers and ultra-dense networks</td></tr>
<tr><td>System Model<br><br><br>Multi-antennas macro BS serving multi-antennas UEs. Macro cells cooperate and provide network assistance to the served UEs in order to improve their interference cancellation or suppression capabilities.<br><br>The macro-cell layer can be complemented by a number of lower-range small-cells.</td><td>Main Idea<br>The work investigates specific inter-cell interference cancellation and suppression receiver algorithms. Those algorithms exploit inter-node coordination and relevant signaling between the transmitting nodes and the UEs.</td></tr>
<tr><td>Test Cases<br>• TC3: Shopping Mall<br>• TC4: Stadium</td><td>Main Benefits<br>• High capacity /km2<br>• Higher typical user throughput<br>• Access for high device density</td></tr>
</table>

**Table 3-13. T3.2 Technology Component 13.**

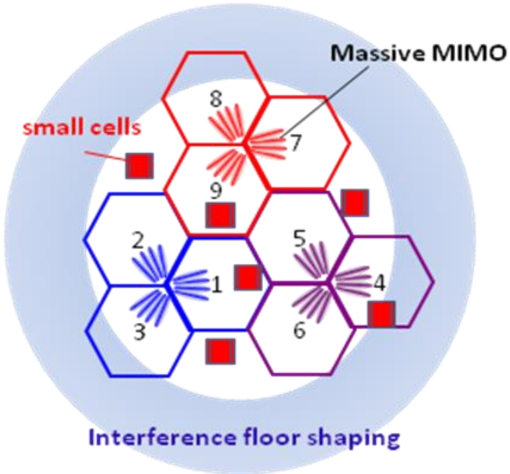
<table>
<tr><td colspan="2">T3.2 Technology component 13<br><br>Extension of IMF-A interference mitigation framework to small cell scenarios and Massive-MIMO</td></tr>
<tr><td>System Model<br><br><br>Homogeneous macro cellular mobile radio system including a reasonable number of small cells as well as Massive-MIMO antenna elements for capacity and coverage enhancements.</td><td>Main Idea<br>The aim of the work is to investigate JT CoMP as part of the Interference Mitigation Framework (IMF-A) introduced in [ART12+D14]. IMF-A considers expanded cooperation areas (CA), and through the introduction of cover shift in the frequency domain allows overlapped CAs to serve users through user-centric clusters. Moreover it introduces the tortoise concept, that by controlling the tilt of transmitted beams in different cover shifts allows shaping the intercluster interference floor. This technique is combined with Massive-MIMO – to provide higher spectral efficiency and coverage and serve more users simultaneously per eNB – and an increased number of small cells, which should be fully integrated into the framework.</td></tr>
<tr><td>Test Cases<ul><li>TC2: Dense Urban Information Society</li></ul></td><td>Main Benefits<ul><li>High capacity /km2</li><li>Higher typical user throughput</li><li>Increased active user density</li><li>Access for high device density</li></ul></td></tr>
</table>

**Table 3-14. T3.2 Technology Component 14.**

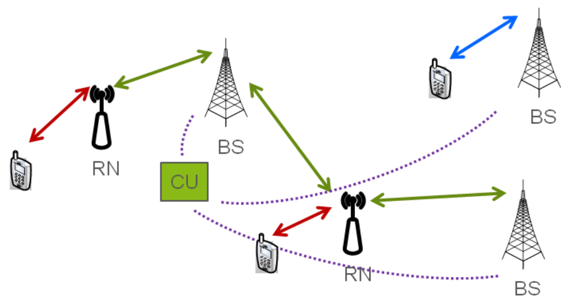
<table>
<tr><td colspan="2">T3.2 Technology component 14<br>Joint dynamic clustering and coordinated scheduling for relaying with Physical Layer Network Coding</td></tr>
<tr><td>System Model<br><br><br>BSs connected to a central unit via fiber optic links, and relays use only in-band wireless backhaul. Focus on TDD transmission.</td><td>Main Idea<br>The work studies a method to jointly form clusters and schedule users in a dynamic way in a TDD system with MIMO-NC relaying. Coordinated scheduling is applied within the clusters with the aim to mitigate the interference introduced by time reversed mode of relayed UEs.</td></tr>
<tr><td>Test Cases<br>• TC4: Stadium<br>• TC9: Open Air Festival</td><td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Low installation and operation cost<br>• Scalable, reliable to changes of topography of the network, easy to rollout, configure and maintain</td></tr>
</table>

**Table 3-15. T3.2 Technology Component 15.**

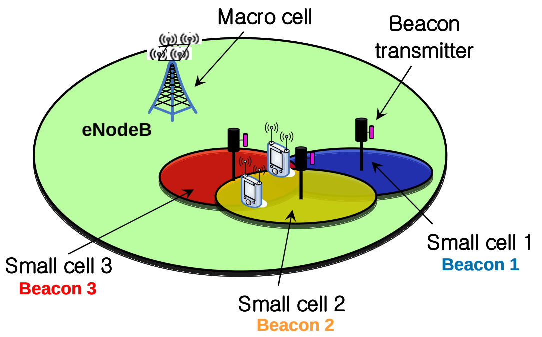
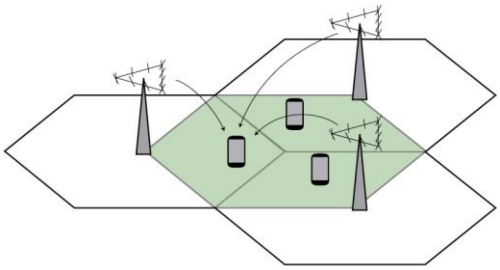
<table>
<tr><td colspan="2">T3.2 Technology component 15<br>Adaptive and energy efficient dense small cells coordination</td></tr>
<tr><td>System Model<br><br>Macro cell coverage with several, densely deployed, small cells placed in order to uniformly cover the area where potential clients are gathering.</td><td>Main Idea<br>The work proposes the introduction of a beacon signal that can be used to facilitate the usage of CoMP schemes (e.g. DPS) in presence of several dense small cells.<br>The beacon should help the system in the creation of cooperation clusters, in complex scenario with high degree of cell density, allowing the detection of small cells that are in sleep mode and switching them on for CoMP transmission. In that way, the beacon allows the possibility to build CoMP scheme with small cells that can be quickly switched on or off depending on traffic demand, so that power consumption can be controlled.</td></tr>
<tr><td>Test Cases<br>• TC3: Shopping Mall<br>• TC4: Stadium</td><td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Higher energy efficiency</td></tr>
</table>

**Table 3-16. T3.2 Technology Component 16.**

<table>
<tr><td colspan="2">T3.2 Technology component 16<br>Non-coherent transmission schemes for practical inter-node coordination systems</td></tr>
<tr><td>System Model<br><br>Multiple BSs from the homogeneous macro deployment, evaluation in dense deployments. High density of user terminals. All devices with multiple antennas. Centralized approach, may consider distributed approaches later.</td><td>Main Idea<br>The work investigates the use of non-coherent detection mechanisms to minimize the waste of resources due to the use of reference signals, at the expense of a certain performance loss.<br>It evaluates different alternatives of non-coherent transmission schemes that can be used for practical inter-node coordination systems, aiming to the design of both single-user and multi-user non-coherent cooperative schemes.</td></tr>
<tr><td>Test Cases<br>• TC4: Stadium</td><td>Main Benefits<br>• High capacity /km2<br>• Access for high device density<br>• Low installation and operation cost<br>• Scalable, easy to roll-out and configure</td></tr>
</table>

## 3.4 Summary of mapping between technology components and test cases

The following table summarizes the impact of the Technology Components investigated in T3.2 on the METIS Test cases defined in [MET+13D11]. Advanced inter-node coordination is seen as a key technology in the scenarios of "Great service in a crowd" and "Amazingly fast", where it can contribute to manage the high level of interference that arises in these scenarios; in particular major impact is expected on Test case 2 (Dense urban information society), 3 (Shopping mall), 4 (Stadium) and 9 (Open air festival), with some impact also present on Test cases 1 (Virtual reality office) and 6 (Traffic jam).

**Table 3-17. Summary of mapping between technology components and test cases for T3.2.**

| | Technology component | Test case number | | | | | | | | | | | | Expected benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Multi-Node Resource Allocation under Imperfect Feedback and Backhaul Channels | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Higher typical user throughput<br>Increased active user density<br>Minimum user required data rates |
| | **TeC2**: CoMP feedback reduction and theoretical analysis of net DoF with delayed CSIT | **1** | **2** | 3 | 4 | 5 | **6** | 7 | 8 | 9 | 10 | 11 | 12 | Higher typical user throughput<br>Fast data transfer<br>*[Definition of theoretical bounds]* |
| | **TeC3**: Distributed Precoding in multicell multiantenna systems with data sharing | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | Higher typical user throughput<br>Increased active user density<br>Minimum user required data rates<br>Low installation cost, scalability, reliability to changes of topology |
| Research cluster 2 | **TeC4**: Alignment of Intra Cell Multi User and Inter Cell Interference in a MU-MIMO Cellular Network | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Low installation & operation cost |
| | **TeC5**: Semi-distributed IA algorithm for MIMO-IC channel, with power control to speed up convergence | 1 | **2** | **3** | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Higher typical user throughput |
| | **TeC6**: Robust decentralized scheme for IA with convergence control | **1** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High data volume / user<br>Uniform experience across users<br>Low installation & operation cost |

| | Technology component | Test case number | | | | | | | | | | | | Expected benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research Cluster 3 | **TeC7**: Dynamic clustering with multiple receive antennas in downlink CoMP systems | 1 | 2 | **3** | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Low installation and operation cost |
| | **TeC8**: Non-orthogonal multiple access (NOMA) with multi-antenna nodes and multi-site extensions | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Higher typical user throughput<br>Increased active user density |
| | **TeC9**: Coordination scheme for medium range interference with message splitting to facilitate efficient SIC | 1 | **2** | **3** | **4** | 5 | **6** | 7 | 8 | 9 | 10 | 11 | 12 | Experienced user throughput<br>Traffic volume density |
| | **TeC10**: Joint linear downlink CoMP with enhanced signal processing at the UEs and bounds for clustered JT | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Minimum user required data rates<br>Low installation & operation cost |
| | **TeC11**: Decentralized interference aware scheduling | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Low installation & operation cost<br>Scalable, reliable, easy to roll-out, and configure |
| | **TeC12**: Network-assisted interference suppressing/cancelling receivers and ultra-dense networks | 1 | 2 | **3** | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Higher typical user throughput<br>Access for high device density |
| | **TeC13**: Extension of IMF-A interference mitigation framework to small cell scenarios and Massive-MIMO | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Higher typical user throughput<br>Increased active user density<br>Access for high device density |
| | **TeC14**: Joint dynamic clustering and coordinated scheduling for relaying with Physical Layer Network Coding | 1 | 2 | 3 | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Low installation & operation cost<br>Scalable, reliable to changes of topography of the network, easy to rollout, configure and maintain |
| | **TeC15**: Adaptive and energy efficient dense small cells coordination | 1 | 2 | **3** | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>High energy efficiency |
| | **TeC16**: Non-coherent transmission schemes for practical inter-node coordination systems | 1 | 2 | 3 | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High capacity /km2<br>Access for high device density<br>Low installation and operation cost; scalable, easy to roll-out and configure |
| | Number of technology components per test case | 2 | 9 | 6 | 7 | 0 | 2 | 0 | 0 | 5 | 0 | 0 | 0 | |

## 3.5 Summary of mapping between technology components and horizontal topics

The relevance of the research efforts in Task 3.2 with respect to METIS HTs is summarized in Table 3-18. As a consequence of the strong focus on the “Great service in a crowd” and “Amazingly fast” scenarios, the horizontal topic with the highest relevance is Ultra-dense networks. Moreover, since the introduction of novel decentralized coordination approaches can be considered for D2D communication, a certain impact can be expected also for this horizontal topic as highlighted for Technical components TeC3 and TeC11. In general, considering that the focus of the whole research work is on multi-point coordination, interactions with the Architecture Horizontal Topic are also expected.

**Table 3-18. Summary of mapping between technology components and horizontal topics for T3.2.**

| | Technology component | Horizontal topic | | | | |
|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Multi-Node Resource Allocation under Imperfect Feedback and Backhaul Channels | D2D | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC2**: CoMP feedback reduction and theoretical analysis of net DoF with delayed CSIT | D2D | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC3**: Distributed Precoding in multicell multiantenna systems with data sharing | **D2D** | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC4**: Alignment of Intra Cell Multi User and Inter Cell Interference in a MU-MIMO Cellular Network | D2D | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC5**: Semi-distributed IA algorithm for MIMO-IC channel, with power control to speed up convergence | D2D | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC6**: Robust decentralized scheme for IA with convergence control | D2D | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC7**: Dynamic clustering with multiple receive antennas in downlink CoMP systems | D2D | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC8**: Non-orthogonal multiple access (NOMA) with multi-antenna nodes and multi-site extensions | D2D | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC9**: Coordination scheme for medium range interference with message splitting to facilitate efficient SIC | D2D | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC10**: Joint linear downlink CoMP with enhanced signal processing at the UEs and bounds for clustered JT | D2D | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC11:** Decentralized interference aware scheduling | **D2D** | MMC | **UDN** | MN | URC |
| Research Cluster 3 | **TeC12**: Network-assisted interference suppressing/cancelling receivers and ultra-dense networks | D2D | MMC | **UDN** | MN | URC |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **TeC13**: Extension of IMF-A interference mitigation framework to small cell scenarios and Massive-MIMO | D2D | MMC | UDN | MN | URC |
| | **TeC14**: Joint dynamic clustering and coordinated scheduling for relaying with Physical Layer Network Coding | D2D | MMC | UDN | MN | URC |
| | **TeC15**: Adaptive and energy efficient dense small cells coordination | D2D | MMC | UDN | MN | URC |
| | **TeC16**: Non-coherent transmission schemes for practical inter-node coordination systems | D2D | MMC | UDN | MN | URC |
| | Number of technology components per horizontal topic | 2 | 0 | 16 | 0 | 0 |

## 3.6 Mapping between T3.2 and the other METIS WPs

In this section we summarize the mapping between the activity in T3.2 and the other METIS WPs, by emphasizing the most relevant connections.

**Table 3-19. Mapping between the activity in T3.2 and the other METIS WPs.**

| | |
|---|---|
| **WP1** | • Implications of channel measurements at various frequencies for studying scenarios with coordinated access nodes. |
| **WP2** | • Effect of new waveforms;<br>• performance and design of novel multiple access approaches (e.g. NOMA)<br>• new air interface supporting flexible frame structure and resource partitioning (e.g. in dense deployments). |
| **WP4** | • Architectural and signaling implications, in particular for coordination and interference management;<br>• implications of novel coordination approaches for WP4 studies. |
| **WP5** | • No major implications. |
| **WP6** | • Architectural implications;<br>• indication of interface requirements, in particular for the backhaul. |

# 4 Multi-hop communications/wireless network coding

This chapter describes the main research directions investigated in Task 3.3 “Multi-hop communications/wireless network coding”. A general overview on relay based communications is first provided followed by a summary of the current state of the art and activities related to standards. Next, we describe the structuring of the research activities into two research clusters. The first research cluster is devoted to infrastructure-based relaying, while the second research cluster is devoted to infrastructure-less /infrastructure-assisted D2D and mobile relays. Within each research clusters, Technology Components (TeC) are defined and connected to the test cases, horizontal topics and other work packages in METIS [MET+13D11]. A concise description of the test cases and horizontal topics is provided in the annex (section 7 and 8).

## 4.1 General overview

The past decade has witnessed a surge of research and performance hopes in wireless technologies based on cooperation and relaying. The phrase “hopes” is still valid, as relay/multi-hopping has not become a consistent solution to a set of wireless problems in the same way in which, for example, multiple antennas have gained acceptance. Performance expectations of relay-based solutions have been centered on throughput improvement, extension of the coverage area and decrease of the energy consumption. Improvements in throughput have often been difficult to get as the relaying nodes operate in a half-duplex manner and therefore necessarily introduce inefficiency in spectrum usage, as multiple time slots are required to receive and then relay the information. Hence, the benefits of using the relays in cellular systems have been decreased and sometimes annulated by the fact that the relay consumes communication resources, originally conceived for use by a single-hop cellular connection. Another problem introduced in multi-hop solutions is the latency, which renders it challenging to be used in real-time communication scenarios.
The emergence of wireless *network coding* (NC) and related techniques has brought a new life to the relay-based solutions. It can be stated that relays now have an increased potential to enable widely-accepted solutions for notoriously difficult wireless problems, such as cell-edge throughput that is closer to the value of the average throughput in a wide-area cell. The idea of NC has originally emerged in wired networks, by allowing the intermediate nodes to combine the packets for multiple independent communication flows rather than only route the communication flows that arrive at the node input. This idea gave rise to spectrally efficient solutions in wireless NC. The main premise in these solutions is that communication protocols should not be built in the usual way, by looking at a single communication flow at a time, but rather multiple communication flows should be processed jointly. Here a *communication flow* denotes a stream of data packets generated at a source node and intended for a particular destination node.
The objective of the research work in this task of the METIS project is two-fold, with scenario-specific and general objectives, respectively. Regarding the scenario-specific objectives, it will produce technologies based on relaying, multi-hopping and wireless NC that appear as solutions to a particular problem posed within a METIS scenario or a test case. On the other hand, research work aims to answer more general questions related to the use of relays in wireless networks, such as the following:

1. Are infrastructure-based relays and wireless NC capable of improving the average throughput in a multi-cell setting and interference?
2. Is wireless backhauling the solution for improving the coverage while providing a minimal predefined data rate?
3. What are the feasible transmission technologies that can provide high rates over a wireless backhaul to a moving relay?

4. Can relaying, both infrastructure-based and device-to-device, be considered as solutions for improving the coverage of a wide-area connection with real-time constraints?

## 4.2 State of the art and benchmarks

### 4.2.1 Literature review

In general, a multi-hop wireless network is a network of devices (nodes) which are connected by wireless communication links; however, due to the limited communications range of radio links, many pairs of nodes cannot communicate directly, and must forward data to each other via one or more cooperating intermediate nodes. A source node transmits a packet to a neighbouring node. The neighbouring node in turn transmits the packet to one of its neighbours, and so on until the packet reaches its ultimate destination. Such a network can operate in isolation such as ad-hoc networks or via an infrastructure such as cellular base stations. In recent years, multi-hop relay communication has been gaining global acceptance as one of the most promising technologies in next-generation wireless cellular networks [SLW+09, PWS+04, WDK+09, LWS+10]. There has been extensive research on multi-hop cellular networks in the last few years under the terminology of relay networks or cooperative diversity. The idea of wireless multi-hop communication was first introduced in [vdM+71]. Information theoretic properties of relay channels have been studied in [CG+79].

The introduction of multi-hop relay breaks the direct link transmission into two or more high quality paths to form a multi-hop path between the transmitter and the receiver. This procedure can overcome the issues of coverage holes and gives the possibility for higher data rates. These cooperating nodes can be user devices or fixed relays deployed in a cellular network. In the former case, user devices cooperate by transmitting each other’s data in addition to their own data, known as user cooperation [SEA+98, SEA+03]. In the latter case, users cooperate via fixed relay nodes to forward their data towards the destination [CKL+06, WK+07, HD+06]. Both cooperation schemes have the potential to provide gain in terms of coverage and throughput.

#### *4.2.1.1 Wireless relaying*

The two main relaying modes are FD and HD relaying. FD relays transmit and receive at the same time and in the same frequency band. Note that sometimes FDD is also referred to as FD as the nodes can transmit and receive simultaneously, but in different frequency bands; however, in this text we use FD in a stricter sense (same time and frequency). In HD relaying, the transmission is done in two time slots. During the first time slot, the relay node receives the data from the source, and during the second time slot the relay node forwards the processed data to the destination. HD relaying is most often adopted due to its implementation simplicity.

**In-band relaying:** A promising deployment approach is based on in-band relays to extend the high throughput coverage of next generation wireless networks. Wireless relays are devices that receive a wireless signal from a source and forward it to a destination. In cellular systems, the destination of the source’s signal can be a base station, a mobile terminal, or a relay node. The signal received from an antenna is processed and retransmitted within the same frequency band. The relay node is usually placed between the source and destination which gives a link budget for both the link to the source and to the destination higher than that of the direct source-destination link. The relay node can process the signal to be forwarded in many different ways such as d*ecode-and-forward* (DF), *amplify-and-forward* (AF), hybrid AF/DF [CYdC+06, DZ+09], *incremental* relaying, *non-orthogonal AF* (NAF) relaying [NBK+04], and other processing strategies.

The destination may be able to receive the signal from both the source and the relay node and gains from cooperation between the two links. We obtain, what is called, cooperative relaying.

In-band relaying is obviously an attractive solution for spectrum saving when the spectrum is limited and we are forced to deploy a universal frequency with some sophisticated interference management techniques. In-band relaying is also attractive when the ratio of load on access and load on backhaul varies dynamically or when nodes can have different roles between which hardware can be shared.

**Out of band relaying:** This configuration can be used when additional spectrum is available. The most common example is the use of microwave link as backhaul for a BS in a cellular network. Here, the signal is received in one frequency band and then forwarded on another frequency band. By using a very high carrier frequency and highly directive antennas, connections can be planned to avoid interference from other links. The same basic configuration has been considered for other applications such as the 5 GHz band IEEE 802.11a, the 3.5 GHz WiMAX, or even the 2 GHz GHz UMTS/3G. The configuration of this relaying scheme is similar to that of an in-band relaying scheme, but the radio resource management is treated separately for the two bands. Out of band relays also provide an alternative that would enable the use of all sub-channels of a carrier on a sector at the base station, thereby enabling greater capacity per sector whilst still being able to get the benefit associated with relays.

**Towards full duplex performance and relaying with buffering:** To reduce the throughput loss of half-duplex relaying, several schemes have been proposed in the literature. The idea is to exploit both relay buffering and channel variations to enhance the system throughput [XFT+08, ZSP+11, ZSP+13]. For instance, the spectral efficiency of HD relaying can be improved through an opportunistic relay selection when multiple relays are deployed in the network [MK+10, WFL+10]. The main idea of those studies is to use a two-relay network where the two relays alternatively forward messages from a source to a destination. In [MK+10] the authors considered multiple antennas at the destination and relays with highly directional antennas to avoid inter-relay interference. In [WFL+10], to deal with inter-relay interference, a successive decoding at the destination with partial and full cancellation was employed by utilizing multiple antennas at the destination. Moreover, this work also considered buffered relays.

In more general networks with multiple relays, several relay selection schemes have been proposed: max-min relay selection [LTW+04], max-max relay selection (MMRS) [IMS+12], max-link relay selection [KCT+12], and space full-duplex max-max relay selection (SFD-MMRS) [IKS+12]. In [IMS+12, KCT+12, IKS+12], additional performance enhancements are possible in terms of spectral efficiency and outage performance by using buffer-aided relays. In the most recent work [IKS+12], the authors have proposed a new relay selection scheme that mimics full-duplex (FD) relaying by allowing simultaneous transmissions of both source-relay and relay-destination links. However, this study considered an idealized assumption with no inter-relay interference and thus the resulting performance of virtual FD relaying will be worse in practice. Other successive relaying protocols utilizing interference subtraction or joint decoding for handling the IRI have been proposed in [FWT+7, TN08, KC10] but rely on strong interference, low rate, or requires high computational complexity.

**Cooperative relay networks:** Another utilization of multiple relays is to achieve cooperative diversity [LW03][BPL+04][MBN+05]. Distributed STC based on linear dispersion codes was considered in [JH+06]. Opportunistic distributed STC combined with direct path has been proposed in schemes such as [ZYZ+12] and group-wise STC is considered in [NCL+09] and in [HAW+09] together with beamforming, in order to utilize complexity-wise simpler STC.

**Full-duplex relaying:** Unlike HD relays which can either transmit or receive at a given time and frequency band, FD relays can transmit and receive simultaneously over the same frequency. Hence, FD relays have the potential to enhance the spectral efficiency of wireless systems. However, for years, full duplex relays have been thought to be impractical due to signal leakage between the output and input of the relay, called loop interference. However, recent advances in antennas and signal processing technology are making the use of full duplex relays feasible.

Many recent works have studied practical implementations of FD relays by mitigating the effects of loop interference through time-domain interference cancellation techniques. Recently, a full-duplex relaying technique that exploits a combination of three cancellation techniques: antenna cancellation, hardware cancellation, and software cancellation has been proposed [CJS+10]. Moreover, a more advanced FD relaying technique based on signal inversion and software cancellation has been proposed [JCK+11]. In these studies, the authors showed the feasibility of FD relaying through an experiment in their test-bed. However, it still has many design limitations such as bandwidth constraints, time-varying wireless channel, multi-path channel, single stream, and so on. Therefore, the FD relaying should be considered premature to implement in practice.

**Moving relays:** The deployment of *moving relay nodes* (MRNs) can offer several benefits to users inside public transportation vehicles [SPS+13]. By proper placement of indoor and outdoor antennas, the MRN can effectively reduce or even eliminate the *vehicle penetration loss* (VPL) that can be as high as 25 to 30 dB in well-isolated vehicles [TJV+08]. In addition, group *handover* (HO) of vehicular *user equipment* (UE) can be performed, which can lower the probabilities of HO failures of UEs with high mobility [LZD+12].

The use of dynamically deployed RNs was studied in [PSH+09]. The authors showed that dynamically deployed RNs, can bring noticeable gains to the mobile communication system. In [PHY+10], the use of cooperative and coordinated relay systems (CCRS) on high speed trains was introduced. In CCRS, the backhaul link can be strengthened by using antenna selection techniques.

The performance of MRNs in a single cell noise limited system has been studied in [SPS+12]. The authors showed that a HD, DF MRN could noticeably lower the outage probability (OP) at a vehicular UE as well as improve the system ergodic capacity. In [SPY+12], the studies have been extended to a two-cell system with the presence of co-channel interference (CCI). In this case, MRNs showed even better performance improvements compared to direct base station (BS) to UE transmission and to FRN assisted transmission. In [LZD+12], by doing system level simulations, the authors showed that the use of MRN could significantly lower the HO failure probability of vehicular UEs.

Furthermore, as MRNs are not limited by power and size as the regular UEs, advanced MIMO schemes and signal processing schemes can also be exploited to further improve the performance [SGA+12, PHY+10]. For example, consider a bus or a tram, where there are two sets of antennas: a set of antennas associated with a communication MIMO array and a second set composed by one or more antennas denoted as prediction antennas. These prediction antennas can be employed to improve the reliability of the channel state information (CSI) feedback, and thereby improve the channel dependent scheduling of the MRN backhaul links [SGA+12] associated with the MIMO array.

**Device to device and relaying:** The works in [KYK11][NKY12] focus on single-antenna relays and consider explicitly that the relays also are users. Cooperation between devices has been considered mostly for forwarding data where one device takes the role of relay. This improves the link of the receiving device but does not give any benefits to the relaying device. To give more balance to this type of cooperation we can allow the relaying device to transmit its own data. Such cooperation can provide direct D2D communication without any extra radio resources.

#### *4.2.1.2 Wireless network coding*

*Network coding* (NC) has been introduced by [ACL+00], in order to improve the throughput in wired networks by performing some processing on received packets at the intermediate nodes. This technique combines the received packets at intermediate nodes, so that these combined packets are transmitted to all the recipients instead of forwarding each packet individually. Most of the initial work on NC assumes fixed transmitters and receivers with static traffic flows etc. However, researchers have soon realized that the broadcast nature of wireless channel makes NC a favourable candidate for combining the signals at nodes. We use the term *wireless network coding (WNC)* to denote network coding operation that combines multiple communication flows over the multiple access channel and/or within the wireless broadcast. For example, physical-layer network coding is a type of WNC in which both the multiple access and the broadcast phases are used to combine flows. On the other hand, in decode and forward with orthogonal uplink transmissions (time-sharing) and broadcasting of the XOR of the decoded packets, the flows are not combined over the multiple access channel, but only in the broadcast phase.

**Multiple-access relay channel:** Employing NC in the *multiple-access relay channel* (MARC) can improve the efficiency of the system from 1/2 to 2/3, a gain of one time slot as compared to conventional MARC. MARC is a model for network topologies where multiple sources communicate with a single destination in the presence of a relay node [KvW+00]. For the case of two users, we have three transmitting nodes using orthogonal channels. The relay operates in HD mode and the cooperative transmission is achieved in two phases [CG+79] for each user. In the first phase, each mobile user transmits its own information data on orthogonal channels. The relay receives and decodes the data of the mobile users. In the second phase, the relay station forwards the user data on orthogonal channels as well. The destination receives both the original data (from the direct links) and the relayed signals, and combines them to decode the user information. This gives a diversity gain of order 2 for each user. However, the transmission phases require a total of four transmissions, two transmissions for the first phase and two transmissions for the second phase. With NC at the relay node, the number of transmission is reduced to three transmissions. This throughput improvement is obtained without affecting the diversity order of the access scheme [CKL+06]. We should mention that most of the research work concerning the MARC scheme is done for the up-link where we have the users trying to convey their information to the base station with the help of the relay node. However, little work has been done for the downlink case where we have one base station trying to send information to different users with the help of a fixed relay node. In the uplink scenario we may permit more complex receivers based on joint detection since the computation is done at the base station. However, for the downlink case it will be interesting to have simple detectors that save power and complexity at the mobile user. This can be done through a proper design of the NC scheme used at the relay node in combination with an appropriate detector.

*Multiple-access multiple relay channel* (MAMRC) with one destination was considered in [LAM+10, XA+09]. Non-binary NC has been considered in [XS+10] and was shown to achieve the full diversity in the case of MAMRC.

**Bidirectional relay channel:** Bidirectional relaying is an access channel where two users want to send data to each other via a relay node [RW+07],[ZLL+06],[LZL+12]. Depending on the relaying protocol used, the efficiency of bidirectional relaying can vary from 1/2 to 1. DF bidirectional relaying with NC requires three transmissions to ensure the exchange of information between the two users [RW+07, WCK+05, LJS05]. AF-bidirectional relaying with *physical layer NC* (PLNC) requires only two transmissions to ensure the exchange of information between the two users [PY+06b, PY+07a, PY+06a]. In this scheme both users transmit the data simultaneously to the relay node in the first time slot. Then the relay node maps the superimposed received signal to a network coded signal and forwards the NC signal to both users in the second time slot. Adaptive *de-noise-forward* (DNF) has been presented in [PY+06b, APT+08, APT+09]. Extensions for *joint channel decoding and PLNC* (JCNC) have been discussed in [ZL+09, Wüb+10, WL+10]. Asymmetric bidirectional communication is addressed for example in [PA+09]. The extension to multi-pair bidirectional communication is considered in [YJC+08, YZG+10, AK+10] assuming multiple-antennas and Tx CSI at the relay.

Reference [PY+06b] was one of the first works to propose the generalization of PLNC from classical two-way relaying scenario towards coordinated schemes [PY+07a, PY+07b, YP+07], which lay the foundation of the so called *wireless flow coupling* (WFC) comprising a more general aggregation of communication flows and intentionally cancellable interference flows. In [TP+11, SPT+12, TPK+11, TPK+12] this was made for single spatial channels. Other works where the coupling of the traffic flows of two users can be found in works such as [YdC+08] and [BLL+09], in the case of relayed users [YLW+10] and [KL+09]. Joint resource allocation of uplink/downlink flows is investigated in [YLW+10] and [KL+09]. The initial attempts to apply WFC with multiple spatial channels [SdCT+12, SdCP+12] reveal that WFC with multi-antenna nodes requires non-obvious generalizations and innovative protocol design.

Bidirectional relaying with MIMO-NC was considered in [Wes+10, OS+08, XBW+10, OO+11]. Assuming a binary symmetric relay channel, it was shown that bidirectional relaying with MIMO-NC performs equivalently to 2x2 V-BLAST MIMO and a 2x1 Alamouti MISO in multiple access phase and broadcasting phase, respectively [XBW+10]. Application of physical layer network coding to the joint design of uplink and downlink transmission, where the base station and the relay have multiple antennas, and all mobile stations only have a single antenna was investigated in [DKT+11]. Latin rectangles were considered in [MR+12] and the application of dual polarized antenna has been studied in [OO+11]. A hardware test-bed was presented in [MMK+10] and its performance was reported in [MMS+10]. An optimal power allocation scheme was considered with MIMO PLNC with zero forcing at source nodes in [JRM+12a], whereas in [JRM+12b] a joint pre-coder decoder design was used to facilitate PLNC.

#### 4.2.1.3 Routing in wireless multi-hop networks

Two classes of routing algorithms are usually occurring in the literature. One is distance vector types, such as the Bellman-Ford algorithm ([BG+92,CLR+09] and references therein), where each node informs its neighbours on the best path to the source and each node only needs local topology knowledge. The other class is Link state algorithms such as the Dijkstra Algorithm ([BG+92, Sni+06] and references therein). One of the necessary and sufficient conditions for these conventional routing algorithms to work is the so called *isotonicity* assumption [Sob+01, Sob+03], meaning that the best out of two routes does not change by adding another common hop. Unlike for a wired network, the isotonicity property will often be violated in metrics for wireless hop mesh networks which take interference into account.

IEEE 802.11s [IEEE+11IEEE11] – the mesh extension for 802.11 WLAN systems – uses an air-time link metric and measurements based on test frames which to our understanding does not accurately reflect route throughput and does not explicitly account for intra/inter-route interference. Finding the optimal route in a wireless mesh network appears to be an NP-hard problem. The joint optimization of resource allocation and route selection therefore becomes intractable even for moderate-sized networks unless one resorts to sub-optimal solutions.

In [YWK03] and [YWK05] an approach to decouple the metrics for node self-interference or interference from its next neighbour node is proposed by means of extending the network to a virtual network. This solves some of the isotonicity problems and for a few possible channels this approach is reasonable, but complexity grows exponentially with the number of possible resource allocations and soon becomes impractical. Further it does not handle inter-flow interference or intra-flow interference from non-neighbouring nodes.

### 4.2.2 Standards

3GPP contains standardization efforts related to the topics in T3.3, some of them already for a longer time (relaying in LTE advanced) and other more recently (D2D communication). In the sequel we summarize these efforts.

#### 4.2.2.1 Relaying in LTEadvanced

Amplify-and-forward relays, also referred to as repeaters, require no standardization except for RF requirements and are supported already from Rel-8 of LTE. Also out of band decode and forward (DF) relaying of sufficient frequency separation for the *backhaul link* (between relay and donor base station) requires no additions to Rel-8 LTE and can operate in full duplex using the Rel-8 radio interface for the backhaul link. In release 10, support for half duplexed decode and forward relaying was introduced [DPS+11, chapter 16], transparent from a Rel-8 user perspective. Donor BS-to-relay transmission is done in free part of MBSFN sub-frames and relay-to-donor BS is assumed to be kept free from access link interference by means of scheduling. Alternatively spatial separation is assumed (e.g. when donor side antennas are located outside a tunnel and access side antennas of the relay is on the inside). Decode and forward full duplex relays, cascaded relays or relay mobility are not supported yet in LTE advanced. A *study-item* (SI) on relay mobility where different mobility management schemes have been studied and compared started in Rel-11 and continues into Rel-12 [3GPP12+36836]. There is still no *work-item* (WI) on the topic. Hence it is unclear if MRNs will be supported in Rel-12.

#### 4.2.2.2 Device-to-device multi-hop communication in LTE advanced

For D2D communication, one SI [3GPP12+22803] has been run in the *Technical Specifications Group Service & Systems Aspects* (SA1) of 3GPP Rel-12 and one is currently ongoing in the *Technical Specification Group Radio Access Networks* (TSG RAN) [3GPP12+RP122009], both under the name of *Proximity Services* (ProSe). In addition to proximity detection for proximity based services and direct device-to-device communications, requirements for devices acting as relays for coverage-limited users have been proposed, in particular for public safety national security application.

## 4.3 Research clusters and technology components

The research activity in T3.3 is structured along two main directions. The first research direction is devoted to infrastructure-based relaying. The goal is to exploit the relays to enhance the overall spectral efficiency by allowing multiple communication flows to co-exist in such a way that the interference between them can be managed efficiently. The second research direction is devoted to infrastructure-less /infrastructure-assisted D2D and mobile relays. The goal is to develop underlay D2D communications that either coexists with a cellular network or work in a D2D-cellular cooperative mode in order to improve the overall system performance. This direction features also consideration of the practical limitations in the design or performance evaluation of network with UE relaying or vehicular relaying.

These research directions are mapped to the following research:

- Research cluster 1: infrastructure-based relaying and wireless backhauling
- Research cluster 2: infrastructure-less /infrastructure-assisted D2D and mobile relays

### 4.3.1 Research Cluster 1 and related technology components: infrastructure-based relaying and wireless backhauling

Herein the aim is to consider deployments with infrastructure-based relays. In order to allow an efficient spatial reuse, the approach followed allows joint service and optimization of multiple communication flows, i.e. direct flows between the BS and a user or flows between one or more relays to the BS. Furthermore, because the nodes are half-duplex, flows between nodes are separated in time or frequency, typically organized as uplink or downlink flows. In general, those flows interfere with each others, calling for novel and practical methods to treat the interference. The overall research problem consists in organizing the aforementioned communication flows in such a way that the interference between them can be managed efficiently, in particular exploiting network coding and cross-layer PHY/MAC techniques. The final goal is to assess whether relays, besides being efficient solutions for coverage enhancement, are also potential candidates for improving the average throughput within the cell.

The technology components promoted within this research cluster can be classified as follows:

- Spectrally efficient solutions for wireless backhauling
- Non orthogonal access techniques
- Buffer-aided relaying

The 5 technology components belonging to research cluster 1 are described below.

**Table 4-1. T3.3 Technology Component 1.**

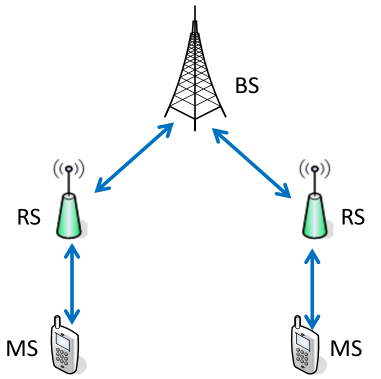
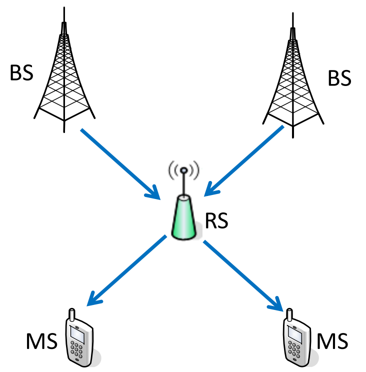
| **T3.3 Technology Component 1**<br><br>**Coordinated multi-flow transmission for wireless backhaul** | |
|---|---|
| **System Model 1**<br><br>Antipodal relays, not interfering with each other. One terminal is connected to one relay and has a two-way traffic with the BS. | **Main Idea: Four way relaying**<br>The four flows, two downlink and two uplink, are served jointly through two transmission phases. In the first phase, the BS broadcasts signals for both terminals to both relays, while each terminal transmits to its relay. In the second phase, each relay broadcasts to its terminal and the BS. Side information at the BS and terminals is used. By coupling all the four flows, the total service time is decreased or, equivalently, the data rates of all nodes are increased. |
| **System Model 2**<br><br>A shared relay is deployed at the intersection of two cells. It uses a buffer and serves flows from two neighbouring base stations to the group of terminals around the relay. | **Main Idea: Shared relay**<br>The shared relay with a buffer receives packets from two BSs and sends packets to the terminals. At each service instant, the relay decides the best links to activate. Due to the possibility to select from many links, it is likely that the best link supports a high data rate. |
| **Test Cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open air festival | **Main Benefits**<br>• Efficient wireless backhaul<br>• Improved overall spectral efficiency<br>• Improved coverage<br>• Access for high device density |

**Table 4-2. T3.3 Technology Component 2.**

| **T3.3 Technology Component 2**<br><br>**Interference aware routing and resource allocation for access and backhaul** |
|---|

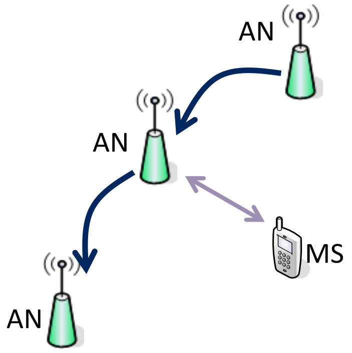
| System Model | Main Idea |
|---|---|
| <br>A multi-hop wireless backhaul with multiple access nodes (AN) in a building and access links sharing the same spectrum. | In order to enhance spectrum efficiency, the wireless backhaul and wireless access share the same spectrum. The purpose is to investigate low complexity sub-optimal algorithms for sharing and coordinating the resources among the backhaul and the access network. In particular, solutions are proposed to route simultaneous users through the mesh to one or several access gateway. |
| **Test Cases** | **Main Benefits** |
| • TC1: Virtual Reality Office | • High spectral efficiency<br>• Access for high device density |

**Table 4-3. T3.3 Technology Component 3.**

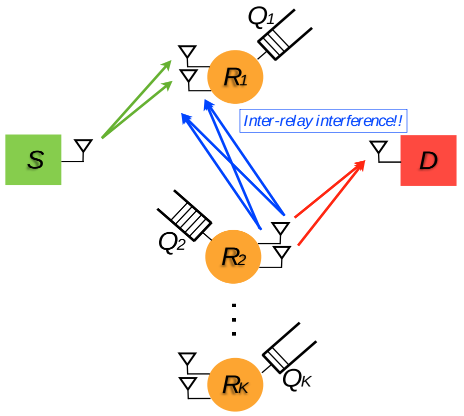
| **T3.3 Technology Component 3**<br>**Virtual Full-Duplex Buffer-Aided Relaying** | |
|---|---|
| **System Model** | **Main Idea** |
| <br>A single source, a single destination, and multiple half-duplex relays with buffers and multiple antennas. The relays interfere with each other. | Buffers at the relay enable a virtual full duplex communication in a network where two relays allow of concurrent transmissions with inter-relay interference cancellation. One relay receives the information from the source while the other forwards the information to the destination. The idea is to find the best relay-pair selection for Source-Relay and Relay-Destination links with an optimal beamforming design at both transmitting and receiving relays. |
| **Test Cases** | **Main Benefits** |
| • TC2: Dense Urban Information Society<br>• TC4: Stadium. | • High spectral efficiency<br>• Reduced energy consumption<br>• Access for high device density<br>• Enhanced end-user data rates |

**Table 4-4. T3.3 Technology Component 4.**

| **T3.3 Technology Component 4**<br>**Distributed Coding for the Multiple Access Multiple Relay Channel** |
|---|

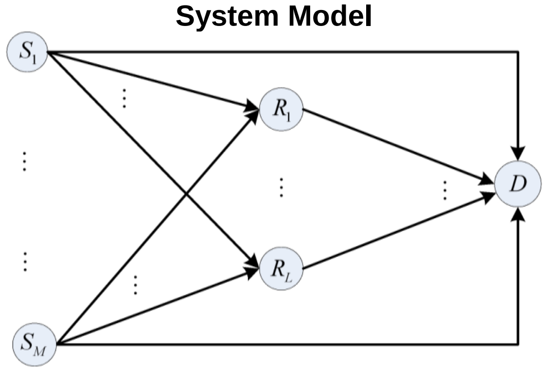
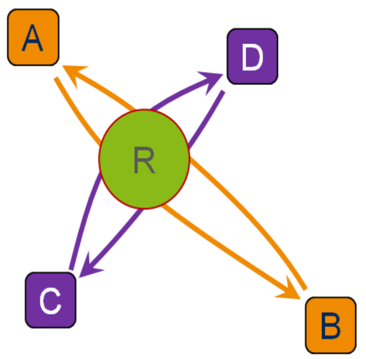
| | |
|---|---|
| **System Model**<br><br><br>Independent users sending to a destination through multiple half-duplex relays. | **Main idea**<br>To reach high spectrum efficiency, non orthogonal access techniques combined with wireless network coding are considered in a cooperative communication setting. The relaying function denoted Selective Decode and Forward (SDF) is applied at the relay, i.e. the relay gathers the messages that it can decode free of errors and forwards a deterministic function of the sources' messages. |
| **Test cases**<br>• TC2: Dense Urban Information Society<br>• TC3: Shopping mall<br>• TC4: Stadium<br>• TC9: Open Air Festival | **Main Benefits**<br>• High spectral efficiency |

**Table 4-5. T3.3 Technology Component 5.**

| **T3.3 Technology Component 5**<br>**Bi-directional relaying with non-orthogonal multiple access** | |
|---|---|
| **System Model**<br><br><br>Two or more communication pairs A-B and C-D are assisted by a half-duplex relay R. The relay and the nodes have one or multiple antennas. | **Main Idea**<br>This work focuses on bidirectional relaying with multiple data flows and multiple communication pairs employing Interleave Division Multiple Access (IDMA) as non-orthogonal multiple access. The application of IDMA offers a high degree of flexibility and allows for the combination with known approaches, such as network coding, in order to create efficient combination of the multiple access (MAC) and broadcast (BC) phases. The impact of IDMA is analyzed in combination with network coding to identify efficient strategies regarding MAC/BC structuring, resource allocation and channel coding for bi-directional communication. |
| **Test Cases**<br>• TC1: Animation Office | **Main Benefits**<br>• High end user throughput with high local reliability<br>• High spectral efficiency<br>• Access for high device density |

### 4.3.2 Research Cluster 2 and associated technology components: infrastructure-less /infrastructure-assisted D2D and mobile relays

The overall scope of this research cluster is to consider both a design and performance evaluation of deployments exploiting D2D (infrastructure-less or infrastructure-assisted) or mobile relays.

D2D communications are considered as an underlay network co-existing with cellular communications. D2D are either direct or facilitated by a relay. When D2D communications goes through a relay, transmission is aided by wireless network coding to enhance the spectral efficiency. Coexistence with the cellular network is insured by multiple antenna interference suppression techniques. Another point of view is to have direct D2D and cellular communications cooperate to achieve a higher overall spectral efficiency by using superposition coding.

Unlike infrastructure-based relaying, mobile relaying is limited by practical constraints. When relaying is performed by a mobile user device, performance is limited by the capabilities of the device in terms of knowledge of the channel state information and computational capacities. A relay belonging to a vehicular network (relay is on top of a public transportation vehicle) limitations include the effect of propagation impairments, handover and co-channel interference.

The technology components promoted within this research cluster can be classified as follows:

- Underlay and cooperative D2D
- MRNs that are studied/designed according to practical limitations.

The 5 technology components belonging to research cluster 2 are described below.

**Table 4-6. T3.3 Technology Component 6.**

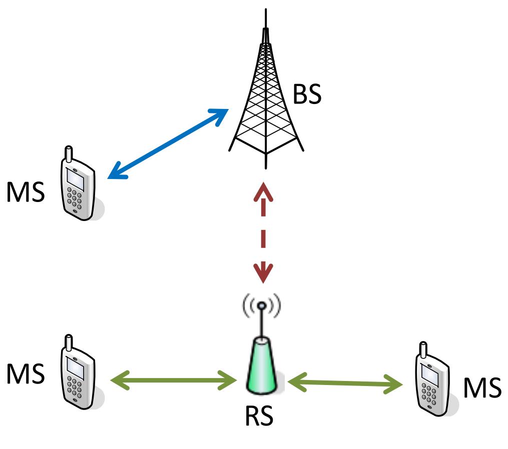
| **T3.3 Technology Component 6**<br>**Underlay D2D communication with physical layer network coding** | |
|---|---|
| **System Model**<br><br>All nodes have multiple antennas. Two-way D2D communication is performed through a relay. One direct user has a two-way traffic to the BS. | **Main Idea**<br>The main idea is to develop multiple antenna techniques at the transmitting or receiving nodes to ensure coexistence of D2D and cellular communications in the same spectrum. The relay node uses physical layer network coding to bring high spectrum efficiency.<br>During the first transmission phase, the two relayed devices and the BS transmit simultaneously. To suppress the mutual interference caused by those simultaneous transmissions, MMSE pre/decoders are used at all nodes. During a second transmission phase, the relay broadcasts the network coded messages while the direct user transmits to the BS. MMSE pre/decoders are used at all nodes to suppress the interference. |
| **Test Cases**<br>• TC2: Dense urban information society.<br>• TC9: open air festivals. | **Main Benefits**<br>• High spectral efficiency<br>• Access for high device density<br>• Coverage extension |

**Table 4-7. T3.3 Technology Component 7.**

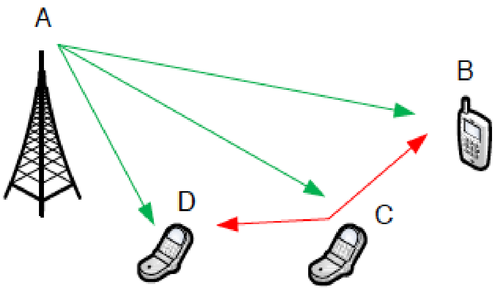
| **T3.3 Technology Component 7**<br>**Cooperative D2D Communications** | |
|---|---|
| **System Model**<br><br>Links AB and CD share the same radio resource via cooperation. | **Main Idea**<br>D2D communication is achieved through cooperation where the interested device relays information from the base station to a mobile user and at the same time gets the opportunity to communicate directly with another device. Hence, by acting as a relay the mobile device can achieve D2D communication with no extra resources. Orthogonal spectrum splitting and superposition coding is considered in the cooperation process. |
| **Test Cases**<br>• TC3: Shopping mall<br>• TC9: Open Air Festival | **Main Benefits**<br>• Access for high device density |

**Table 4-8. T3.3 Technology Component 8.**

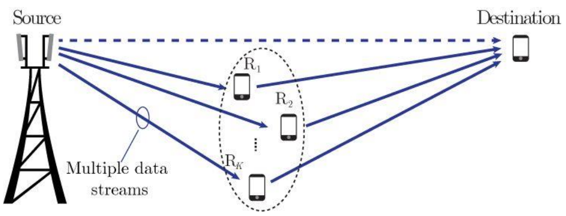
| **T3.3 Technology Component 8**<br>**Closed-loop and open-loop techniques in a network with D2D relaying** | |
|---|---|
| **System Model**<br><br>Communication from a multi-antenna base station and to a multi-antenna destination user, assisted by multi-antenna users acting as relay nodes. The dashed line shows the target *logical* connection between the source and the destination. | **Main Idea**<br>Multiple streams intended to an out-of-reach user are relayed by a group of user terminals. All the nodes are equipped with multiple antennas. The work focuses on practical limitation linked to the use of user terminal as relays: a) no cooperation among UEs, b) CSI unavailability at the UE inducing open-loop transmission for D2D relaying, such as space-time coding and directional beamforming, c) limited computation capabilites and d) limited number of antennas. |
| **Test Cases**<br>• TC5: Teleprotection in Smart Grid Network<br>• TC10: Emergency Communications | **Main Benefits**<br>• Connectivity of high number of devices with high reliability.<br>• Coverage extension |

Table 4-9. T3.3 Technology Component 9.

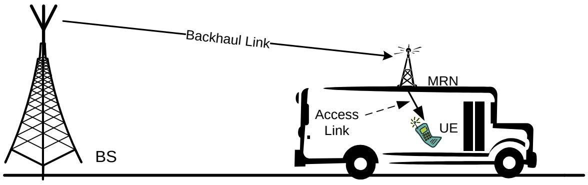
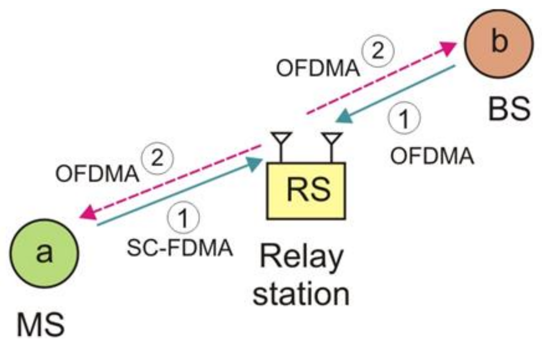
| **T3.3 Technology Component 9<br>Studies of deploying moving relay nodes** | |
|---|---|
| **System Model**<br><br>A vehicular UE is located inside a bus moving along the high way. A moving relay node is placed on top of the bus. | **Main Idea**<br>This task focuses on the usage of MRNs and their impacts on current mobile communication systems. The goal is to understand the benefits as well as challenges of deploying MRNs to the current cellular systems, such as the effect of propagation impairments, handover and co-channel interference. |
| **Test Cases**<br>• TC8: Real-time remote computing for mobile terminals | **Main Benefits**<br>• Improved QoS and QoE<br>Reduced energy consumption for UE |

Table 4-10. T3.3 Technology Component 10.

| **T3.3 Technology Component 10<br>Combining physical layer network coding and MIMO for TDD wireless systems with relaying** | |
|---|---|
| **System Model**<br><br>One mobile station and one base station with two-way traffic through a relay with multiple antennas in an LTE-like system using OFDMA in downlink and SC-FDMA in uplink. | **Main Idea**<br>This work considers the joint application of network coding and MIMO transmission with the aim at improving reliability and robustness in two-way relaying scenario. Multiple antennas at the relay station are used to separate data blocks received on the same radio resources by utilizing the spatial dimension. After the decoding of the separated data blocks, network coding is applied and the re-encoded data block is broadcasted. Comparison to a scheme with MU-MIMO as an alternative to network coding is made as well. |
| **Test Cases**<br>• TC7: Blind Spots. | **Main Benefits**<br>• High spectral efficiency<br>• Decreased delay |

## 4.4 Summary of mapping between technology components and test cases

Following the overall methodology used in METIS architecture, each of the technology components that are researched by the individual partners or through collaboration among several partners, should eventually make a meaningful contribution to the required performance in one or more of the test cases. The way technology components are related to the test cases is shown in Table 4-11. It can be seen that there are three among the 12 test cases that are not targeted by the technologies from T3.3.

**Table 4-11. Summary of mapping between technology components and test cases for T3.3.**

| | Technology component | Test case number | | | | | | | | | | | | Expected benefit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Coordinated multi-flow transmission for wireless backhaul | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | Efficient wireless backhaul<br>Improved overall spectral efficiency; Improved coverage<br>Access for high device density |
| Research cluster 1 | **TeC2**: Interference aware routing and resource allocation for access and backhaul | **1** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High spectral efficiency<br>Access for high device density |
| Research cluster 1 | **TeC3**: Virtual Full-Duplex Buffer-Aided Relaying | 1 | **2** | 3 | **4** | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High spectral efficiency<br>Enhanced end-user data rates<br>Reduced energy consumption<br>Access for high device density |
| Research cluster 1 | **TeC4**: Distributed Coding for the Multiple Access Multiple Relay Channel | 1 | **2** | **3** | **4** | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High spectral efficiency |
| Research cluster 1 | **TeC5**: Bi-directional relaying with non-orthogonal multiple access | **1** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | High end user throughput with high local reliability<br>High spectral efficiency<br>Access for high device density |
| Research cluster 2 | **TeC6**: Underlay D2D communication with physical layer network coding | 1 | **2** | 3 | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | High spectral efficiency<br>Access for high device density<br>Coverage extension |
| Research cluster 2 | **TeC7**: Cooperative D2D Communications | 1 | 2 | **3** | 4 | 5 | 6 | 7 | 8 | **9** | 10 | 11 | 12 | Access for high device density |
| Research cluster 2 | **TeC8**: Closed-loop and open-loop techniques in a network with D2D relaying | 1 | 2 | 3 | 4 | **5** | 6 | 7 | 8 | 9 | **10** | 11 | 12 | Connectivity of high number of devices with high reliability<br>Coverage extension |
| Research cluster 2 | **TeC9**: Studies of deploying moving relay nodes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | **8** | 9 | 10 | 11 | 12 | Improved QoS and QoE<br>Reduced energy consumption for UE |
| Research cluster 2 | **TeC10**: Combining phy layer network coding and MIMO for TDD wireless systems with relaying | 1 | 2 | 3 | 4 | 5 | 6 | **7** | 8 | 9 | 10 | 11 | 12 | High spectral efficiency<br>Decreased delay |
| | Number of technology components per test case | 2 | 4 | 3 | 3 | 1 | 0 | 1 | 1 | 4 | 1 | 0 | 0 | |

## 4.5 Summary of mapping between technology components and horizontal topics

The technology components can also be related to the horizontal topics (HT). Note that test cases (TC) are related to the HTs, but that does not imply that a technology component that can be used for TCx is related to all the horizontal topics related to TCx. Table 4-12 summarizes the mapping between the technology components and the HTs. Note that the HT of Architecture is related to all technology components and is therefore not explicitly included in the table.

**Table 4-12. Summary of mapping between technology components and horizontal topics for T3.3.**

| | Technology component | Horizontal topic | | | | |
|---|---|---|---|---|---|---|
| Research cluster 1 | **TeC1**: Coordinated multi-flow transmission for wireless backhaul | D2D | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC2**: Interference aware routing and resource allocation for access and backhaul | **D2D** | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC3**: Virtual Full-Duplex Buffer-Aided Relaying | D2D | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC4**: Distributed Coding for the Multiple Access Multiple Relay Channel | **D2D** | MMC | **UDN** | MN | URC |
| Research cluster 1 | **TeC5**: Bi-directional relaying with non-orthogonal multiple access | D2D | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC6**: Underlay D2D communication with physical layer network coding | **D2D** | MMC | UDN | MN | URC |
| Research cluster 2 | **TeC7**: Cooperative D2D Communications | **D2D** | MMC | UDN | MN | **URC** |
| Research cluster 2 | **TeC8**: Closed-loop and open-loop techniques in a network with D2D relaying | **D2D** | MMC | **UDN** | MN | URC |
| Research cluster 2 | **TeC9**: Studies of deploying moving relay nodes | D2D | MMC | UDN | **MN** | URC |
| Research cluster 2 | **TeC10**: Combining phy layer network coding and MIMO for TDD wireless systems with relaying | D2D | MMC | **UDN** | **MN** | URC |
| | Number of technology components per horizontal topic | 5 | 0 | 7 | 2 | 1 |

## 4.6 Mapping between T3.3 and the other METIS WPs

In this section we summarize the mapping between the activity in T3.3 and the other METIS WPs, by emphasizing the most relevant connections.

**Table 4-13. Mapping between the activity in T3.3 and the other METIS WPs.**

| | |
|---|---|
| **WP1** | • Application of D2D and backhaul-type channel models to multi-hop and relays. |
| **WP2** | • Flexible air-interface, in particular for moving networks;<br>• signaling and MAC schemes for massive machine access;<br>• air interface design for D2D links, e.g. symmetric air interface investigated in RT1. |
| **WP4** | • Interference identification, smart and coordinated resource usage and smart signaling for mobility;<br>• implications of relay/network coding approaches for WP4 studies. |
| **WP5** | • Spectrum studies targeting D2D and wireless backhaul. |
| **WP6** | • Architectural implications of relay/network coding.<br>• guidelines on system-level-simulations with relays. |

# 5 Conclusion

In this document we discussed the research activity in WP3 and positioned it with respect to the state-of-the-art in the academic literature and in the standardization bodies. Moreover, we set the research objectives to be achieved in each task and we grouped the different activities (or technology components) into research clusters with similar research objectives. The research objectives have been set to achieve an ambidextrous purpose: providing the METIS system with those technological components that are a natural but non-trivial evolution of 4G, and seeking for disruptive technologies that could radically change 5G with respect to 4G. Overall, we strongly believe that WP3 is very well positioned to provide both evolutionary and revolutionary components in the “5G=4G + evolution+revolution” equation.

ConcerningT3.1, the state-of-the-art assessment shows that, due to the fact that Massive-MIMO gained a significant attention only in the last years, the works available in literature only partially assess the impact of real-world impairments on a system-level perspective. These real-world challenges include, for example, channel estimation and pilot design, antenna calibration, link adaptation, antenna design, propagation effects. On the other hand, being still a fresh concept, Massive-MIMO also needs some further investigations to allow a better understanding of its theoretical foundations and its interplay with other technologies. Moreover, Massive-MIMO is an important enabler for MMW communications, due the need of maximizing the array gain in order to reach a sufficient link budget. These two different aspects (real-world challenges and better understanding of the theoretic foundations) have been tackled in two different research clusters.

Concerning T3.2, we started by reviewing the large literature on CoMP. Then, and in order to approach this wide subject, we divided the research work in different research clusters that aim at providing results that can impact the field both on a short and on a long term. Concerning “classical” CoMP techniques, like joint processing and coordinated scheduling, their gains are still object of debates in the research community, and they are mainly limited by the effects of clustering, channel estimation/feedback and backhaul throughput and latency. Further studies in “classical” CoMP in T3.2 have therefore been set in order to bring the expected gains of CoMP to realistic systems. Moving from this classical approach, novel CoMP concepts are also explored, as for example the theoretically promising IA technique, which is addressed in a realistic framework, in order to assess its feasibility and the gain that can be expected in real life system. In the end, other research directions consider novel approaches to coordination than can arise as a consequence of evolution in the network access technique or improvements or new enablers available in future UEs.

Concerning T3.3, the state-of-art analysis showed that in the past and the existing wireless cellular networks, wireless relaying and multi-hop communications have been considered as an additional feature to the core wireless infrastructure, with a very limited application. However, the trends of network densification, reliability and support of moving networks, promote relays towards becoming one of the central elements in the wireless architecture. The approach in this task addresses relay-based techniques through a set of component technologies classified into two research clusters. The first research cluster addresses the problem of network densification through the use of infrastructure-deployed relays and techniques for wireless backhauling. Specifically, using ideas of wireless network coding, buffer-aided relaying, and joint processing of interfering flows brings high promises to make wireless a viable option for efficient in-band backhauling. The second research cluster targets scenarios and techniques based on moving relays and D2D communication.

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# 7 Annex – List of Test Cases

The aim of the test cases is to provide distinct problem descriptions, requirements, and Key Performance Indicators (KPIs) from the end-user perspective. They will be used by the METIS project as a basis for designing and evaluating technical solutions. A detailed description of each test case can be found in [MET+13D11].

**Table 7-1 – List of Test Cases**

| | |
|---|---|
| TC1 | Virtual reality office |
| TC2 | Dense urban information society |
| TC3 | Shopping mall |
| TC4 | Stadium |
| TC5 | Teleprotection in smart grid network |
| TC6 | Traffic jam |
| TC7 | Blind spots |
| TC8 | Real-time remote computing for mobile terminals |
| TC9 | Open air festival |
| TC10 | Emergency communications |
| TC11 | Massive deployment of sensors and actuators |
| TC12 | Traffic efficiency and safety |

# 8 Annex – List of Horizontal Topics

A detailed description of each horizontal topic can be found in IR 6.3 and will be put in D6.2.

**Table 8-1 – List of Horizontal Topics**

| | |
|---|---|
| ARCH | **Architecture (ARCH).** This is an overarching horizontal topic, identified as a fundamental and technology-oriented HT concerning any wireless communications system. Its role is to integrate all the technology components to system-level solutions. |
| D2D | **Direct Device-to-Device (D2D).** D2D links are integrated with the infrastructure in terms of services and security, which unveils new opportunities for the operators to offer services and applications over the short-range D2D links that offer peer-to-peer (P2P) connectivity. This HT addresses the following problem: *How to efficiently enable direct D2D links among wireless mobile devices, which performance parameters can be improved and which new services can be supported by the D2D links?* |
| MMC | **Massive Machine Communication (MMC).** MMC is concerned with the introduction of massive number of low-cost, low-energy devices connected to the wireless mobile infrastructure. MMC also brings a quantitative novelty in the systems, due to the unprecedented number of connected devices and novel traffic patterns that need to be managed. Machine-related communications will be associated with a wide range of characteristics and requirements (e.g., data rate, latency, cost, availability and reliability) that will often deviate substantially from those of human-centric communications in current systems. This HT addresses the question: *How should the system support a massive number of low-cost, low-energy devices, where each subset of devices can be associated with different services, and there can be massive variation in the service requirements?* |
| UDN | **Ultra Dense Networks (UDN).** This HT can be understood as a quantitative extension of the communication networks featured in today's systems. UDN looks at technologies and system solutions that will sustain the required increase of bits per second per square meter. It addresses the question: *How should the system provide and sustain increasingly higher data rates when an increasing number of users and devices reside in a confined area?* |
| MN | **Moving Networks (MN).** MN is extending the traditional cellular architecture in a qualitative way. For example, a car-mounted relay can provide wireless services, thereby changing the paradigm of a fixed Base Station into a Mobile Base Station. This is only one aspect of MNs, but in general MN addresses the issue of moving devices, groups of devices and moving networks through the question: *How can the current infrastructure be extended with the moving networks in order to bring the traditional wireless services to the moving/nomadic nodes, but also support new services specific to the moving networks?* |
| URC | **Ultra-Reliable Communications (URC).** URC represents a new performance feature that needs to be targeted in designing the future wireless systems. Very high reliability can only be achieved by accounting for it during the design of the technology components, as well as t. It addresses the following question: *Which technology components should be used and how should they be integrated to provide connectivity with almost 100% reliability?* |