Publishable Summary

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Chapter 1 Publishable Summary

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Grant Agreement: **619086**
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Mission of MAMMOET *was to advance the development of Massive MIMO (MaMi), a new and highly promising trend in mobile access. MAMMOET showed the benefits – and overcame the practical limitations – of MaMi and developed complete technological solutions leveraging on innovative low-cost and drastically more efficient and flexible hardware.*

The MAMMOET Project:

- Advanced the development of Massive MIMO (MaMi), a new and highly promising trend in mobile access.
- Showed the benefits and overcame the practical limitations of MaMi.
- Developed innovative technological solutions including digital signal processing solutions and low-cost and drastically more efficient and flexible hardware.
- Demonstrated MaMi operation at record spectral efficiency.
- Realized a great publication output and engaged in wide dissemination activities: dedicated tutorials and workshops were organized at leading conferences, and a Massive MIMO info-point (www.massivemimo.eu) was maintained which has been consulted very actively and broadly.

Motivation:

The internet of the future will, to a large extend, rely on mobile networks. Mobile data grew by 70% in 2012 and is predicted to grow 13-fold in the next years. This puts very high demands on the development of mobile access technology.

Multiple-antenna (MIMO) technology for wireless communications is becoming mature and incorporated into emerging wireless broadband standards like long-term evolution (LTE). Basically, the more antennas the transmitter and the receiver are equipped with, the higher the number of possible signal paths and the better the performance in terms of data rate and link reliability. The price to pay is increased complexity of the hardware (number of RF amplifier frontends) and the complexity and energy consumption of the signal processing at both ends. Therefore MAMMOET investigated a complete technological solution leveraging on innovative low-cost and drastically more efficient and flexible hardware.

Expected Impact:

Given the outstanding capacity and energy efficiency potential of this technology, the progress towards convincing proof of concept has stimulated the take up by standards. MAMMOET results are most likely to end up in 5G networks and (hardware) systems.

Specifically, through a widespread dissemination of the project expertise and progress, both broad and in-depth knowledge of Massive MIMO technology was raised. Particular project results can also be used beyond the Massive MIMO focus, as for example the channel characterization and the power efficient transmitters.

<u>Description of the work performed and results since the beginning of the project</u>

The MAMMOET project started on the 1st January 2014 and ended after 36 months in December 2016.

During the first project phase the focus was placed on the analysis of on specifying relevant and realistic scenarios, outlining a system approach/architecture and analysing requirements. During the second project phase the focus was placed on kick-off of WP4 in M13 and completion of WP1 in M18, and a major priority was given to the analysis of the overall implementation solutions and progressing efficient (hardware) solutions. Within the third project period (M25-M36) the implementations and baseband and FE component design have been ready and hardware measurements were performed. The overall system was assessed and validated. The validation included actual experiments in the real-life testbed in diverse situations (indoor and outdoor, including mobile scenarios)..

WP1 (System approach, scenarios and requirements)

WP1 started in M01 and ended in M18. Main objective was for all the partners in MAMMOET to collectively set the scene for the project. The work was organized in two major tracks. The first track consisted of work on fundamental limits, practical trade-offs and specifications (T1.1) and on scenarios, system outline and performance metrics (T1.2). The outcome was reported in M12 deliverable D1.1 and in about a dozen of scientific publications. Specifically, the entire consortium was involved in the definition of a minimum set of diverse and challenging 5G mobile broadband scenarios that are mostly relevant to massive MIMO. Scenarios definitions amounted on specifying the values of a set of parameters that are common to all scenarios and elaborating the main characteristics that are specific to each scenario. The selection of the prioritized scenarios was driven by both technical and business related criteria to ensure that MAMMOET results will focus on demonstrating substantial capacity and energy gains while maximizing the potential impact from commercial exploitation. Moreover, the main operation of massive MIMO was outlined focusing on physical layer technical functionality. The uplink and downlink signaling were defined in a TDD-based transmission protocol and pilot-based channel estimation in the uplink was described. The average spectral efficiencies achieved in such a system with a diverse selection of linear precoding/combining schemes were derived. Also, the power consumption was modeled taking into account all the different components of the innovative transmitter architecture developed in MAMMOET. Theoretical investigations were contacted on power combining of constant and non-constant envelope signals from transmitter arrays. These were complemented by evaluations in a high-level PA simulation platform of different PA architectures as Class - B, F, D, E, DE in terms of output power capability, gain and efficiency for constant and non-constant envelope driving signals. The spectral efficiency achieved by massive MIMO in a variety of different setups was illustrated. An asymptotic analysis was performed first and was then complemented by simulation results of optimized performance evaluations. The effect of the main scenario parameters and the impact of hardware impairments were investigated. The behaviour of massive MIMO was analyzed also in low traffic situations. Moreover, scaling behaviors and practical trade-offs were derived. These results provide fundamental limits of the massive MIMO performance and the conclusions yield a valuable first insight that are used to steer the MAMMOET WP3 research on algorithm development around the topics of channel estimation, pilot allocation, and phase-coherent precoding/combining. The second track consisted of work on large array channel measurements and analysis, aiming to characterize massive MIMO channels. The outcome was reported in M18 deliverable D1.2 and its accompanying MATLAB implementation (D1.3). Specifically, channel measurements were taken in the open exhibition scenario, corresponding to an outdoor urban massive MIMO environment. Special emphasis in the measurement campaign was given on the crowd scenario, which is considered as one of the most challenging scenario for today’s cellular networks. Additionally, channel measurements in indoor lecture hall were performed for several different scenarios. The results intended to cover and make it possible to compare and model crowded and not crowded lecture halls and the influence of different access point/base station locations. The measurement procedure and equipment were described. The channel measurements were used for directional estimations and for extraction of cluster parameters. Then, these were used to set and validate parameters of the proposed massive MIMO channel model, which builds on an extended COST 2100 model. The initial validation performed showed that the model is capable of reproducing the statistics in terms of temporal behavior of the user separability, singular value spread, capacity and sum-rate and directional characteristics. The MATLAB implementation of the MAMMOET massive MIMO channel model was documented and a user manual was generated.

WP2 (Efficient FE Solutions):

WP2 started with a study of different transmitter architectures. In context of MaMi the need was for a transmitter that would be low cost (have a small area), flexible (able to support multiple standards) and power efficient. After an extensive study a motivation was built for time based digital-RF transmitters. A bandpass MATLAB equivalent model was designed. This model was then used to study the effect of quantization (number of bits) on the signal quality and out of band noise. Errors like phase mismatch between signal paths and differential non-linearity in the phase modulator were also studied. These studies came under T2.1. After this circuit level building blocks for the transmitter were designed and simulated. The top level simulation of the circuit blocks was done in collaboration with IFAT. Modulated signals were used even at circuit level simulation. The simulations were done on a parallel platform provided by IFAT (T2.2). Once the circuits for the block were designed at transistor level, next step was their layout and fabrication (T2.5). This was a layout intensive design because of its asynchronous nature. Path delays had to be matched accurately in the layout to ensure proper operation. Critical blocks had to be again simulated after layout and parasitic extraction. The design support and CAD tools were provided by IFAT which fall under T2.4. After extensive simulations three different RF-PWM modulator chips (an all-digital RF-PWM modulator chip which has been designed by KU Leuven and two additional mixed-signal RF-PWM modulator chips designed by IFAT) were sent for tapeout (T2.5). High speed pcb were designed for the testing of the all-digital RF-PWM chip. A dynamic methodology to characterise the non-linearity of this chip was developed which was used to generate a look up table for pre-distortion of the outphasing signals. The all-digital RF-PWM modulator chip was characterized and the results were documented under D4.3 along with the measurements of an output bandpass filter and a high-efficiency dual input Doherty PA that have been designed by IFAT in order to get closer to a full system implementation. In T2.3, the impact of the non-reciprocity of the transceivers on the channel state acquisition and hence the performance of massive MIMO systems was also evaluated. Different mitigation approaches were also introduced. The results were documented in D2.4.

WP3 (Baseband Solutions):

WP3 started its activities in April 2014 and has essentially progressed according to plan both in period one and two. WP3 partners have performed investigations on many important topics related to massive MIMO baseband processing and now have a very comprehensive grip on how to perform baseband signal processing in MaMi systems. The choice between single- and multi-carrier massive MIMO has been studied and initial conclusions are that there are no major differences in performance or implementation complexity. Baseband algorithm performance vs. complexity trade-offs have been studied and optimized for massive MIMO specific scenarios. In particular, it has been identified to what extent the averaging of noise and uncorrelated distortions from hardware impairments over the different antennas allow for relaxed design constraints. The analysis shows that quality of each individual antenna branch can be greatly relaxed. Investigations of the impact from word-lengths and number of quantization bits have also been studied, both from achieved communication performance and energy consumption perspectives. Linear and non-linear precoding techniques have been developed and studied, where the non-linear precoding is aimed at bringing lower power variations on individual antennas relaxing power amplifier requirements. Promising results have been obtained for non-linear precoders, but the implementation complexity depends heavily on the objective.

An overview of different hardware platforms for massive MIMO baseband processing has been compiled and a processing hardware architecture has been proposed. Initial experiences from the massive MIMO testbed showed that a critical part of realizing massive MIMO is related to reducing the amount of data that needs to be exchanged between different processing nodes when using distributed processing. In the early stages of the project, we have used highly flexible solutions, such as software-defined radios, while more specific implementations have gradually been developed . Hardware (ASIC) implementations of both linear and nonlinear precoders are now available, and they have been implemented and characterized in terms of processing speed and power consumption. The complexity and power consumption of massive MIMO systems has been investigated in detail. A state-of-the-art model was enhanced in order to estimate the power consumption of the different components in flexible Massive MIMO scenarios, taking implementation aspects into account. The relative importance of signal, noise, and interference terms has been studied in order to model the system performance in different scenarios. Moreover, the impact of PA distortion when entering the saturation region has been shown to be limited on the system performance. The third period was focused on consolidating and refining recommendations for baseband processing, where a broader scope was analysed. New knowledge produced by this and other WPs has ben put together in a more complete analysis of MaMi baseband processing strategies. In particular, with more knowledge available about performance, energy consumption, and power consumption, of individual parts it is now possible to do more far-reaching trade-offs between different design choices. This knowledge has been transferred to WP4 and used there in the larger perspective for system simulations and validation.

WP4 (Validation and proof-of-concept):

WP4 aims at exploring and validating our Massive MIMO proposal and the findings of other WPs at three different levels: simulation-based validation (task T4.1), testbed-based validation (task T4.2) and hardware-based validation (task T4.3).

Simulation-based validation builds on a Matlab simulator that has been fully created and delivered (D4.1). This software performs end-to-end simulation of the physical baseband including all digital signal processing operations and models of various impairments. Those impairments include transceiver hardware impairments as well as effects from propagation, noise and interference. The simulator has been created in order to be very flexible and support many different scenarios. A large list of parameters is included and they can be set by the end-user from a single file. For example, the performance can be simulated while changing the number of antennas, precoder choice, channel training options, amplifier non-linearity, output power normalization, quantization, analog non-idealities, etc.

Typical configurations have been selected in line with scenarios of WP1. Moreover, a number of Massive MIMO deployment aspects have been investigated, in order to connect the simulations to perform to relevant application-level cases.

Concerning testbed-based validation, the final processing architecture for the testbed has been put in place with a baseline implementation of OFDM-based massive MIMO system ready for real-time concept validation and performance evaluation in real-life propagation environment. Flexibility has been considered as a key feature of the testbed that different system parameters can be testified, for instance different serving antenna numbers, modulation schemes, pre-coding/detection algorithms, etc. D4.2 has described the testbed architecture and reported the successful operation tested for a number of different scenarios, including indoor and outdoor, and some high-mobility scenarios up to 50 km/h. Results have also confirmed theoretical findings such as the significantly better performance of zero-forcing over maximum-ratio precoders. Tests were performed with up to 100 antennas and up to 12 users.

Hardware measurements of the taped-out digital-RF modulator have been performed and reported in D4.3. This deliverable validates the excellent signal performance of the hardware component, measured as both in-band error vector magnitude and out-of-band leakage. Its power consumption is also reaching the target and enabling power savings. Additional components were also implemented and measured in order to get closer to a full system, i.e., an output bandpass filter and a high-efficiency (Doherty) PA. Measurements of these components were also reported in D4.3. The final line-up of all components is expected to confirm the relevance of the approach for a high spectral and power efficiency design.

The overall validation of the Massive MIMO concept has been performed by combining the different elements and reported in D4.4. The role of the propagation channel in the simulation environment was investigated, building on the dedicated measurement-based channel model developed in WP1. Combined with proper channel estimation, normalization and power control strategies, it confirms the good performance of Massive MIMO, simulated over scenarios derived from WP1 requirements. Simulations have also validated the absence of degradation introduced by the digital-RF modulator, based on its measured signal quality. Finally, an overall power assessment based on the selected architecture and algorithms for target performance has confirmed a reduction by more than a factor 10 of the overall power consumption, as compared to traditional architectures.

WP5 (Project management including Dissemination, Standardisation and Exploitation)

Within WP5 the early established robust IT infrastructure (website, SVN repository including web access, mailing lists and mailing lists archives) was updated regularly. MAMMOET has also advertised by web pages, press releases and newsletters were published and distributed, amongst others, to industrial partners contacted in the context of the project results. Hardcopies of the MAMMOET project leaflet were distributed by partners at various events. To summarize, the achievements and work towards the project goals during the third project year for dissemination and standardisation include: 15 peer-reviewed scientific publications, 13 presentations in conferences or organized events with an international audience and very good feedback, contributions to privacy and cloud technology standards in international standardisation bodies. The project is visible on twitter and LinkedIn. Newsletters have been published and distributed, amongst others, to industrial partners contacted in the context of the project results. A list of dissemination activities has been compiled and updated periodically.

Further, this WP was responsible for the effective organization of the project and covered all relevant management components, including risk and innovation management.

Final results and their potential impact and use

In general the prospect is that MAMMOET significantly increased the overall understanding, state-of-the art and confidence level of Massive MIMO technology. The technical progress has been considerable on both the overall system level and specific components of the technology: exploring the theoretical limits, realizing efficient algorithms and hardware solutions for the digital baseband as well as the analogue/RF front-end, prototyping of components, and system-level validation including experiments in the very large testbed. Given the outstanding capacity and energy efficiency potential of this technology, the progress towards convincing proof of concept has stimulated the take up by standards. At the beginning of the project Massive MIMO was probably mostly considered an interesting academic idea. Meanwhile, the technology has matured a lot and its value has been recognized and proven, amongst others by impressive demonstrations. A clear consensus exists now that Massive MIMO is a key technology for 5G networks. The MAMMOET project and its partners have been at the forefront of this impressive progress. We are confident that the results of the project will end up in 5G networks and (hardware) systems. Specifically, through a widespread dissemination of the project expertise and progress, both broad and in-depth knowledge of Massive MIMO technology was raised. Indeed exceptional dissemination results have continued to confirm the relevance of the project and its results, and the exceptional expertise of the consortium. The experts have taken up a large responsibility in sharing the knowledge, and engaged in numerous tutorials, workshops, and invited talks. Particular project results can also be used beyond the Massive MIMO focus, as for example the channel characterization and the power efficient transmitters and power amplifiers.

The MAMMOET Consortium: The academic and research institute partners in MAMMOET include pioneers in MaMi and groups with extensive experience in circuit design for wireless communications. The industrial partners are leaders in their fields and cover the entire chain from component manufacturing to systems development and service provisioning. This means the MAMMOET consortium was well-positioned to achieve its objectives by bringing together a European team with 8 project partners from 4 different countries.

MAMMOET project public websites: The official MAMMOET project website is available at the following link: http://www.mammoet-project.eu. Furthermore, the Massive MIMO Info Point website was created, in order to provide lists of research papers accessible for public. The Info Point can be found at the following link: http://www.massivemimo.eu/