Publishable Summary

Project number:	619086
Project acronym:	MAMMOET
Project title:	Massive MIMO for Efficient Transmission
Start date of the project:	01.01.2013
Duration:	36 months
Programme:	FP7/2007-2013

Date of the reference Annex I:	01.10.2013
Periodic report:	Publishable Summary (as part of D5.3 "2nd periodic report according to EC regulations of the model contract")
Period covered:	01.01.2015 – 31.12.2015
Work packages contributing:	All
Due date:	December 2015 – M24
Actual submission date:	February 25th, 2016

Project Coordinator:	Dr. Klaus-Michael Koch Technikon Forschungs- und Planungsgesellschaft mbH (TEC)
Tel:	+43 4242 233 55 00
Fax:	+43 4242 233 55 77
E-Mail:	coordination@mammoet-project.eu
Project website:	www.mammoet-project.eu

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement n° 619086.

Chapter 1 Publishable Summary

Project name: **MAMMOET**
Grant Agreement: **619086**
Project website: http://www.mammoet-project.eu
Contact: coordination@mammoet-project.eu

Start date: 1st January 2014
Duration: 36 months

Mission of MAMMOET *is to advance the development of Massive MIMO (MaMi), a new and highly promising trend in mobile access. MAMMOET shows the benefits – and overcomes the practical limitations – of MaMi and develops complete technological solutions leveraging on innovative low-cost and drastically more efficient and flexible hardware.*

The MAMMOET Project aims to:

- Advance the development of Massive MIMO (MaMi), a new and highly promising trend in mobile access.
- Show the benefits and overcome the practical limitations of MaMi.
- Develop complete technological solutions leveraging on innovative low-cost and drastically more efficient and flexible hardware.

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 5 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 will investigate 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 can stimulate the take up by standards. Eventually, MAMMOET results will then 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 will be raised. Indeed the quite exceptional dissemination results in view of the early project phase, illustrate the timeliness of the project and recognizes the expertise available in the consortium. 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 in the second project period</u>

The MAMMOET project started on the 1st January 2014 and is set to run for 36 months. During the second project phase, corresponding to the second project year, 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. The partners with their specific expertise have cooperated intensely to acquire full picture on the complexity of the system, and master it consequently. Three dedicated technical workshops of the MAMMOET were held in 2015, and a follow up in the beginning of 2016. The scientific advisors joined us at one of these occasions, and have provided us with appropriate feedback and inspiration. All work packages were active in this year, and produced altogether 10 deliverables (including this second Periodic Report) throughout the second project year. The progress achieved by all work packages within the first project year is in line with the initial plan and can be summarized as follows.

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 conducted 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 is 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. Another major result of WP2 in the second project year has been the analysis of the impact of non-reciprocal transceivers on Channel State Information (CSI) acquisition, and the proposal of potential solutions, which has been reported on in deliverable D2.4. In this deliverable, first the problem is analysed in more details as the structure of the problem reveals potential calibration approaches to resolve the problem. The impact of the non-reciprocity was studied for Massive MIMO transmission specifically. The results show that Massive MIMO communication is less sensitive to non-reciprocity of the transceiver circuits. Several calibration solutions, as proposed in the state of the art, are extended to the case with a large number of antennas and the performance is assessed. It is concluded that the transceivers non-reciprocity has to be taken care of in order to enable high performance MaMi. Yet, calibration solutions are known and can be applied also for the large number of antennas. It is therefore not expected that this effect would hamper the eventual large-scale deployment of MaMi systems. This is to be further substantiated in real-life validations.

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 the quality (in terms of precision) of each individual antenna branch at the base station can be greatly relaxed. 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. 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 characterized in terms of processing speed and power consumption. 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. 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. With a more complete set of baseband processing techniques investigated in WP3, the third period will be focused on consolidating and refining recommendations for baseband processing, where a broader scope is analysed, new knowledge produced by this and other WPs will be 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.

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). The third task is not active yet, given that it starts by month M28 only, yet has been prepared importantly by the tape-out realized in WP2. 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 is now active and in place, and tests have been running already. The project will define which further tests should be run on the testbed. Components are being upgraded for best performance. A baseline implementation of OFDM-based massive MIMO system is ready for 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.

WP5 (Project management including Dissemination, Standardisation and Exploitation): WP5 consists of two parts – the project management, and dissemination, standardisation and exploitation activities. The project management was responsible for the effective organization of the project and covered all relevant management components. Some of the main achievements so far have been: the organization of meetings (e.g. GA, AB Meetings), monthly EB Telcos, monitoring of the work plan (Interim Management Reporting), supporting partners in everyday issues (handling day2day requests), etc. For the Dissemination, Standardisation and Exploitation part, the early established robust IT infrastructure (web site, SVN repository including web access, mailing lists including mailing list archives) was regularly updated. MAMMOET has also been advertised by web pages, press releases and internal partners' newsletters. Hardcopies of the MAMMOET project flyers have been distributed by partners at various events. The project is visible on twitter and LinkedIn. Several newsletters have been published and distributed, amongst others, to industrial partners contacted in the context of the project results. Dissemination activities are announced via http://mammoet-project.eu/news. A list of dissemination activities has been compiled and updated periodically. Details regarding dissemination activities can be found in D5.5 “Updated plan and initial report on dissemination, standardisation and exploitation” which includes all dissemination, standardisation and training activities that were performed by the MAMMOET consortium. Further, a detailed exploitation report of all partners is included. As great highlights, we can report that Massive MIMO is well on the way to become a standard technology for 5G systems (specifically in the context of 3GPP-LTE). Also, the project was able to continue the great publication output, both in number of representations and in quality (including several high-impact journal papers and a unique contribution for the January 2016 edition of the IEEE communication society news).

Expected final results and their potential impact and use

In general the prospect is that MAMMOET will significantly increase 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 can stimulate the take up by standards. Eventually, MAMMOET results will then 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 is raised. Indeed exceptional dissemination results have continued to confirm the relevance of the project and its results, and the exceptional expertise of the consortium. Particular project results can also be used beyond the Massive MIMO focus, as for example the channel characterization and the power efficient transmitters.

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 is 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/