# Mobile communications going massive

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**Mobile communications have undergone an amazing development over the last few decades**, with new generations coming out roughly every ten years. Each transition from one generation to the next has brought new capabilities and improved technology. The first generation was based on analogue technology and supported only traditional phone calls, while subsequent generations have become increasingly digital, making them more efficient, flexible and capable. Today a mobile phone is much less "a phone" than it is a centre for our social networks, a diary, a personal assistant, a camera, and the way we keep updated on the latest news. No matter how we measure the development of mobile communications, curves tend to show exponential growth without signs of slowdown. In this sense it is obvious that mobile communications are "going massive", but it is a different aspect of going massive on which this text focuses. Current estimates show that worldwide mobile data traffic will grow from a current 3 ExaBytes per month (3 000 000 000 000 000 000 Bytes) to around 20 ExaBytes per month (20 000 000 000 000 000 000 Bytes) by the year 2020[1]. There are no existing systems that can efficiently supply this increase in

1 These numbers are equivalent to the contents of 6 million and 40 million full 512 GByte hard disks per month respectively.

data traffic. The radio spectrum is already crammed with mobile services, and mobile communication technologies are performing near their theoretical maxima. To take the necessary leap forward we need to open up a new dimension in mobile communications. The spatial dimension, i.e. the location of mobile terminals in space, is still to be efficiently exploited. Massive increases in data traffic, through massive increase of spatial resolution, require massive numbers of antennas in our mobile systems. It is from this perspective we perform research in our project where we investigate *mobile systems going massive*.

**To understand the fundamental principles** of how spatial resolution can help us increase efficiency of a mobile communication system, we will use very simple optical light-based communication as an analogy. Assume that our mobile terminals are transmitting signals to a base station by switching a light source on/off, using for example Morse code. The base station has an omni-directional light detector, which you may think of as watching the world through a ping pong ball, where strength and colour of incoming light can be distinguished, but not its direction. This is a fairly close analogy of how current mobile communication systems operate. To separate signals from different terminals, there have to be some distinguishing features to exploit. One possibility is to use colours, where each terminal is assigned a unique colour. The base station can then separate signals by using colour filters. The corresponding technique in mobile communications is to assign different radio frequencies to each terminal. Another approach is to organise communication from different terminals in a strict time schedule, so that only one terminal is transmitting to the base station at any moment in time. A critical observation regarding both these techniques is that more resources are needed whenever a new terminal enters the system. In the first case, an additional colour/frequency is required, while in the second case another time-slot has to be assigned. Even the latest, fourth, generation mobile systems operate to a large extent according to these basic principles.

**Now, let us take the conceptual leap** of replacing the omni-directional light sensor at the base station with a digital camera. Suddenly, the base station can distinguish not only intensity and colour, but also the direction from which a light signal is coming. With this new arrangement, each little dot, pixel, in the image sensor of the camera can be used in the same way as the omni-directional light sensor in the previous example. As long as the image of transmitting light sources of two terminals fall on different pixels, they are easily separated by the base station even if they transmit at the same time. Only when they fall in the same pixel do they have to be separated using colour/frequency or time as in the first example. In principle, our communication capacity is multiplied by the number of available pixels on our camera sensor, without the need for more colour/frequency or time resources. By using a massive number of light sensors/pixels, communication capacity can be massively increased. The same basic principles can be used in radio-based mobile communication systems, with some minor conceptual changes. Light sources on terminals are replaced by antennas and the digital camera on the base station by a massive array of antennas. The two major differences between the light analogy and real radio-based mobile communication are that *i)* the focusing of light performed by a lens in the first case is replaced by digital processing of antenna signals in the second and *ii)* while light travel essentially in straight lines, radio signals can bend around corners, making it possible to communicate also out of the line of sight.

**Improving wireless communication** by using multiple antennas is usually called multiple-input/multiple-output (MIMO) communication, and it has been employed on a small scale in existing systems. Up to eight antennas are specified in fourth generation systems, while we in our research are taking the number of antennas to the extreme in what is called massive MIMO. Theoretical studies are performed with arbitrary numbers of antennas at the base station and real-time experimental tests are performed on a flexible 100-antenna testbed, where new algorithms and concepts can be verified. The custom-made testbed that we have developed at Lund University in cooperation with National Instruments can be seen as a fully programmable base station, where every aspect of the radio transmission and reception on all 100 antennas can be controlled in great detail. It is the largest and most capable testbed of its kind in the world.

**Together with colleagues** at Linköping University we identified the potential of massive MIMO at a very early stage, and the formation of the strategic research area ELLIIT (Excellence Center at Linköping – Lund in Information Technology) enabled us to join forces and gather the critical mass to exploit different aspects of massive MIMO, spanning the entire range from pure theoretical analysis of possibilities and limitations to the testbed implementation where we bring advanced lab technology all the way to a real world deployment. ELLIIT researchers are seen as pioneers in the area and as a result of the establishment of ELLIIT we have built up a world-leading position together with our colleagues in Linköping.

**The wide range of research disciplines** needed to fully understand massive MIMO makes it a truly multi-disciplinary effort, where many fundamental questions land on the border between traditional research areas. Interaction between the propagation environment and the antennas is much stronger than in traditional systems, bringing antenna design and wireless propagation studies closer together than ever before. The specific properties of the resulting communication channel has a major impact on how antenna signals should be processed to obtain


**IMAGE »** The Lund University massive MIMO testbed, LuMaMi, with all its antenna elements at the front and the radio units behind. The testbed, including the antenna, is 1.2 m wide and 1.5 m tall.


maximum performance at a minimum of processing effort, using novel hardware solutions. Entirely new approaches are required and this brings together the areas of communication theory, signal processing, and analogue/digital hardware design.

**Massive MIMO results open up** for many challenges when it comes to both fundamental research and implementation-related issues. Challenges include, for example, wave propagation in a massive MIMO context and the interaction between the wireless propagation channel, the massive antenna, and the signal processing algorithms, i.e. the mathematical calculations that are applied to attain high efficiency and separate the users that are transmitting at the same time on the same frequency. Radio waves do not behave exactly like light, so the analogy above with the camera is slightly oversimplified; in order to design and optimise algorithms that separate users transmitting simultaneously we need a deep understanding of the propagation behaviour. This behaviour is of course the same whichever radio-based technique we are using for transmission, but the importance of various properties changes with the transmission technology used. In conventional cellular systems, the base station antenna typically has a limited size and there are typically only up to four antennas simultaneously serving a user in the most advanced cellular systems of today. When we put hundreds of antennas at the base station, not all antenna elements experience the same channel properties, and this has to be taken into account in both system and algorithm design. Going back to the camera example, there can be very bright light in parts of the picture and very dark areas in the picture at the same time. This creates a problem for the detection and transmission algorithms as it can be hard to see the fine details in the darker areas, details which are needed to separate the users from each other. Also, in order to achieve the promises of highly energy-efficient transmission using massive MIMO, algorithms have to learn, follow and adjust to the instantaneous channel condition thousands of times per second. It is therefore crucial that the complexity of detection and transmission algorithms is reduced to a level where processing requirements actually can be managed. It is still an open question how algorithms and shuffling of data inside the base station is to be implemented in the most energy-efficient and cost-efficient way, and hence this is another very important area of research. The energy and cost efficiency aspect is also essential when it comes to the hardware design. Massive MIMO offers new design challenges for the hardware, but also provides opportunities for efficient silicon implementations. The excess number of the antennas at the base station can to some extent be used to relax the requirements of, for example, highly accurate amplifiers, which in turn translates to even better energy efficiency and lower costs for the whole system. The highly parallel structure used to handle the many antennas in the base station also allows for efficient hardware implementation. As opposed to conventional wireless and cellular systems, the massive MIMO system is not dependent on a single antenna behaviour, including its radio and signal processing parts, but relies on the combined effect of hundreds of such radio chains. This opens up possibilities for using low-cost, low-power technology even in base stations that are traditionally based on more expensive and highly accurate components.

**On top of the above-mentioned challenges** to get a massive MIMO system to work and provide the basic service, i.e. transmitting bits from one place to another, with high efficiency from a transmission and energy perspective, there are all the other challenges typically encountered in any large-scale communication system. These are also dealt with within ELLIIT and concern applications, additional services, software development, etc. The breadth of expertise of the ELLIIT researchers has made it possible to include those aspects at an early stage in the discussions and solutions for a complete system.

The successful work on massive MIMO has attracted a lot of international interest both in academia and in industry. Since the technology is a main candidate to be adopted in the next generation of wireless systems, 5G, we are cooperating with industrial partners both in Sweden and internationally to further develop the technology, to identify any possible bottlenecks and to establish best practice for how to apply and implement it. In January 2014 we started a new EU project, Massive MIMO for Efficient Transmission (MAMMOET), to take the technology from the lab to reality together with our partners: the research institute Imec in Belgium, the operator Telefonica in Spain, the Swedish systems provider Ericsson, the chip manufacturer Infineon and the coordinator Technikon in Austria and the universities of Linköping and Leuven, in Sweden and Belgium. We also cooperate with the originator of massive MIMO, Thomas Marzetta at Alcatel-Lucent Bell Labs in the US who is also in the advisory groups of both ELLIIT and MAMMOET.

**All in all, the promising initial results** that we saw already in 2010 spurred us to take new initiatives and gather a critical mass for exploitation of this new technology in the field of ICT. The coherent multidisciplinary effort would probably not have taken place without the creation of the strategic research area, and this has enabled us to move many traditional research areas forward. Seen from an academic perspective, these efforts have already paid off in terms of reputation, publications, citations and new interesting research projects, and we are convinced that in the near future they will also pay off from an industrial perspective by keeping the Swedish telecommunications industry at a highly competitive level and opening up new opportunities for the future.


**IMAGE »** Part of the Lund University massive MIMO testbed, LuMaMi, with 20 of the 100 antenna elements at the front and some of the radio units behind.

# More info & contact

For further information visit our webpage: www.eit.lth.se

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