MIMO technology is a way of using multiple antennas to simultaneously transmit multiple streams of data in wireless communication systems. MIMO in cellular systems brings improvements on four fronts:

- **improved data rate**, because the more antennas, the more independent data streams can be sent out;
- **improved reliability**, because the more antennas the more possible paths that the radio signal can propagate over;
- **improved energy efficiency**, because the base station can focus its emitted energy into the spatial directions where it knows that the terminals are located; and
- **reduced interference** because the base station can purposely avoid transmitting into directions in which spreading interference would be harmful.

Basically, the more antennas the base station (and terminal) are equipped with, the better performance in all these four respects. MIMO technology for wireless communications in its conventional form is maturing, and being incorporated into recent and evolving wireless broadband standards like 4G LTE and LTE-advanced. For example, the LTE standard allows for up to 8 antenna ports at the base station.

**Massive MIMO** is an emerging technology, that scales up MIMO by an order of magnitude compared to current state-of-the-art. We think of systems that use antenna arrays with a few hundred antennas, that simultaneously serve many tens of terminals in the same time-frequency resource. The basic premise behind massive MIMO is to reap all the benefits of conventional MIMO, but in a much greater scale. Overall, massive MIMO is an enabler for the development of future broadband (fixed and mobile) networks which will be energy-efficient, secure, and robust, and will use the spectrum efficiently. As such, it is an enabling technology for the future digital society infrastructure that will connect the Internet of people, Internet of things, with clouds and other network infrastructure. Many different configurations and deployment scenarios for massive MIMO can be envisioned, see Figure 1.

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Massive MIMO technology relies on phase-coherent but computationally very simple signal processing of signals from all the antennas at the base station. The specific characteristics of a massive MIMO system are:

- Massive MIMO can increase the capacity 10 times or more, owing to aggressive spatial multiplexing. Simultaneously, massive MIMO can improve the energy-efficiency in the order of 10-100 times.

The fundamental principle that makes this possible is that with large number of antennas, energy can be focused extremely sharply into small regions in space. Fig. 2 illustrates this. The underlying physics is coherent superposition: By appropriately shaping the signals sent out by the antennas, the base station can make sure that all radio wave fronts collectively emitted by all antennas interfere constructively at the intended terminals, but destructively almost everywhere else.

More concretely, Fig. 3 depicts the fundamental tradeoff between energy efficiency in terms of bits transmitted per Joule of energy spent, and spectral efficiency in terms of bits transmitted per unit radio spectrum consumed. The figure illustrates the relation for the uplink (from the terminals to the base station). The figure shows the tradeoff for three cases:

- a reference system with one single antenna serving single terminal (green)
- a system with 100 antennas serving a single terminal using conventional beamforming (blue)
- a massive MIMO system with 100 antennas serving multiple (about 40 here) terminals simultaneously (red)

The massive MIMO system uses maximum-ratio combining at the terminal—a computationally nearly trivial signal processing technique, which consists of multiplying the
received signals with the conjugate of the channel response. This operation can be performed in a distributed fashion, independently at each antenna unit. The prediction in Figure 3 is based on an information-theoretic analysis that takes into account interference as well as the bandwidth and energy cost of using pilots to acquire channel state information.\(^2\)

With massive MIMO, we would likely operate in the nearly noise-limited regime of information theory. This means providing each terminal with a rate of about 1 bit per complex dimension (1 bps/Hz). Consequently, multiuser interference and effects from hardware imperfections, that constitute limiting factors for conventional MIMO, mostly drown in the thermal noise in massive MIMO systems. This is also why simple signal processing techniques work so well. Since many tens of terminals are served simultaneously, in the same time-frequency resource, the overall spectral efficiency is 10 times higher than in conventional MIMO, as seen in Fig. 3.

- Massive MIMO can be built with inexpensive, low-power components.

Massive MIMO is a game-changing technology and represents a paradigm shift in the way of thinking both with regards to theory, systems and implementation. Conventional MIMO technology requires extremely accurate hardware components in order to work. With massive MIMO, expensive, ultra-linear 50 Watt amplifiers are replaced by hundreds of low-cost amplifiers with output power in the milliWatt range. The contrast to classical array designs, which use few antennas fed via coaxial cables from a high-power amplifier, is significant. Several expensive and bulky items, such as large coaxial cables, can be eliminated altogether. (The typical coaxial cables used for tower-mounted base stations today are more than four centimeters in diameter!) The ultimate vision of very large MIMO systems is that the antenna system would consist of small active antenna units, plugged into an (optical) fieldbus. The same property that makes massive MIMO resilient against fading also makes the technology extremely robust to failure of one or a few of the antenna units.

Massive MIMO reduces the constraints on accuracy and linearity of each individual amplifier and RF chain. All what matters is the combined action of all. In a way, massive MIMO relies on the law of large numbers to make sure that noise, fading and hardware imperfections average out when signals from a large number of antennas are combined in the air together. In addition, a massive MIMO system has a surplus of degrees of freedom: with 200 antennas serving 20 terminals, 180 degrees of freedom are unused. These degrees of freedom can be used for hardware-friendly signal shaping. Concretely, this means that each antenna can transmit signals with very small peak-to-average ratio\(^3\) or


Figure 2: Focusing of energy sharply into small regions in space with massive MIMO. Left: received wavefield with a 10-element array. Right: received wavefield with a massive (100-element) array. The color map shows the focusing of energy in space – red represents large power and blue represents low power. The intended terminal is located at the center of the map.

Figure 3: Half the power—twice the force: Improving uplink spectral efficiency 10 times and simultaneously reducing electricity consumption 100 times with massive MIMO technology, using extremely simple signal processing (maximum ratio combining) and taking into account the costs of obtaining channel state information.
Figure 4: Conventional MIMO beamforming, contrasted with per-antenna constant-envelope transmission in massive MIMO. Left: conventional beamforming. The signal emitted by each antenna has a dynamic range from 0 to $\sqrt{P|u|}$. Right: per-antenna constant-envelope transmission. Each antenna sends out a signal with unit magnitude. Nonwithstanding that, the effective channel between the base station and the terminals, can take any constellation as input and does not require the use of PSK-type modulation. An interpretation is by choosing the phase angles per antenna, the base station generates a wavefield such that when this field is sampled at the locations of the terminals, each terminal will see the signal that we desire to communicate.

even constant envelope$^4$ at a very modest performance penalty. Such per-antenna constant envelope or near-constant envelope signaling in a massive MIMO system must not be confused with beamforming techniques used in conventional MIMO, see Fig. 4.

The drastically improved energy efficiency enables massive MIMO systems to operate with a total output RF power an order of magnitude less than with current technology. This matters, because the electricity consumption of cellular base stations is a growing concern worldwide. As a bonus, the total emitted power can be dramatically cut and therefore the base station will generate substantially less EMF interference. This is important owing to the increased concerns of electromagnetic exposure.

- Massive MIMO enables a significant reduction of latency on the air interface.

  The performance of wireless communications systems is normally limited by fading. The fading can render the received signal strength very small at some times. This happens when the signal sent from a base station travels through multiple paths before it reaches the terminal, and the wave patterns resulting from these multiple paths interfere in a

Massive MIMO relies on the law of large numbers in order to average out fading effects, so that fading no longer limits latency.

- **Massive MIMO simplifies the multiple-access layer.**
  
  Each terminal can be given the whole bandwidth, which eliminates the need for frequency-scheduling and makes most of the physical-layer control signaling redundant.

- **Massive MIMO increases the robustness to intentional jamming.**
  
  Intentional jamming of civilian wireless systems is a growing problem, especially for public safety applications. During the EU summit in Gothenburg, Sweden, in 2001, the situation went chaotic when demonstrators used a jammer located in a nearby apartment to destroy the police’s communication. During critical phases of the riots, the chief commander could not reach any of the engaged 700 police officers.\(^5\) The physical basis for the robustness of massive MIMO is the same as what enables energy-efficient transmission (Fig. 2): the base station can focus its attention on a small spatial region where the terminal is located, and ignore signals that originate from everywhere else.

Massive MIMO relies to a large extent on a property of the radio environment called *favorable propagation*. Simply stated, favorable propagation means that propagation channel responses from the base station to different terminals are sufficiently different. One way of quantifying

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how different the channel responses to different terminals are, is to look at the spread between
the smallest and largest singular value of the channel. Figure 6(a) illustrates this for a computer-
simulated “i.i.d.” channel. This ideal case represents the best we can hope for. More specifically
the figure shows the cumulative density function for the smallest respectively the largest singular
value for two cases:

- a conventional array of 6 elements serving 6 terminals (red curves), and
- a massive array of 128 elements serving 6 terminals (blue curves)

For the 6-element array, the singular value spread is about 30 dB, meaning that 1000 times more
power would be required to serve all six terminals, as compared to the power required to serve
just one of them. With the massive array, the gap is less than 3 dB. Since the blue curves have
no substantial tails, the probability of seeing a power gap that is substantially larger than 3 dB
is negligible.

To what extent do channels in reality have the favorable propagation property that ideal channels
(Fig. 6(a)) have? To answer this, measurements were conducted using an indoor 128-antenna
base station consisting of four stacked double polarized 16 element circular patch arrays, see
Fig. 5. To what extent do channels in reality have the favorable propagation property that ideal channels
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Fig. 5.1 Three of the terminals are indoors at various positions and 3 users are outdoors. The
measurements were performed at 2.6 GHz with a bandwidth of 50 MHz, and the results were
averaged over this bandwidth and over a physical displacement of 10 meters. The blue curves

Figure 6: Singular value spread of massive MIMO channels.
in Fig. 6(b) show the corresponding singular value distributions. It is striking how well reality resembles the ideal case in Fig. 6(a). The spread between the smallest and the largest singular value is a bit larger than for the ideal case, but the probability that the spread exceeds 10 dB is negligible. As a reference, Fig. 6(b) also shows the result when only 6 of the 128 elements are activates (red curves). Overall, there is compelling evidence that the assumptions on favorable propagation that underpin massive MIMO are substantially valid in practice.