ECE573 Project Report

Massive MIMO

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Introduction

Two timeless truths are evident: first, demand for wireless throughput will always grow; second, the quantity of available electromagnetic spectrum will never increase. The fundamental and perennial wireless problem is a physical layer problem: how to provide ever-increasing total wireless throughput reliably and uniformly throughout a designated area [1, 2]. Massive multiple-input multiple-output (MIMO) is an emerging technology that scales up MIMO by possibly orders of magnitude compared to the current state of the art. In this article, we follow up on our earlier exposition [1], with a focus on the developments in the last three years; most particularly, energy efficiency, exploitation of excess degrees of freedom, time-division duplex (TDD) calibration, techniques to combat pilot contamination, and entirely new channel measurements.

With massive MIMO, we think of systems that use antenna arrays with a few hundred antennas simultaneously serving 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 on 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 enabler for the future digital society infrastructure that will connect the Internet of people and Internet of Things with clouds and other network infrastructure. Many different configurations and deployment scenarios for the actual antenna arrays used by a massive MIMO system can be envisioned (Fig. 1), such as Linear, rectangular and Cylindrical.

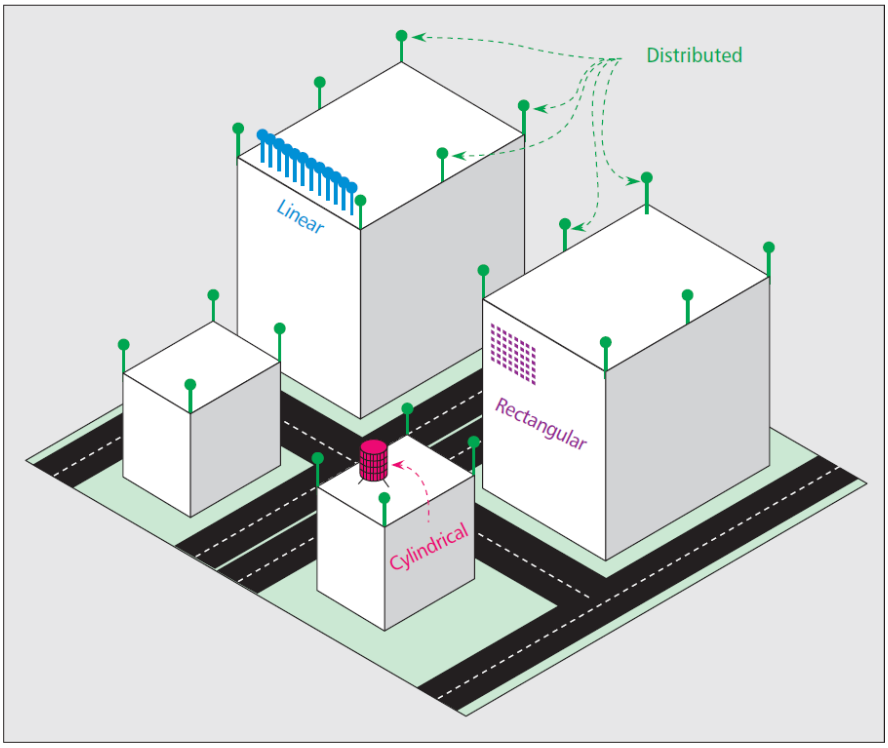

Fig 1.

Massive MIMO relies on spatial multiplexing, which in turn relies on the base station having good enough channel knowledge, on both the uplink and the downlink. On the uplink, this is easy to accomplish by having the terminals send pilots, based on which the base station estimates the channel responses to each of the terminals. The downlink is more difficult. In conventional MIMO systems such as the Long Term Evolution (LTE) standard, the base station sends out pilot waveforms, based on which the terminals estimate the channel responses, quantize the thus obtained estimates, and feed them back to the base station. This will not be feasible in massive MIMO systems, at least not when operating in a high-mobility environment, for two reasons. First, optimal downlink pilots should be mutually orthogonal between the antennas. This means that the amount of time-frequency resources needed for downlink pilots' scales with the number of antennas, so a massive MIMO system would require up to 100 times more such resources than a conventional system. Second, the number of channel responses each terminal must estimate is also proportional to the number of base station antennas. Hence, the uplink resources needed to inform the base station of the channel responses would be up to 100 times larger than in conventional systems. Generally, the solution is to operate in TDD mode, and rely on reciprocity between the uplink and downlink channels, although frequency-division duplex (FDD) operation may be possible in certain cases [3].

Advantages

Massive MIMO technology relies on phase coherent but computationally very simple processing of signals from all the antennas at the base station. Some specific benefits of a massive MU-MIMO system are the following points.

Massive MIMO can increase the capacity 10 times or more and simultaneously improve the radiated energy efficiency on the order of 100 times. The capacity increase results from the aggressive spatial multiplexing used in massive MIMO. The fundamental principle that makes the dramatic increase in energy efficiency possible is that with a large number of antennas, energy can be focused with extreme sharpness into small regions in space. The underlying physics is coherent superposition of wavefronts. By appropriately shaping the signals sent out by the antennas, the base station can make sure that all wavefronts collectively emitted by all antennas add up constructively at the locations of the intended terminals, but destructively (randomly) almost everywhere else. Interference between terminals can be suppressed even further by using, for example, zero-forcing (ZF). This, however, may come at the cost of more transmitted power

Massive MIMO can be built with inexpensive, low-power components. Massive MIMO is a game changing technology with regard to theory, systems, and implementation. With massive MIMO, expensive ultra-linear 50 W amplifiers used in conventional systems are replaced by hundreds of low-cost amplifiers with output power in the Milli-Watt range. The contrast to classical array designs, which use few antennas fed from high-power amplifiers, is significant. Several expensive and bulky items, such as large coaxial cables, can be eliminated altogether.

Massive MIMO reduces the constraints on accuracy and linearity of each individual amplifier and RF chain. All that matters is their combined action. 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. 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 unit(s).

Massive MIMO enables a significant reduction of latency on the air interface. The performance of wireless communications systems is normally limited by fading. Fading can render the received signal strength very small at certain times. This happens when the signal sent from a base station travels through multiple paths before it reaches the terminal, and the waves resulting from these multiple paths interfere destructively. It is this fading that makes it hard to build low-latency wireless links. If the terminal is trapped in a fading dip, it has to wait until the propagation channel has sufficiently changed until any data can be received. Massive MIMO relies on the law of large numbers and beamforming in order to avoid fading dips, so fading no longer limits latency.

Massive MIMO simplifies the multiple access layer. Due to the law of large numbers, the channel hardens so that frequency domain scheduling no longer pays off. With OFDM, each subcarrier in a massive MIMO system will have substantially the same channel gain. Each terminal can be given the whole bandwidth, which renders most of the physical layer control signaling redundant.

Massive MIMO increases the robustness against both unintended man-made interferences and intentional jamming. Intentional jamming of civilian wireless systems is a growing concern and a serious cybersecurity threat that seems to be little known to the public. Simple jammers can be bought off the Internet for a few hundred dollars, and equipment that used to be military-grade can be put together using off-the-shelf software radio-based platforms for a few thousand dollars. Numerous recent incidents, especially in public safety applications, illustrate the magnitude of the problem. During the EU summit in Gothenburg, Sweden, in 2001, demonstrators used a jammer located in a nearby apartment, and during critical phases of riots, the chief commander could not reach any of the 700 police officers engaged [4].

Due to the scarcity of bandwidth, spreading information over frequency just is not feasible, so the only way of improving robustness of wireless communications is to use multiple antennas. Massive MIMO offers many excess degrees of freedom that can be used to cancel signals from intentional jammers. If massive MIMO is implemented using uplink pilots for channel estimation, smart jammers could cause harmful interference with modest transmission power. However, cleverer implementations using joint channel estimation and decoding should be able to substantially diminish that problem.

Limitations

Pilot Contamination

Ideally, every terminal in a massive MIMO system is assigned an orthogonal uplink pilot sequence. However, the maximum number of orthogonal pilot sequences that can exist is upper-bounded by the duration of the coherence interval divided by the channel delay spread.

The effect of reusing pilots from one cell to another and the associated negative consequences is termed pilot contamination. More specifically, when the service array correlates its received pilot signal with the pilot sequence associated with a particular terminal, it actually obtains a channel estimate that is contaminated by a linear combination of channels with other terminals that share the same pilot sequence. Downlink beamforming based on the contaminated channel estimate results in interference directed at those terminals that share the same pilot sequence. Similar interference is associated with uplink transmissions of data.

Channel Reciprocity

Time-division duplexing operation relies on channel reciprocity. There appears to be a reasonable consensus that the propagation channel itself is essentially reciprocal unless the propagation is affected by materials with strange magnetic properties. However, the hardware chains in the base station and terminal transceivers may not be reciprocal between the uplink and the downlink.

Note that calibration of the terminal uplink and downlink chains is not required in order to obtain the full beamforming gains of massive MIMO: if the base station equipment is properly calibrated, the array will indeed transmit a coherent beam to the terminal. (There will still be some mismatch within the receiver chain of the terminal, but this can be handled by transmitting pilots through the beam to the terminal; the overhead for these supplementary pilots is very small.) Absolute calibration within the array is not required. Instead, as proposed in [3], one of the antennas can be treated as a reference, and signals can be traded between the reference antenna and each of the other antennas to derive a compensation factor for that antenna. It may be possible to entirely forgo reciprocity calibration within the array; for example, if the maximum phase difference between the uplink and downlink chains were less than 60°, coherent beamforming would still occur (at least with MRT beamforming), albeit with a possible 3 dB reduction in gain.

There are also other limitations such as radio propagation and orthogonality of channel responses.

Conclusion

The technology offers huge advantages in terms of energy efficiency, spectral efficiency, robustness, and reliability. It allows for the use of low-cost hardware at both the base station and the mobile unit side. At the base station the use of expensive and powerful, but power-inefficient, hardware is replaced by massive use of parallel low-cost low power units that operate coherently together. There are still challenges ahead to realize the full potential of the technology, for example, computational complexity, realization of distributed processing algorithms, and synchronization of the antenna units. This gives researchers in both academia and industry, a gold mine of entirely new research problems to tackle.

Reference

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