Massive MIMO

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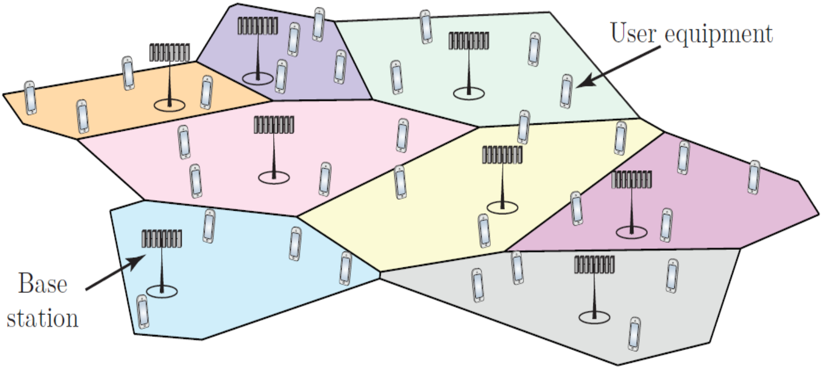
Outline

Introduction

- Cellular network :
  A set of base stations (BSs) and a set of user equipments (UEs).



Emil Björnson, Jakob Hoydis and Luca Sanguinetti (2017), "Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency", Foundations and Trends® in Signal Processing

Introduction

Each UE is connected to one of the BSs.

- Downlink (DL)
  Signals sent from the BSs to their respective UEs
- Uplink (UL)
  transmissions from the UEs to their respective BSs

This presentation focuses on the wireless communication links between BSs and UEs. remaining network infrastructure is assumed to function perfectly.

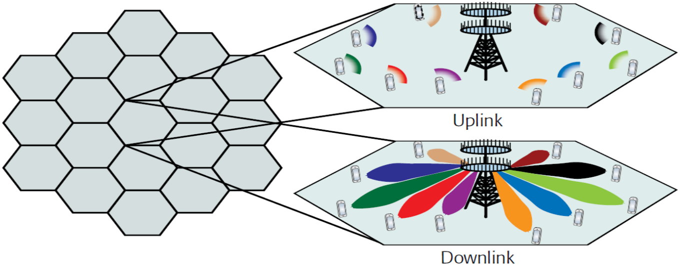
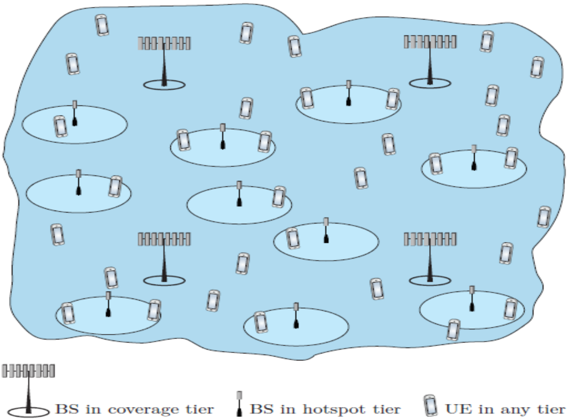


Figure: E. Bjornson, E. G. Larsson and T. L. Marzetta,"Massive mimo: ten myths and one critical question", IEEE Commun. Mag, vol. 54, pp. 114-123,2016.

Introduction

several branches of wireless technologies
they form a heterogeneous network consisting of two main tiers:
Coverage tier & Hotspot tier



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Introduction

1. Coverage tier: Outdoor cellular BSs
   - coverage, elevated base stations
   - Outdoor-to-indoor coverage: Operate ¡6 GHz
   - High spectral efficiency is desired

2. Hotspot tier: Indoor BSs(mainly)
   - High cell density, short range per cell
   - Wide bandwidths in mm-wave bands
   - Spectral efficiency less important

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Improving Cellular Networks

Formula for Network Throughput $[bit/s/km^2]$:

$$\underbrace{Throughput}_{\mathbf{bit/s/km^2}} = \underbrace{Available\ spectrum}_{\mathbf{Hz}} . \underbrace{Cell\ density}_{\mathbf{Cell/km^2}} . \underbrace{Spectral\ efficiency}_{\mathbf{bit/s/Hz/Cell}} \quad (1)$$

Consequently, three main ways to improve the area throughput of cellular networks:

1. Allocate more bandwidth;
2. Densify the network by deploying more BSs;
3. Improve the SE per cell.

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The Success of Wireless Communications

- More devices and data traffic every year
  - 10% more devices
  - 47% more traffic (33% more per device)

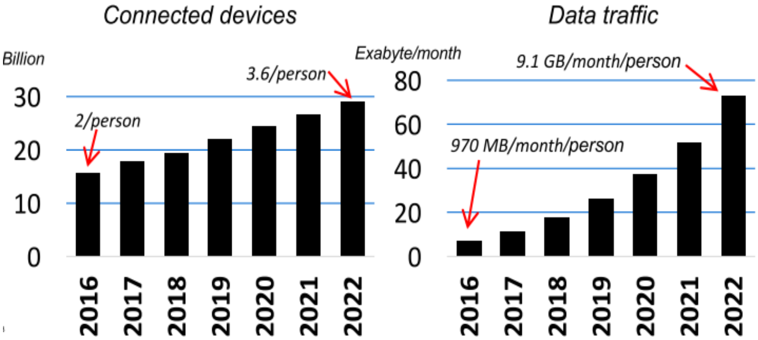

Figure: Data source:Ericsson Mobility Report (July, November 2017)

Improving Cellular Networks

"the 1000$\times$ data challenge"
posed by Qualcomm for next 15–20 years

such a network can handle the three orders-of-magnitude increase in wireless data traffic if the annual traffic growth rate continues to be in the range of 41%–59%.

higher data rates, larger network capacity, higher spectral efficiency, higher energy efficiency, and better mobility

How can handle according to the formula in (1)?

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Improving Cellular Networks

- *increase the bandwidth ?*

Currently more than 1GHz of bandwidth below 6GHz range

$1000\times$ bandwidth

$\Rightarrow$ more than 1 THz of bandwidth

This is physically impractical

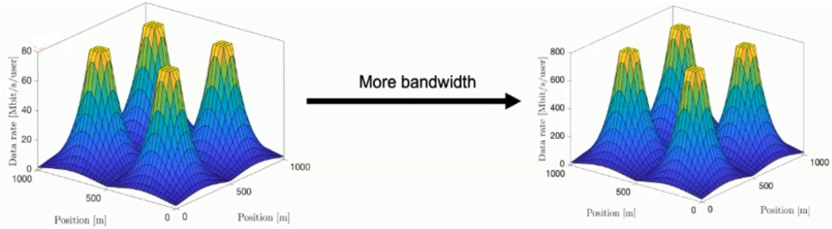

Figure: More BandWidth is not a solution

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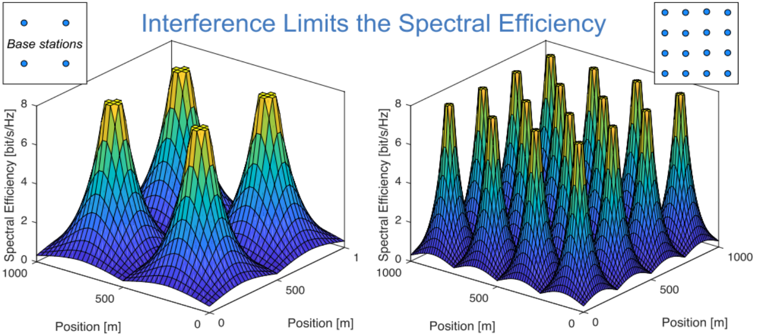
Interference Limits the Spectral Efficiency

- *Densify the cellular network ?*

1. Limited number of locations
2. high deployment costs
3. inter-cell interference issues
4. not suitable for mobile UEs



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YouTube channel: Wireless Future

How to Achieve More Uniform Coverage?

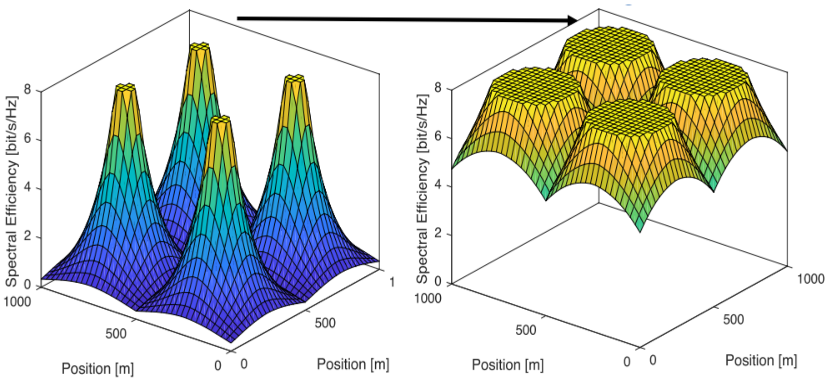

Figure: Desired: Stronger signal, same interference levels

source: YouTube channel: Wireless Future

Definition of Spectral Efficiency

The Nyquist-Shannon sampling theorem implies that the band-limited communication signal that is sent over a channel with a bandwidth of B Hz is completely determined by 2B real-valued equal-spaced samples per second

$$f < 2B$$

Spectral efficiency:
The SE of an encoding/decoding scheme is the average number of bits of information, per complex valued sample, that it can reliably transmit over the channel(bit/s/Hz).

$$\mathrm{SE} = \log_2\left(1 + \frac{\mathrm{Transmit\,signal\,power}\cdot \mathrm{Pathloss}}{\mathrm{interferencepower} + \mathrm{N}_0 \cdot \mathrm{bandwidth}}\right)$$

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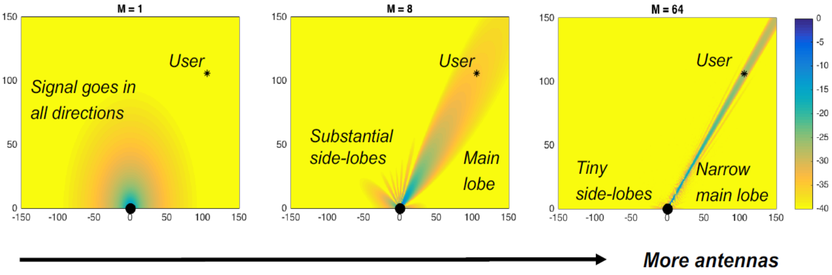
Beamforming is the Solution!



Same transmit power

- Color indicates path loss in dB
- M base station (BS) antennas
- Main lobe focused at user

More antennas

- Narrower beams, laser-like
- Array gain: $10\log_{10}(M)$dB larger at user
- Less leakage in undesired directions

source: YouTube channel: Wireless Future

What is massive MIMO?

Massive MIMO is a scaled up version of the conventional small scale MIMO systems
A multiuser communications solution that employs a large number of antenna elements to serve simultaneously multiple users.

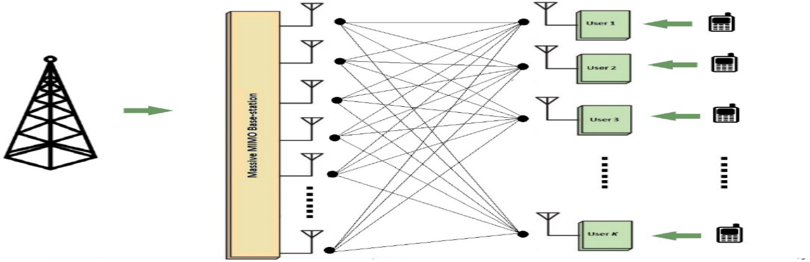


Figure: Base Station Massive MIMO channel User Equipments

M. A. Albreem, M. Juntti and S. Shahabuddin, "Massive MIMO detection techniques: A survey", IEEE Commun. Surv. Tutor, 2019.

What is massive MIMO?

New wireless access technology in 5G, in both sub-6 GHz and mmWave bands

The core technology that likely will be utilized in all future wireless technologies.

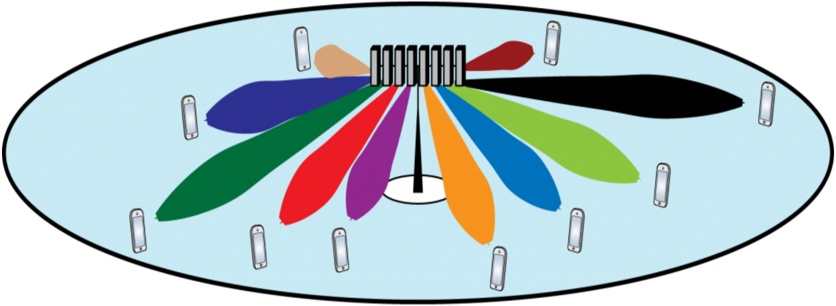


Figure: Illustration of downlink Massive MIMO in line-of-sight communication

source: ma-mimo.ellintech.se

What is massive MIMO?

The key concept is to equip base stations with arrays of many antennas, which are used to serve many terminals simultaneously, in the same time-frequency resource.
The word “massive” refer to the number of antennas and not the physical size.

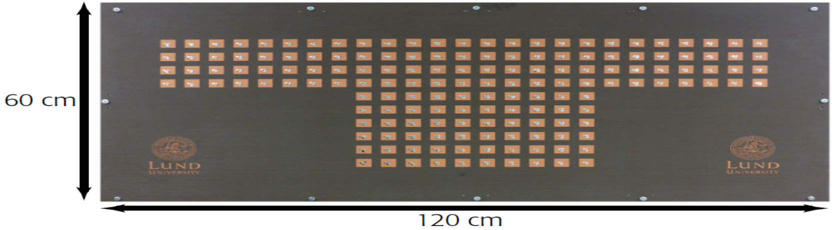


Figure: The array consists of 160 dual-polarized patch antennas. It is designed for a carrier frequency of 3.7 GHz, and the element spacing is 4 cm (half a wavelength).

E. Bjornson, E. G. Larsson and T. L. Marzetta,”Massive mimo: ten myths and one critical question”, IEEE Commun. Mag, vol. 54, pp. 114-123,2016.

Canonical Massive MIMO network Definition:

- A multicarrier cellular network with L cells
- Operate according to a synchronous TDD protocol
- $with\ M_j \geq 1\ antennas$
- $BS\ j\ communicates\ with\ K_j\ UEs\ on\ each\ time/frequency$
- $with\ antenna - UE\ ratio\ M_j/K_j > 1$

Each BS operates individually and processes its signals using:

- linear receive combining
- linear transmit precoding

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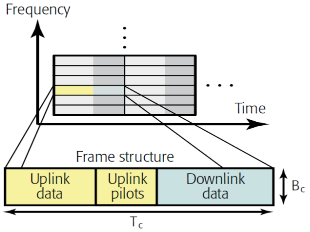
Canonical Massive MIMO network Definition:

The canonical Massive MIMO system operates in TDD mode *reasons*:

- First, only the BS needs to know the channels to process the antennas coherently.
- Second, the UL estimation overhead is proportional to the number of terminals, but independent of M
- basic estimation theory tells us that the estimation quality (per antenna) cannot be reduced by adding more antennas



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Why Massive MIMO?

Massive MIMO relies on increasing the spatial multiplexing gain and the diversity gain by adding the number of antennas at the BS with relatively simple processing of signals from all the antennas

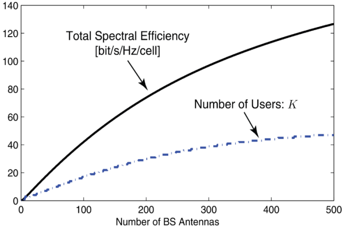
The potential benefits of massive MIMO:

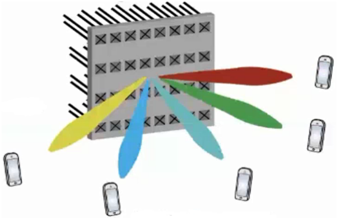
- Capacity and link reliability
- Spectral efficiency
- Energy efficiency
- Security enhancement and robustness improvement
- Cost efficiency
- Signal processing

M. A. Albreem, M. Juntti and S. Shahabuddin, "Massive MIMO detection techniques: A survey", IEEE Commun. Surv. Tutor, 2019.

Why Massive MIMO?

- Capacity and link reliability:
  - Massive MIMO increases the diversity gain, and hence, provides link robustness as it resists fading
  - The capacity increases without a bound as the number of antenna increases





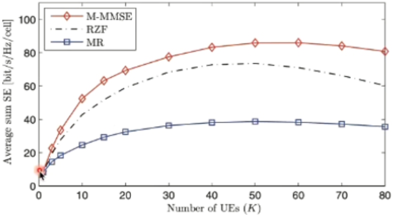
$$\color{red}{\text{Multiplexed users}} \cdot \color{blue}{\text{BW}} \cdot \log_2\left(1 + \frac{\text{Transmit signal power} \cdot \color{green}{\text{Pathloss}}}{\color{green}{\text{interferencepower}} + \text{N}_0 \cdot \color{blue}{\text{BW}}}\right)$$

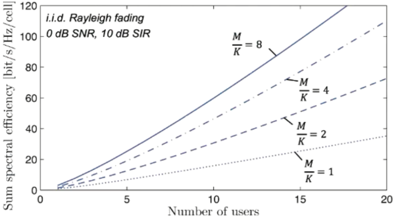
M. A. Albreem, M. Juntti and S. Shahabuddin, "Massive MIMO detection techniques: A survey", IEEE Commun. Surv. Tutor, 2019.
Inaugural talk from (SIIR) Group at Manchester Metropolitan University, UK on "Evolving the Mobile Broadband Connectivity Towards 6G"
YouTube channel: Wireless Future

Why Massive MIMO?

- Spectral efficiency
  - improves the SE of the cellular network by spatial multiplexing of a large number of UEs per cell
  - Numerous antennas
    $\Rightarrow$ more spatial data-streams, more throughput, more multiplexing gain
    $\Rightarrow$ high spectral efficiency

overall spectral efficiency in the massive MIMO can be ten times higher than in the conventional MIMO





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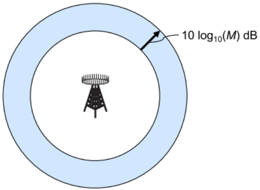
IEEE Signal Processing Society Gujarat Section Expert talk on "MIMO communication in 5G and beyond"

Why Massive MIMO?

Energy efficiency:

- Due to coherent combining, the transmitted power is inversely proportionate to the number of transmit antennas($\propto \frac{1}{n_t}$)
- the throughput increases by increasing the number of transmit antennas and without increasing the transmit power



Same range with reduced power

- Higher rates to already covered places
- Reach new places (e.g., indoor)

Use same transmit power

- Increase battery lifetime in UL
- Low power per antenna in DL 40W then 4W per BS, 40mW/antenna

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YouTube channel: Wireless Future

Why Massive MIMO?

- Security enhancement and robustness improvement:

  mMIMO leads to a large number of degrees of freedom which can be used to cancel the signals from intentional jammers

- Cost efficiency:
  - mMIMO eliminates the need for bulky items such as coaxial cables
  - mMIMO uses cheap mwatts amplifier instead of a multiple expensive HPA
  - can reduce the radiated power$\times$1000 and at the same time drastically maximize the data rates

M. A. Albreem, M. Juntti and S. Shahabuddin, "Massive MIMO detection techniques: A survey", IEEE Commun. Surv. Tutor, 2019.

Why Massive MIMO?

Signal processing:

- A large number of antennas eliminates the:
  - interference effects
  - fast fading
  - uncorrelated noise
  - thermal noise

  $\Rightarrow$ simplifies the signal processing

- channel responses from the base station to user terminals are different (mutually orthogonal, i.e., the inner products are zero).

M. A. Albreem, M. Juntti and S. Shahabuddin, "Massive MIMO detection techniques: A survey", IEEE Commun. Surv. Tutor, 2019.