Towards 6G:

Massive MIMO is a Reality—What is Next?

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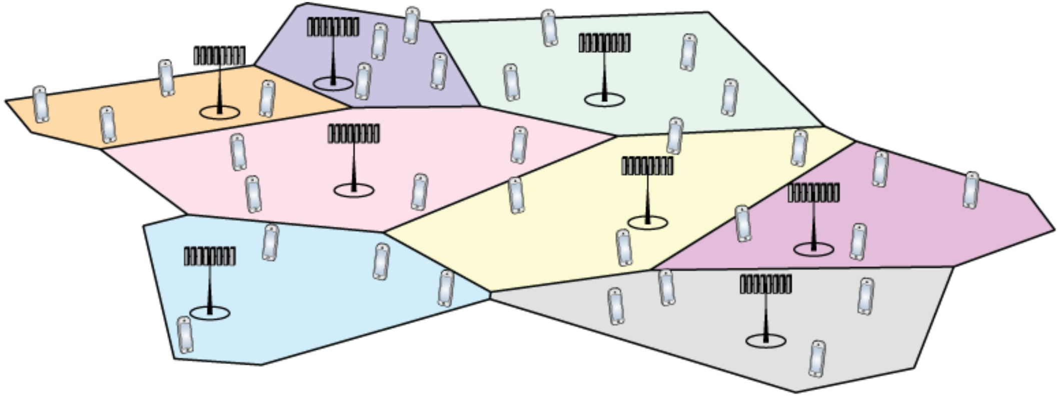
MASSIVE MIMO IS A REALITY

WHAT IS NEXT?

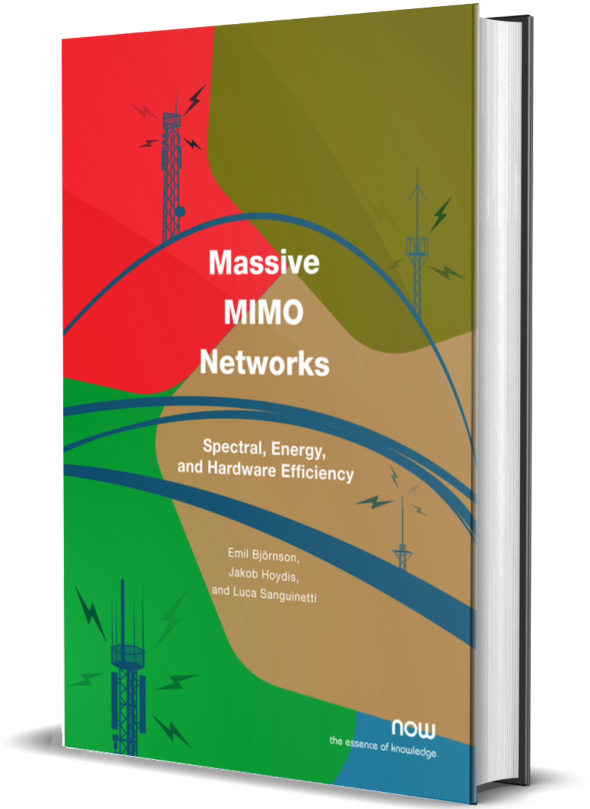
What is Massive MIMO (multiple-input multiple-output)?



- Cellular network
  - Many antennas M per base station
  - Spatial multiplexing of many users K
  - Antenna-user ratio: $M/K > 1$

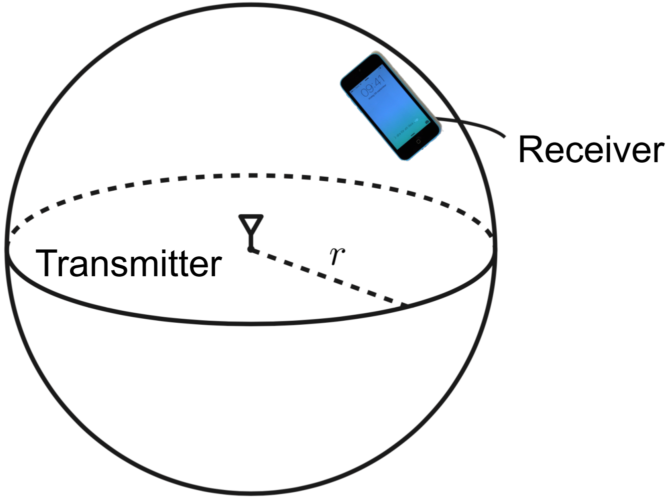
$M \geq 64$

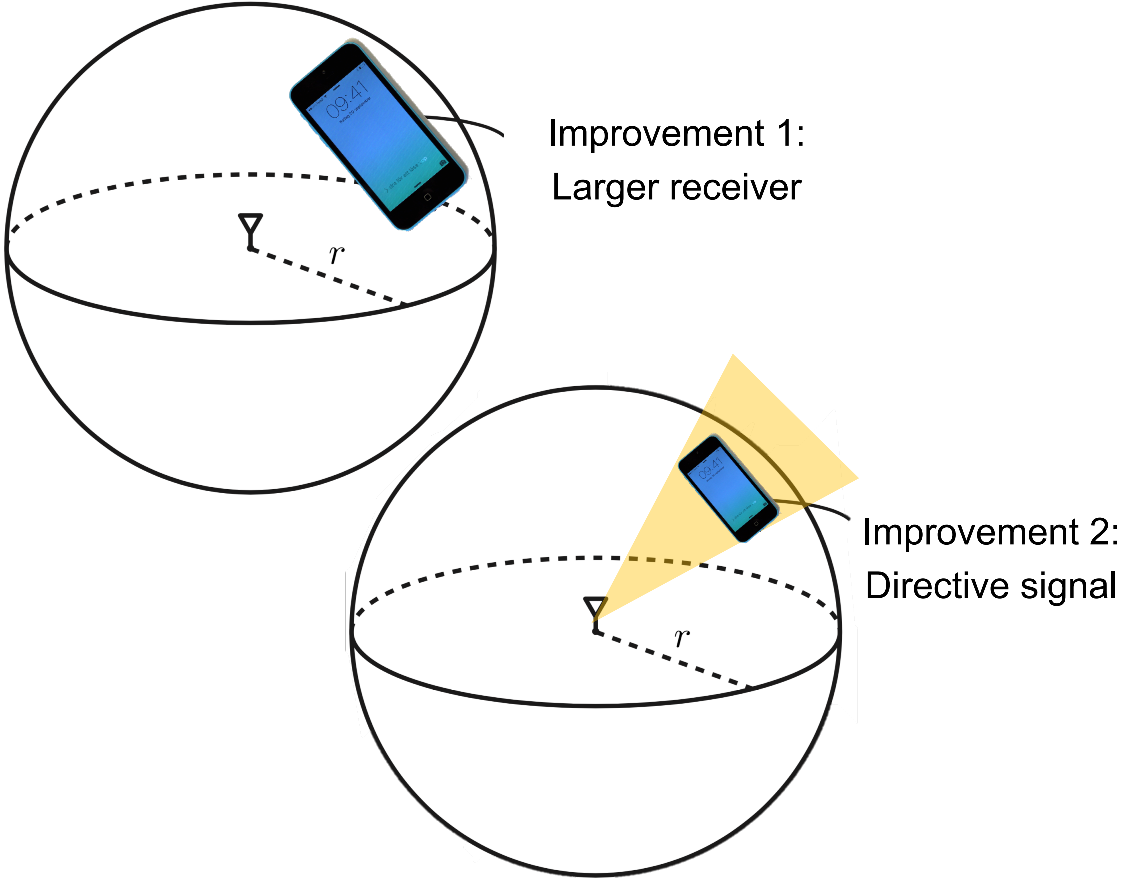
$K \geq 8$



Why is this important in 5G?

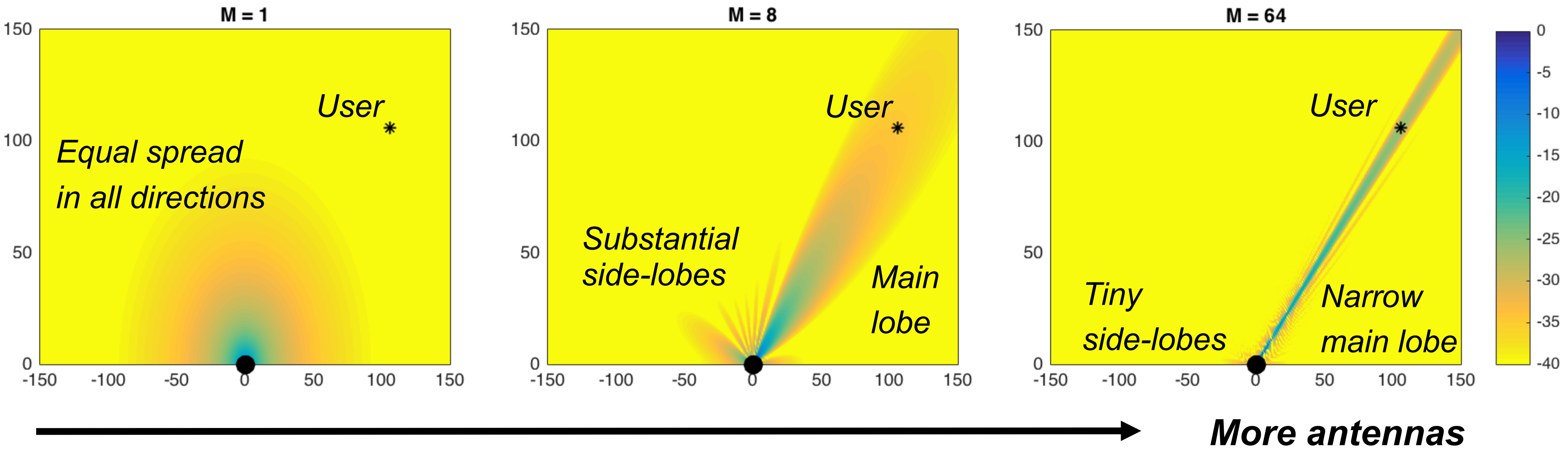
Signal Strength Decays Rapidly With Distance





0.001% received at 1 m
0.00001% received at 10 m
Faster decay in non-line-of-sight

Beamforming is the Solution!



Same transmit power

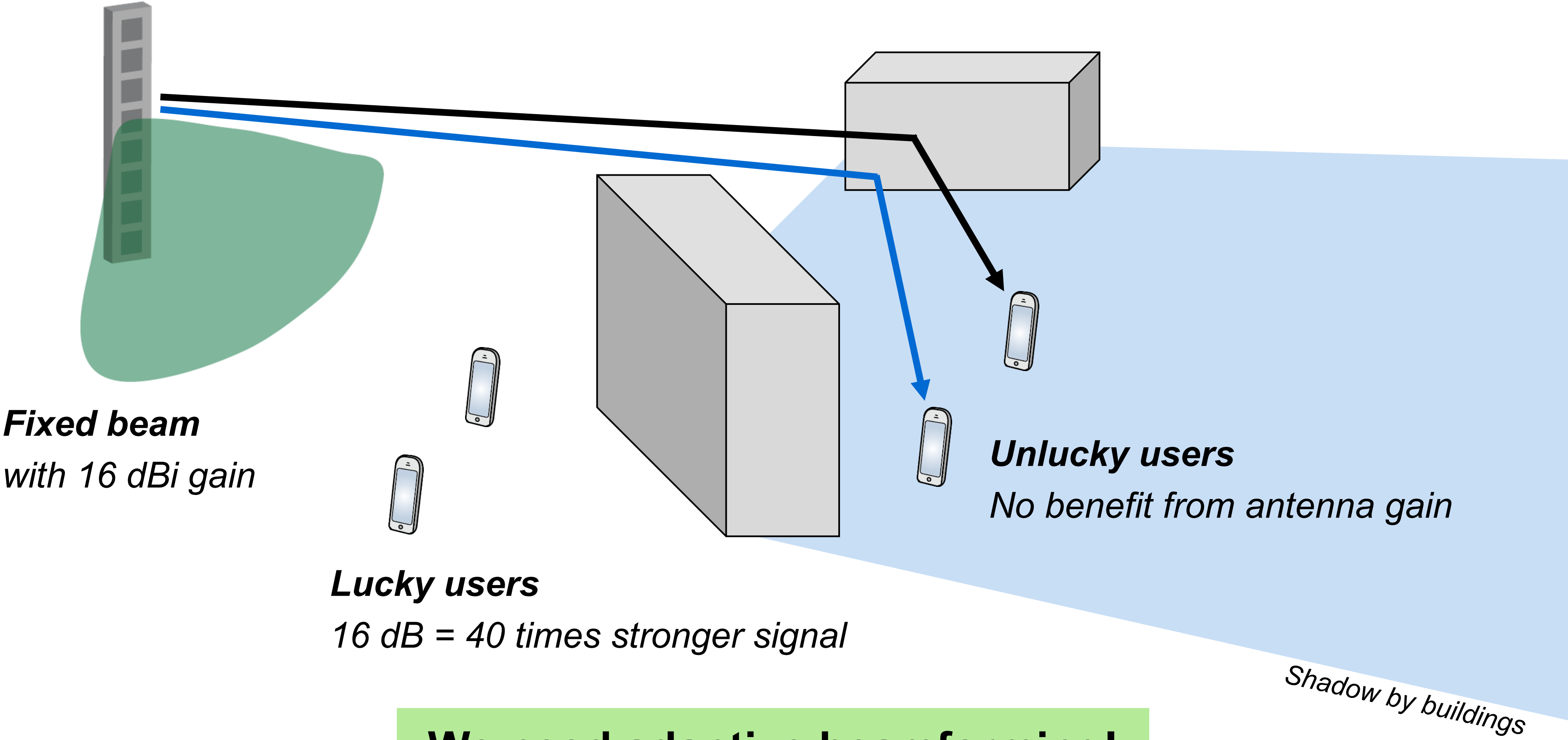
- Color indicates path loss in dB
- Main lobe focused at user

More antennas

- Narrower beams, laser-like
- Less leakage in undesired directions

M antennas → M times stronger received signal

Fixed Beamforming Only Helps Lucky Users



We need adaptive beamforming!

Adaptive Beamforming Using MIMO (multiple-input multiple-output)

Space-division multiple access
Multi-user MIMO

Concept from late 80s, early 90s
Information theory in 00s
Patents submitted in early 90s

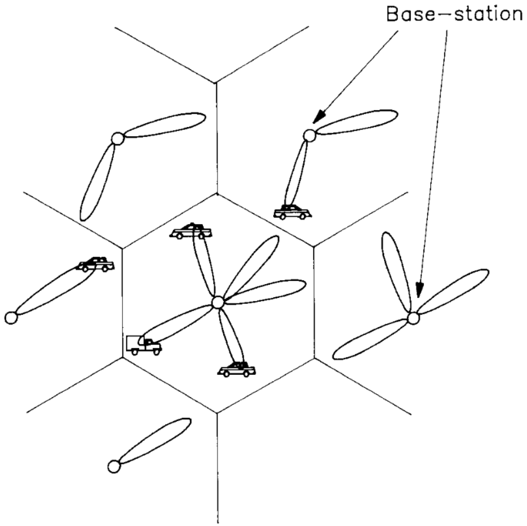
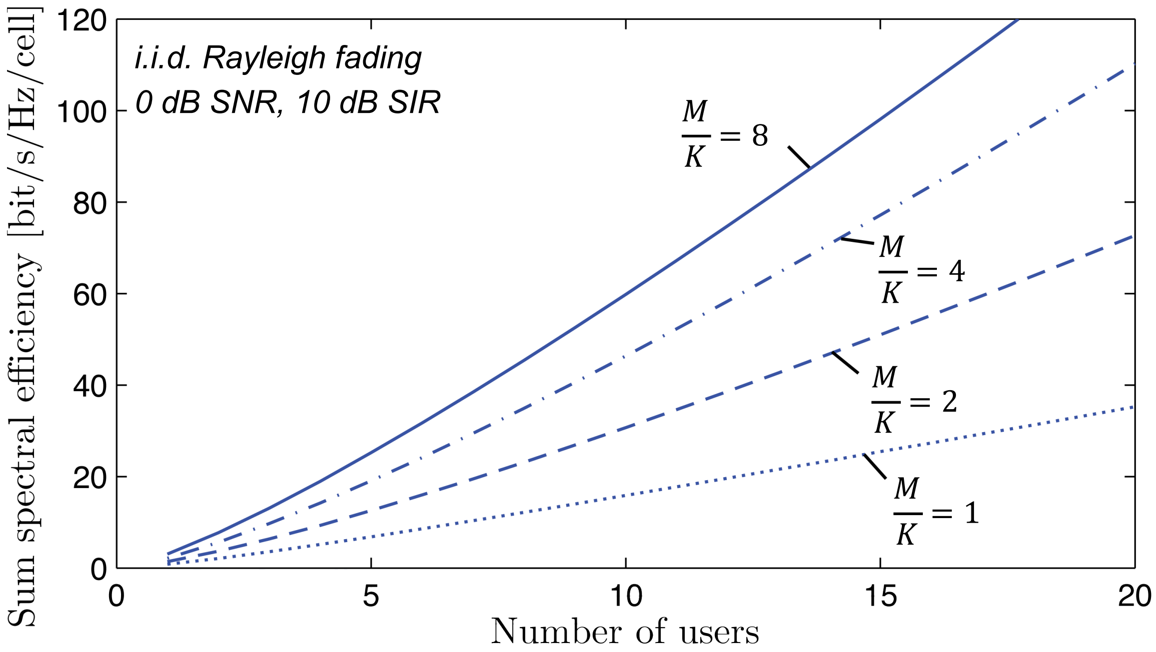


Fig. 2. Tracking of mobiles with multiple beams.

Motivation: Data rate grows with number of antennas M and users K



No Immediate Success

MIMO experiments in the 90s and 00s

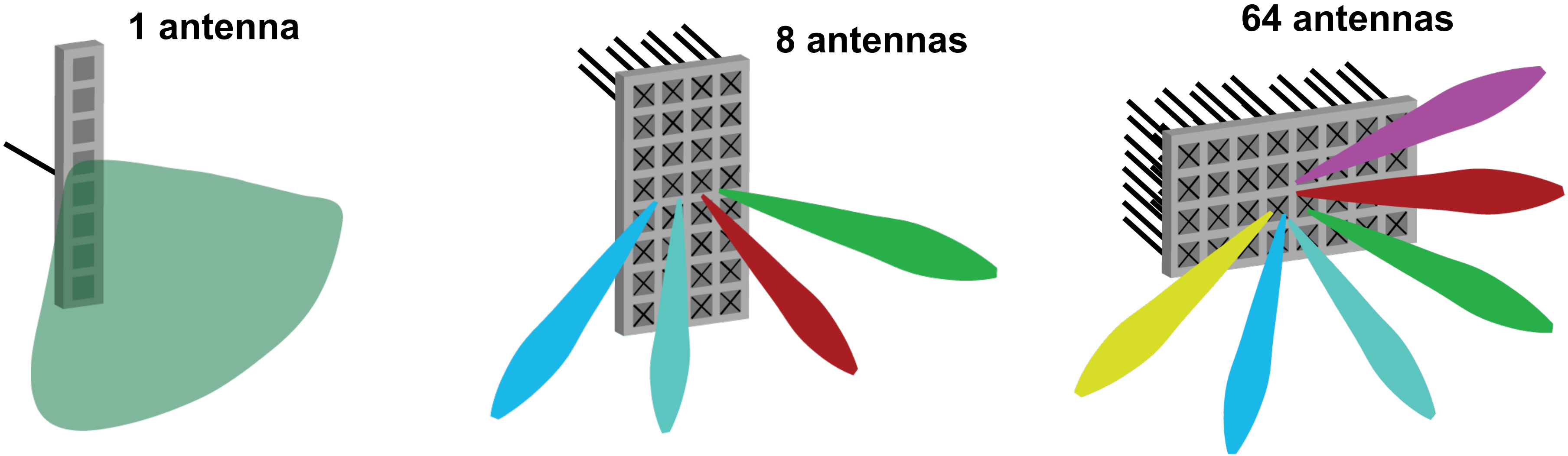
- A few deployments – no commercial success

Negative experience of MIMO:

1. Circuit-switched voice services
2. Complicated to build hardware
3. Communication theory was not ready
4. Number of antennas was fairly small

Photo from ArrayComm, 12 antennas

Last Decade's Evolution of Adaptive Beamforming

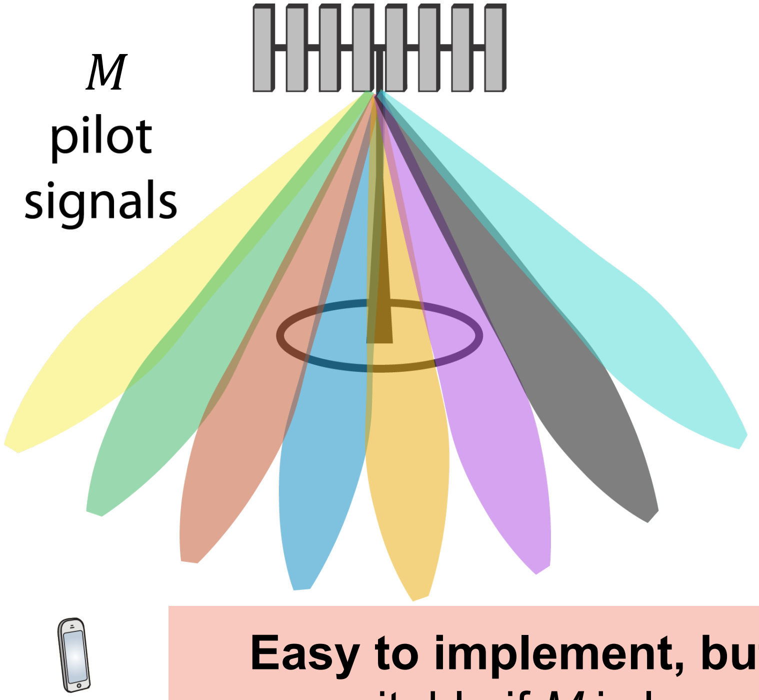


Sector antenna	**Classical antenna array**	**Massive antenna array**
8 elements (7 dBi each)	64 elements (32 per polarization)	64 elements
1 transceiver chain	8 transceiver chains (2 per column)	64 transceiver chains
Fixed beam 16 dBi	Up to 8 horizontal beams	Up to 64 3D beams

Antenna = A set of elements connected to a transceiver chain

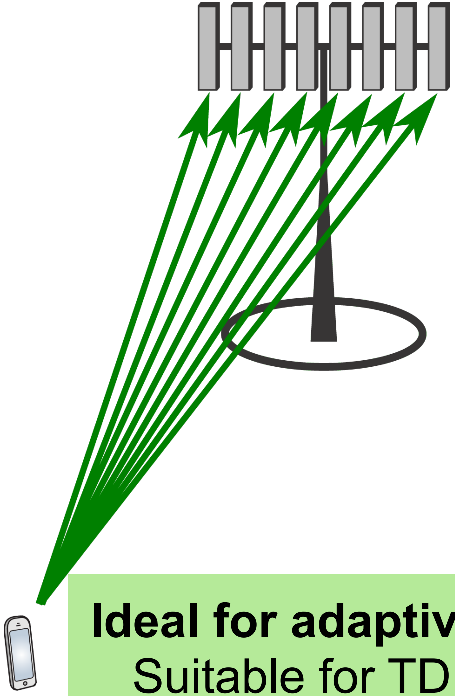
Learning Where to Point a Beam

1: Grid of beams



Easy to implement, but
unsuitable if M is large

2 : Pilots from users, reciprocity



Ideal for adaptive beamforming
Suitable for TDD, not for FDD

TDD = Time-division duplex, FDD = Frequency-division duplex

From Science Fiction to Mainstream in 10 Years…

MIMO in 1990s

Not competitive

- Easier to deploy more base stations
- Too small: $M \approx K \approx 8$
- Insufficient communication theory
- FDD bands dominated

Skeptical voices…

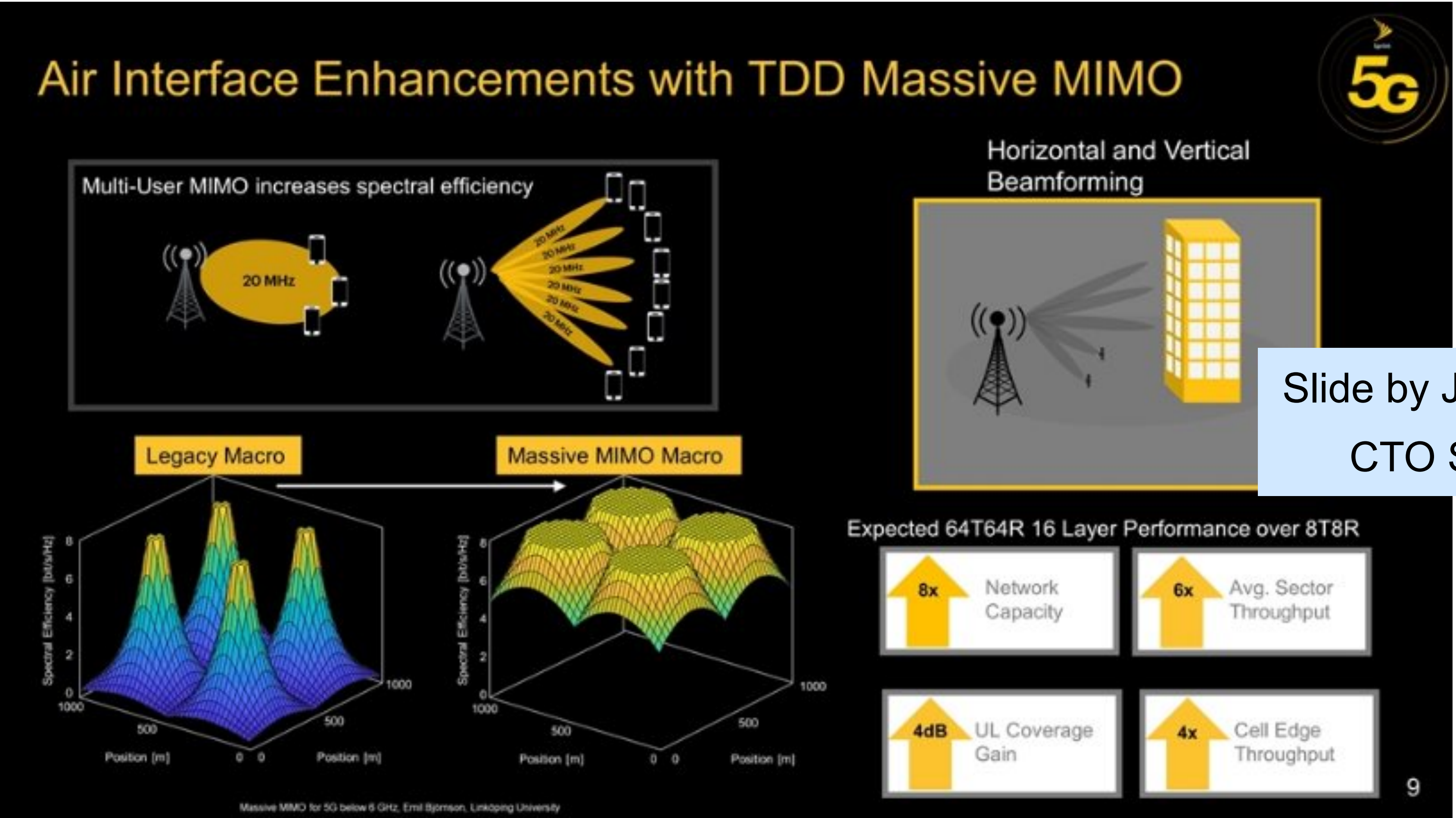
Too large and expensive

Too high complexity

No practical gains

Today:
A mainstream technology

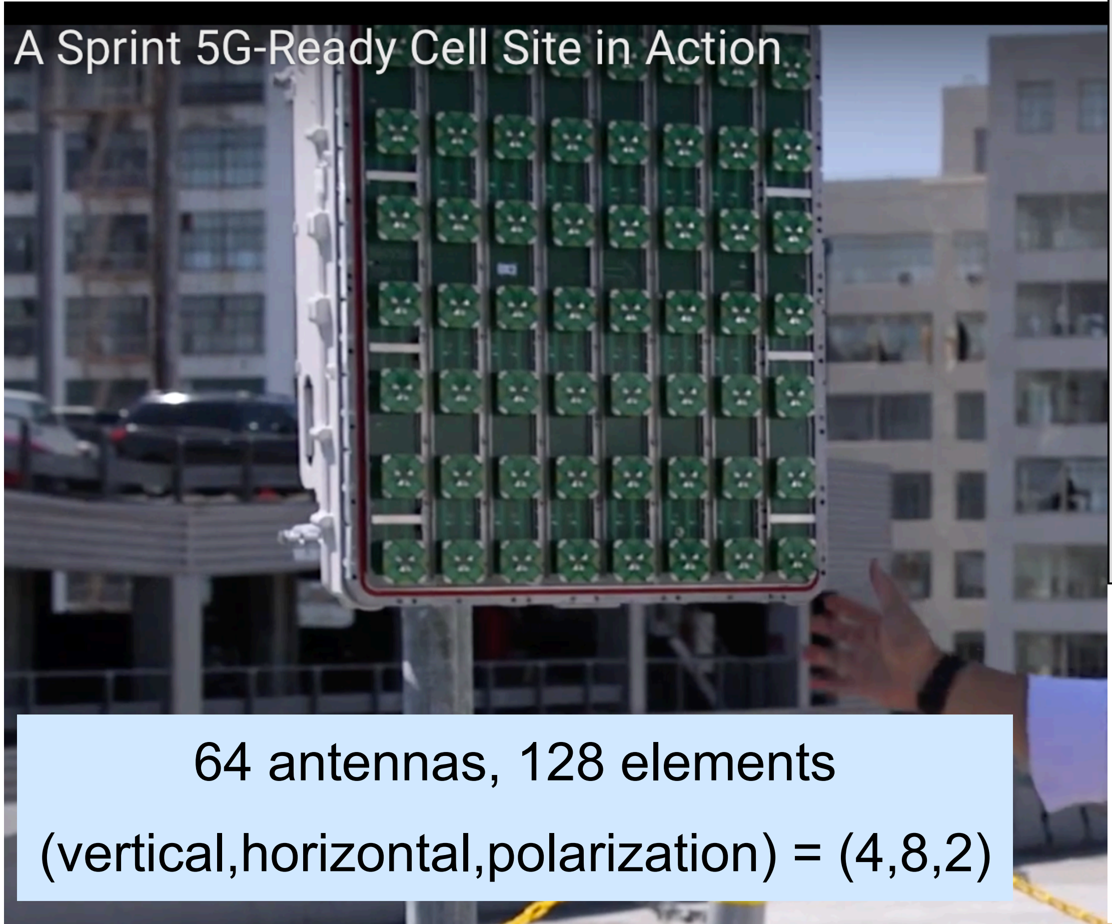
Sprint Deployed 1000 Massive MIMO Base Stations in 2019!



Slide by John Saw

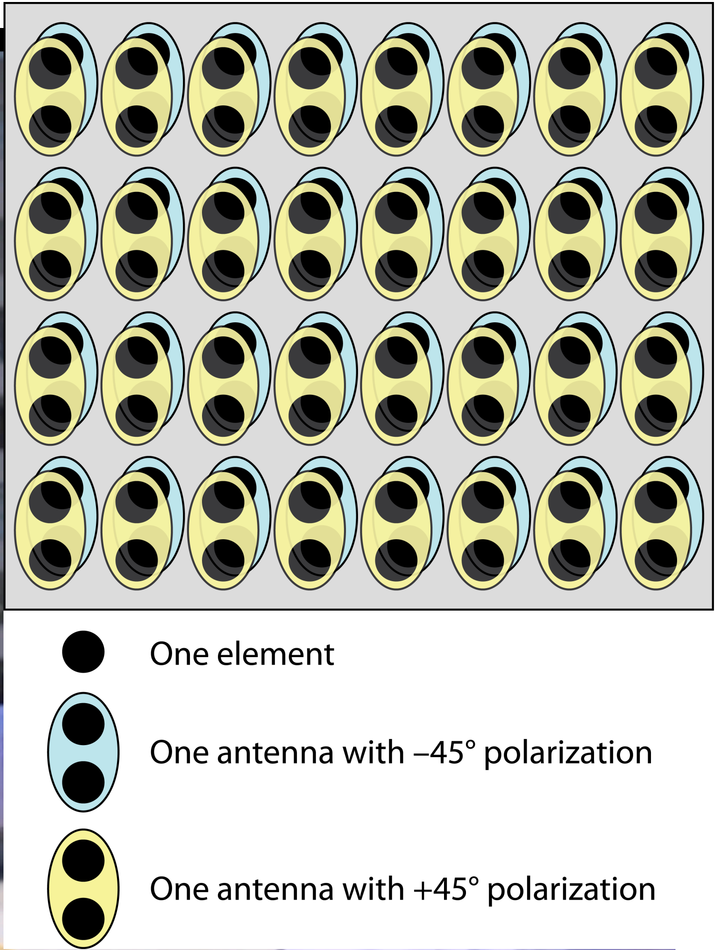
CTO Sprint

Example of Massive MIMO Site (2.5 GHz)



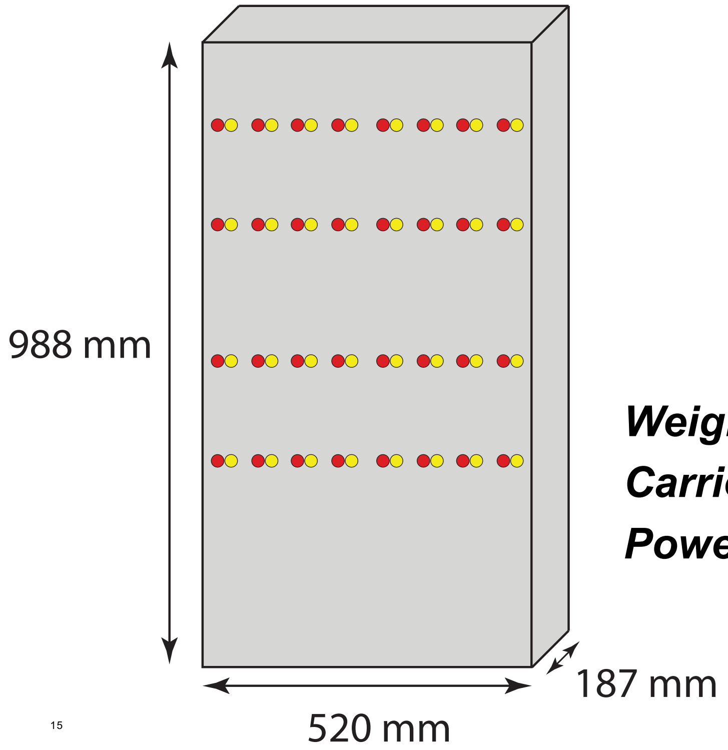
64 antennas, 128 elements

(vertical,horizontal,polarization) = (4,8,2)

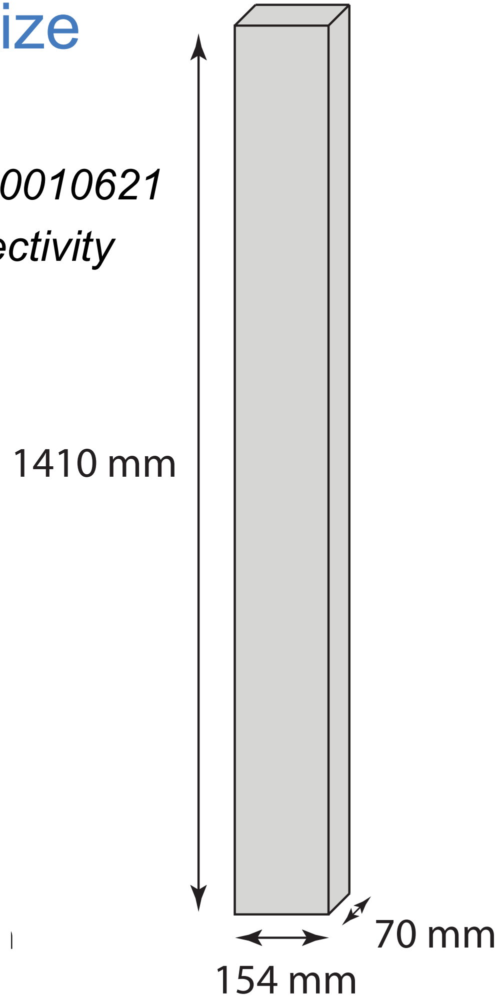


Massive in Numbers – Not in Size

Ericsson AIR 6468, 64-antenna array
2.5 GHz band



Kathrein 80010621
16 dBi directivity

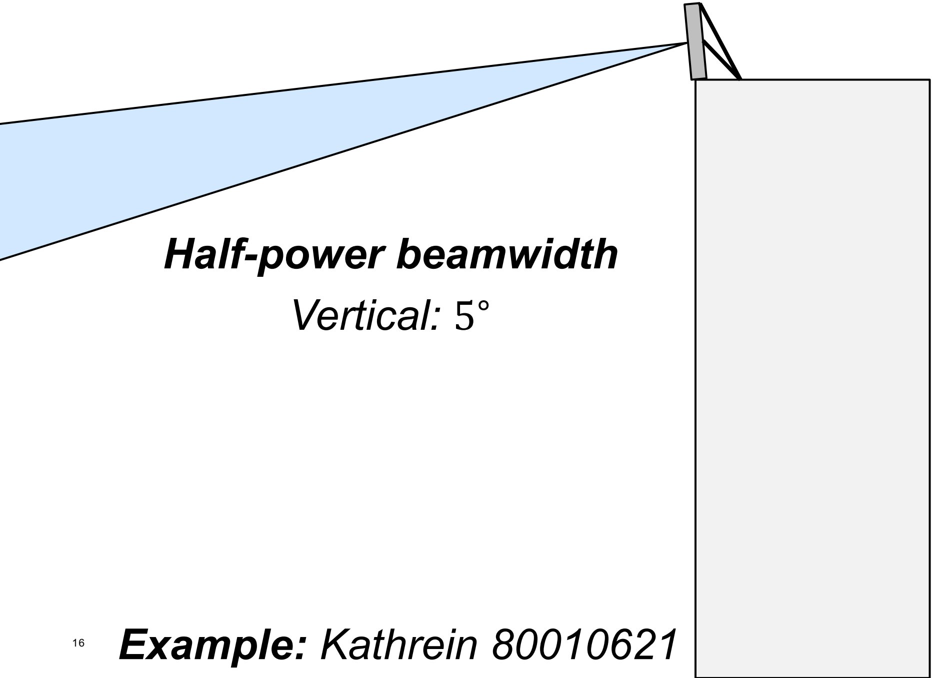


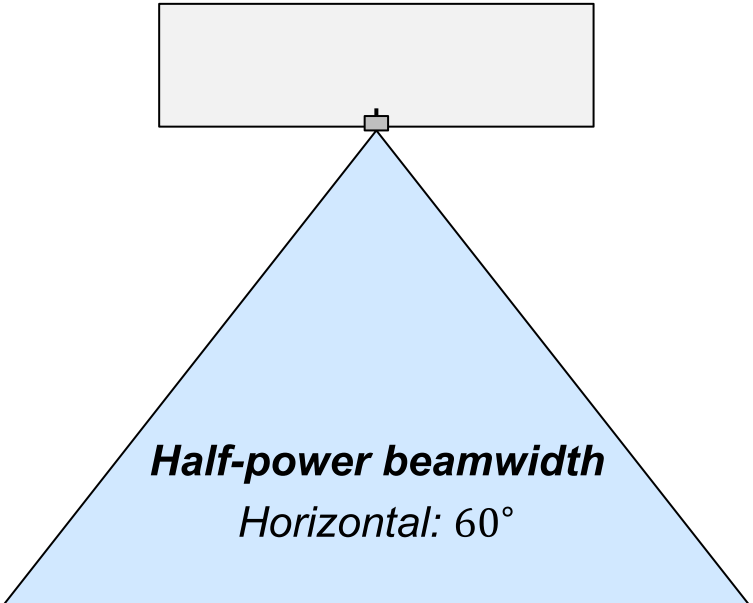
Weight: *60.4 kg*
Carrier aggregation *3 x 20 MHz*
Power: *40 W per band*

Most Users Are Separable Only in Horizontal Domain

People live on the ground!

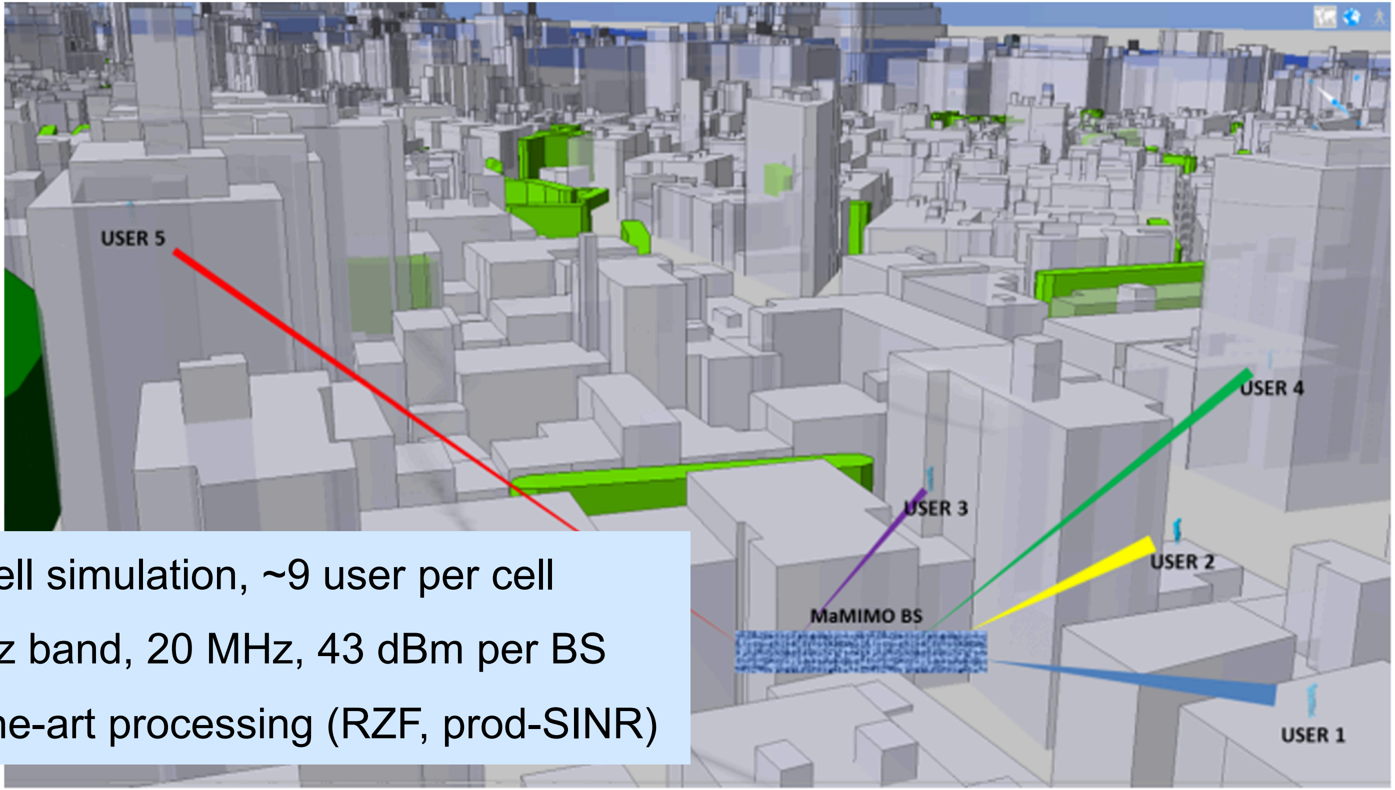
Height differences are rather small





Example: *Kathrein 80010621*

Does Massive MIMO Perform as Expected?



16 cell simulation, ~9 user per cell

3.5 GHz band, 20 MHz, 43 dBm per BS

State-of-the-art processing (RZF, prod-SINR)

M. Aslam, Y. Corre, E. Björnson, E. G. Larsson, "Performance of a Dense Urban Massive MIMO Network From a Simulated Ray-Based Channel," EURASIP Journal on Wireless Communications and Networking, 2019.

Answer: Depends on Antenna Deployment

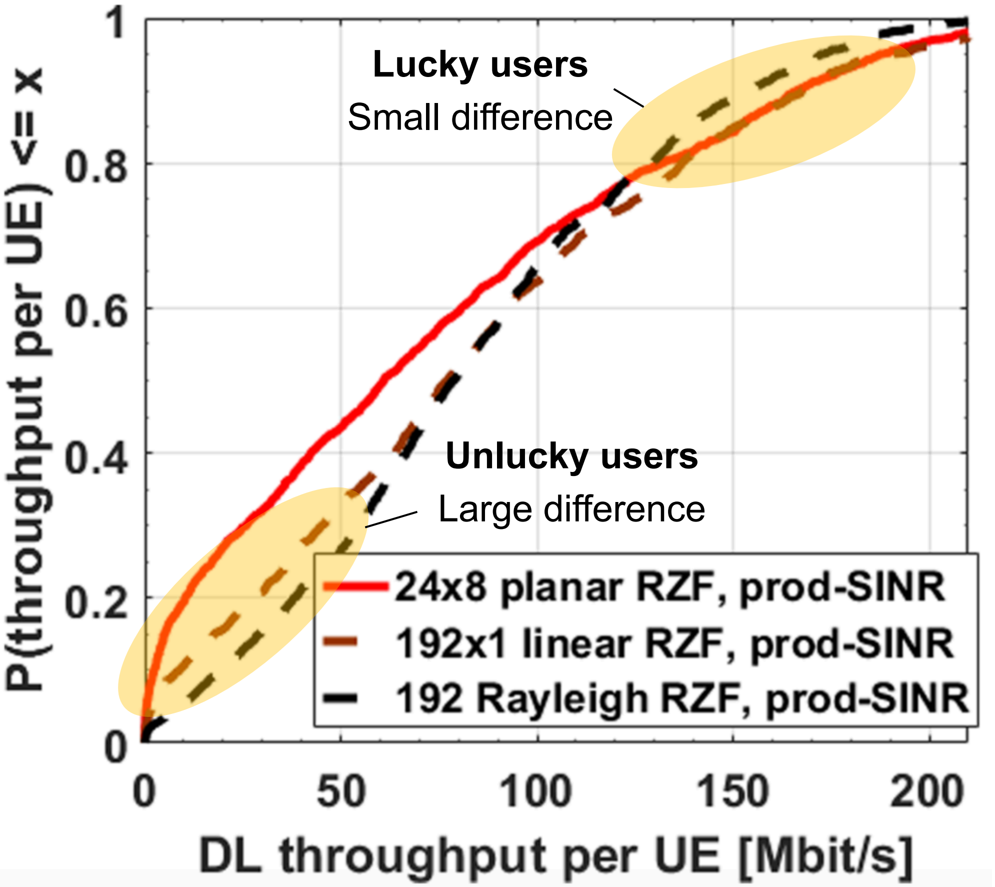
Marzetta's baseline:

i.i.d. Rayleigh fading

Two deployments:

Planar array (24 x 8): 1 m x 0.34 m

Linear array (192 x 1): 8 m x 0.04 m

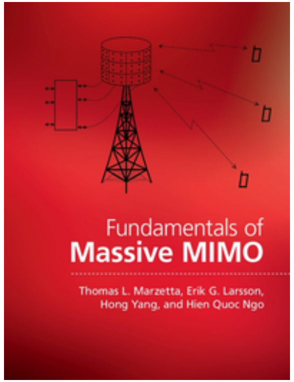


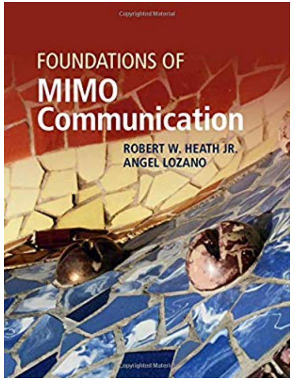
We need a very large horizontal array!

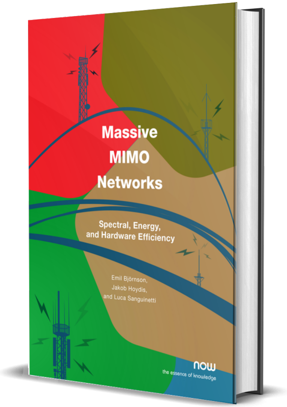
Not possible on conventional base stations

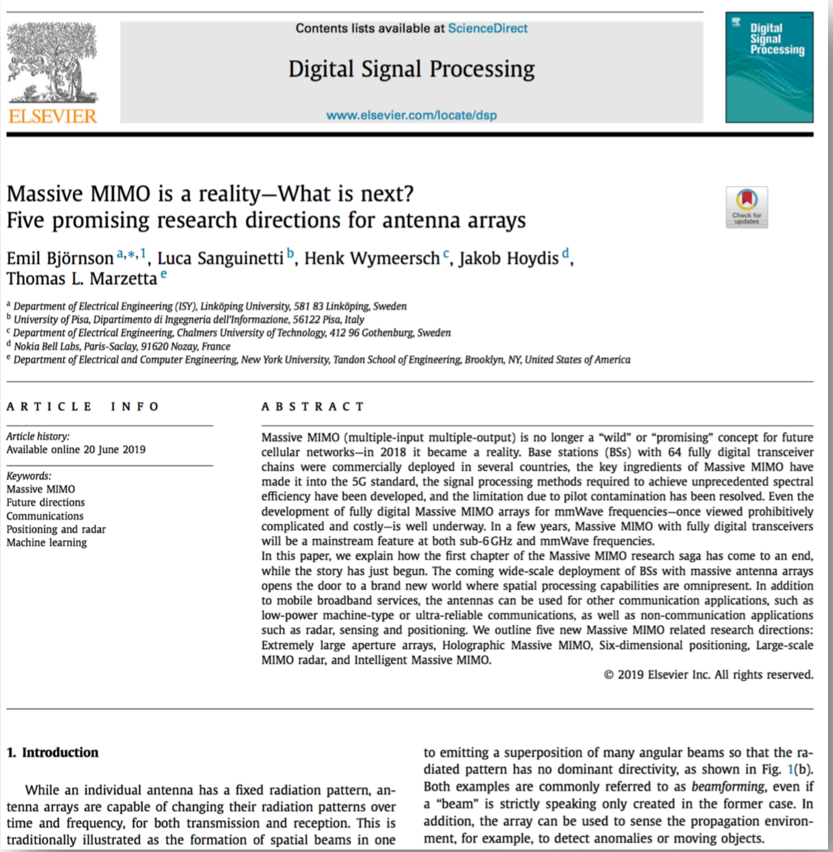
Many Open Problems Have Been Closed

- Algorithmic complexity
  - Only basic matrix operations and FFTs
- Beamforming accuracy
  - Estimate channels from uplink pilots
- Cost and size
  - Use many handset-grade components
- Pilot contamination
  - Dealt with using spatial correlation (resource allocation)









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Massive MIMO is a reality—What is next? Five promising research directions for antenna arrays

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ABSTRACT

Massive MIMO (multiple-input multiple-output) is no longer a "wild" or "promising" concept for future cellular networks—in 2018 it became a reality. Base stations (BSs) with 64 fully digital transceiver chains were commercially deployed in several countries, the key ingredients of Massive MIMO have made it into the 5G standard, the signal processing methods required to achieve unprecedented spectral efficiency have been developed, and the limitation due to pilot contamination has been resolved. Even the development of fully digital Massive MIMO arrays for mmWave frequencies—once viewed prohibitively complicated and costly—is well underway. In a few years, Massive MIMO with fully digital transceivers will be a mainstream feature at both sub-6 GHz and mmWave frequencies.

In this paper, we explain how the first chapter of the Massive MIMO research saga has come to an end, while the story has just begun. The coming wide-scale deployment of BSs with massive antenna arrays opens the door to a brand new world where spatial processing capabilities are omnipresent. In addition to mobile broadband services, the antennas can be used for other communication applications, such as low-power machine-type or ultra-reliable communications, as well as non-communication applications such as radar, sensing and positioning. We outline five new Massive MIMO related research directions: Extremely large aperture arrays, Holographic Massive MIMO, Six-dimensional positioning, Large-scale MIMO radar, and Intelligent Massive MIMO.

1. Introduction

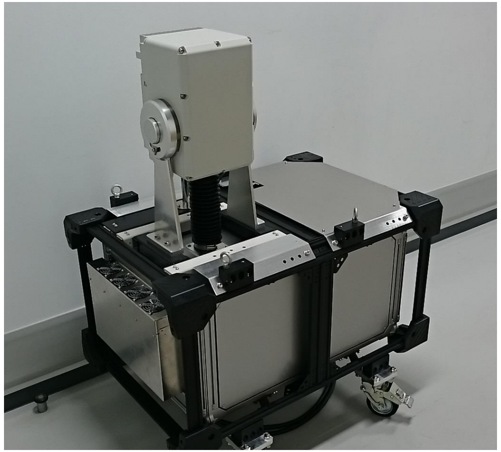
While an individual antenna has a fixed radiation pattern, antenna arrays are capable of changing their radiation patterns over time and frequency, for both transmission and reception. This is traditionally illustrated as the formation of spatial beams in one to emitting a superposition of many angular beams so that the radiated pattern has no dominant directivity, as shown in Fig. 1(b). Both examples are commonly referred to as *beamforming*, even if a "beam" is strictly speaking only created in the former case. In addition, the array can be used to sense the propagation environment, for example, to detect anomalies or moving objects.

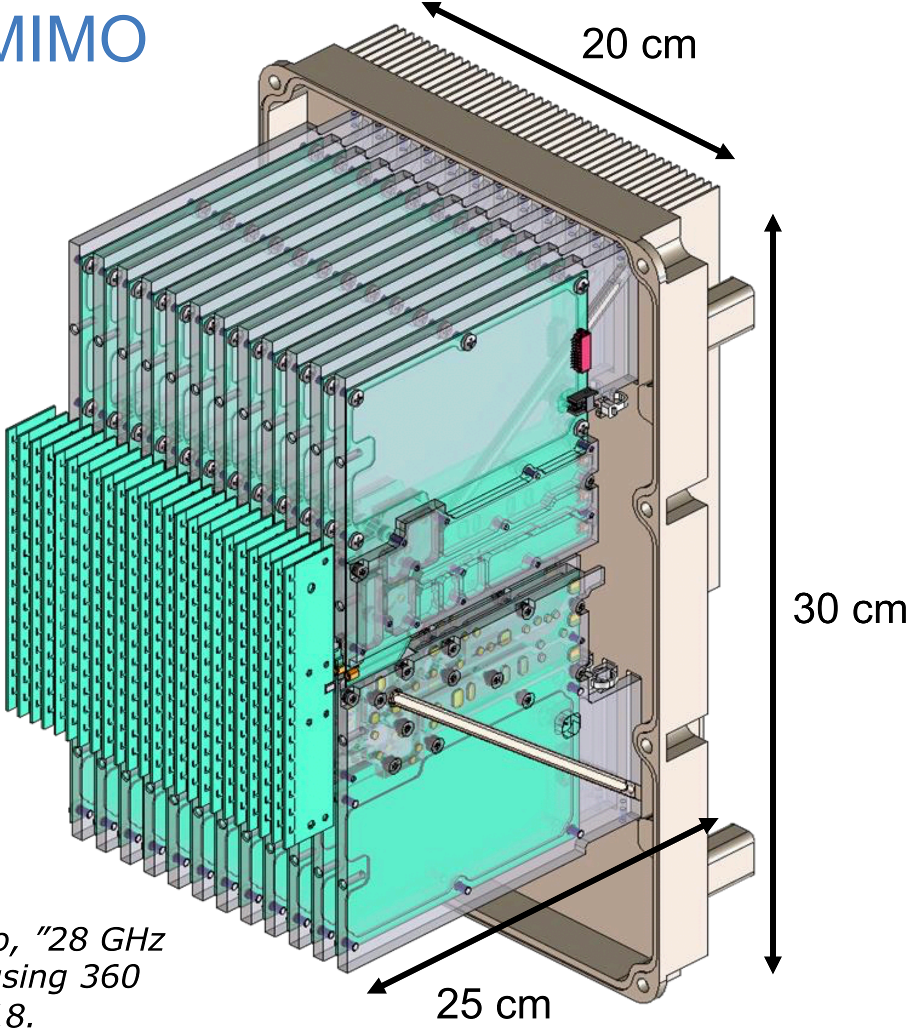
Fully Digital mmWave Massive MIMO Are Within Sight

24 antennas, 15 elements each

Digital adaptive horizontal beamforming

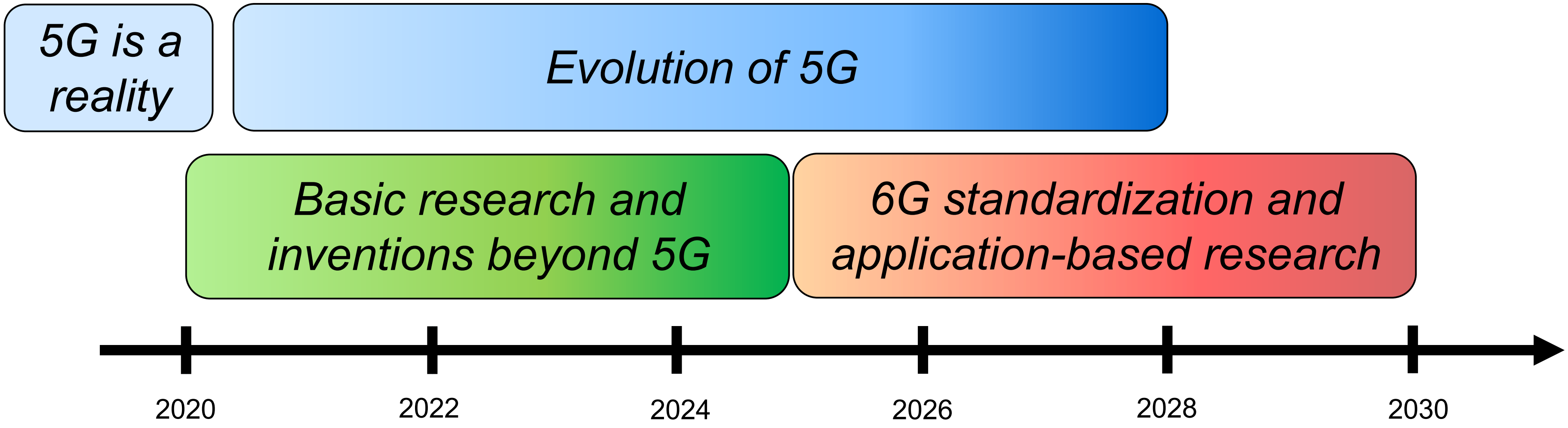
NEC Corporation





N. Tawa, T. Kuwabara, Y. Maruta, M. Tanio, T. Kaneko, "28 GHz Downlink Multi-User MIMO Experimental Verification using 360 Element Digital AAS for 5G Massive MIMO," EuMC 2018.

Aiming Towards the Future of Wireless



This is the right time to take a step back to prepare for the next leaps forward!

- How can 5G be evolved? Which issue will not be solved by 5G?
- What is needed beyond 5G?

What Are the 6G Applications?

- **We still don't even know what the 5G applications are!**

All papers with 6G applications are just speculations!

Some applications appear earlier, other not at all

3G was introduced in 1998

Believed 3G Applications

Video calling

Mobile e-commerce

Location-based services

Games and sports events

Broadband Internet access

Broadband video services

Facetime in 2010

iPhone 3G in 2008

OECD (2004-09-14), "Development of Third-Generation Mobile Services in the OECD", OECD Digital Economy Papers.

Start from performance metrics – Identify new technology solutions

Cannot do all of this simultaneously

Must look for new *radical* solutions

10x improvements, not 10%!

Way too early to talk about applications!

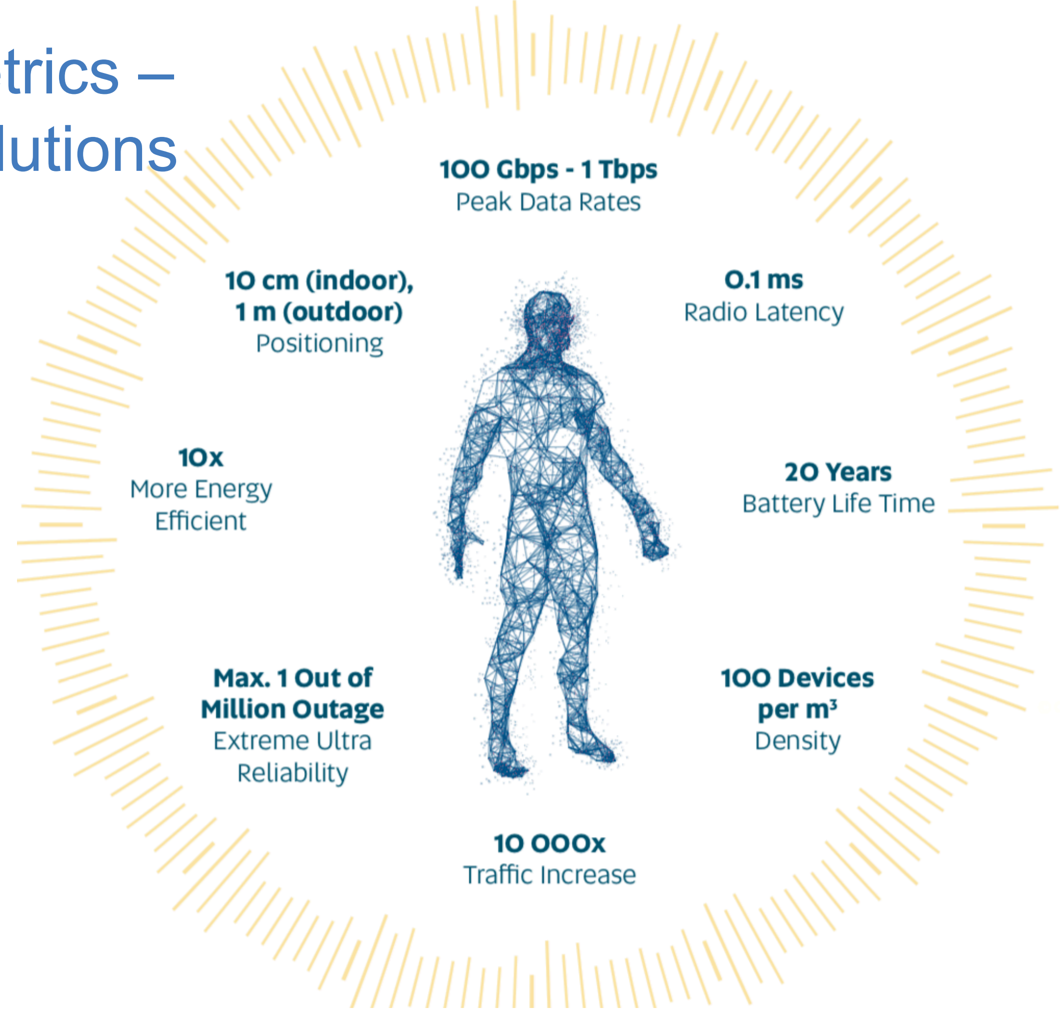


Image source: 6G Flagship, "Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence," 2019

What is Next?

Massive MIMO in 2010 → Massive MIMO in 2019

Seemingly unrealistic “science fiction” concept from:

T. L. Marzetta, “Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas,” IEEE Trans. Wireless Communications, 2010

Commercial reality:

Which “science fiction” idea from 2020 will become reality in 2029?

Three research directions that might give 10x improvements