Massive MIMO: It Really Works!

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The future: augmented reality everywhere

- Throughputs: 100 – 1000x
- Latency: 1/10 – 1/100x

Timeless truths about wireless

- Demand for wireless throughput, both mobile and fixed, will always increase: 10x, 100x, 1000x
- The quantity of available electromagnetic spectrum will never increase
  - The best spectrum is below 5 GHz
  - you can't lay down more of this!

Spectrum below 5 Ghz: the most valuable resource in the world!

- FCC AWS-3 spectrum auction, January 2015
  - 65 MHz: 1695-1710 MHz, 1755-1780 MHz, 2155-2180 MHz
  - $41.3 billion
  - $630/Hz

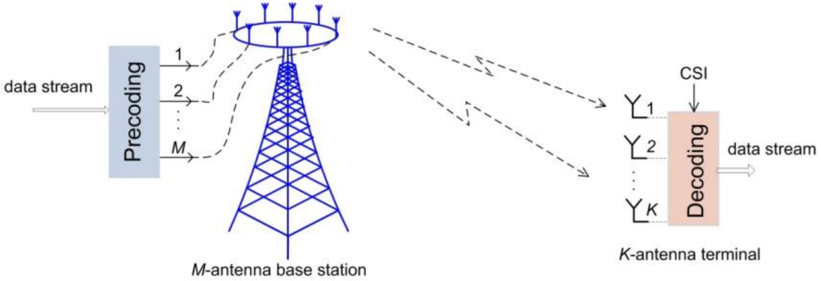
Outline

- Taxonomy of MIMO
- How to distinguish Massive MIMO from impostors
- Numerical case studies
- New research directions

Taxonomy of MIMO

Point-to-Point MIMO

Roy & Ottersten (1991); Paulraj & Kailath (1993); Foschini (1995); Raleigh & Cioffi (1998); Telatar (1999)



- ❑ Brilliant invention
- ❑ But not scalable
  - unfavorable propagation
  - time required for training grows with system size
  - disappointing multiplexing gains at cell edges

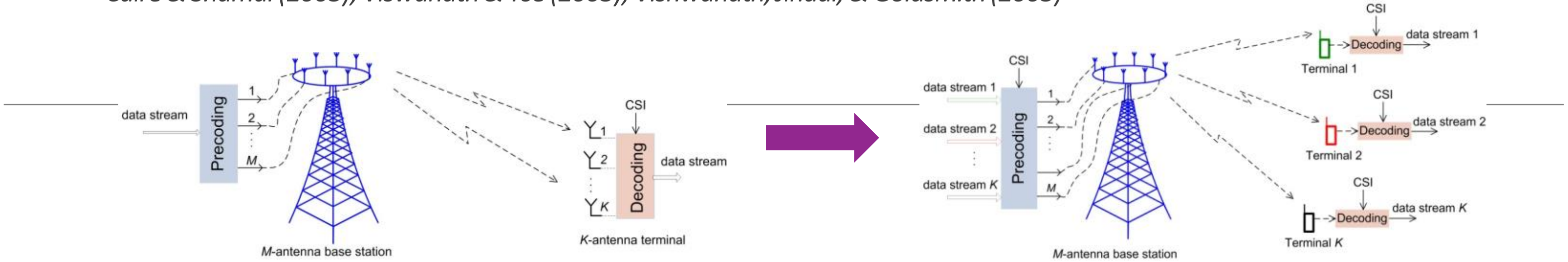
8x4 link, -3.0 dB SNR

# base station antennas	1	2	4	8
bits/second/Hz	1.51	1.83	2.06	2.19

In every wireless standard, but no further practical development possible

Multi-User MIMO

Caire & Shamai (2003); Viswanath & Tse (2003); Vishwanath, Jindal, & Goldsmith (2003)

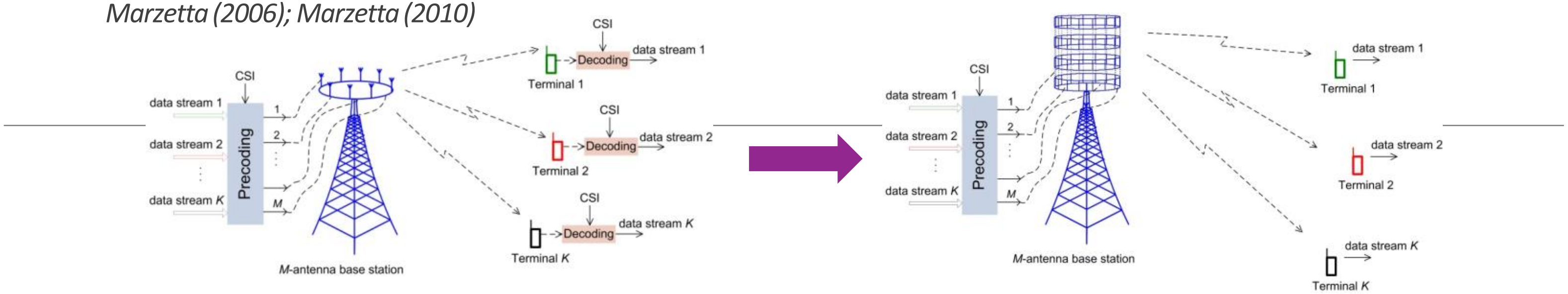


- ❑Splitting the multi-antenna user into autonomous single-antenna users doesn't decrease the sum-throughput!
- ❑Only single-antenna terminals required
- ❑Propagation is almost always favorable
- ❑But not scalable in its original form
  - dirty-paper coding/decoding needed
  - both ends of link have to know channel state information (CSI)

Dual CSI requirement → fundamentally unscalable

Massive MIMO

Marzetta (2006); Marzetta (2010)



- ❑ Add many more base station antennas
- ❑ CSI isn't everything: it's the only thing!
  - channel state information (CSI) only available to the base station
  - use linear pre-coding/de-coding instead of dirty-paper
  - users don't do any signal processing

A practical Massive MIMO system can be much bigger than an orthodox-Shannon system

Benefits of Massive MIMO

- ❑ Area spectral efficiency (bits/sec/Hz/square-kilometer)
- ❑ Scalability
- ❑ Great service to *all* users via power control
- ❑ Energy efficiency (bits/Joule)
- ❑ Simplicity

A game-changer

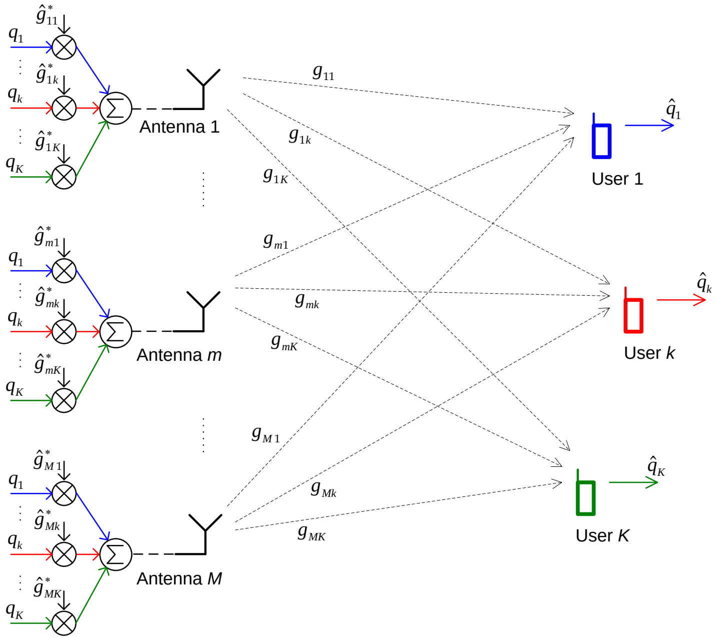
How to Distinguish Massive MIMO From Impostors

More than just many antennas

- Many physically small, low power, individually controlled antennas
  - channel orthogonality
  - channel hardening
- Create parallel flat virtual connections between base station and terminals
  - every terminal uses *all* time/frequency resources
- Utilize *measured* channels rather than *assumed* channels

Downlink data transmission: Maximum-Ratio

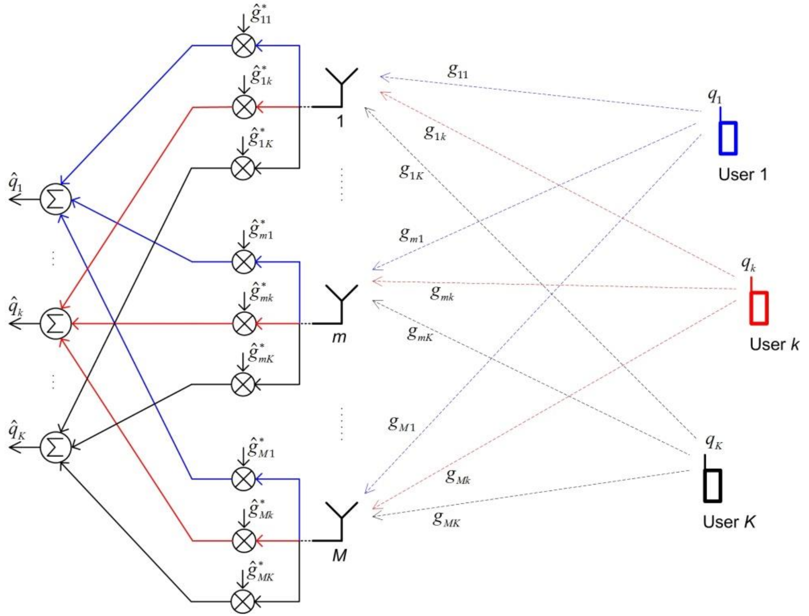
antennas transmit the weighted message-bearing symbols to arrive in-phase at the intended user & out-of-phase elsewhere



The simplest possible pre-coding, but often very effective

Uplink data transmission: Maximum-Ratio

base station weights and adds received signals for constructive reinforcement of the transmission from each user



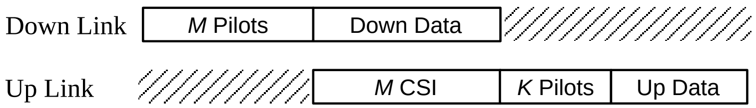
Maximum-ratio permits decentralized signal processing

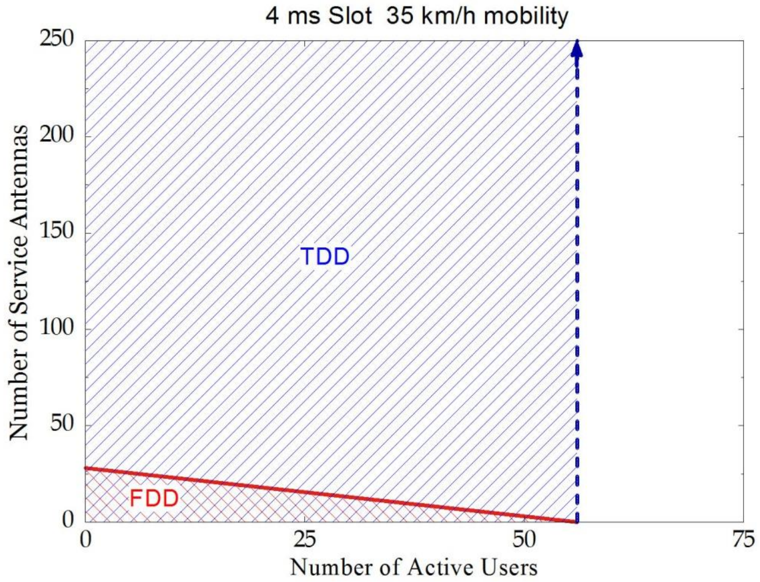
TDD slot structure ensures timely CSI: *M* service-antennas, *K* users, unlimited *M*

- TDD slot: training $\propto K$

Up Data	*K* Up Pilots	Down Data

- FDD slot: training $\propto 2M + K$

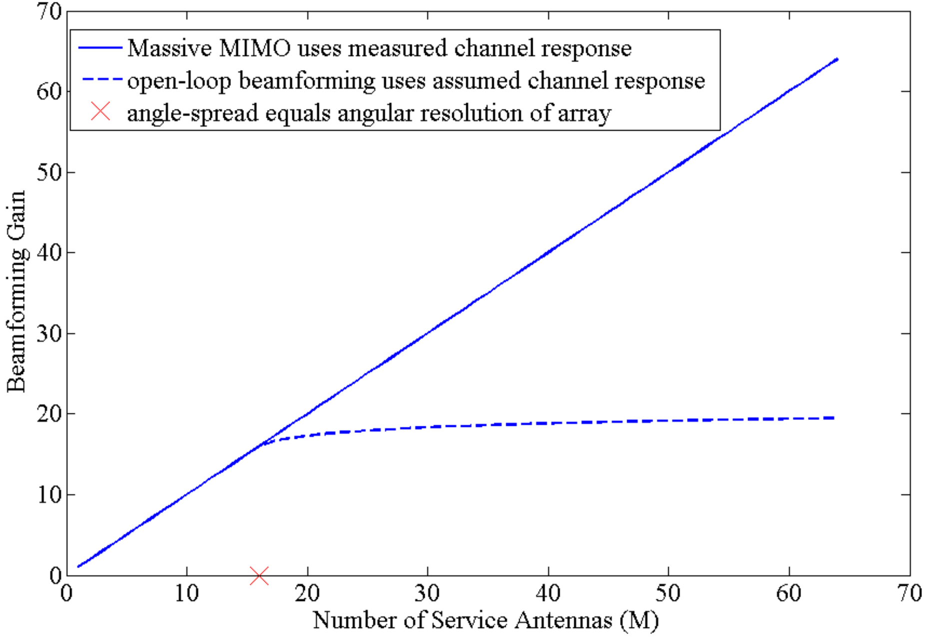




Mobility limits the number of active users; FDD is a disaster!

Why so important to utilize *measured* propagation?

- *Measured* channels
  - scalable
  - gain grows linearly with number of antennas
    - irrespective of noisiness of CSI
    - no tightening of array tolerance required
- *Assumed* channels
  - not scalable
  - gain eventually grows only logarithmically



If channels are assumed, then not Massive MIMO!

Scientific foundations of Massive MIMO

- Using *measured* channels: Beamforming gain grows linearly with number of antennas, irrespective of the noisiness of the measurements
- Frequency-independent power control: Based solely on long-scale (slow) fading; exceedingly effective
- Pilot contamination: Ultimate limitation in non-cooperative multi-cell systems

No new mathematics, but a new philosophy!

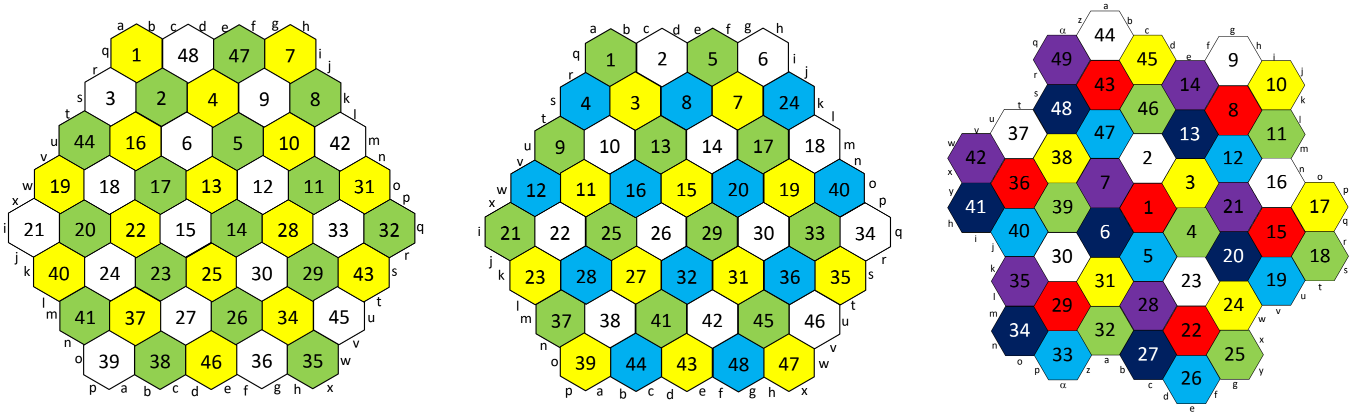
Experimental validation of Massive MIMO

	Service antennas	Terminals	System spectral efficiency (b/s/Hz)
Bristol University / Lund University	128	12	80 → 140
Bell Labs "FutureCell"	64	2 → 10	20 → 100
Facebook "Project ARIES"	*96*	*24*	*71 → 100*
Google	*32*	*32*	*20*

Numerical Case Studies

Mitigation of pilot contamination: Pilot re-use Factor 3, 4, 7

re-use of pilot sequences causes coherent inter-cell interference



The cost: extra training overhead

Dense-urban/suburban cellular access

optimum pilot re-use factor? maximum-ratio Or zero-forcing?

	Dense Urban	Suburban
Carrier frequency(GHz)	1.9	1.9
TDD spectral bandwidth (MHz)	20	20
Slot duration (ms)	2	1
User allowed mobility (km/h)	71	142
Uplink radiated power/user (mW)	200	200
Number of service antennas	64	256
Total downlink radiated power (W)	1	1
Active users/cell	18	18
Cell radius (km)	.50	2.0
Power control	Max/min	Max/min
Pilot re-use factor	7	3
Pre-coding/de-coding	Maximum-ratio	Maximum-ratio
95% likely throughput/terminal Mb/s	4.5 down, 3.1 up	3.2 down, 1.1 up

Max-min power control: uniformly good service *everywhere*!

Fixed wireless access: 3000 rural homes, each 20 Mbps down, 10 Mbps up

- 3000 homes randomly distributed over 11.3 km radius

- ❑ Target down-link throughput: 20 Mbps for every home simultaneously
- ❑ Target up-link throughput: 10 Mbps for every home simultaneously
- ❑ 10 W total downlink radiated power
- ❑ 1 W uplink radiated power per terminal
- ❑ 50 ms coherence time
- ❑ 800 MHz carrier frequency
- ❑ 20 MHz spectral bandwidth

How many antennas are needed?

How many antennas are needed?

- Zero-forcing: 3200 antennas (11m x 11m)
- Maximum ratio: 8200 antennas (17m x 17m)

Total system throughput: 90 Gbs; 4500 b/s/Hz !!!

New Research Directions

Massive MIMO extensions

- Unlicensed spectrum operation
  - mitigation of non-cooperative interference

- Massive MIMO of Things: MMOT
  - huge numbers of things
  - sporadic service
  - short-duration messages

- Limit behavior of Cell-Free Massive MIMO
  - continuum of access points (*holographic MIMO*)

“a mathematical theory of communication” →“a physical theory of communication”

is 10x beyond Massive MIMO possible?

- Rigorously combine electromagnetic theory with communication theory
- Re-examine old concepts
  - Super-directivity
  - Resonant evanescent wave coupling
- Meta-materials (negative dielectric constant) for antenna arrays
- What is the minimum power that we have to draw from an antenna?
  Eb/N0 > ln 2: a purely *mathematical* construct
- Concepts from near-field optical sub-wavelength imaging?

Multidisciplinary effort: wave propagation, electronics, mathematics, …

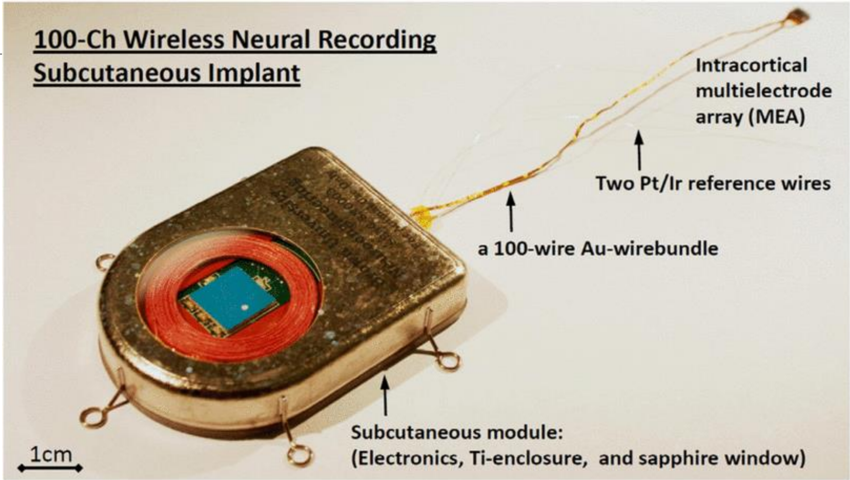
Resonant evanescent wave coupling

***WITRICITY* (MIT, 2007): 60 Watts, 2 meters, @ 10 MHz, 40% efficient**

- Wavelength 30 meters
- Near-field dominated by evanescent waves
  - Exponential decay
  - Reactive power only
- Tuned receiver coil alters boundary conditions, and pulls in power

Wireless neurosensing: implantable intercranial transmitter

Yin, Borton, Aceros, Patterson, & Nurmikko, IEEE Trans. Biomed. Circuits Syst., April 2013

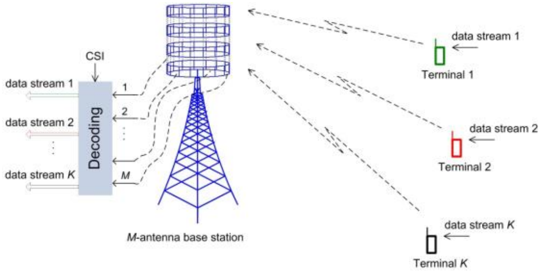


- 100 7.8 kHz neural channels: 3.2 – 3.8 GHz
- Could MIMO handle 1000, 10000, … channels?
- What are the ultimate limitations of near-field wireless communication?

Massive sensor telemetry

Continuous recording of signals from vast numbers of sensors

- “Sensor networks” paradigm
  - Impossible to collect all data wirelessly at one access point
  - We couldn’t process so much data, even if we could collect it
  - We have to pre-process and prune data

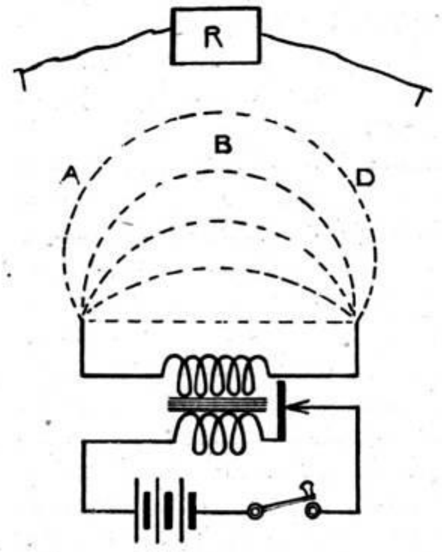


- Massive MIMO changes the game!
  - We can collect *all* of the data, intact
  - Data governed by mathematical physics should be sampled at the Nyquist rate
    - Big Data easier to process than Small Data (computer tomography, SAR, seismic exploration)
- Potential applications of Massive Sensor Telemetry
  - 3D exploration seismic surveys
  - Monitoring of volcanoes
  - Structural health monitoring

MIMO in nonstandard media

Electromagnetic propagation isn't the only way

- Still more hyperbolic MIMO
  - Acoustic waves
  - Elastic waves
- Parabolic MIMO: heat equation
  - Time scales as the square of distance
  - Nanocommunications?
- Elliptic MIMO: electrical conduction
  - Updated version of Ground Telegraphy
    - Lee Deforest, Arnold Sommerfeld, Richard Courant



Conclusions

- Future apps, such as Augmented Reality will require revolutionary developments at the physical layer
- Massive MIMO is the only technology that can fully utilize the sub-5 GHz bands
- Wireless communications will continue to be a vital research area, ***BUT*** future breakthroughs will result from multi-disciplinary collaborations