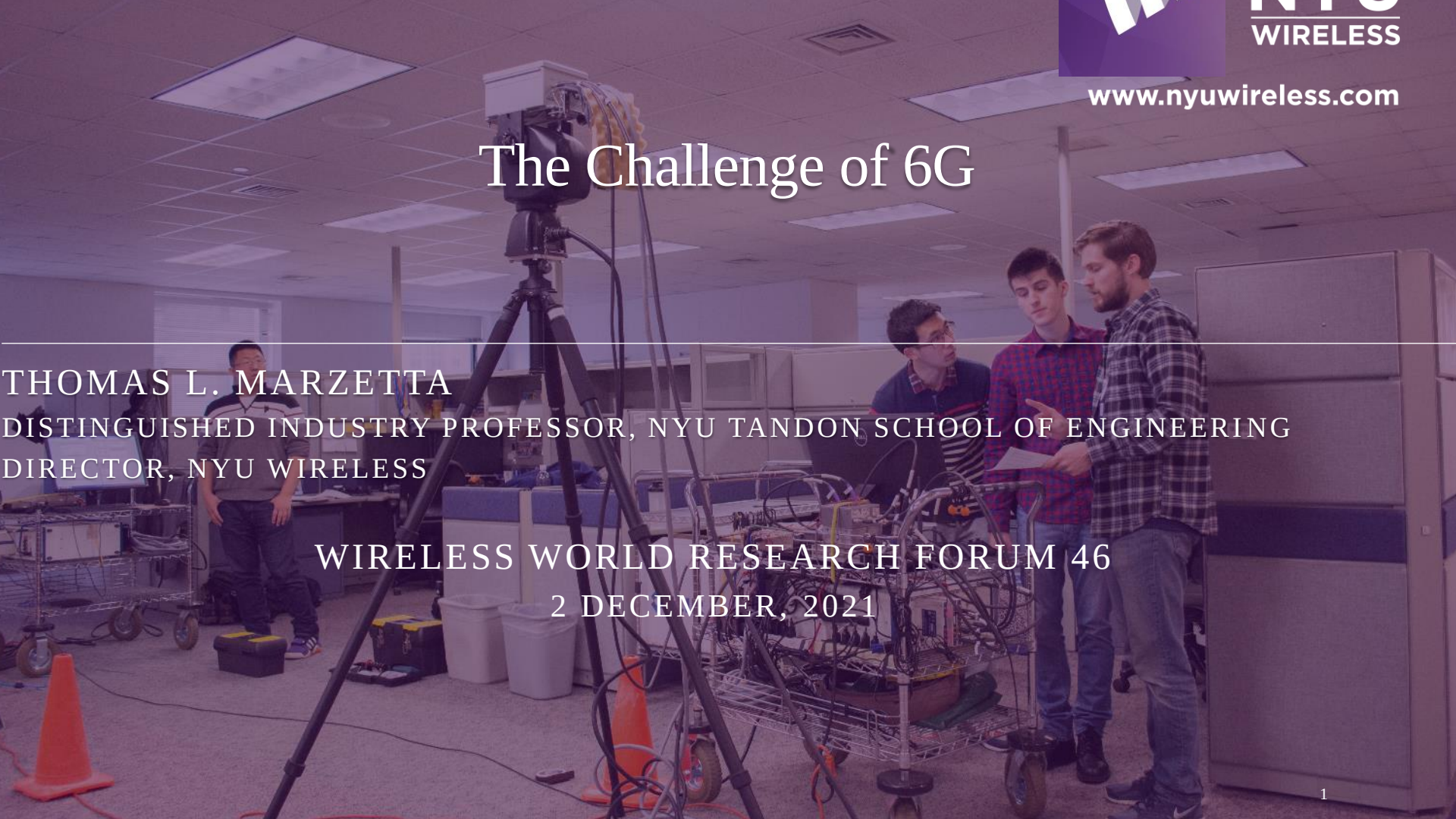


NYU WIRELESS

www.nyuwireless.com

The Challenge of 6G

THOMAS L. MARZETTA

DISTINGUISHED INDUSTRY PROFESSOR, NYU TANDON SCHOOL OF ENGINEERING

DIRECTOR, NYU WIRELESS

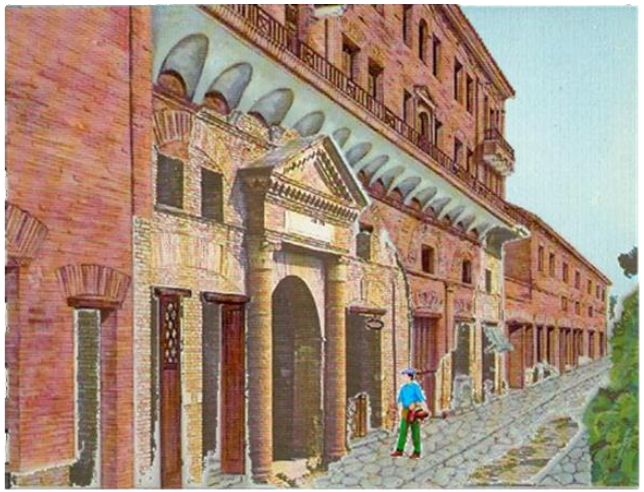
WIRELESS WORLD RESEARCH FORUM 46

2 DECEMBER, 2021

The Next Level in Human-to-Human Communications: Ubiquitous Augmented/Virtual Reality

- Covid-19 pandemic has established that reliable, high-speed wireless is a vital necessity
  - how could we have functioned during the past 1 ½ years without Zoom?
  - but the Zoom experience wears thin
- People will demand - and pay for – a truly transforming, realistic communication experience: ubiquitous augmented/virtual reality (AR/VR)

Horrea Epagathiana, Ostia, Italy

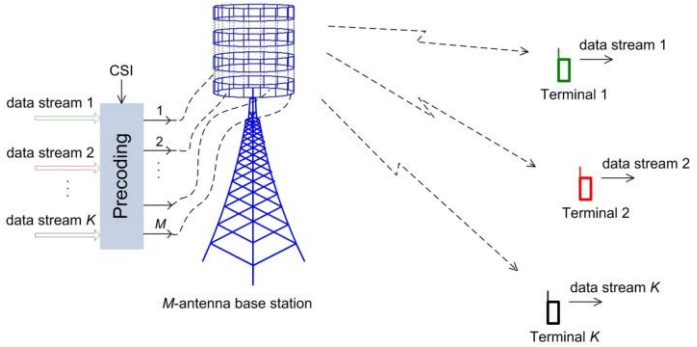


Augmented reality has staggering requirements: 3 Gb/s/user, 10 ms latency

Massive MIMO: The Most Effective Technology Yet Devised for Efficient Use of Spectrum

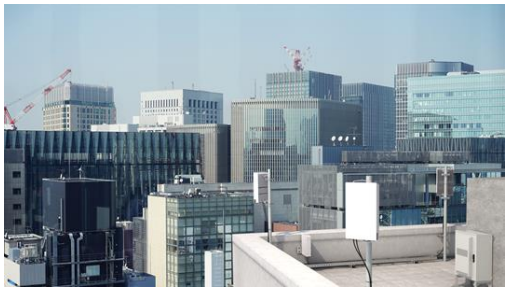
T.L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas", *IEEE Trans. on Wireless Communications*, Nov 2010

- What is Massive MIMO?
  - many individually controlled, physically small, low power antennas (the more, the better!)
  - base station transmits focused beams of information
  - aggressive spatial multiplexing: everybody is served in *all* time-frequency resources
  - utilize *measured* channel frequency response for multiplexing/de-multiplexing
- Benefits
  - spectral efficiency
  - simplicity
  - great service to all users via simple, effective power control
  - energy efficiency



Ericsson AIR 6419

- 64 antenna-integrated radios
- 1 x ½ meter
- 20 kg



How to Deliver 2000 Mb/s/user? Problematic!

Mb/s MHz bit-streams SNR

$$R = B \times N \times \log_2(1+\rho)$$

B (MHz)	N	ρ (dB)
20	1	300
20	10	30
20	100	0
200	1	30
200	10	0
2000	1	0

- B = 20 MHz available in mid-band, but 100 bit-streams/user?
- B = 200 MHz available in mmWave, but 10 bit-streams/user?
- B = 2000 MHz available in THz. Multiplexing to many users?

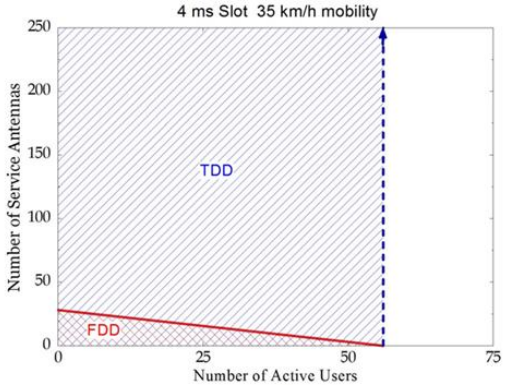
Relative Cost of Spectrum

FCC Auction	Spectrum	Total Bandwidth	Total Cost	Specific Price
AWS-3 Jan 2015	1.695 – 2.180 GHz	65 MHz	$44.9B	$691/Hz
1002 March 2017	.614 - .698 GHz	74 MHz	$19.8B	$268/Hz
101 Jan 2019	27.5 – 28.3 GHz	850 MHz	$0.70B	$0.83/Hz
102 May 2019	24.25-24.45, 24.75-25.25 GHz	700 MHz	$2.0B	$2.86/Hz
103 March 2020	37 – 47 GHz	3400 MHz	$7.6B	$2.24/Hz
107 Jan 2021	3.7 – 3.98 GHz	280 MHz	$81.2B	$290/Hz

- Cost of spectrum inversely proportional to the *square* of carrier frequency!
- Massive MIMO is more likely to be used in mid-band than in mmWave/THz
- Great, new physical layer inventions will have greatest impact in mid-band!

Under 5G, Massive MIMO Will Fail to Attain its Full Potential

- In the U.S., FDD (Frequency Division Duplex) instead of TDD (Time Division Duplex) is pervasive in the most valuable sub-6 GHz bands *(recent auctions mandate TDD!)*
  - AT&T, Verizon, T-Mobile traditionally have FDD only; Sprint had TDD (merged with T-mobile)
  - even with TDD, efficient reciprocal training is not used

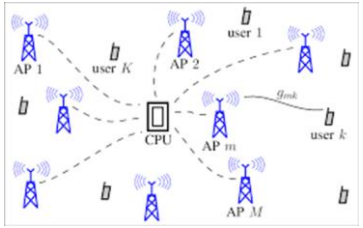


- Grid-of-beams is used rather than multiplexing beamforming based on directly measured channel state information → severely limits the scalability of Massive MIMO
- What went wrong?
  - de-facto mandate for back-compatibility – a thoroughly bad idea for a new generation of wireless!
  - The U.S. is doomed to inferior service in its most valuable spectrum

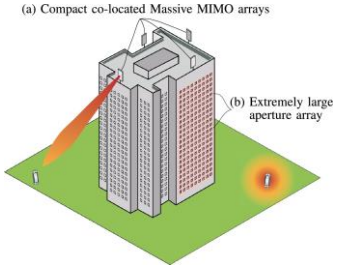
Candidate MIMO Technologies for 6G

E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, T.L. Marzetta, "Massive MIMO is a reality—What is next?: Five promising research directions for antenna arrays", 2019

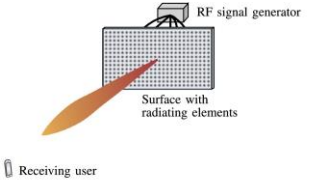
- Cell-Free Massive MIMO



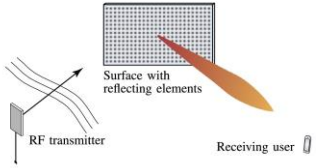
- Extremely Large Aperture Arrays



- Intelligent Reflecting Surfaces

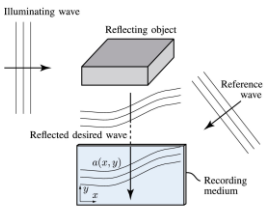


(a) Contiguous surface with an RF signal generator at the backside.

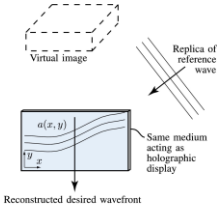


(b) Contiguous surface with an RF signal generated at another location.

- Holographic MIMO

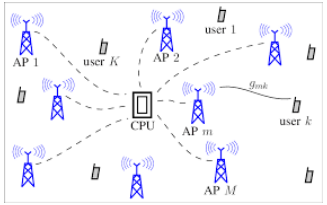


(a) Holographic recording



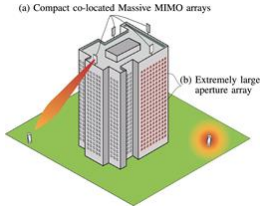
(b) Holographic reconstruction

Cell-Free Massive MIMO



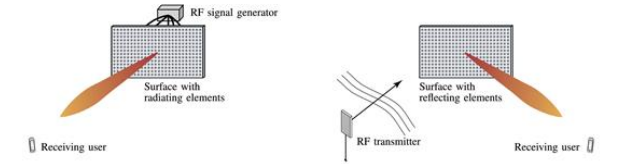
- Randomly-distributed access points serve users
  - Every user served by all access points
  - No cell boundaries; no handover
- Potential advantages over cellular Massive MIMO
  - Shadow-fading diversity
  - Transmit multiple streams to each user under line-of-sight conditions
- Issues
  - Backhaul
  - Installation costs

Extremely Large Aperture Arrays



- Great for fixed wireless access
  - CSI can be acquired for large numbers of users
- Number of mobile users limited by CSI acquisition
  - Eventually extra antennas only confer logarithmic improvements in throughput
- What if we surround the users with antenna arrays?
  - The converse of conventional cellular operation (e.g., users surrounding antenna arrays)

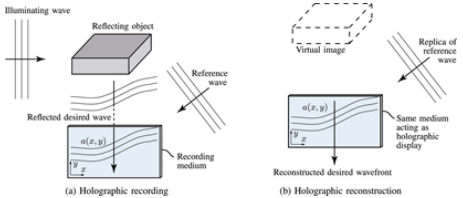
Intelligent Reflecting Surfaces



(a) Contiguous surface with an RF signal generator at the backside. (b) Contiguous surface with an RF signal generated at another location.

- Potentially much cheaper than arrays of active antennas
  - Possible enabler for mmWave/THz
- Anything that an intelligent reflecting surface can do, an active antenna array can also do

Holographic MIMO



- Transmit/receive over a continuous aperture
- Could be cheaper than discrete active arrays – if it could be made to work
- Fundamental question: is there any advantage to controlling/measuring the electromagnetic field on a sub-Nyquist (half wave-length) scale?

6G: Not So Easy to Deliver a Genuinely New Generation!

- 2010
  - 4G was introduced
  - mmWave and Massive MIMO were waiting in the wings for 5G
- 2021
  - 5G is here
  - We have no sure-fire physical layer technologies for 6G!

The Case for Physics-Based Communication Theory

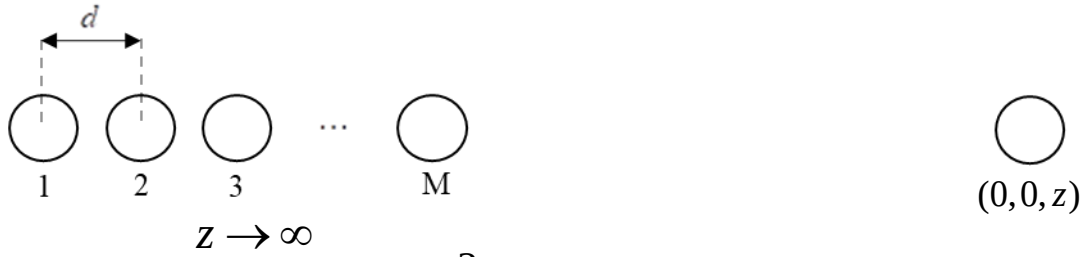
- The theory underlying all existing wireless systems (*including Massive MIMO!*) is based on highly simplified models for the function of antennas and the propagation of radio waves
- Shannon information theory has been a huge enabler for wireless technology, but is fundamentally a *mathematical* theory (*A **Mathematical** Theory of Communication*)
  - Connections to physical reality don't happen automatically
- R.F. engineers and communication theorists work independently
  - Few researchers are comfortable with both Maxwell's equations and Shannon theory

Super-Directive Antenna Arrays

For example, consider a transmitting horn antenna, with an aperture about 10 wavelengths on a side, located in outer space roughly aimed at the earth, With a one wavelength diameter supergain antenna on the earth it is possible to receive virtually all of the power radiated by the horn antenna. [G. J. Foschini and M. J. Gans, Sept. 1995]

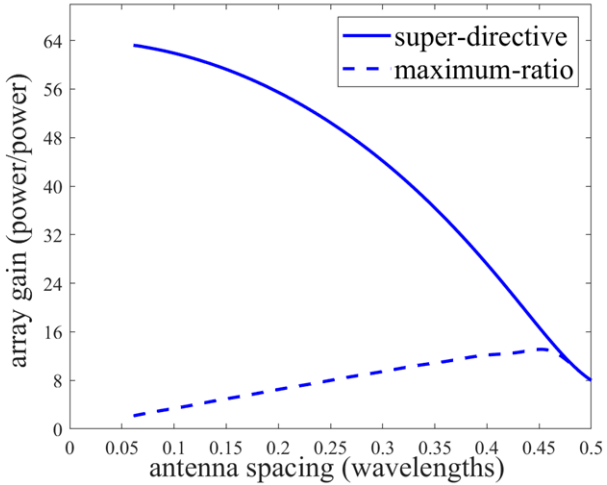
- Super-Directivity
  - at variance with all our wireless experience
  - a purely classical electromagnetic phenomenon! [S.A. Schelkunoff, 1943]
- Exploits strong mutual coupling among closely-spaced antennas
- Currently realizable only on a small scale
  - short dipole: equivalent to two monopoles driven by equal and opposite currents
  - compact receiver arrays for handsets
- Nobody has discovered how to scale up super-directivity to large arrays

Super-Directivity: $M=8$ Antennas



- Asymptotic super-directive gain: $M^2 = 64$ vs $M = 8$ for maximum-ratio

Array Gain Relative to Single-Antenna



New Graduate Course:
A Linear System Approach to Wave Propagation

- Maxwell's equations $\nabla\times\mathbf{E}=-\mu\frac{\partial\mathbf{H}}{\partial t}\quad \nabla\times\mathbf{H}=\varepsilon\frac{\partial\mathbf{E}}{\partial t}+\mathbf{J}\quad \varepsilon\nabla\bullet\mathbf{E}=\rho\quad \mu\nabla\bullet\mathbf{H}=0$
- Physicist's way: potentials $\mathbf{E}=-\nabla\phi-\frac{\partial\mathbf{A}}{\partial t}\quad \mu\mathbf{H}=\nabla\times\mathbf{A}\quad \nabla\bullet\mathbf{A}=-\frac{1}{c^2}\frac{\partial\phi}{\partial t}$
  - spherical coordinates
  - separation of variables
  - spherical harmonics

$$\left(\nabla^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi=\rho,\quad \left(\nabla^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{A}=-\mu\mathbf{J}$$

- Linear system approach: space/time Fourier transforms

$$\int\int\int\int dtdxdydz\left\{\mathbf{Maxwell}(t,x,y,z)\right\}e^{i\omega t}e^{-i(k_x x+k_y y+k_z z)}$$

algebraic equations: $i\mathbf{k}\times\mathbf{E}=i\omega\mu\mathbf{H}\quad i\mathbf{k}\times\mathbf{H}=-i\omega\varepsilon\mathbf{E}+\mathbf{J}\quad i\varepsilon\mathbf{k}\bullet\mathbf{E}=\rho\quad i\mu\mathbf{k}\bullet\mathbf{H}=0$

general solution: $\begin{bmatrix}\mathbf{E}(\omega,\mathbf{k})\\ \mathbf{H}(\omega,\mathbf{k})\end{bmatrix}=\frac{1}{\mathbf{k}^{\mathrm{T}}\mathbf{k}-k^2}\cdot\begin{bmatrix}-\left(\frac{k^2\mathbf{I}-\mathbf{k}\mathbf{k}^{\mathrm{T}}}{i\omega\varepsilon}\right)\\ i\mathbf{k}\times\end{bmatrix}\cdot\mathbf{J}(\omega,\mathbf{k})\quad \mathbf{k}^{\mathrm{T}}=\begin{bmatrix}k_x & k_y & k_z\end{bmatrix}\quad k=\frac{\omega}{c}=\frac{2\pi}{\lambda}$

two-pole system: $\mathbf{k}^{\mathrm{T}}\mathbf{k}-k^2=\left(k_z-\sqrt{k^2-k_x^2-k_y^2}\right)\left(k_z+\sqrt{k^2-k_x^2-k_y^2}\right)$ residues $\rightarrow$ plane-waves

Conclusion

- All existing wireless schemes are operating far from any limits imposed by nature!
  - We need much greater investment in fundamental research to narrow this gap