Keysight Technologies

Massive MIMO: Answering Some Common Questions

by
Roger Nichols
Keysight Technologies

White Paper

KEYSIGHT TECHNOLOGIES

Introduction

Watching television as a child in a rural town in eastern Colorado was often frustrating due to the "ghost" image that distorted our black & white television screen during my favorite programs. I remember my parents reassuring me that the TV was not broken but rather the antenna was picking up an "echo". This echo was apparently from the front range of the Rocky Mountains some fifty miles away. It was not until much later that I learned the physics of multipath interference and the varied techniques used in analog communications to alleviate its impact. The advent of digital communications, the miniaturization of digital radio transceivers, and their enablement with significant computational capability has now enabled us to not only "fix that echo" but to take advantage of it to get more information from transmitter to receiver.

$$C = \mathbf{M} \times B \times \log_2\left(1 + \frac{S}{N}\right)$$

C = Channel capacity in $\frac{\text{bits}}{\text{second}}$

M = Number of channels, the MIMO order

B = Bandwidth in Hz

$\frac{S}{N}$ = Signal to noise ratio (linear power ratio)

Figure 1: Simplified Shannon-Hartley Theorem: Note what M can do for capacity.

Multiple In, Multiple Out: This act of adding an advantageous term to the Shannon-Hartley theorem (Fig. 1) to squeeze a few more bits per second from our precious spectrum is presently enjoying more attention than ever in the history of wireless communications. MIMO in 5G is dominated by the discussion of "Massive MIMO" which some suggest is a relatively new concept.

But MIMO technology has some very early roots in work done by Ernst F. W. Alexanderson[1] and later by H. H. Beverage and H. O. Peterson of R.C.A. Communications[2] and then followed by remarkable work by D. G. Brennan[3]. More serious attention came in the mid 1990's with works by Foschini (Bell Laboratories), Raliegh and Cioffi, and Alamouti which highlighted mathematical models for the channel and approaches to vastly increase channel capacity given large numbers of antennas. I recommend all my fellow radio-history fans read these older papers—not just to get some perspective on our industry—but to realize that technologies that smell a lot like MIMO go back to a time when the founders of radio communication were but recently in their graves.

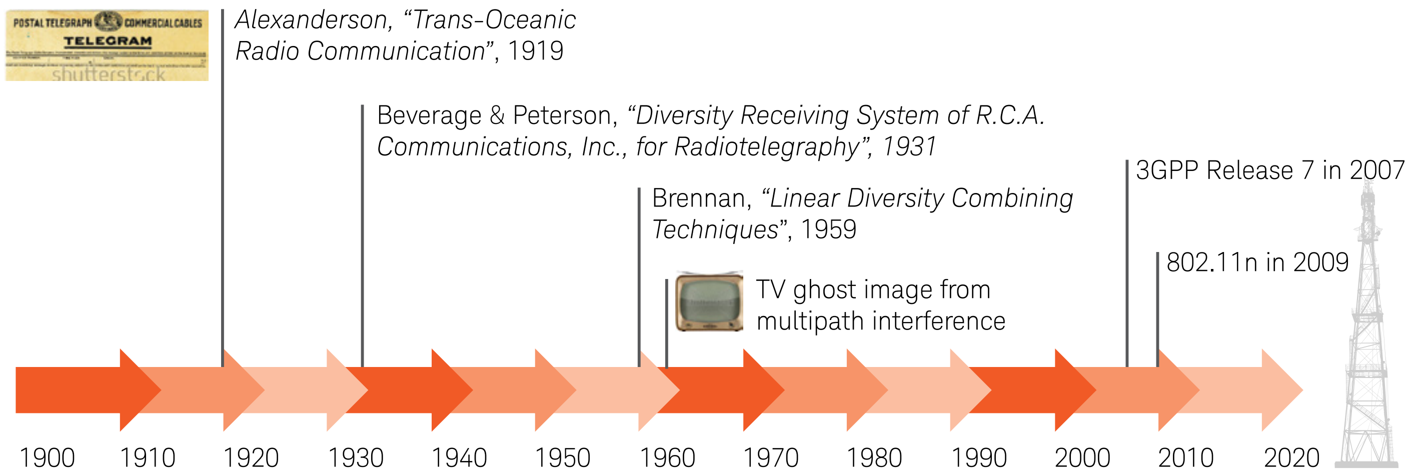


Figure 2: Illustrating key MIMO milestones

MIMO and associated MIMO antenna technology has been in the WiFi standards since 802.11n (2009) and in cellular mobile radio since 2007 (3GPP Release 7 in UMTS/WCDMA/HSDPA). But what is "MIMO"? In seminars and papers, this term is often followed by complex and opaque equations using both cases of the entire Greek alphabet; and that is before you get to the linear algebra. This is not to belittle this mandatory step to building the physical and computational models. We have a problem of either overly complex mathematics or grossly simplified cartoon diagrams with antenna arrays apparently sending lightning bolts through different paths to users—one bouncing off a mountain, for instance.

---

1 Alexanderson, Ernst F. W., "Trans-Oceanic Radio Communication": Transactions of the American Institute of Electrical Engineers Volume XXXVIII, Issue: 2, July 1919

2 Beverage, H. H., Peterson, H. O., "Diversity Receiving System of R.C.A. Communications, Inc., for Radiotelegraphy": Proceedings of the Institute of Radio Engineers, Volume 19, Number 4 April 1931

3 Brennan, D. G., "Linear Diversity Combining Techniques": Proceedings of the Institute of Radio Engineers, Volume 47, pp. 1075-1102, June 1959

Implementing MIMO technology assumes that the air, cars, trees, houses, and mountains in the proximity between and around the transmitter and receiver cause radio signals to follow multiple independent (orthogonal) paths. The very smart baseband systems connected through independent antennas and transceiver chains use those complex mathematical models mentioned above to split apart or reassemble the signals from these different paths to create multiple useful communications channels out of what used to be just one. This is then used to do any of the following:

1. Use more than one path to decrease the error rate of a single set of data (send the same information down multiple paths, adding redundancy and effectively decreasing the resulting bit error rate and increasing reliability)
2. Use more than one path for different sets of data (send different information down different paths thereby using multiple channels to increase capacity)
3. Manipulate the inherent nature of multipath interference to either cancel (destructive interference) or augment (constructive interference) the signal at any physical location in the radio channel.

The last decade has driven plenty of complication to the topic by a new concept now known as “Massive MIMO”. Some important terms arise in the more recent discussions:

– **SU-MIMO: Single-User MIMO**—using multiple radio paths to improve communications with a single user
– **MU-MIMO: Multi-User MIMO**—using multiple radio paths and multiple users’ unique-and-superimposed signals such that the capacity of the channel for multiple users is increased
– **FD-MIMO: Full-Dimension MIMO** (3GPP Release 13 term referring to the use of 2-dimensional antenna arrays to take advantage of a 3-dimensional channel (distance, breadth, height) and also allows for 3D beamforming
– **Massive MIMO:** A special case of MU-MIMO augmenting a multi-path channel with a large transceiver array to increase channel capacity, spectral efficiency, and energy efficiency

“I have been witness to some fascinating and heated discussions on these topics and I enjoy them because it is in these that I learn the most about the subject.”

Frequently-Asked MIMO Questions

I have been witness to some fascinating and heated discussions on these topics and I enjoy them because it is in these that I learn the most about the subject.

Here are a few of the more interesting topics over which I have seen and even participated in heated debate:

Is “MIMO” the same as “Beamforming”?

Definitely No. “Beamforming” refers to the manipulation of the direction and “shape” of a transmitted radio signal. At least some of the MIMO antenna technology approaches described above include “forming” these beams using phase-relationships of the active antenna elements. MIMO can thus take advantage of beamforming; and indeed FD MIMO has two modes that are strictly characterized by “MIMO beamforming”. But phased array beamforming is done in many non-MIMO applications.

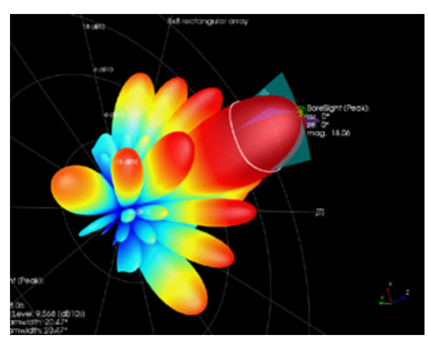


Figure 3: Beamforming example

"Massive" means lots of antennas. How many?

The answer varies. I think of the founder of 5G Massive MIMO as Dr. Thomas Marzetta of Nokia Bell Labs[4]. Marzetta states that the base-station MIMO antenna array count is "much greater" than the user count. This is where the confusion starts. Marzetta is explicit about stipulating not only many antennas ("the more, the better"), but also that each is part of an independent base-station transceiver chain. Massive MIMO's promise of increasing capacity, decreasing energy-per-bit, and improving spectral efficiency all translate to cost-savings for mobile operators. But realizing those savings will require the massively scaled baseband processing to consume less incremental energy and cost than what the new technology saves. How many antennas? One credible paper I read suggested that such a point was probably below 500 given technology that could be anticipated in the coming decade.[5]

"How many antennas? ... Probably below 500 given technology ..."

Is FD-MIMO also Massive MIMO? Which one is 5G Massive MIMO?

An FD MIMO antenna array has 64 elements so it could be deemed "massive". Another recent paper specifically refers to FD-MIMO as "massive"[6]. But Dr. Marzetta's definition states a few things that characterize the unique idea that he and industry and academic colleagues are pushing:

- Enough antennas appropriately spaced for channel orthogonality and "channel hardening" (this term refers to phenomenon that causes random radio channels to behave more deterministically as the MIMO antenna count is increased).
- A single link to each UE and the simultaneous use of time-frequency "resource blocks"; i.e. UEs in different locations communicate in the exact same frequency and time. Hence the term "spatial diversity"
- The use of measured rather than assumed channel state information.

Most MIMO systems require a "training" process for the system to build and maintain model of the channel. In cellular systems, this is done via the transmission of a pre-defined waveform known as a "pilot". The amplitude and phase response of the resulting demodulated pilot shows the receiver the nature of the multi-path elements in the channel. From this, algorithms are implemented either:

- At the receiver to separate the necessary data streams from orthogonal paths in the channel; or
- At the transmitter to pre-code the data transmitted so it arrives at the receiver antennas such that each antenna gets exactly (and only) the orthogonal signal it needs.

4 Marzetta, Thomas L., "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas": IEEE Transactions on Wireless Communications, vol 9, no. 11, pp. 3590-3600, Nov 2010

5 Jakob Hoydis, Stephan ten Brink, Mérouane Debbah, "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?", IEEE Journal on Selected Areas on Communications, Vol 31, No. 2. February 2013

6 Hyoungju Ji, Younsun Kim, ,Joho Lee, Eko Onggosamusi, Younghan Nam, Jianzhong Zhang, Byungju Lee, Byongyo Shim; "Overview of Full-Dimension MIMO in LTE-Advanced Pro", IEEE Communications Magazine, Vol. 55 Issue: 2

3GPP LTE MIMO use pilots generated by the base station (eNodeB or eNB) and interpreted by the user equipment (UE). The UE's then send channel information back to the eNB so it can pre-code the next transmitted signals. This places the burden of channel assessment on the UEs and adds the uplink signaling overhead of the UE sending their interpretations back to the eNB. Marzetta states that MIMO will not scale unless this burden is reversed—that the UE's send the pilot signals and the eNB does all of the algorithmic work. So while FD MIMO does have a relatively high antenna count, it still relies upon the UE to interpret the pilot signals.

Can you do Massive MIMO in FDD communications?

3GPP Release 13 allows for FDD LTE systems to use FD-MIMO. If one accepts that FD-MIMO is "massive", one could say that the answer to this question is "yes". But this channel training takes time. And the time available is limited by two primary factors:

1. One can assume the channel to be constant over only a limited period of time (channel coherence time) after which the channel state information is no longer valid and the pilot/channel assessment process has to be repeated.
2. Some of the channel coherence time must be reserved for the transmission of user payload data.

I was fortunate enough to attend Dr. Marzetta's tutorial on massive MIMO at WCNC in San Francisco last March. He has two beefs with the scalability of FDD MIMO. The first is that the channel state information is assumed for one of the links. Pilots are sent only on the downlink so the system must assume that the uplink, which is on a different frequency, has the same channel characteristics. Perhaps more importantly, his work shows that this channel training time dependencies vary depending on whether the system is FDD or TDD. In a TDD system, the training time is proportional only to the number of K users in the cell. But in FDD it is proportional to the sum of the number of users and twice the number M of base-station antennas (K + 2M). Given that "Massive" first and foremost means lots of base station antennas he stated (and I quote): "FDD is a disaster. End of story."

Given that "Massive" first and foremost means lots of base station antennas he stated (and I quote): "FDD is a disaster. End of story."

Is Massive MIMO only usable as a millimeter wave technology?

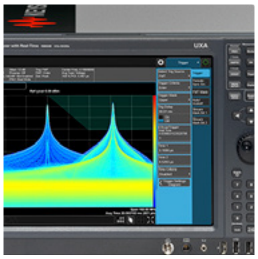
Absolutely not. Most Massive MIMO research to date has been done assuming wavelengths associated with frequencies below 6GHz. The first commercial deployments of Massive MIMO will definitely be in bands below 6GHz.

5G: MIMO's next major step

Will it work? Will we get Massive MIMO in 5G that will improve capacity, energy efficiency, and spectral efficiency? Yes. The industry has shown some impressive research and more recently some compelling demonstrations (e.g. MWC in late February 2017). And the promise of using our new digital technologies to take full advantage of a rich radio channel continues to drive innovation in the industry. I look forward to it just like I look forward to the next heated discussion about what it is, whether it will work, and how soon we will see it.

Evolving Since 1939

Our unique combination of hardware, software, services, and people can help you reach your next breakthrough. We are unlocking the future of technology.
From Hewlett-Packard to Agilent to Keysight.


myKeysight
www.keysight.com/find/mykeysight
A personalized view into the information most relevant to you.

KEYSIGHT SERVICES
Accelerate Technology Adoption. Lower costs.

Keysight Services
www.keysight.com/find/service
Keysight Services can help from acquisition to renewal across your instrument's lifecycle. Our comprehensive service offerings—one-stop calibration, repair, asset management, technology refresh, consulting, training and more—helps you improve product quality and lower costs.

Three-Year Warranty
www.keysight.com/find/ThreeYearWarranty
Keysight's committed to superior product quality and lower total cost of ownership. Keysight is the only test and measurement company with three-year warranty standard on all instruments, worldwide. And, we provide a one-year warranty on many accessories, calibration devices, systems and custom products.

Keysight Assurance Plans
www.keysight.com/find/AssurancePlans
Up to ten years of protection and no budgetary surprises to ensure your instruments are operating to specification, so you can rely on accurate measurements.

Keysight Channel Partners
www.keysight.com/find/channelpartners
Get the best of both worlds: Keysight's measurement expertise and product breadth, combined with channel partner convenience.

www.keysight.com/find/
www.keysight.com/find/

KEYSIGHT TECHNOLOGIES

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at:
www.keysight.com/find/contactus

Americas

Canada	(877) 894 4414
Brazil	55 11 3351 7010
Mexico	001 800 254 2440
United States	(800) 829 4444

Asia Pacific

Australia	1 800 629 485
China	800 810 0189
Hong Kong	800 938 693
India	1 800 11 2626
Japan	0120 (421) 345
Korea	080 769 0800
Malaysia	1 800 888 848
Singapore	1 800 375 8100
Taiwan	0800 047 866
Other AP Countries	(65) 6375 8100

Europe & Middle East

Austria	0800 001122
Belgium	0800 58580
Finland	0800 523252
France	0805 980333
Germany	0800 6270999
Ireland	1800 832700
Israel	1 809 343051
Italy	800 599100
Luxembourg	+32 800 58580
Netherlands	0800 0233200
Russia	8800 5009286
Spain	800 000154
Sweden	0200 882255
Switzerland	0800 805353
	Opt. 1 (DE)
	Opt. 2 (FR)
	Opt. 3 (IT)
United Kingdom	0800 0260637

For other unlisted countries:
www.keysight.com/find/contactus
(BP-6-20-17)

DEKRA Certified
ISO9001 Quality Management System

www.keysight.com/go/quality
Keysight Technologies, Inc.
DEKRA Certified ISO 9001:2015
Quality Management System

Published in USA, July 13, 2017
5992-2452EN
www.keysight.com