Moving from 4G to 5G: Some research directions

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Outline

4G cellular networks today

Inside 4G: Key aspects

What now? From 4G to 5G

Massive MIMO

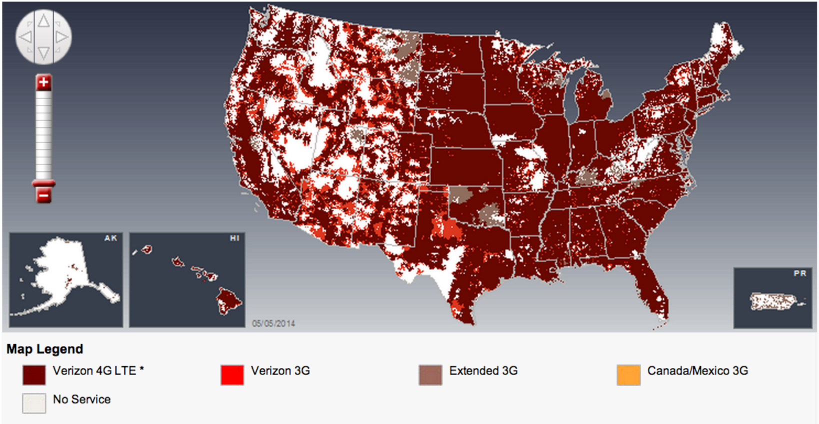
Millimeter Wave Cellular Communications

Conclusions and future work

4G at the speed of light

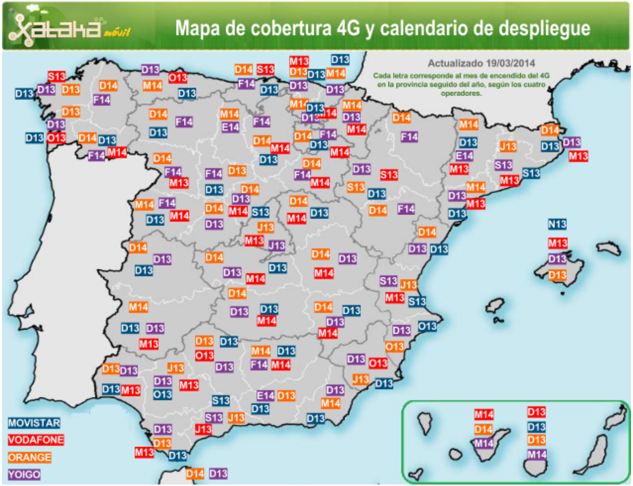
Source: Laptopmag

4G coverage US



Source: Verizon

4G coverage Spain



Source: Xataka Movil

Today's talk

- Do we need 5G?
- What is 4G (and what is not)?
- What is 5G (and what is not)?
- What is yet to be done/known?

Today's talk

- Do we need 5G? $\rightarrow$ We can make it happen
- What is 4G (and what is not)? $\rightarrow$ Key aspects inside 4G
- What is 5G (and what is not)? $\rightarrow$ From 4G to 5G
- What is yet to be done? $\rightarrow$ Massive MIMO & mmWave

Today's talk

Disclaimer!

- PHY layer
- Communication theory
- No maths please!

Inside 4G: Key aspects

Capacity

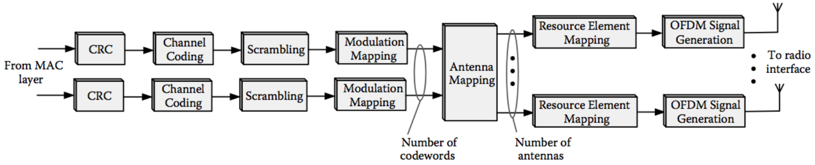
$C = B\log(1 + SNR)$

Basic features of PHY

- OFDM
- MIMO
- Adaptive Modulation and Coding

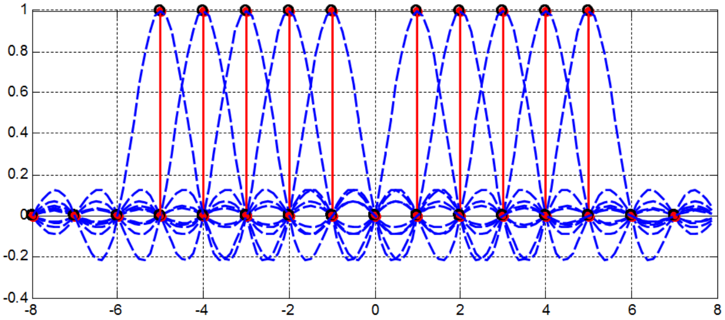
Inside 4G: Key aspects

LTE PHY overview



Inside 4G: Key aspects

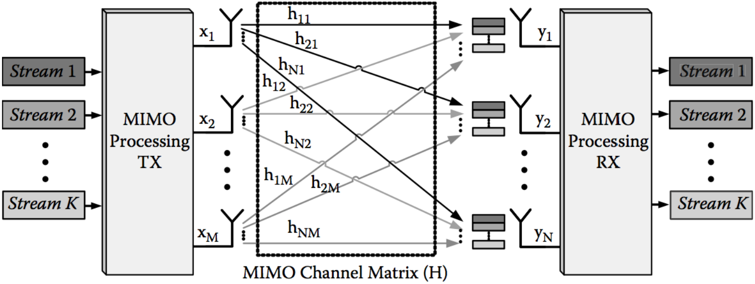
OFDM



- BW efficiency
- Sensitivity to ICI

Inside 4G: Key aspects

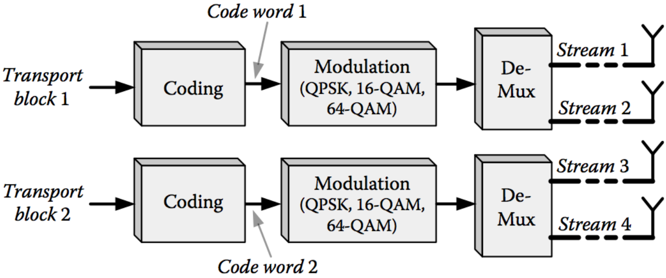
MIMO



- Multiplexing
- Beamforming

Inside 4G: Key aspects

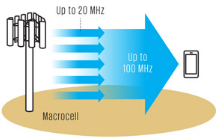
Adaptive Modulation and Coding



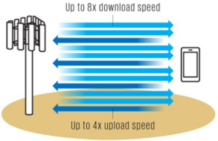
- Turbocoding
- QPSK up to 64-QAM

THE LTE-ADVANCED ADVANTAGE

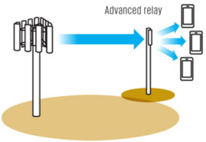
Known as "true 4G," LTE-Advanced includes a menu of wireless technologies that will boost the capacity of current 4G LTE networks and make possible mobile download rates as high as 3 gigabits per second. Here are five key features that distinguish the new standard from its predecessors.



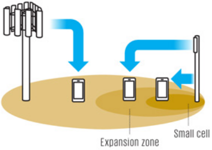
WIDER BANDWIDTH
Using a technology called **carrier aggregation**, operators can combine up to five LTE frequency channels, or carriers, as wide as 20 megahertz that reside in different parts of the radio spectrum.



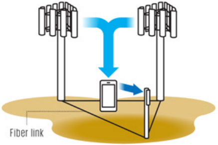
MORE DATA STREAMS
LTE-Advanced supports more sophisticated **multiple input, multiple output** (MIMO) techniques, which enable several antennas to send and receive data. One use of MIMO, called spatial multiplexing, separates transmissions into many parallel streams, increasing data rates in proportion to the number of antennas used.



SMARTER RELAYS
Conventional radio repeaters, such as those used in LTE networks, simply amplify transmissions from a base station. LTE-Advanced allows for more **advanced relays**, which first decode the signals and then forward only those meant for nearby users, increasing the total number each relay can serve.



SUPPORT FOR SMALL CELLS
A protocol called **enhanced inter-cell interference coordination** (eICIC) alleviates interference to a small cell—a low-power base station whose coverage zone lies inside a traditional macrocell. The two cells can dynamically coordinate their use of spectrum, letting the small cell expand its transmission range.



COORDINATED TRANSMISSIONS
To improve reception, LTE-Advanced introduces **coordinated multipoint** (CoMP). It permits several base stations to form a single cell, allowing a mobile unit to connect with all of them at the same time. For example, the unit could receive downloads from high-power towers while uploading to a nearby small cell.

Source: IEEE Spectrum

What now? From 4G to 5G

Generation	Requirements	Comments
1G	No official requirements. Analog technology.	Deployed in the 1980s.
2G	No official requirements. Digital Technology.	First digital systems. Deployed in the 1990s. New services such as SMS and low-rate data. Primary technologies include IS-95 CDMA and GSM.
3G	ITU's IMT-2000 required 144 kbps mobile, 384 kbps pedestrian, 2 Mbps indoors	Primary technologies include CDMA2000 1X/EV-DO and UMTS-HSPA. WiMAX now an official 3G technology.
4G	ITU's IMT-Advanced requirements include ability to operate in up to 40 MHz radio channels and with very high spectral efficiency.	No technology meets requirements today. IEEE 802.16m and LTE-Advanced being designed to meet requirements.

Source: Rappaport, T.S.; Shu Sun; Mayzus, R.; Hang Zhao; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," Access, IEEE , vol.1, no., pp.335,349, 2013

What now? From 4G to 5G

The advent of 5G: Some facts

- 5G will be first a commercial nickname than a reality
- Roughly 10 years between generations
- Deploying a brand-new network $$$
- Changes must be fundamental compared to 4G

What now? From 4G to 5G

How will 5G technology look like? (Native requirements)

- Heterogeneus Networks (HetNets)
- Cognitive Radio (CR)
- Millimeter Wave (mmWave)
- Device to Device (D2D)
- Machine to Machine (M2M)
- Massive MIMO

Source: Boccardi, F; Heath, R.W.; Lozano, A.; Marzetta, T.L.; Popovski, P., "Five disruptive technology directions for 5G," IEEE Communications Magazine , vol.52, no.2, pp.74,80, February 2014

What now? From 4G to 5G

We will focus on

- ~~Heterogeneus Networks (HetNets)~~
- ~~Cognitive Radio (CR)~~
- **Millimeter Wave (mmWave)**
- ~~Device to Device (D2D)~~
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What now? From 4G to 5G

HetNets

Aspect	Traditional Cellular	HetNet
Performance Metric	Outage/coverage probability distribution (in terms of SINR) or spectral efficiency (bps/Hz)	Outage/coverage probability distribution (in terms of *rate*) or area spectral efficiency (bps/Hz/m^2)
Topology	BSs spaced out, have distinct coverage areas. Hexagonal grid is an ubiquitous model for BS locations.	Nested cells (pico/femto) inside macrocells. BSs are placed opportunistically and their locations are better modeled as a random process.
Cell Association	Usually connect to strongest BS, or perhaps two strongest during soft handover	Connect to BS(s) able to provide the highest data rate, rather than signal strength. Use biasing for small BSs.
Downlink vs. Uplink	Downlink and uplink to a given BS have approximately the same SINR. The best DL BS is usually the best in UL too.	Downlink and uplink can have very different SINRs; should not necessarily use the same BS in each direction.
Mobility	Handoff to a stronger BS when entering its coverage area, involves signaling over wired core network	Handoffs and dropped calls may be too frequent if use small cells when highly mobile, overhead a major concern.
Backhaul	BSs have heavy-duty wired backhaul, are connected into the core network. BS to MS connection is the bottleneck.	BSs often will not have high speed wired connections. BS to core network (backhaul) link is often the bottle-neck in terms of performance and cost.
Interference Management	Employ (fractional) frequency reuse and/or simply tolerate very poor cell edge rates. All BSs are available for connec-tion, i.e. "open access"	Manage closed access interference through resource allocation; users may be "in" one cell while communicat-ing with a different BS; interference management hard due to irregular backhaul and sheer number of BSs

Source: Andrews, J.G., "Seven ways that HetNets are a cellular paradigm shift," Communications Magazine, IEEE , vol.51, no.3, pp.136,144, March 2013

What now? From 4G to 5G

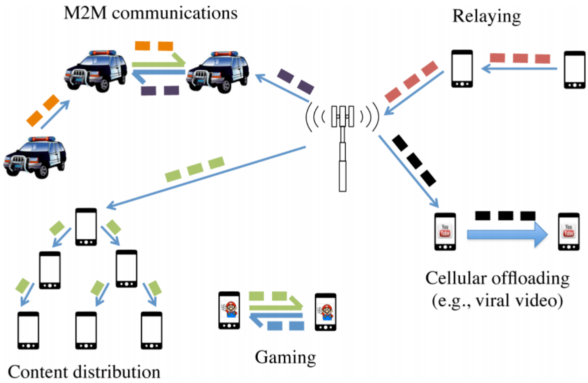
Cognitive Radio

- Interweave
- Underlay
- Overlay

Source: Goldsmith, A.; Jafar, S.A.; Maric, I.; Srinivasa, S., "Breaking Spectrum Gridlock With Cognitive Radios: An Information Theoretic Perspective," Proceedings of the IEEE , vol.97, no.5, pp.894,914, May 2009

What now? From 4G to 5G

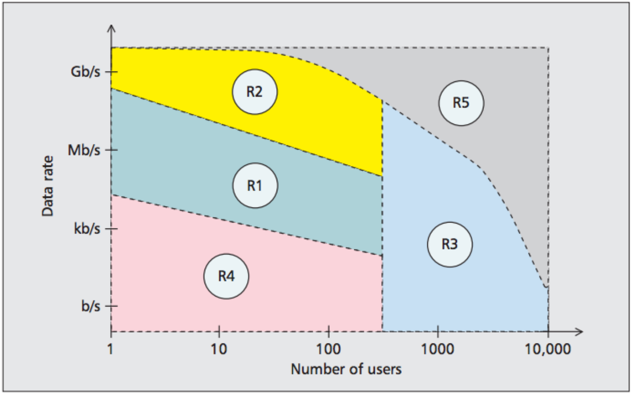
Device to Device Communications



Source: Asadi, A.; Wang, Q.; Mancuso, V., "A Survey on Device-to-Device Communcation in Cellular Networks," To appear in IEEE Communications Surveys & Tutorials 2014

What now? From 4G to 5G

Machine to Machine Communications



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What now? From 4G to 5G

We will focus on

- ~~Heterogeneus Networks (HetNets)~~
- ~~Cognitive Radio (CR)~~
- **Millimeter Wave (mmWave)**
- ~~Device to Device (D2D)~~
- ~~Machine to Machine (M2M)~~
- **Massive MIMO**

Massive MIMO

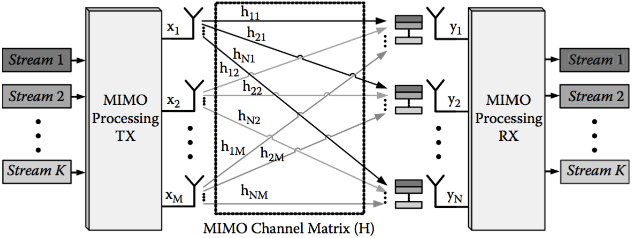
a.k.a. Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO, Full-Dimension MIMO...

- Key aspects of Massive MIMO
- Practical issues
- Current research and open problems
- Our work

Must read: Marzetta, T.L., "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," IEEE Transactions on Wireless Communications, vol.9, no.11, pp.3590,3600, November 2010

Massive MIMO: Key Aspects

A conventional single user MIMO system:



- Massive MIMO is a multiuser system
- Massive MIMO is not a MIMO system!
- $M \to \infty$, N single antenna users.
- Uses TDD by definition

Massive MIMO: Key Aspects

Benefits

- Increases capacity
- Reduces transmit power
- Effects of noise and fading are vanished
- Robustness and reliability
- Inexpensive HW

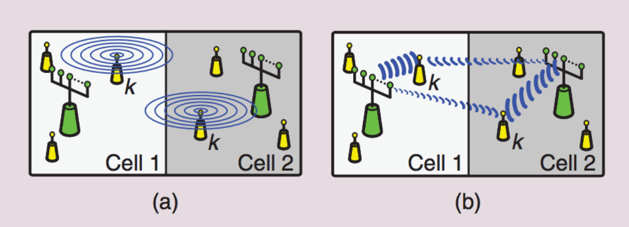
But...

- How many antennas is ∞?
- Is there any drawback to it?

Massive MIMO: Practical issues

Pilot contamination

- Due to channel estimation in TDD
- Finite number of orthogonal sequences
- Depends on shadowing and path loss
- Consequence of linear precoding and detection schemes



Source: Rusek, F.; Persson, D.; Buon Kiong Lau; Larsson, E.G.; Marzetta, T.L.; Edfors, O.; Tufvesson, F., "Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays," IEEE Signal Processing Magazine, vol.30, no.1, pp.40,60, Jan. 2013

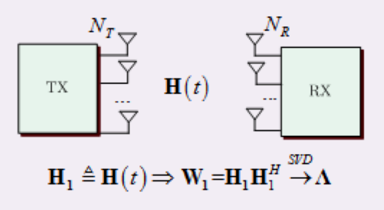
Massive MIMO: Current research and open problems

- How to overcome pilot contamination?
- Channel estimation
- Effect of cell size
- Effect of user mobility
- Propagation
- Efficient Implementation
- HW impairments?
- Internal power consumption

More in: Larsson, E.; Edfors, O.; Tufvesson, F.; Marzetta, T., "Massive MIMO for next generation wireless systems," IEEE Communications Magazine, vol.52, no.2, pp.186-195, February 2014.
Check also http://www.commsys.isy.liu.se/∼egl/vlm/vlm.html

Massive MIMO: Our work

Dynamic behavior of a MIMO channel



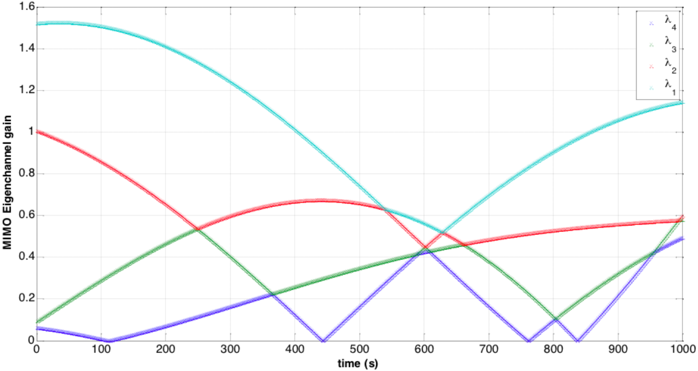
"On the Dynamics of the Extreme Eigenvalues of a Central Wishart Matrix with Application to MIMO Systems"

with E. Martos-Naya, J.F. Paris and A. Goldsmith, to be submitted to IEEE Transactions on Information Theory.

Presented in part at Information Theory Workshop 2013, Communication Theory Workshop 2014.

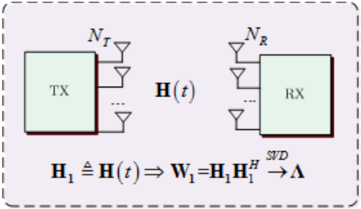
Massive MIMO: Our work

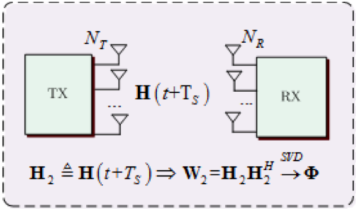
Dynamic behavior of a MIMO channel



Massive MIMO: Our work

Dynamic behavior of a MIMO channel





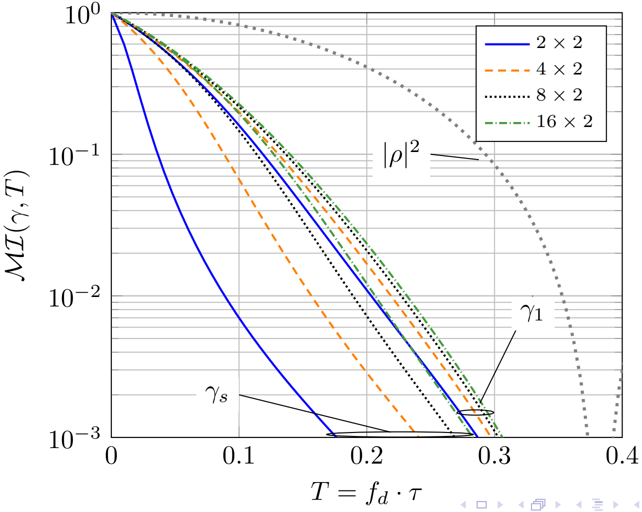
Massive MIMO: Our work

Dynamic behavior of a MIMO channel

- Can we characterize the dynamic behavior of the parallel channels separately?
- Do they all have the same behavior?
- What happens in a Massive MIMO setup?

Our metric: Mutual information between $X = \Pr(\gamma(t) < \gamma_{th})$ and $Y = \Pr(\gamma(t + T) < \gamma_{th})$

Massive MIMO: Our work



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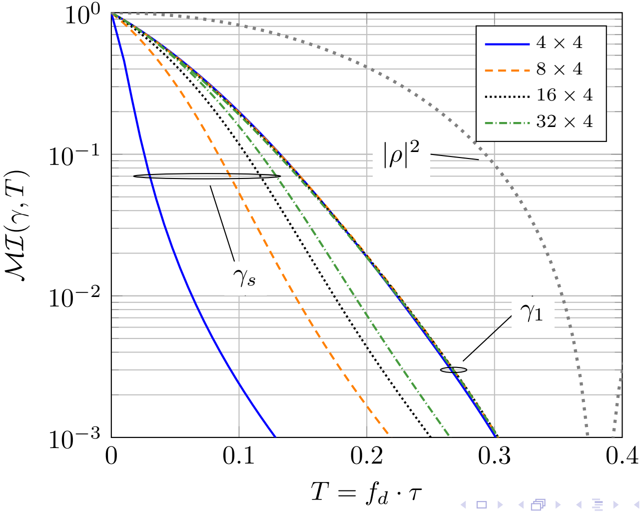


Massive MIMO: Our work

Dynamic behavior of a MIMO channel: Some conclusions (I)

- The dynamics of the best eigenchannel are barely affected by using more BS antennas.
- The dynamic behavior of the worst eigenchannel is dramatically affected by the value of N_R.
- This indicates that the worst channel decorrelates faster as N_R is reduced.
- The best channel takes longer to decorrelate as N_T grows, but this difference is comparatively smaller.
- The worst channel rapidly tends to exhibit a similar behavior than the best one as $N_T/N_R \uparrow$.

Massive MIMO: Our work

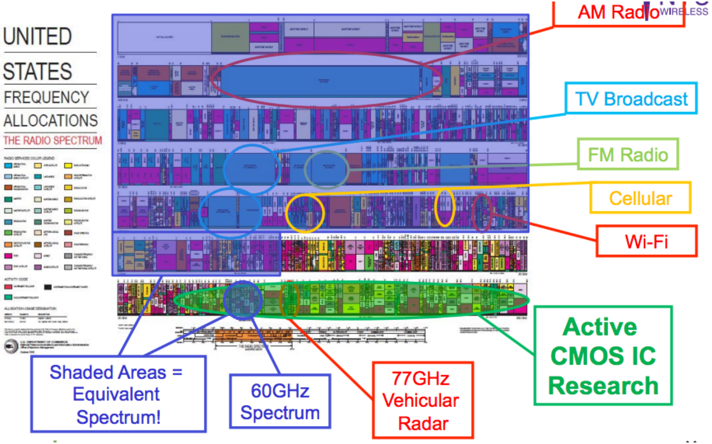
Dynamic behavior of a MIMO channel: Some conclusions (II)

- Increasing both N_T and N_R causes that the worst channel has a much faster rate of change.
- The worst channel tends to be more stable as N_T is increased.

[Larsson14]: For $N_T \sim 10 N_R$, the spread between the best and worst channels is reduced and a stable performance can be ensured even in non favorable propagation conditions.

Our results suggest that **this performance can be also sustained in time with a similar behavior for all K users: User channel variation in massive MIMO systems seems similar for users with the same mobility**

Millimeter Wave Cellular Communications



Source: Theodore S. Rappaport Plenary Talk VTS'12

Millimeter Wave Cellular Communications

Main motivation?

Capacity

$C = B \log(1 + SNR)$

MmWave communications before (and today):

- LOS links for Wireless Access Networks
- 60 GHz standardization for WPAN (802.15.3c) and WLAN (802.11ad)
- Backhaul in cellular networks

The key is in the word **cellular**

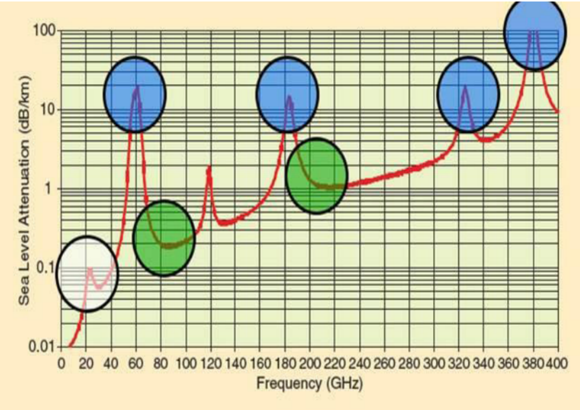
Millimeter Wave Cellular Communications

- Myths and realities
- Key aspects and practical issues
- Current research and open problems
- Our work

Must read: Rangan, S.; Rappaport, T.S.; Erkip, E., "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," Proceedings of the IEEE , vol.102, no.3, pp.366,385, March 2014

Millimeter Wave Cellular Communications

Myths and realities: Propagation is an issue



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Millimeter Wave Cellular Communications

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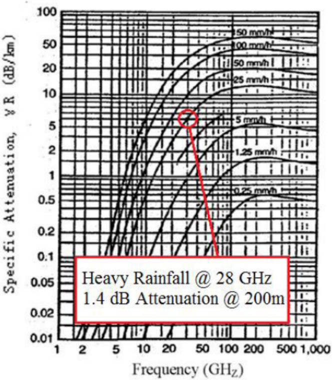

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Millimeter Wave Cellular Communications

Myths and realities: Waste of power

- Very high directive beams (antenna gains)
- Signal attenuation facilitates small cells
- Signal attenuation reduces interference
- Very LOS propagation

Millimeter Wave Cellular Communications

Key aspects and practical issues

- ✓ Larger available BW
- × Meaning higher noise power
- ✓ Directive beams allow for concentrating power
- × But also more sensitive to blockage
- ▶ Need for large antenna arrays

Millimeter Wave Cellular Communications

Current research and open problems

- Measurement campaigns (path loss characterization)
- Behavior in NLOS scenarios
- Small scale fading modeling
- Heavy shadowing (blockage) modeling
- Efficient HW implementation
- Effect of mobility?
- Spectrum regulation
- Marriage with Massive MIMO?

Millimeter Wave Cellular Communications

Our work: Small scale fading in LOS conditions

"Statistics, System Performance Metrics and Extensions for the Two Wave with Diffuse Power Fading Model" with M. Rao, M.S. Alouini and A. Goldsmith, to be submitted to IEEE Transactions on Wireless Communications.

Presented in part at IEEE 48th Annual Conference on Information Sciences and Systems (CISS 2014).

$$y = hx + n$$

- Classical LOS model: Rice $\rightarrow (\bar{\gamma}, K)$
- TWDP model: Similar to Rice but two LOS components

$$h = V_1 e^{j\phi_1} + V_2 e^{j\phi_2} + V_{diff}$$

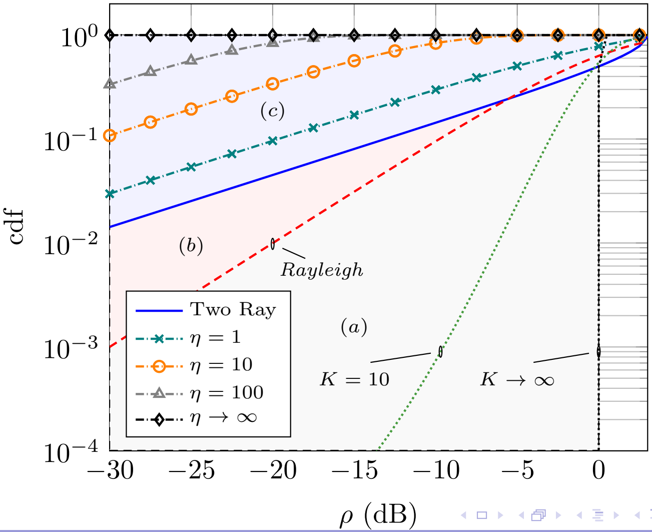
$$\Delta = \frac{2V_1V_2}{V_1^2+V_2^2}, \quad K = \frac{V_1^2+V_2^2}{2\sigma^2}, \quad \bar{\gamma} = (1+K)2\sigma^2/N_0$$

Millimeter Wave Cellular Communications

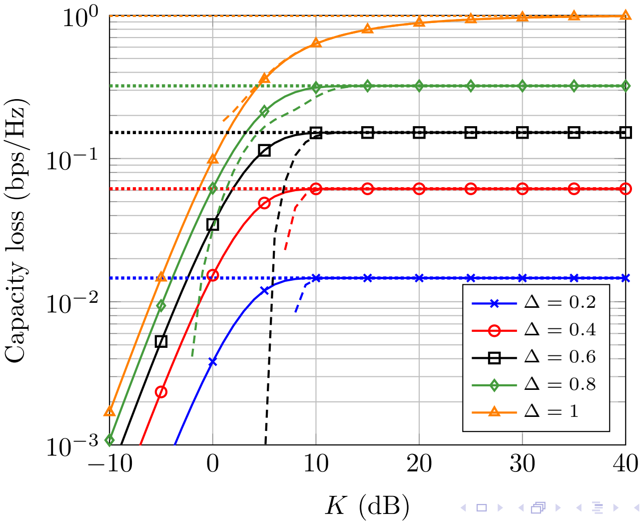
Our work: Small scale fading in LOS conditions

- TWDP fading is LOS
- LOS can be also detrimental if $\Delta = 1$
- Complicated statistical characterization
- Our contribution: A way to analyze this fading model
- Extensions: Distribution of phases is other than uniform

Millimeter Wave Cellular Communications



Millimeter Wave Cellular Communications



Millimeter Wave Cellular Communications

Our work: Small scale fading in LOS conditions

- Is it good to model mmWave small-scale fading?
- How can we introduce shadowing?
- Can we model blockage?

Conclusions and future work

- Massive MIMO and mmWave will be part of 5G
- Alone or together?
- Are they as good as they look?
- When will people start talking of 6G?