Why 5G is Not 4G++
Technology Insights and Challenges

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What is 5G?

Today, 5G is best described today as:

A generally agreed to set of new requirements for wireless communications systems that mature beyond 2020.

**Speed**  “10GB/s” “100 times faster than 4G”

**Very low latency**: 1 mSec for: Augmented Reality, “Tactile Internet”

**Mobility**: “Experience follows you” “Gigabit everywhere” “No cell edge”

**Density**: “Very Dense Crowds of users”

**Low Cost, Low Energy (Green), Large Device Count** for M2M / IoT

Requirements cannot be met by any single radio access technology (RAT)

5G will likely be described by most as *revolutionary*, not *evolutionary*

- Revolutionary Technology such as mmWave and massive MIMO
- Revolutionary Applications
Revolutionary Shifts Initiated by **Access more than by Speed**

**High Reliability, Low Latency Connectivity (5G)**
- Always Available Mobile Network Access
  - Medical monitoring and remote drug delivery
  - Cloud-intelligent Devices: Robotics, autonomous vehicles, other

**Mobile Data (2.5-4G, 802.11)**
- Mobile Network Access
  - Instant sharing
  - Price comparisons, restaurant selection
  - Cloud Services (e.g. data, Siri & maps)

**Dial-up (Phone Modem) to Always On (DSL / Cable Modem)**
- Always-On Network Access (fixed locations)
  - Instant access to news, email, and social networks
  - Distributed File Sharing & Computing

**Voice**
- **Telephones to Cell Phones (1-2G)** (voice and SMS)
- **In-Person to Telephones**
- **Access to People -- Anywhere**
  - Changed Relationships
- **Access to people at a distance (fixed locations)**
Channel Models are critical for 5G

*Very little experience with radio-access technologies in the mmWave bands.*
- Directional antennas required. New concept for mobile devices
- Propagation through materials. Signals will pass through walls, even at 60 GHz.
- Channel dynamics affects signal design and beam forming (algorithms and MAC design)
- Interference (sidelobe performance requirements, null steering)

Need 3D models

*For Massive MIMO the channel model affects:*
- Choice of frequencies for the technology. 3, 6, 15, 28, 39, 60, 70GHz?
- Antenna design, Number of antennas required
- Amplifier design (dynamic range, power, ACPR and other nonlinear behaviors such as AM/PM)
- Signal design (coherence time)
- Reciprocity calibration accuracy
- Total Power requirements (especially for the BTS)
Massive MIMO
Understanding Massive MIMO

**Description:** Number of BTS antennas >> Number of UE antennas

**Motivation:** Higher Reliability, Higher Throughput, Lower TX Power

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### The Graphics

*Overly Simplified!

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### The Math

*Not Completely Intuitive!

\[
\hat{y}_j = \hat{G}^\dagger_{jj} \hat{x}_j
\]

\[
= \left[ \sqrt{\rho_p} \sum_{\ell=1}^L G_{j\ell} \hat{e}_\ell + V_j \right]^\dagger \left[ \sqrt{\rho_t} \sum_{\ell_2=1}^L \tilde{G}_{j\ell_2} \tilde{a}_{\ell_2} + \tilde{w}_j \right],
\]

\[
\frac{1}{M \sqrt{\rho_p \rho_t}} y_{kj} \rightarrow \beta_{jk} a_{kj} + \sum_{\ell \neq j} \beta_{jk\ell} a_{k\ell}.
\]

\[
\hat{x}_\ell = \sqrt{\rho_t} \sum_{j=1}^L \tilde{G}_{j\ell}^T \tilde{G}_{jj}^* \tilde{a}_j + \tilde{w}_\ell,
\]

\[
= \sqrt{\rho_t} \sum_{j=1}^L \tilde{G}_{j\ell}^T \left[ \sqrt{\rho_p} \sum_{\ell=1}^L G_{j\ell} + V_j \right] \tilde{a}_j + \tilde{w}_\ell
\]

Equations from "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas", by Thomas L. Marzetta
2D Massive MIMO, Free-space Path Loss Only
Reference configuration with 4 users: Total TX Power 0dB relative

Target UE (solid)
Victim UEs (hollow)

50 omni elements
Linear Array
½ λ Spacing

UE2
UE3
UE4
2D Massive MIMO, Free-space Path Loss Only
Antenna Spacing increased to $1\lambda$: Total TX Power -3.2 dB
2D Massive MIMO with Scattering
Reference configuration with 4 users: Total TX Power 0dB -5.6dB

Significant Power Savings with only a few scattering elements
Amplifier Power Distribution Across Antenna Array
Requirements affected by channel, antenna design, algorithms

- 50 ant, 0.5λ spacing, free space
- 50 ant, 0.5λ spacing, structured scattering
- 200 ant, 1λ spacing, free space
- 200 ant, 1λ spacing, random scattering
Massive MIMO free space
200 ant, 1 \( \lambda \), Total Power relative to reference: -12.6 dB

Saved in transmit power, but will the total power, including processing be less?
Massive MIMO with Random Scattering
200 ant, $1\lambda$, Total Power relative to reference: $-14.5\text{dB}$
Massive MIMO is not simple Beam Steering
*Focus should be on Victim UE’s and their SIR*

Quiz: Which UE is likely to have the lowest Signal-to-Interference Ratio?

Closest UE
Massive MIMO is not simple Beam Steering
Focus should be on Victim UE’s and their SIR

Quiz: Which UE is likely to have the lowest Signal-to-Interference Ratio?
Answer: It’s the UE closest to the antenna

SIR Factors
- Wavelength (size of null)
- Accuracy of Channel State Estimation (pilot contamination)
- Reciprocity calibration of TX and RX signal Paths
- Amplifier Performance (Gain Linearity, AM/PM)
- Other Phase Errors (e.g. differential phase noise, clock jitter)
- 3D Channel Characteristics (e.g. coherence time)
- Number of Antennas and antenna design (less energy in unhelpful directions)
Possible Sources of Reciprocity Error

Sources of reciprocity error may include:
- Calibration error (isolation, quadrature)
- AM/PM distortion in the PA
- Gain Compression in the PA
- Phase and gain shifts in adjustable components (such as the AGC)
- Differential Phase error (element-to-element)
- Low Channel Coherence Time

For each antenna \( n \), reciprocity requires that \( TX_n(f) = k(f) \cdot RX_n(f) \)

In words, if an antenna element has 1 psec delay mismatch between the transmit receive paths at frequency \( f \), then all other antenna elements must also have a 1 psec mismatch at that frequency. This also applies to amplitude match.
Many Massive MIMO Challenges

Methods for managing SIR
- Better algorithms (Zero Forcing too simple)
- Combine with other interference reduction technologies (e.g. orthogonal signaling)

Complete and accurate channel models required
- Amplifier and antenna requirements
- PHY and MAC design
- Digital vs RF Power Consumption

Early Testing
- Channel Sounding
- Emulation and Simulation
- Design/Algorithm Validation