# Looking Ahead to 5G
(and the Promise and Perils of Ultradensification)

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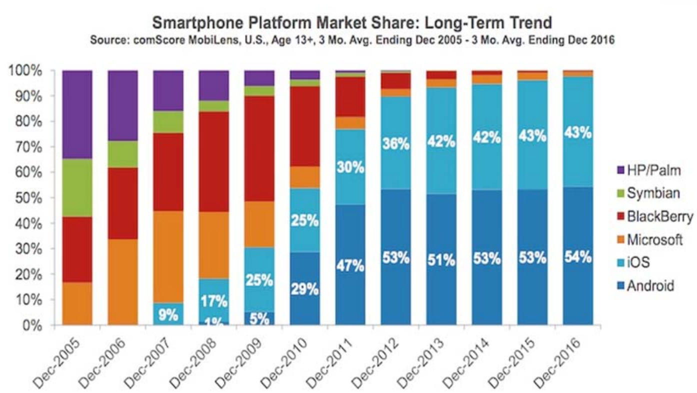
# The Road to 5G

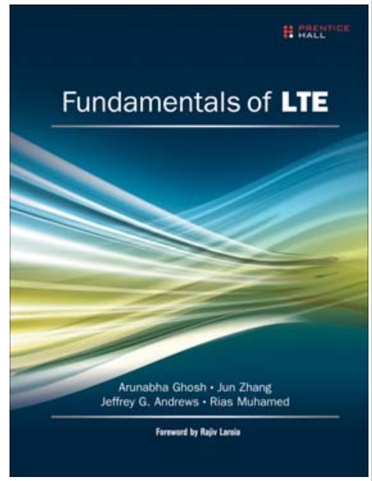
- The Mobile Internet era began around 2007
  - Revisionist history attributes to iPhone launch
- Cellular industry got somewhat lucky that LTE was almost standardized
  - Standard completed (Rel. 8) at end of 2008
  - Launched Sept. 2010 in US



# Key Features of LTE

3GPP Release 8 (2010 Commercial launch):

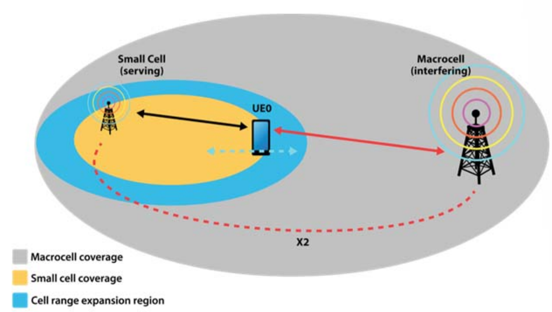
- OFDMA-based physical layer
  - Usually 1024 narrowband (15 KHz) subcarriers
  - Uplink uses SC-FDMA (DFT-precoded OFDMA)
  - Very robust to multipath
  - Computationally and bandwidth efficient
- Highly flexible scheduling via time-frequency "resource blocks" which are reallocated every 1 millisecond
- Flat IP architecture, no notion of a "call"
- Variable bandwidth, but usually 10 MHz *paired* FDD spectrum (wasteful)
- Multi-antenna techniques synergize nicely with OFDMA
- Rapid retransmissions via hybrid ARQ (5-10 msec delay)




# LTE Releases 9 through 14

- Roughly one new release every 1.5-2 years.
- Key additional features:
  - **HetNets**: Enables dense overlays of small cells via biasing and eICIC (interference control)
  - **Carrier aggregation**: UE (user equipment) can use up to 5 bands simultaneously
  - **Unlicensed spectrum:** Use 5 GHz bands when possible (LTE-U, LAA). A form of carrier aggregation.
  - **Enhanced MIMO** (FD-MIMO, MU-MIMO…)
  - **Coordinated Multipoint:** Base station cooperation over wired connections
  - **Machine-Type Communication (MTC):** Enhanced support for various IOT applications

Very Simple Two-Tier HetNet



# Stepping Back to Look Forward

5G Cellular:
How and why it will differ from 4G

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- How did I do in my predictions about 5G given here four years ago?
- In other words, why should you believe anything this guy predicts today?

# Self-Scoring from 2014

## The What, Why, and When of 5G

- 5G generically refers to:
  - The next suite of standards after LTE
  - Something nontrivially different and "better" than LTE
  - Whatever the person using it wants it to mean
- 5G is needed to manage the demands on the mobile Internet expected in the 2020's
  - Support the applications we just discussed, inc. HD video *
  - Support M2M, 1000x traffic increase vs. 4G (10 years)
- When?
  - Standardization will begin in a few years
  - Perhaps 5.0G completed around 2020
  - Commercial products in early 2020's: exactly when depends a lot on what 5G turns out to be

## Assembling all this: A view of 5G

5G will consist of:

1. A dense mmWave network (new 5G standard, ~2020)
2. A more "cellular-like" WiFi network
   - Trends in WiFi include more centralized control, better allocation of resources
   - "Hotspot 2.0" includes further features for cellular integration and load balancing, handoffs
   - Enterprise WiFi networks already closely resembling cellular networks
   - Key thing in my view is to provide better mechanisms for AP sharing (i.e. automated password sharing), which is mostly about backhaul sharing
3. LTE providing the "control" and connectivity backbone at conventional licensed frequencies
4. A great deal of integration between these standards

*Applications I discussed earlier included Tactile Internet (ultra low latency), Cloud, Massive MTC, VR/AR

# The 5G "Holy Trinity" of Use Cases

eMBB: The usual smartphone-centric stuff

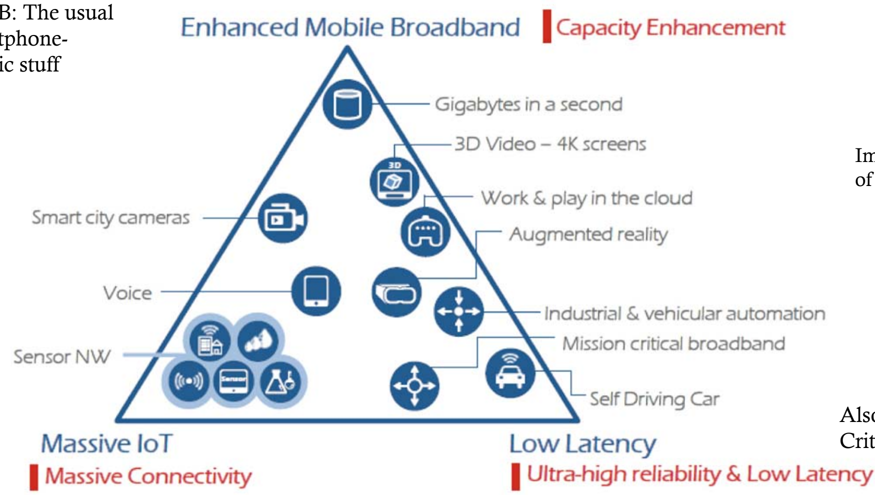


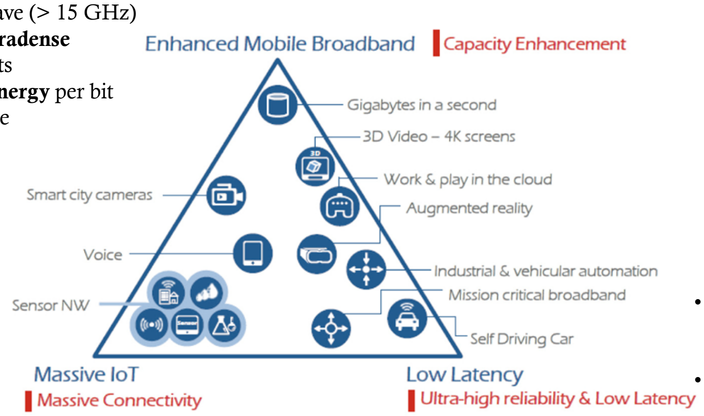

Image courtesy of IEEE

Also called Massive Machine Type Communication (mMTC)

Also called Critical IOT

# Key Engineering Challenges per 5G Use Case

- **Support many new bands**: esp. mmWave (> 15 GHz)
- **Enable Ultradense** deployments
- **Cost and energy** per bit must tumble

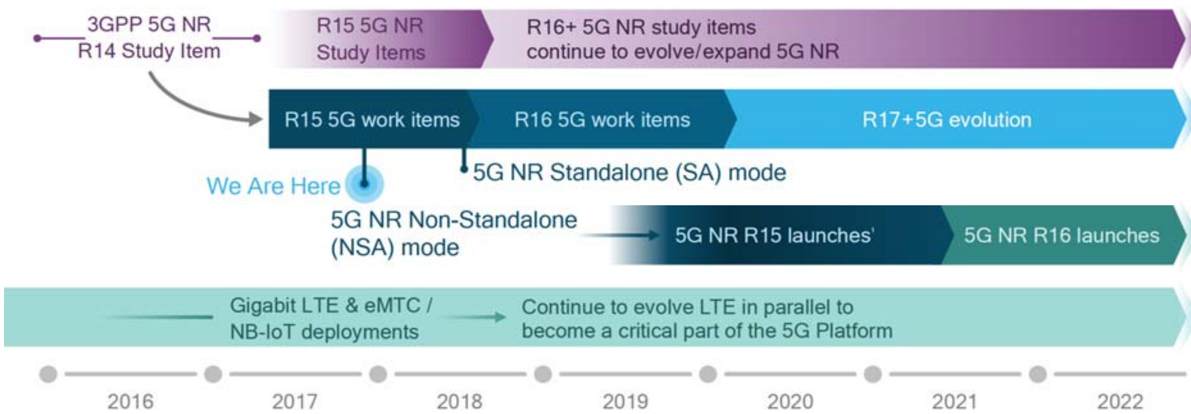



- **Very long range**: 164 dB path loss, ~1000x (30dB) more than LTE
- **Ultra low power**: 10 year battery life
- **Ultra high density:** Support 1 million devices/km$^2$

- **Ultra Low Latency**: 1 millisecond, 10-20x less than LTE
- **Reliability:** Block error rate (BLER) of $10^{-5}$, about 10,000x stricter than LTE

# 5G Roadmap

Source: Qualcomm




5G New Radio (NR, Release 15) ratified on Dec. 20, highly accelerated timeline

# Key Features of 5G NR Release 15 (R15)

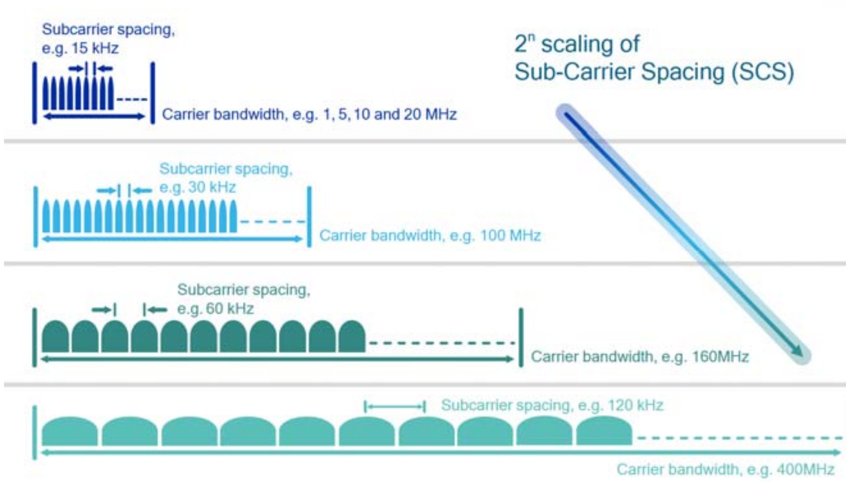
- Support for many more bands
  - Mobile Millimeter Wave (mmWave) support, e.g. beam acquisition and tracking
  - Carrier aggregation on steroids
- More flexible Physical Layer, but largely continuous with LTE
  - Still OFDMA, same basic modulation types
  - Better support for TDD, asymmetric loads, different traffic types
  - More MIMO, new improved error correction codes, etc.
- “Non Stand-Alone” (NSA) for R15: must use in conjunction with LTE for control signaling and fallback

# New Spectrum (US)

- <u>New 5G "Sub 6" Bands</u>
  - 600 MHz (beachfront, 2x35 MHz)
  - 3.55-3.7 GHz (CBRS, unique "tiered license" band)
  - 3.7-4.2 GHz (licensed)
- Existing: About 500 MHz used for 3G and LTE
- <u>New mid-range band:</u>
  - 5.9-7.1 GHz (unlicensed)
- <u>High Frequency Bands</u>
  - 24-28 GHz (1.5 GHz of licensed spectrum)
  - 38 GHz (3 GHz, licensed)
  - 64-71 GHz (Unlicensed)
- The high frequency bands are often called mmWave (wavelength of 10 mm for a 30 GHz carrier)
- Probably used for outdoor UEs primarily, and require strong beamforming

# Scalable OFDMA: How and Why

- Subcarriers are a factor of 2 multiple of 15 KHz
- Built for cross NR compatibility, and with LTE
- Wider subcarriers:
  - For larger bandwidths
  - More efficient for short range, indoor (small cells)
- Many expected a more radical departure from LTE



# Flexible time-frequency slicing: Illustrative example

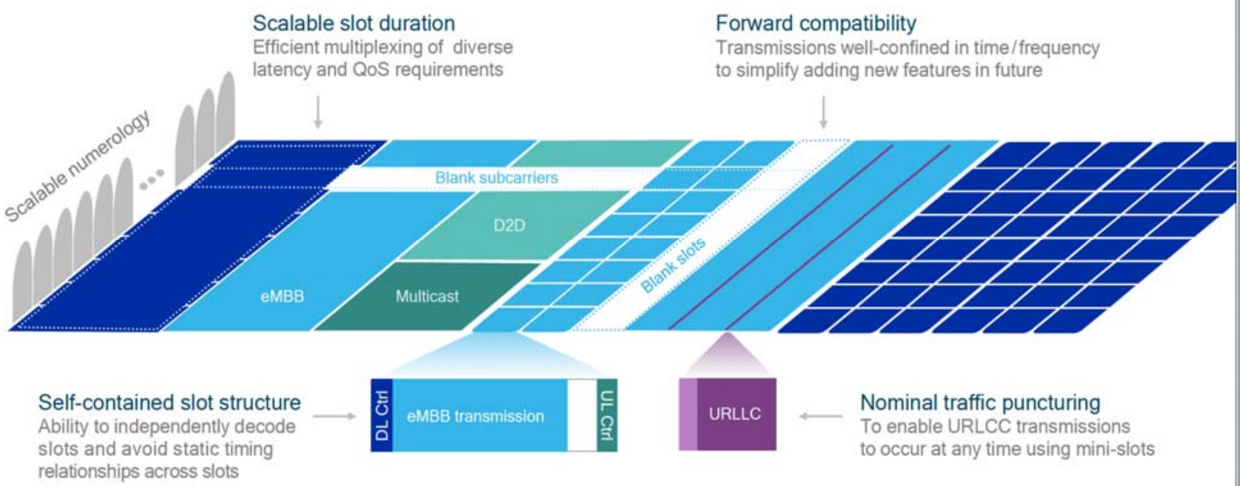
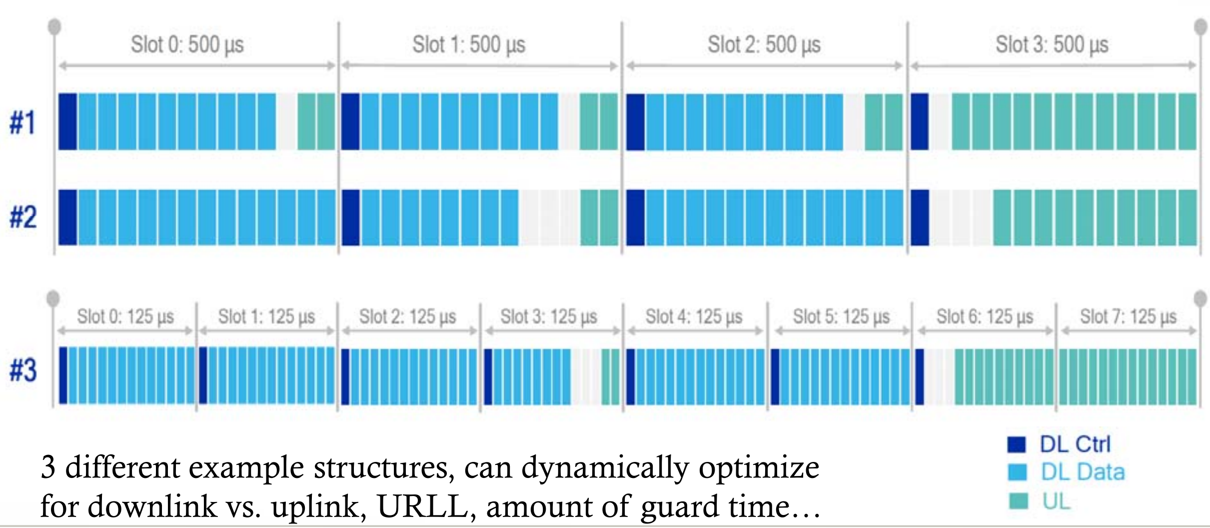



Figure courtesy of Qualcomm

# Dynamic Time Division Duplexing (TDD) In Action



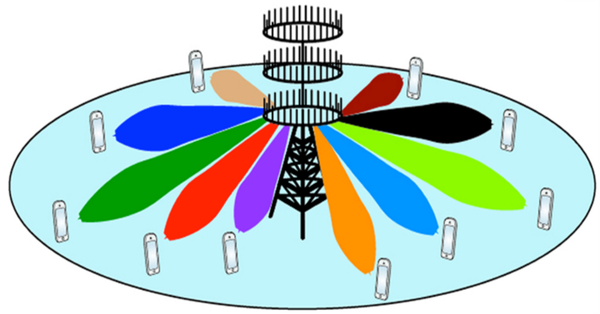

3 different example structures, can dynamically optimize for downlink vs. uplink, URLL, amount of guard time…

Figure courtesy of Qualcomm

# Massive MIMO: New 5G Feature

What is Massive MIMO?

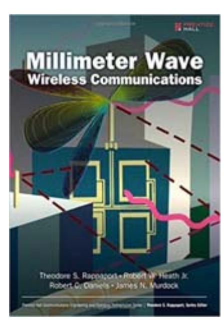
- Many antennas at BS (e.g. 64, 256, even 1024)
- A few (2, 4, 8) antennas at UE
- BS estimates channels to UEs via channel reciprocity (TDD)
- Use massive BS antenna array to create nearly independent beams to several UEs at once, aka "multiuser MIMO"



- Here, 10 UEs are being served by same BS in same time-frequency block
- Substantial spectral efficiency gains possible (**2-5x** depending on exact assumptions, metrics)

# Millimeter Wave: Key to 5G Capacity Gains

- Most new 5G bandwidth is at high frequencies:
  - 24-28 GHz (total of 1.5 GHz of licensed spectrum)
  - 38 GHz (3 GHz, licensed)
  - 64-71 GHz (7 GHz, Unlicensed)
- More than 10 GHz in all!
- Most novel aspect of 5G vs. 4G is the use of mmWave

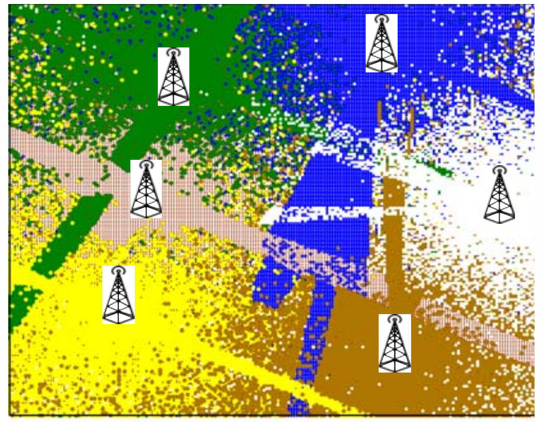



mmWave in Texas:

- mmWave cellular largely pioneered by Samsung in Dallas (Khan, Pi, Zhang)
- Top mmWave textbook & much leading research originated at UT Austin
- AT&T's 5G mmWave mobile testbed is being built in NW Austin
  - Multi-vendor, unique worldwide
  - Lead: Dr. Arun Ghosh

## Several Tough Challenges for mmWave

1. **Blocking**: mmWaves do not penetrate through walls, water, people, …
2. **Directional Beamforming:** Small antennas (~mm square), need many to radiate/collect sufficient energy, meaning:
   - Link establishment is very hard (chicken/egg problem)
   - Mobility support is very hard
3. **Implementation.** Size, cost, power consumption, …



Simulated max-power coverage areas in an urban outdoor mmWave network (S. Singh and J. Andrews)

## Key Solution for 5G NR: Dual Connectivity

- Tightly integrate 5G NR mmWave with LTE, "Non standalone"
  - Use LTE as an anchor carrier, providing continuous connectivity
  - Separation of user (data) and control planes
- Use mmWave bands opportunistically, especially for outdoor UEs or other targeted deployments (e.g. stadiums, malls, etc.)

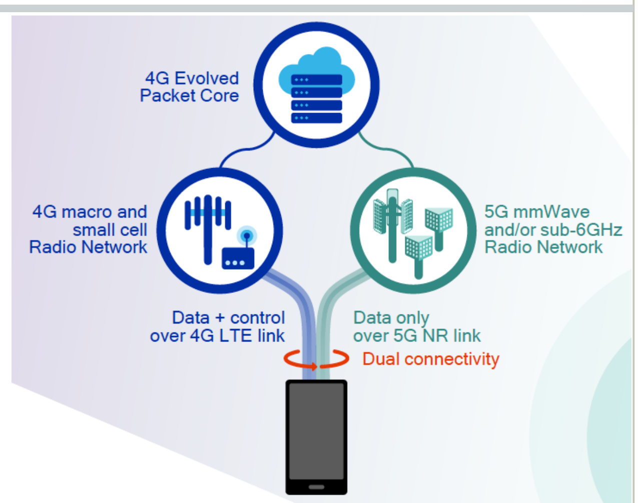
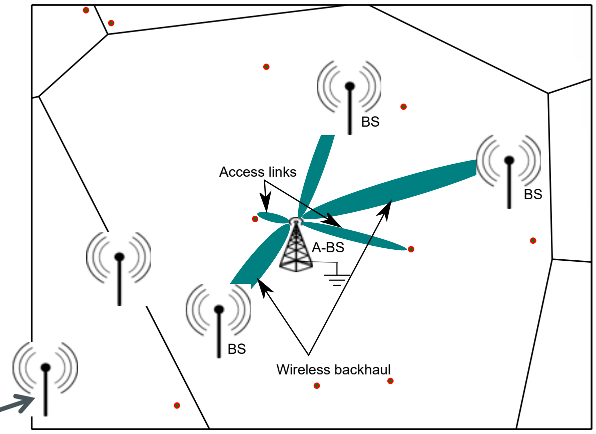



Figure: Qualcomm

# Potential Benefits of mmWave

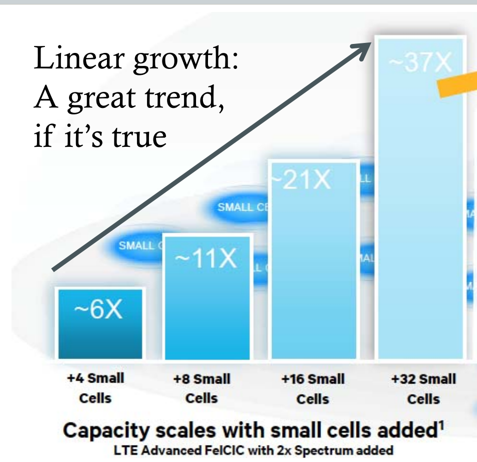
- Most important benefit is unlocking 10+ GHz of spectrum
- While challenging, blocking and directional beamforming also offer useful features:
  - Isolation of links
  - Interference reduction
- This leads to several interesting possibilities beyond R15
  - Spectrum sharing
  - In-band backhauling (IAB)




S. Singh, M. Kulkarni, A. Ghosh, and J. G. Andrews, "Tractable Model for Rate in Self-Backhauled Millimeter Wave Cellular Networks", *IEEE Journal on Sel. Areas in Comm.*, Oct. 2015

# Key Enabler of 5G: Network Densification

- Dense deployments absolutely essential for mmWave (need at least 20 BSs/km$^2$)
- The main benefit of cellular network densification (Sub6GHz) is "cell splitting"
- Cell splitting in a nutshell:
  1. Double the number of BSs in a high demand area, which…
  2. Halves the load per BS (on average), which…
  3. Doubles everyone's share of the time-frequency resources, which thus
  4. Doubles their throughput
- This has been the main method until now for increasing the exploding data demand




From Qualcomm's "1000x: More small cells" presentation", 2015

# Densification Challenges

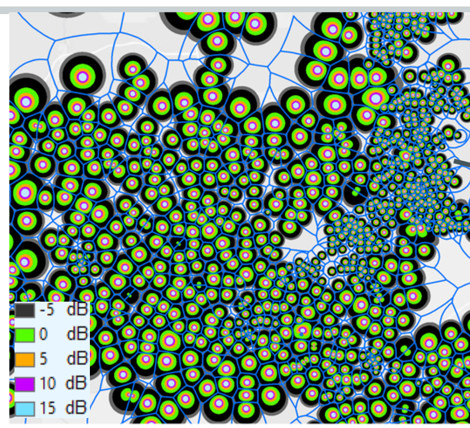
- Cost/Logistics:
  - Backhaul connection (now needs to be Gbps, e.g. fiber)
  - Permitting (city, NIMBY, etc.) and installation/configuration
  - OpEx: site rental, power, maintenance, etc.
  - BS cost is not the bottleneck
- Interference:
  - More transmitters per area means more interference
  - More on this in a moment

Solutions

- Wireless Backhaul, especially "Integrated Access and Backhaul" (IAB).
  - Key R16 study item
- Broad political push to ease permitting rules, allow dense deployments
  - E.g. https://texas5galliance.com/
  - Helps that these new BSs are tiny, low power, possibly self-backhauling
- Self-optimizing networks (e.g. using machine learning) to reduce OpEx

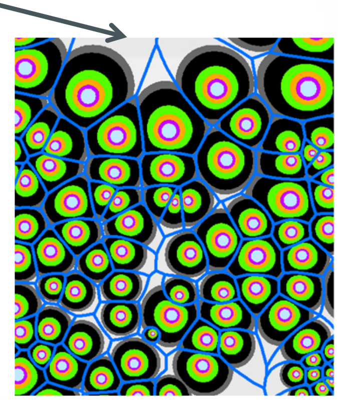
# Key to Cell Splitting Gains: SINR Invariance

- ***SINR Invariance***: As the network density increases, the SINR distribution becomes independent of the density.
  - SINR is the key signal quality metric
  - SINR = Signal/(Interference + Noise)
  - If S and I scale at the same pace, then the SINR Invariance property holds
- SINR Invariance is visible at "normal" network densities




SINR Heat Maps for AT&T's 700 MHz LTE Network in Phoenix, AZ (Network data provided to J. Andrews by Crown Castle)

- Zooming in by ~10x, SINR pattern is unchanged.
- This is SINR Invariance



# What affects SINR Invariance?

**Irrelevant to SINR Invariance:**

- BS Layout (grid, random, combo)
- Transmit powers of BSs, including having different powers as in a HetNet
- Channel statistics

**SINR Invariance requires:**

- Power law path loss
- Unbounded path loss formula (no minimum Tx-Rx separation)
- Open access network (can connect to strongest BS)

**The Ultradense Network (UDN) regime is where SINR Invariance falls apart**

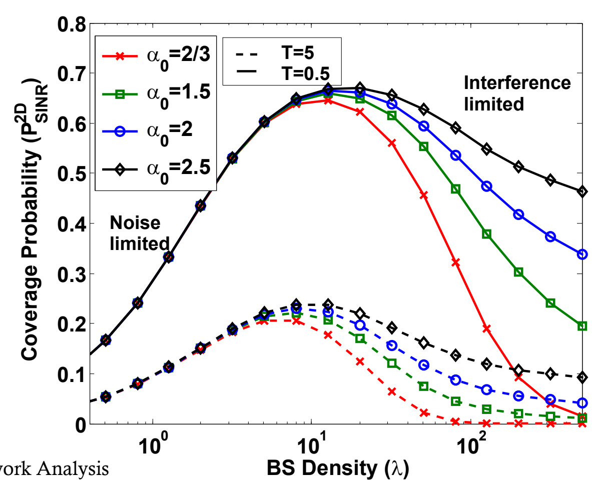
J. G. Andrews, X. Zhang, G. Durgin, and A. Gupta, "Are We Approaching the Fundamental Limits of Wireless Network Densification?", *IEEE Communications Magazine*, Oct. 2016.

# UDN Scenario 1: Multislope Path Loss

- Minor tweak to path loss formula to make it more realistic and general (as done by 3GPP):

$$P_r = P_t K_0 d^{-\alpha_0},\ d \le R_c$$
$$P_r = P_t K_1 d^{-\alpha_1},\ d > R_c \qquad \alpha_0 \le \alpha_1$$

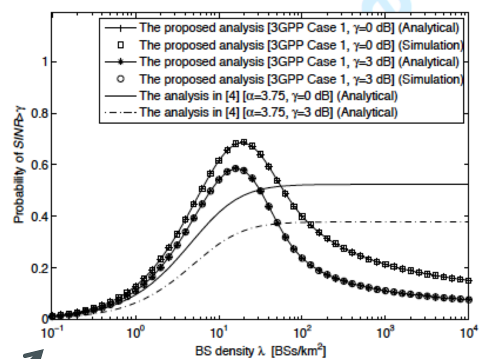
- Has major implications on capacity scaling with density, can result in a plateau or collapse




[ZhaAnd15] X. Zhang and J.G. Andrews, "Downlink Cellular Network Analysis with Multi-slope Path Loss Models", *IEEE Trans. on Communications*, May 2015.

# UDN Scenario 2: NLOS to LOS Transition

- The multislope model can be generalized to include LOS/NLOS path loss exponents [DinWan16]
  - Similar trends to [ZhaAnd15] are observed (see figure) for SINR and throughput as the network densifies
  - Uses 3GPP channel models
- Similar properties for mmWave networks with strong blocking [BaiHea15]
- Overall, we observe trouble starting at around 20 BSs/km$^2$
  - This is exactly the threshold density for mmWave in 5G NR




[DinWan16] M.Ding, P. Wang, D. López-Pérez, G. Mao, and Z. Lin, "Performance Impact of LoS and NLoS Transmissions in Dense Cellular Networks," *IEEE Transactions on Wireless Communications*, March 2016.

[BaiHea15] T. Bai and R. W. Heath Jr. "Coverage and rate analysis for millimeter wave cellular networks." *IEEE Transactions on Wireless Communications*, Feb 2015.

# Takeaways for Ultradense Networks

- At a certain density, the interference stacks up and adding more BSs does not improve the data rates
- Our very recent work [AlaAndBac17] proves mathematically that capacity gains from densification must saturate and cannot possibly continue indefinitely, unless strong interference suppression techniques are employed
- We are rapidly approaching the ultradense regime, will become relevant in the 5G life cycle (my prediction), i.e. next 10 years
  - This is unprecedented and will have major impact on future network deployments and capacity

A. Alammouri, J. G. Andrews, and F. Baccelli, "A Unified Asymptotic Analysis of Area Spectral Efficiency in Ultradense Cellular Networks", submitted to *IEEE Trans. on Information Theory*, Dec. 2017.

# Parting Remarks on 5G and its Future

- First version (5G NR R15, Dec. '17) is a bit of a teaser
  - Smaller departure from LTE than many had predicted
  - However, it came out quickly, and we expect many new features in next 2-3 years
  - First products in late 2019, early 2020
- mmWave is the most exciting feature in R15, but:
  - Will it really work in the field, like its advocates say?
  - Or will it bomb, due to the technical challenges?
  - Or will Apple just decide it is too expensive/power-hungry to put it in the iPhone?
- Densification is a big part of the puzzle for Sub6GHz and mmWave, but cannot be taken for granted

Accessible References on 5G:

- Qualcomm NR Tutorial (Dec '17) https://www.qualcomm.com/invention/technologies/5g-nr
- Ericsson Whitepaper (July '17): https://www.ericsson.com/en/publications/ericsson-technology-review/archive/2017/designing-for-the-future-the-5g-nr-physical-layer
- J. G. Andrews et al, "What Will 5G Be?", IEEE JSAC, 2014 (most cited survey paper on 5G, Google it to find the PDF)