Riding the Mobile Traffic Tsunami –

Opportunities and Threats in the Making of 5G Mobile Broadband

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Content Drives Demand for Capacity

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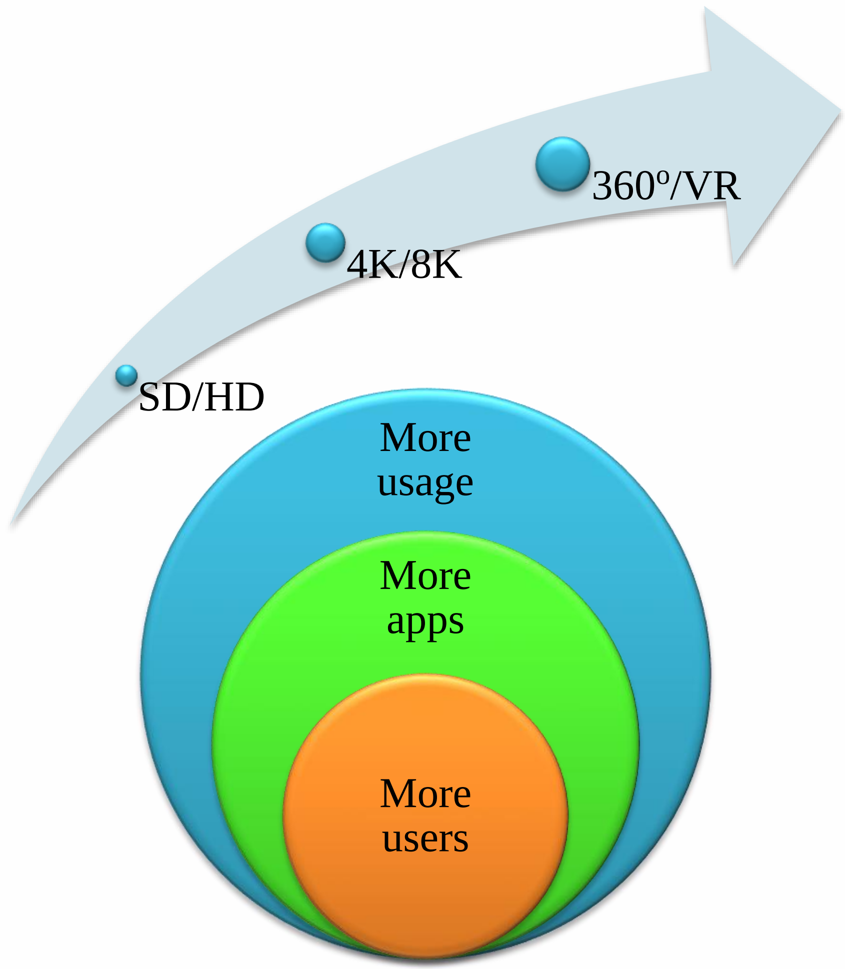

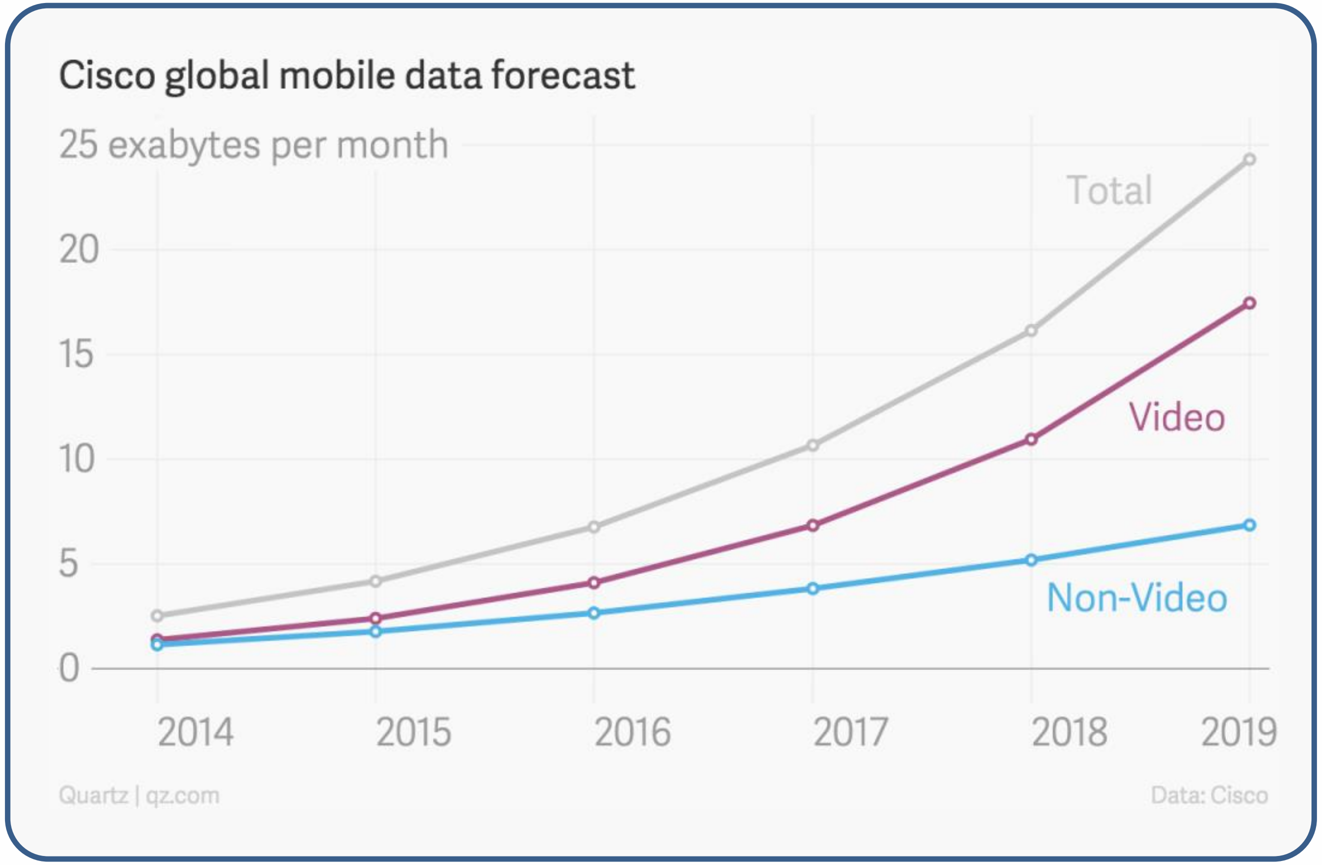

Video to drive >60% of mobile traffic

Commerce Drives Demand for Availability

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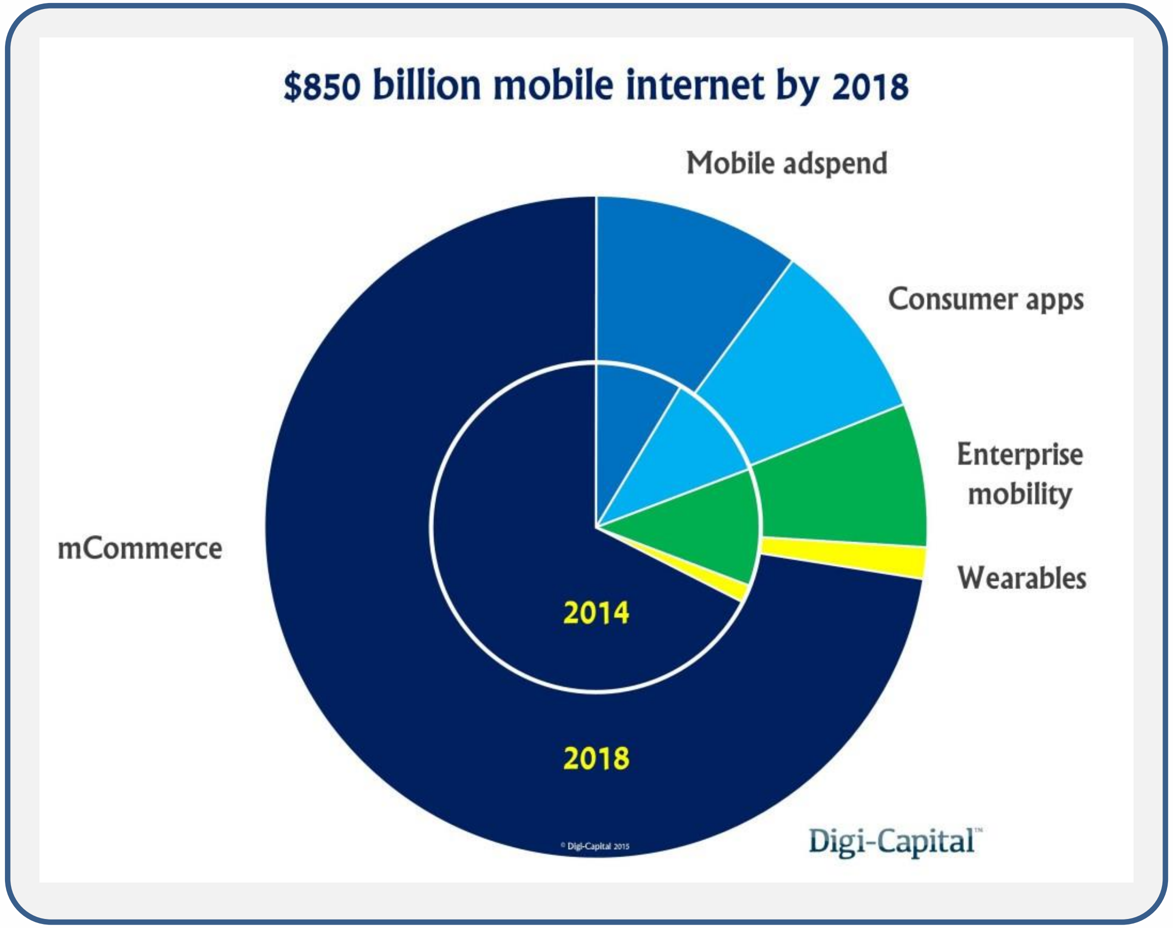
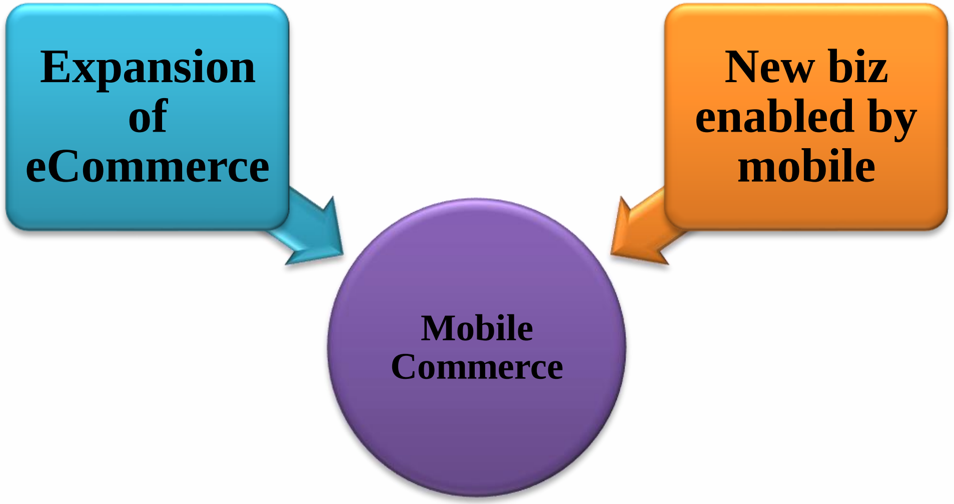


Commerce to generate >70% of mobile Internet revenue



New Possibilities for Disruption

5G Core Value

Gbps

Mobility

Mobile IoT

Technology

- Mobile Broadband
- Cameras & sensors
- Signal processing
- Intelligence

Disruption

- Transportation
- Retail
- Service
- Lifestyle

Example – Autonomous Vehicles

Cellular Between a Rock and a Hard Place

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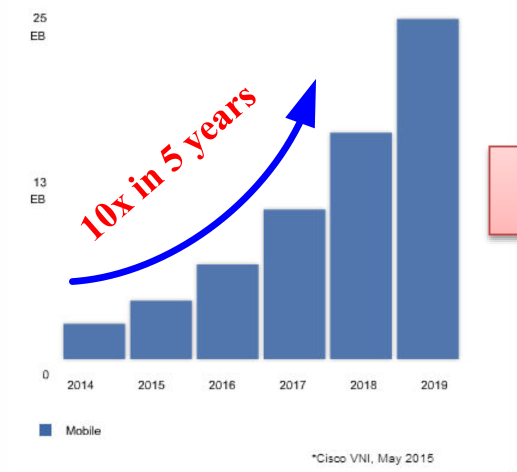
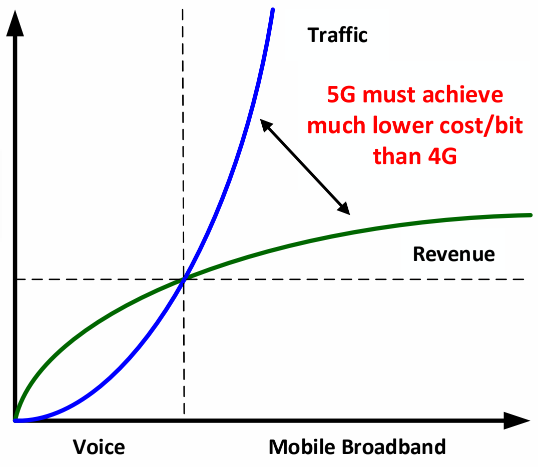
Mobile traffic grows at 60% CAGR



Traditional cellular spectrum <6 GHz – not enough nor economically viable to meet the growing mobile broadband demand

The widening traffic revenue gap



5G in millimeter wave frequencies

- 2010 – Two fundamental concepts (Millimeter-wave Mobile Communication & Massive MIMO)
- Significant technology milestones – NTT DoCoMo ('13), Samsung ('13, '14), Ericsson ('14), Nokia ('14)
- Feasibility corroborated by extensive channel measurement studies (*e.g.*, Rappaport in UT and NYU)
- Recognized as one of the core technologies for 5G in global standardization bodies

Overarching 5G goals can only be met with multi-gigahertz millimeter wave spectrum

- 1000x capacity increase over 4G, wide-area Gbps mobility, 1 ms latency

Straight Path 5G Vision

Gbps
- Gbps user experience
- Multi-Gbps cell throughput

Mobility
- Wide area cellular networks
- Vehicle-speed mobility

Typical Value	LTE R8	5G
Bandwidth	20 MHz	500 MHz
Sector Spectral Efficiency	2.5 bits	10 bits
Cell throughput	150 Mbps (3-sector)	20 Gbps (4-sector)
Cell-edge throughput	~1 Mbps	~100 Mbps
50%-tile throughput	~10 Mbps	~1 Gbps
Outdoor cell radius	100 m – 10 km	100 m – 1 km

A Sea Change Upon the Entire Ecosystem

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10 ~ 100 Mbps	→	1 ~ 10 Gbps
$10 ~ $100 / GB	→	$0.1 ~ $1 / GB
1 ~ 10 antennas	→	10 ~ 1000 antennas
0.6 ~ 6 GHz	→	6 ~ 60 GHz

- Services
- Applications
- Devices
- Networks
- Baseband
- Transceivers
- Components

Opportunities? Threats?

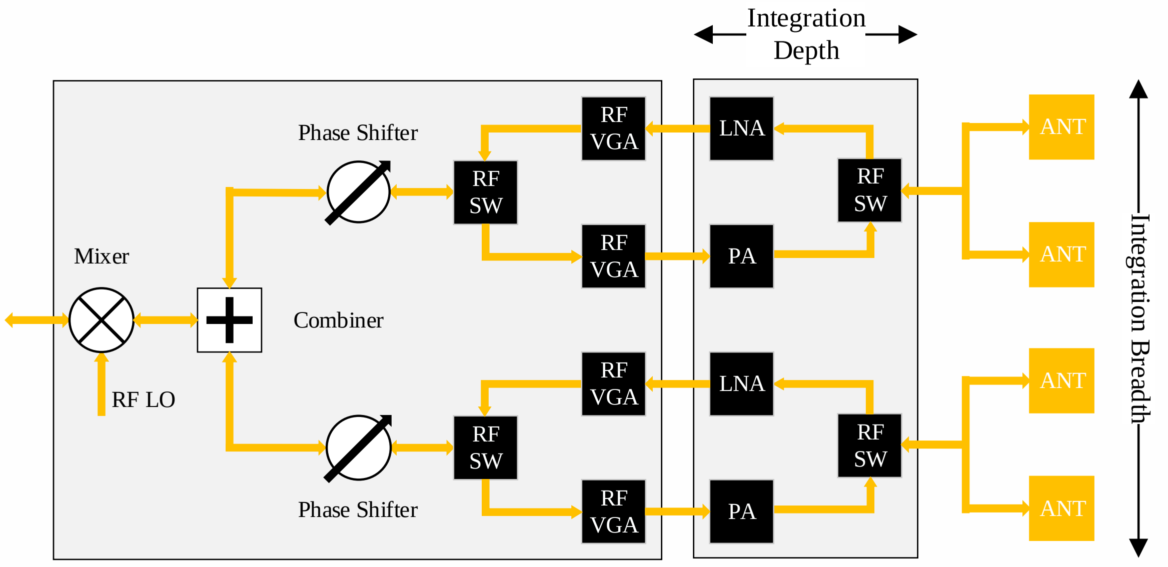
Transceivers & Components

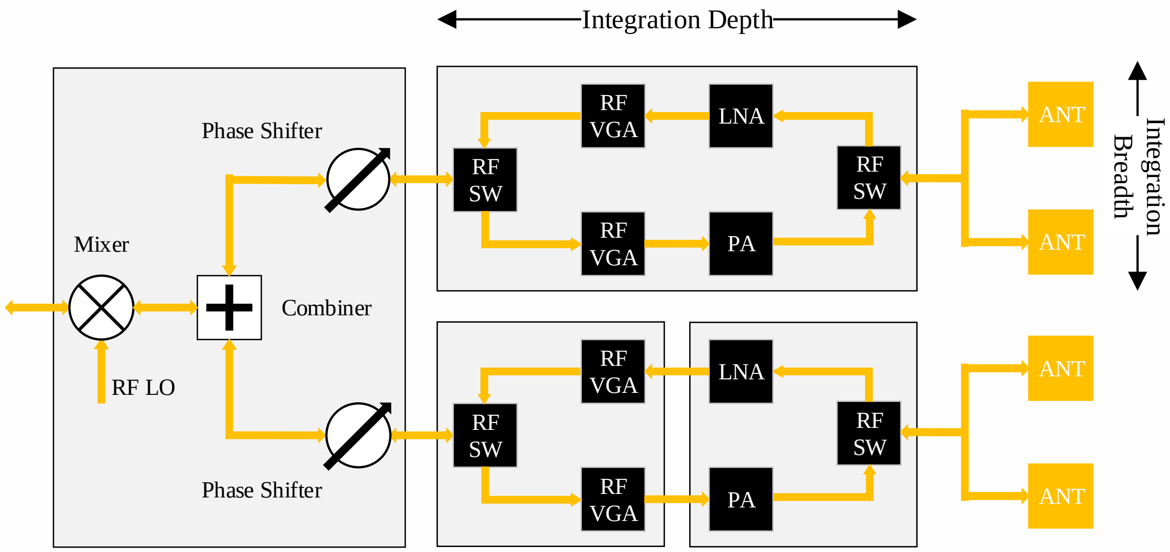
Integration

- Front End
  - Power
  - Amplification
- RFIC
  - Phase Shifting
  - Mixing
  - Combining

Efficiency

- Power Efficiency
  - PA class
  - Fabrication process
- Linearization
  - Analog Pre-Distortion
  - Average Power Tracking





Baseband & Air Interface

Coverage	• 150 – 160 dB link budget • 100 m – 1km cell radii	Beamformed Control
Capacity	• 100 MHz – 1 GHz system bandwidth • 100 MHz cell edge, 1 Gbps typical, >10 Gbps peak	Massive MIMO
Mobility	• Wide area coverage • Vehicular speed	Beamformed MAC

5G Network – Outdoor & Indoor

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Outdoor

- Small base station (laptop size) with high EIRP (~60 dBm)
- Large footprint (up to 1km in urban area, >1 km in suburban and rural areas)
- Higher deployment density than 4G with same CAPEX/OPEX
- Higher antenna gain at BS & MS increases SNR
- Directional transmission reduces interference

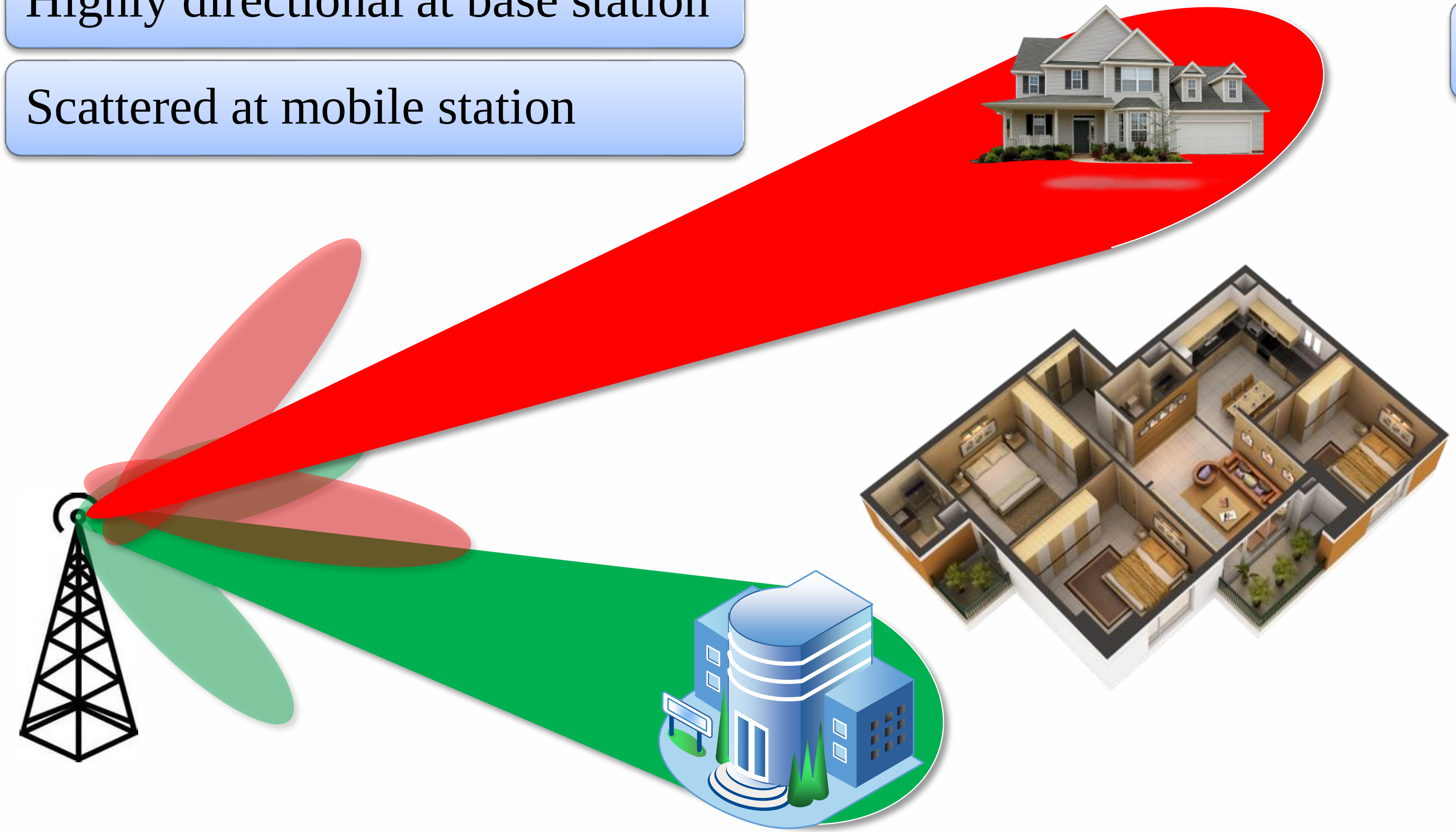
Indoor

- 10 – 20 dB higher EIRP and much larger footprint than Wi-Fi Access Point (with same size)
- Less congested spectrum and lower interference than Wi-Fi
- Enclosed space often leads to LOS propagation loss less than free space
- Manageable penetration loss for most building interior materials

5G Network – Outside-in

Highly directional at base station

Scattered at mobile station



How it works

- Higher EIRP (>60 dBm)
- Higher deployment density (with same CAPEX/OPEX as 4G)
- Higher antenna gain at BS & MS
- Reduced inter-cell interference
- Less penetration loss with small windows, small openings, re-bar
- Meaningful penetration through brick and concrete[1, 2]
- Penetration loss of interior materials generally small[1, 2]
- Promising preliminary results[3]

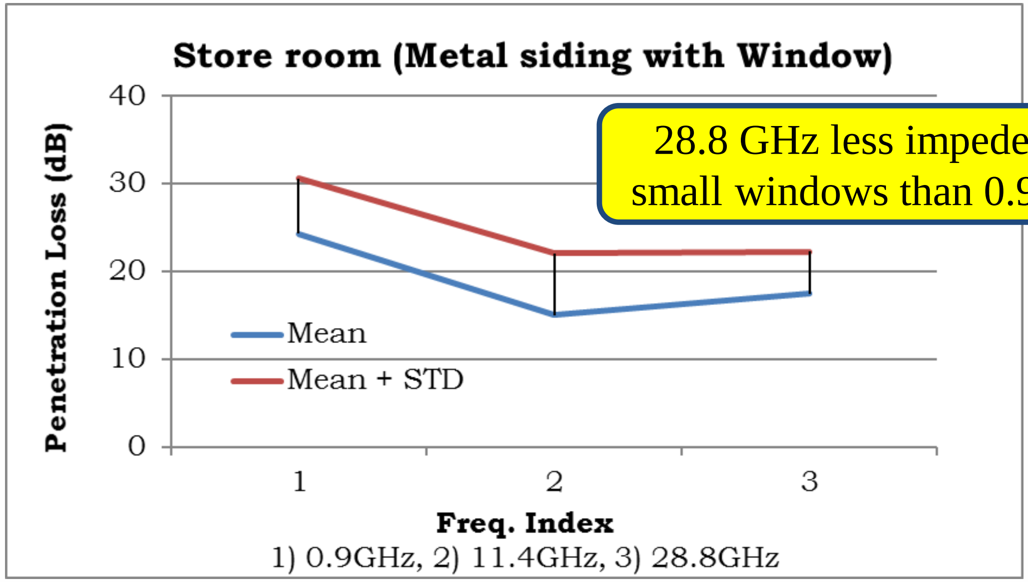
1. NTIA Report 94-306, "Building penetration loss measurements at 900 MHz, 11.4 GHz, and 28.8 GHz"
2. NTIA Report 88-239, "Millimeter-wave propagation characteristics and channel performance for urban-suburban environments"
3. "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," in *Communications Magazine, IEEE* , vol.52, no.2, pp.106-113, February 2014

Penetration Loss based on NTIA report

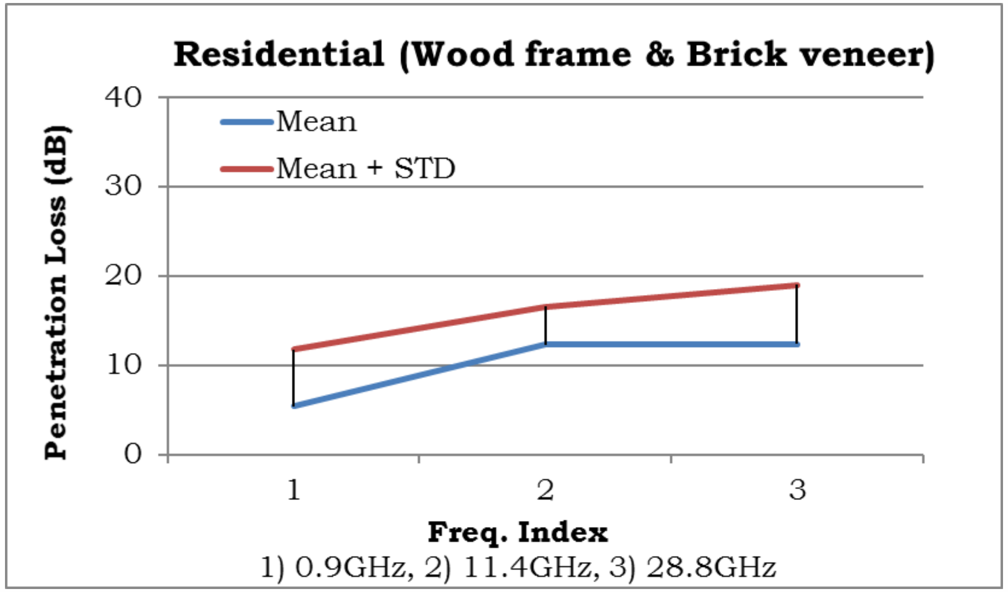
Penetration loss in 28.8 GHz vs. 0.9 GHz

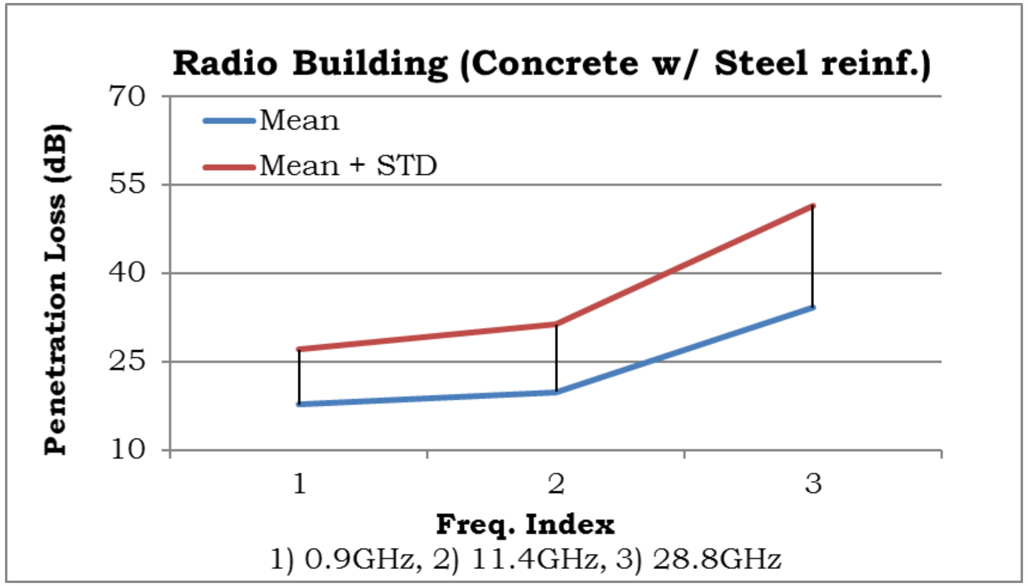
- 7 dB more for “Residential” (wood frame with brick veneer)
- 17 dB more for “Radio Building” (concrete wall with steel reinforcement)
- 7 dB **less** for “Store Room” (metal siding with window)

1. NTIA Report 94-306, “Building penetration loss measurements at 900 MHz, 11.4 GHz, and 28.8 GHz”



28.8 GHz less impeded by small windows than 0.9 GHz





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Make 5G happen or let 5G happen to you