Understanding 5G Standards

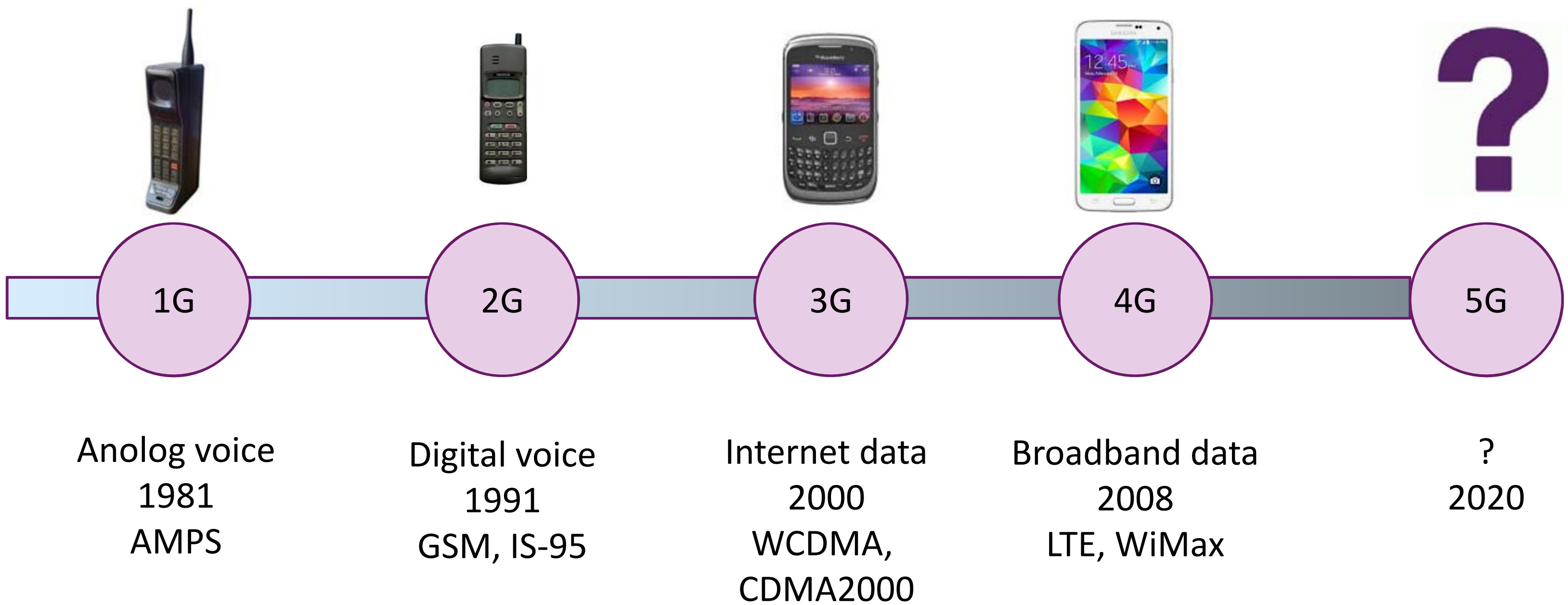
SUNDEEP RANGAN, DIRECTOR, NYU WIRELESS

DEC 14, 2016

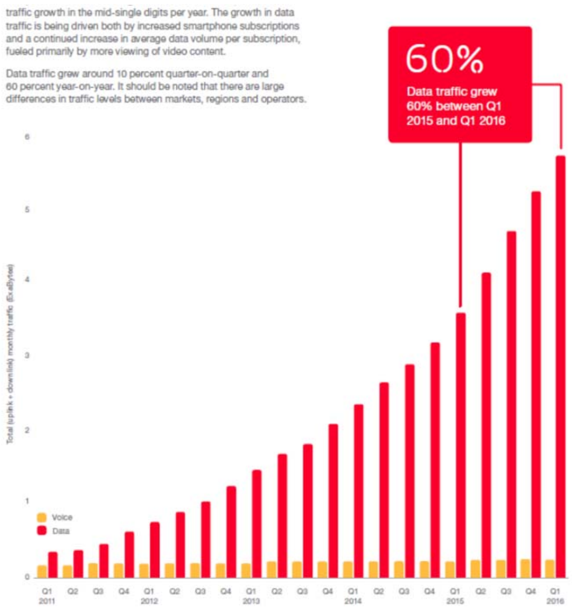
Outline

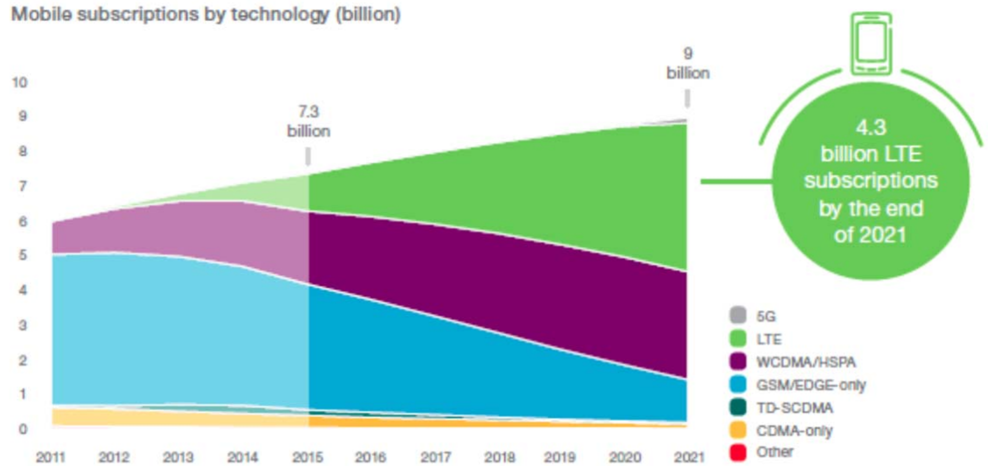
- Motivation, vision and enabling technologies
- 3GPP 5G standardization process and activities
- Channel models above 6 GHz
- PHY & MAC design
- Networking issues
- Summary and outlook

Cellular Generations



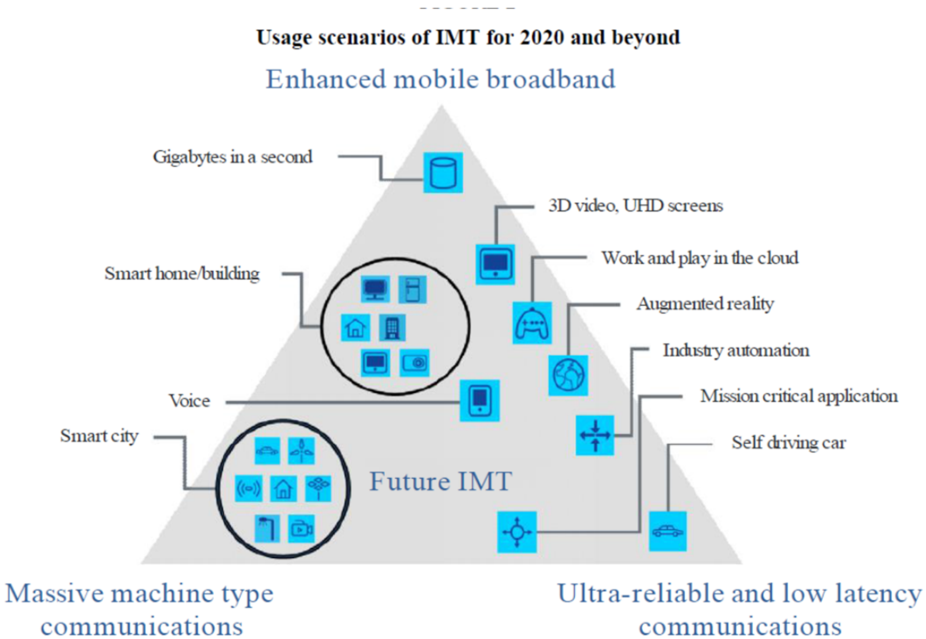
Success of 4G





Ericsson Mobility Report 2016

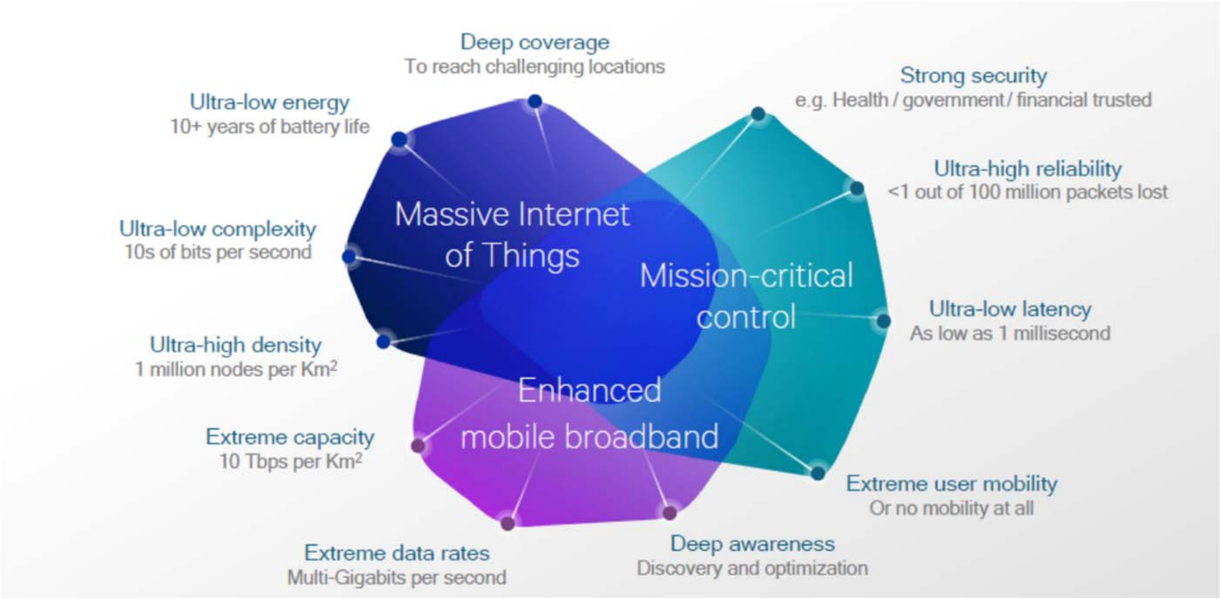
What Will 5G Do?



- Many new use cases for cellular
  - Massive connectivity
  - AR / VR
  - Autonomous driving
  - …

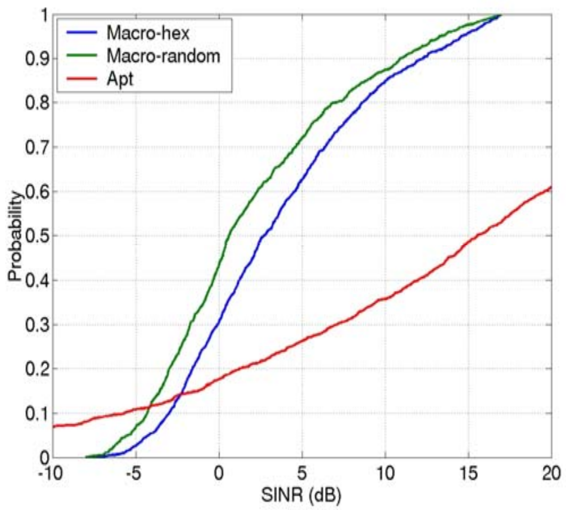
IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond, Sept 2015

5G Requirements: Many Dimensions



- From Roberto Padovani, “The Road to 5G”, Jack Wolf Lecture, NYU, Sept 2016.

Understanding Rate



Rangan, New strategies for femto-macro cellular interference control, 2013

- Cellular user experience a distribution of rate
  - Variability due to many factors
  - Interference, location, blockage, …
  - Loading, density / layout of cells, …

- Various metrics for rate
  - Peak rate
  - Average rate
  - Edge of cell (5%)

How to Increase Rate in Cellular?

- Shannon Formula

$$C = W \log_2(1 + SINR)$$

C: Rate per user

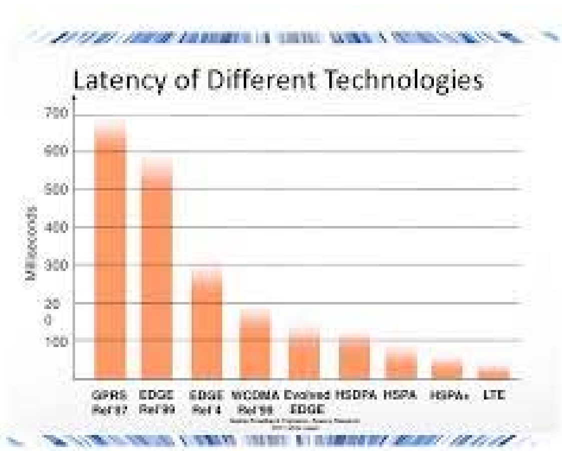
W: Bandwidth per user, antenna degrees of freedom

$\log_2(1 + SINR)$: Spectral efficiency

- Current coding methods close to spectral efficiency bound

- Most techniques for 5G: Increase degrees of freedom
  - Number of cells → Densification, greater bandwidth per user in each cell
  - Bandwidth → Millimeter wave
  - Number of antennas → Massive MIMO, higher spatial degrees of freedom

Reducing Network Latency

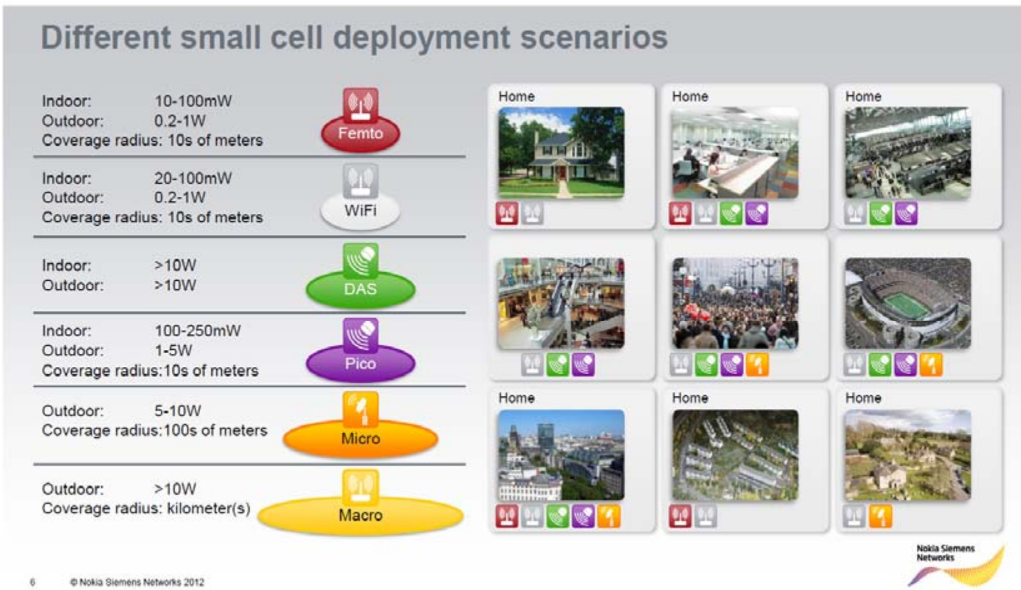


Rysavy Research,
Mobile Broadband Explosion:
3GPP Broadband Evolution to IMT-Advanced

- 5G goals:
  - 1 to 4 ms data plane latency (user already connected)
  - 10 ms control plane (user starts in idle mode)
- Total delay has multiple components

Processing →	Faster decoding, hardware
Queuing →	Simplified network, congestion control
Transmission →	Higher data rate, HARQ, MAC
Propagation →	Bring content closer, less hops

Small Cells and Densification



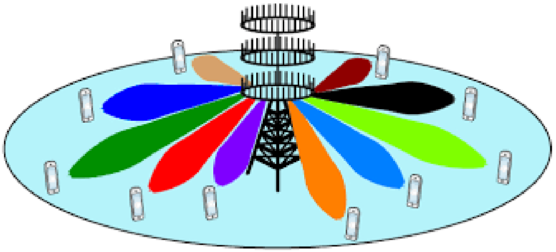
Via: 3g4g.blogspot.com

- ❑Cell splitting
  - Key driver for capacity increase up to 4G
- ❑Creates heterogeneous networks
  - Cell sizes / power
  - Backhaul
  - Indoor / outdoor
- ❑Considerable work in 4G / LTE-A
  - Intercellular interference coordination
  - Self-organizing networks
- ❑Practical challenges
  - Backhaul
  - Site acquisition

Massive MIMO

Lund-NI massive MIMO prototype
128 elements, 30.72 Mbps in 20 MHz

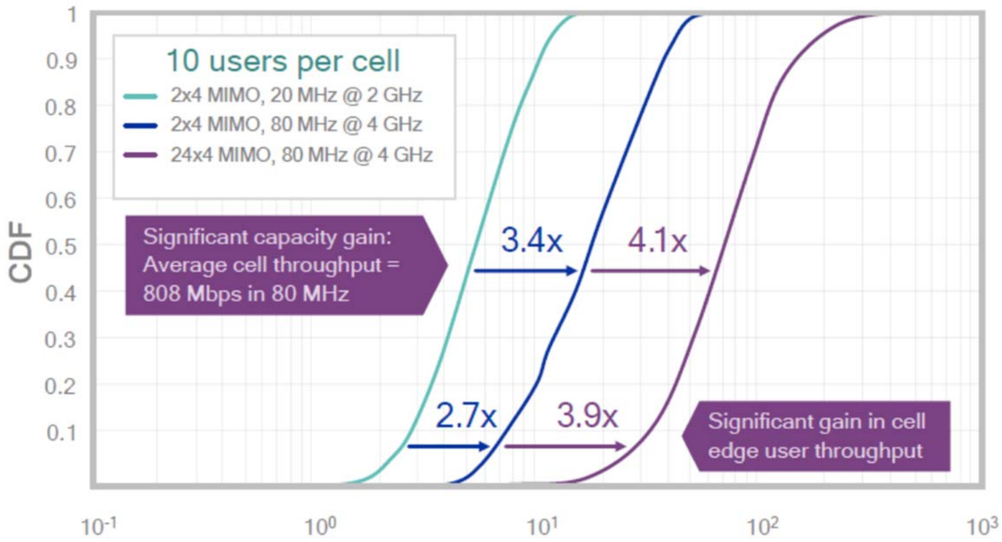
Erik Luther, 5G Massive MIMO Testbed: From Theory to Reality, ni.com



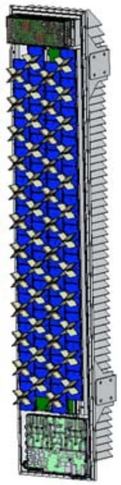
Emil Björnson, Radio Resource Management in Massive MIMO Communication Systems, Linkoping Univ

- Massive number of antennas
  - Typically > 100
- Large number of spatial streams
  - Tens of UEs simultaneously
  - Spatial division multiple access
- Targeted for macro base station
  - 1-2 meter panel

Capacity Gains via Massive MIMO



Qualcomm simulation,
Macro site 1.7km ISD
46 dBm transmit power

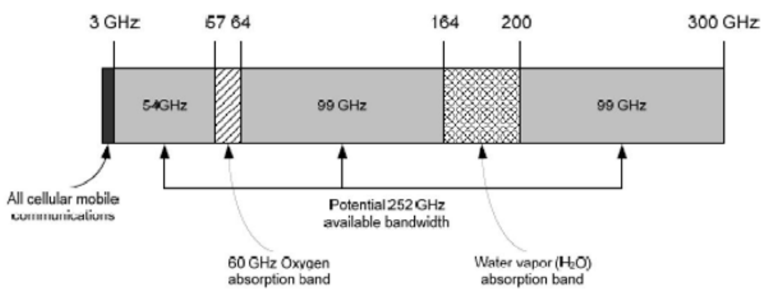


BLUE DANUBE™

Massive MIMO trial system, Woodstock, VA. PCS band

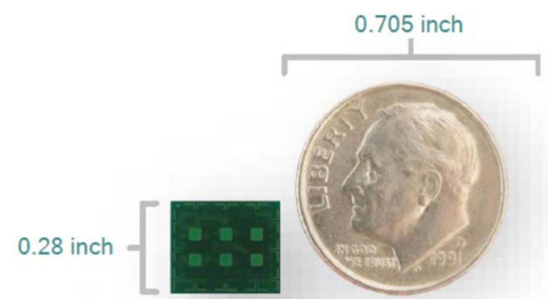
4x12x2 elements, 52 dBm TX
Image courtesy Blue Danube

Millimeter Wave



From Khan, Pi “Millimeter Wave Mobile Broadband: Unleashing 3-300 GHz spectrum,” 2011

- 1-10 mm wavelength = 30 to 300 GHz
- Up to 100x bandwidth
- Very high-dimensional antenna arrays
- This talk:
  - MmWave = above 10 GHz
  - (10-30 GHz sometimes called cm-wave)



Qualcomm® VIVE™ 802.11ad technology with a 32-antenna array element

Massive Bandwidth with MmWave

System antenna	Duplex BW	fc (GHz)	Antenna	Cell throughput (Mbps/cell)		Cell edge rate (Mbps/user, 5%)	
				DL	UL	DL	UL
mmW	1 GHz TDD	28	4x4 UE 8x8 eNB	1514	1468	28.5	19.9
		73	8x8 UE 8x8 eNB	1435	1465	24.8	19.8
Current LTE	20+20 MHz FDD	2.5	(2x2 DL, 2x4 UL)	53.8	47.2	1.80	1.94

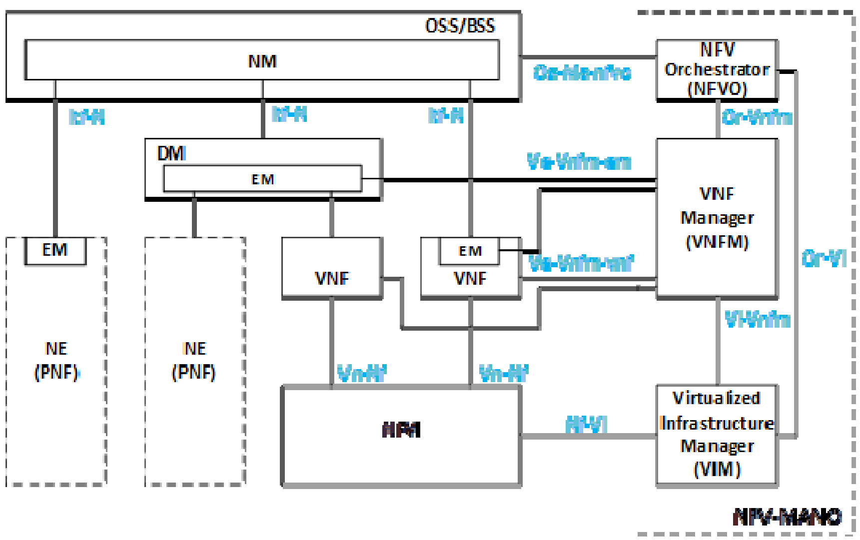
~ 25x gain

~ 10x gain

- Sim assumptions:
  - 10 UEs per cell
  - Hex cell layout, ISD=200m
  - LTE estimates for 36.814
- Further gains with spatial mux, subband scheduling and wider bandwidths

Akdeniz, Mustafa Riza, et al. "Millimeter wave channel modeling and cellular capacity evaluation." *IEEE JSAC, 2014*

NFV and SDN



From 3GPP 32.842

- Network function virtualization
- Software defined networking
- Reconfigurable resources
- Move content closer to edge
  - Reduce latency
  - Reduce backhaul
- Distributed mobility
- Multiplexing of resources

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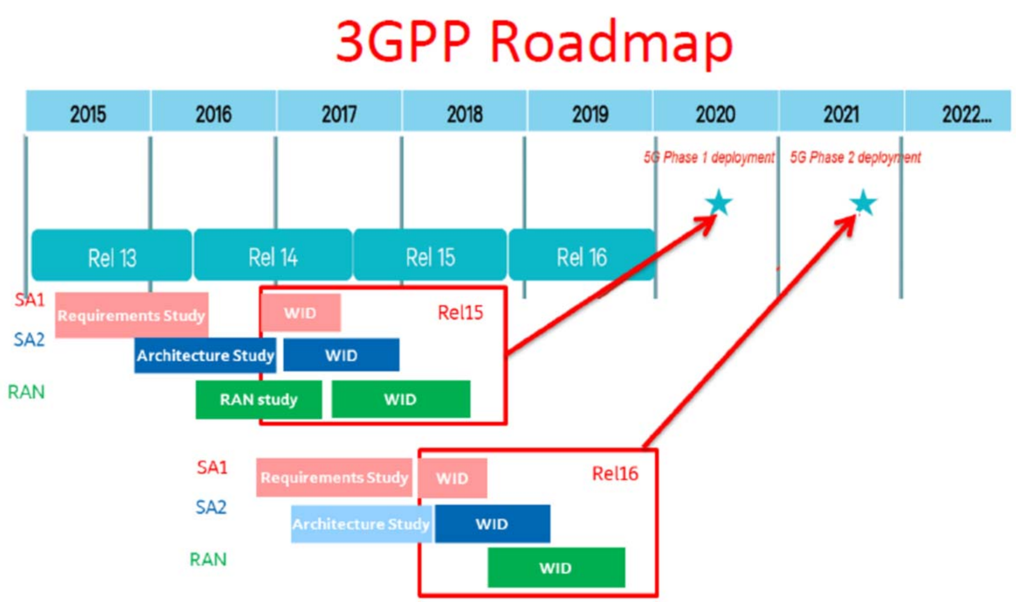
5G “New Radio”

- ❑ Single unified framework for diverse applications
- ❑ Not backward compatible with LTE
- ❑ Phase 1 (Rel 15, 2018)
  - Non-standalone
  - Focus below 40 GHz
- ❑ Phase 2 (Rel 16, 2019)
  - Standalone
  - Include above 40 GHz

From Qualcomm blog, Acceleration of the 5G NR global standard gains industry momentum, Sept 2016

Timelines



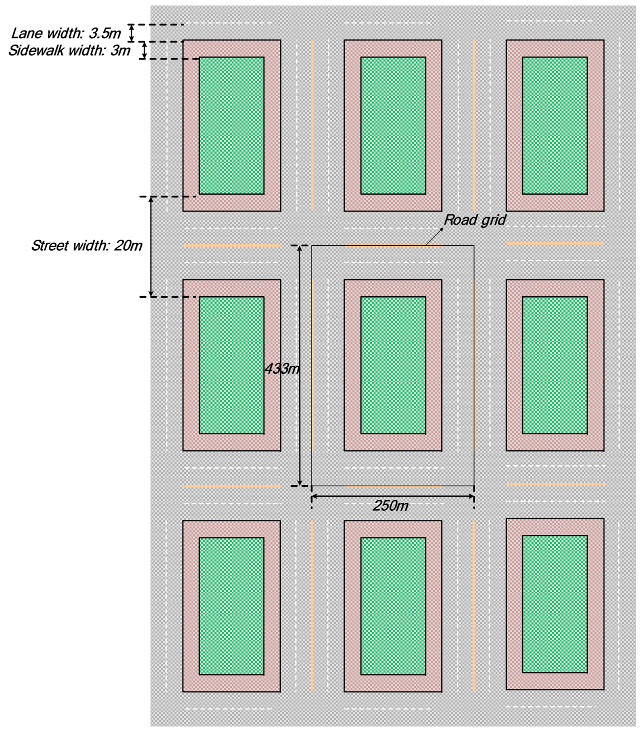
From Giovanni Romano, TIM, 3GPP progress on “5G”, 2016

- ❑Very aggressive schedule
- ❑Three key studies
  - Requirements
  - Architecture
  - RAN
- ❑SA1-RAN interaction

Selected Use Cases in 3GPP 38.913

Use case	Carrier (GHz)		Bandwidth (GHz)		Layout
	<6	>6	<6	>6	
Indoor hotspot	4	30, 70	200M	1	ISD 20m, 20 UEs per TRP
Dense urban	4	30	200M	1	ISD 200m, micro+macro, 10-20 UEs per TRP
Rural	2, 4		20,200M		ISD 1732, 5000m, mobility
Urban macro	4	30	200M	1G	ISD 500m, Focus on ubiquitous coverage
Extreme rural	<3		40M		100km cell range, up to 160km/h
Massive connection	<3		TBD		1732, 500m, Connection density TBD
Highway	< 6		TBD		Inter-RSU 100m, macro 500m
Urban grid for connected car	< 6		TBD		RSU at each intersection, Macro 500m

Example: Urban Connected Car



- ❑Macro only or Macro + road-side unit (RSU)
- ❑Currently focused below 6 GHz

Attributes	Values or assumptions
Carrier Frequency NOTE1	Macro only: Below 6 GHz (around 6 GHz) Macro + RSUs NOTE2: 1) For BS to RSU: Below 6 GHz (around 6 GHz) NOTE3 2) RSU to vehicles or among vehicles: below 6 GHz
Aggregated system bandwidth NOTE4	[TBD] MHz (DL+UL)
Layout	Option 1: Macro only Option 2: Macro + RSUs NOTE2
ISD	Macro cell: ISD = 500m Inter-RSU distance = [100m] NOTE5
BS antenna elements	Tx: Up to [32 Tx] Rx: Up to [32 Rx]
UE antenna elements	RSU Tx: Up to [32 Tx] RSU Rx: Up to [32 Rx] Vehicle Tx: Up to [8 Tx] Vehicle Rx: Up to [8 Rx]
User distribution and UE speed	100% in vehicles Average inter-vehicle distance (between two vehicles' center) in the same lane is [1sec * average vehicle speed] (average speed: [100-300km/h])
Traffic model	[50 messages] per 1 second with absolute average speed of [100-250 km/h] (relative speed: 200 – 500km/h)

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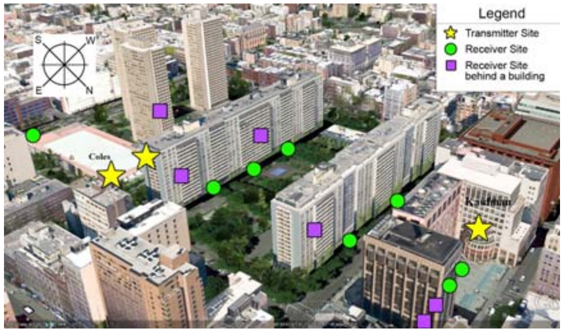
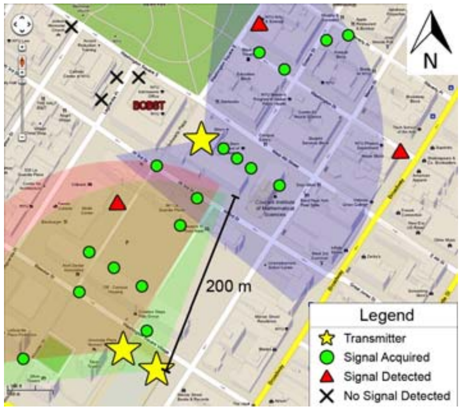
Initial NYU MmWave Measurements





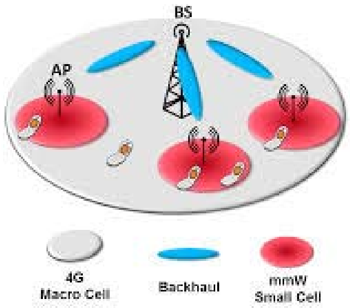
- Millimeter wave: It can work!
  - First measurements in urban canyon environment
  - Distances up to 200m
  - Propagation via reflections
- Sufficient for cellular system at current density
  - Measurements made urban macro-cell type deployment
  - Rooftops 2-5 stories to street-level

Rappaport, Theodore S., et al. "Millimeter wave mobile communications for 5G cellular: It will work!." *IEEE access* 1 (2013): 335-349.

Key Challenges for mmWave

❑Directionality

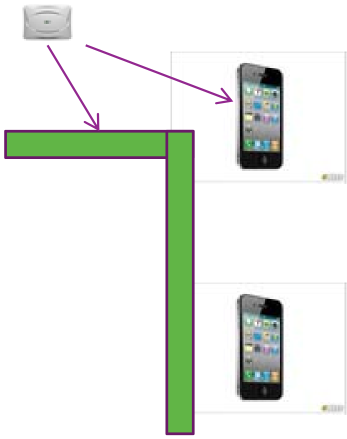
- High isotropic path loss
- Compensated by directional beams
- Impacts all aspects of cellular design



http://www.miwaves.eu/

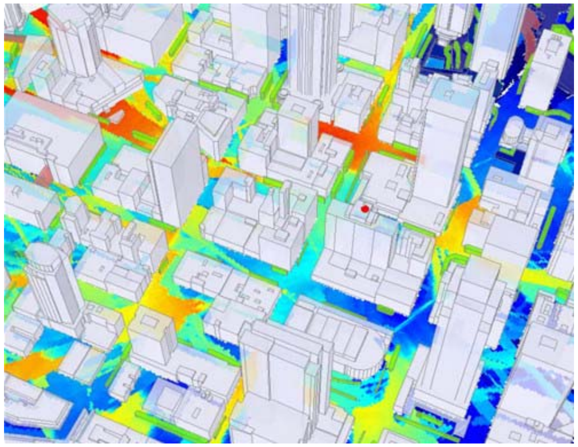
❑Blockage

- MmWave signals blocked by many common materials
- Brick > 80 dB, human body > 25 dB
- Leads to highly intermittent channels



3GPP 38.900: Initial Channel Model Spec

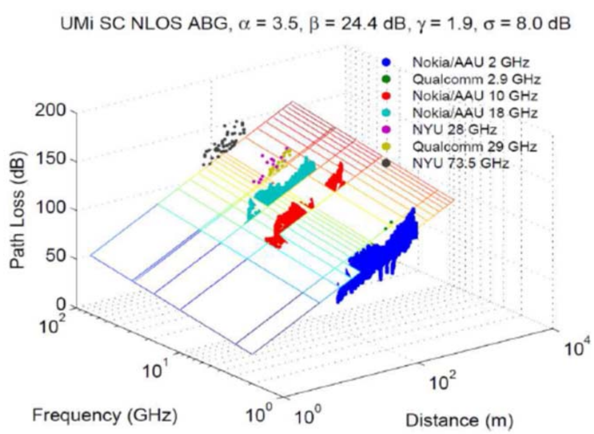
- ❑ Massive industry effort at wide range of bands, scenarios
- ❑ Focus on four key scenarios:
  - Urban macro
  - Urban micro
  - Indoor Hotspot (open and mixed office)
  - Rural macro (up to 7 GHz supported)
- ❑ Wide range of bands
- ❑ Some use cases may need further study
  - Vehicular (including below 6 GHz)
  - Massive connection, …



https://www.siradel.com/portfolio-item/hetnet-deployment-strategy/

See discussion in Ericsson, Telstra, Vodafone, CMCC,
5G channel modeling way forward,RP161179, June 2016

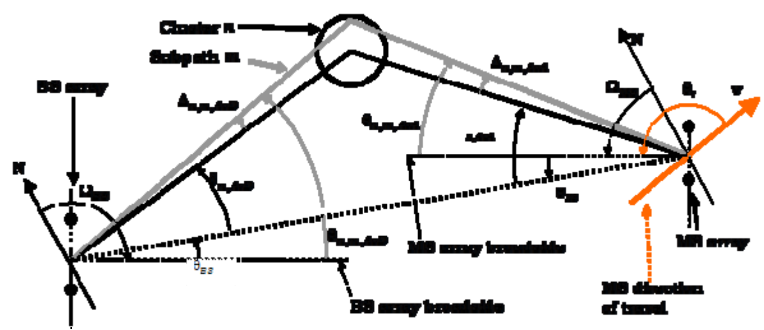
Path Loss and Fading



U Mi pathloss models

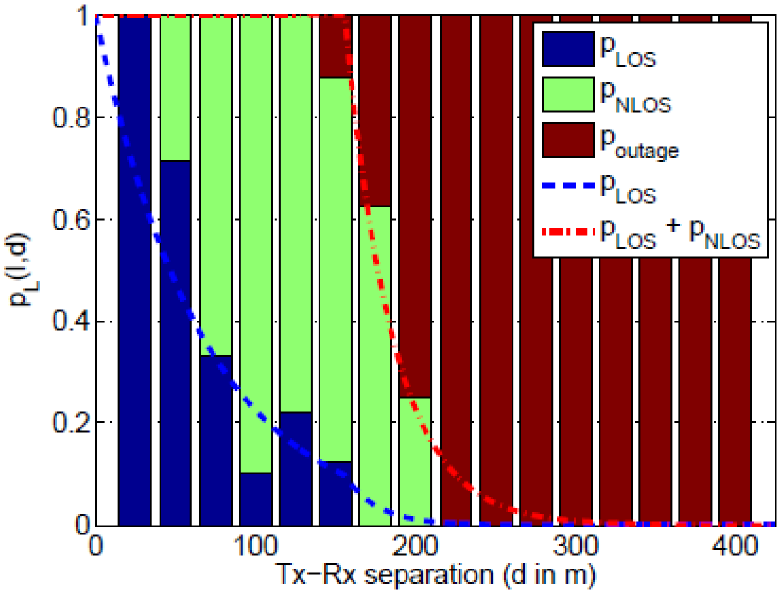
Sun et al, Propagation Path Loss Models for 5G Urban Microand Macro-Cellular Scenarios, IEEE VTC 2016

- ❑Path loss, propagation, I-O penetration
- ❑Antenna models
- ❑Extends 3GPP spatial cluster channel model
  - Captures spatial characteristics of the channel
  - Essential for high-dimensional arrays



From TR 25.996

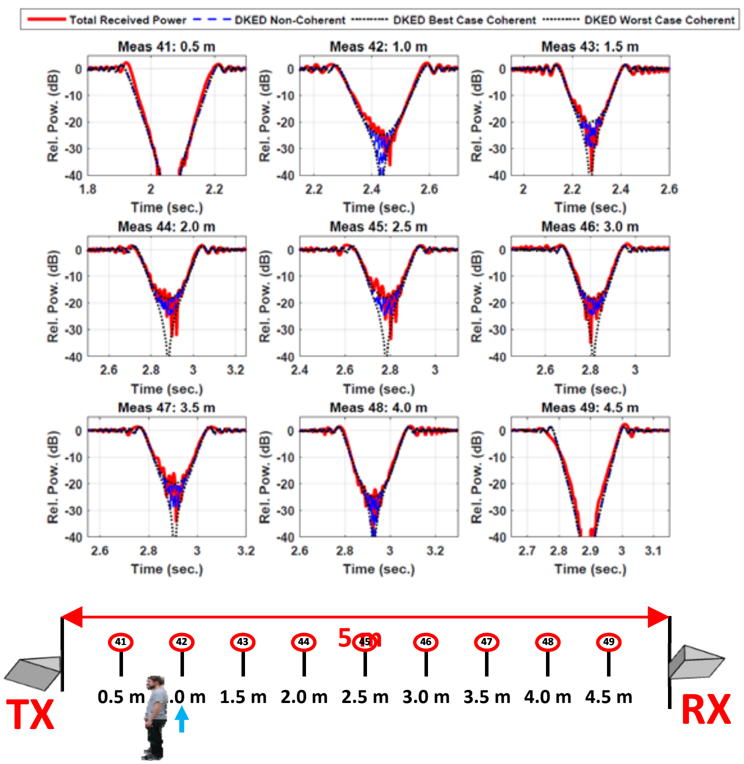
LOS and Outage



Akdeniz, Mustafa Riza, et al. "Millimeter wave channel modeling and cellular capacity evaluation." *IEEE journal on selected areas in communications*32.6 (2014): 1164-1179.

- Three state link models:
  - LOS, NLOS and outage
- Captures loss of signals from blockage
- 3GPP has detailed LOS models
  - Various scenarios
  - Includes spatial consistency
- Outstanding issues:
  - Correlations in multiple cells
  - Required for macro-diversity

Blockage and Channel Dynamics



- ❑MmWave signals blocked by many materials
  - Body, hand, cars, …
- ❑Key cause of intermittency
- ❑Several new studies to understand time scales
- ❑Integrated to 3GPP 38.900
  - Analytic models (e.g. knife edge diffraction)
  - Simplified models with mobility

G. R. MacCartney, Jr., S. Deng, S. Sun, and T. S. Rappaport, “73 GHz Millimeter-Wave Human Blockage and Dynamic Measurements,” IEEE 84th Vehicular Technology Conference Fall (VTC 2016-Fall), Sept. 2016.

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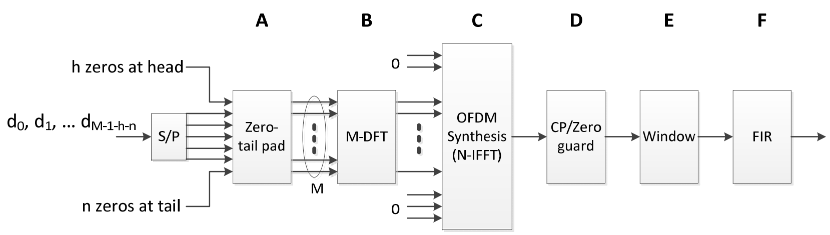
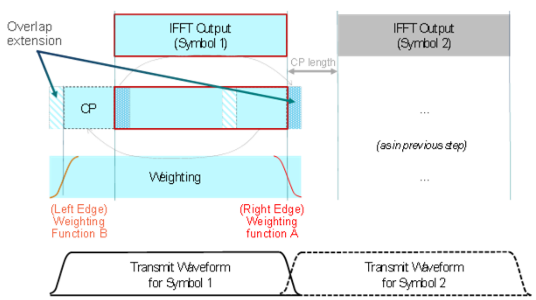
OFDM Waveform Options



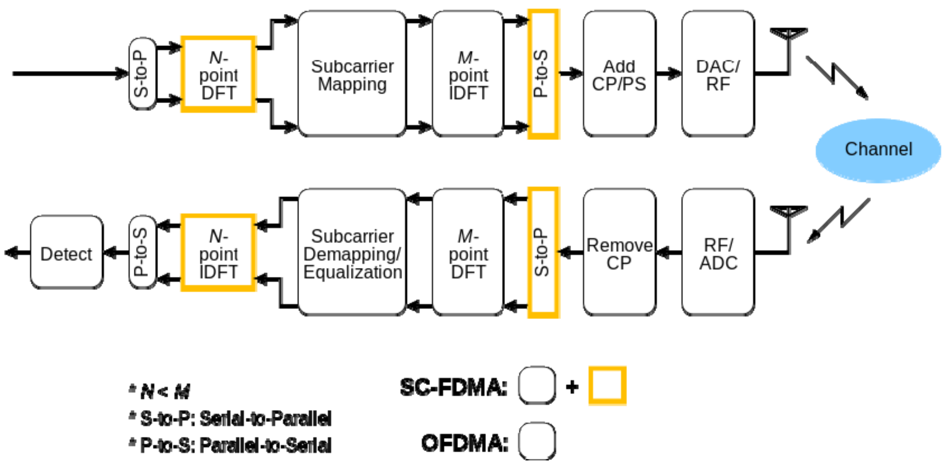


Qualcomm, R1-162199, "Waveform candidates", Apr 2016

- Many flavors of OFDM considered:
  - CP-OFDM
  - WOLA (windowed overlap and add)
  - UFMC (universal filter multi-carrier)
  - GFDM
  - …

- Key issues
  - CP overhead flexibility
  - Out of band / adjacent carrier
  - PAPR
  - Multiplexing flexibility
  - Equalization complexity

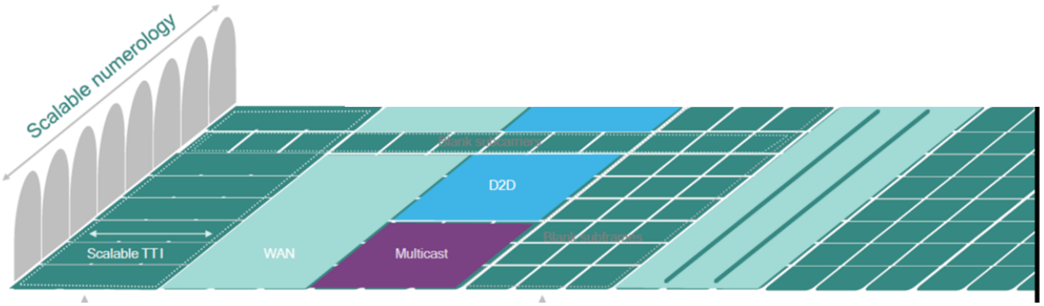
DFT-Spread OFDM

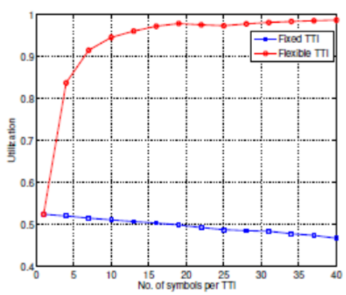


- DFT followed by IDFT
- Effectively signals in time-domain
- Reduce PAPR
  - For QPSK modulation
  - Important in mmWave
    Low PA efficiency
- But, reduced multiplexing flexibility
- Equalize in frequency-domain
- Used in LTE uplink
  - control and data channels

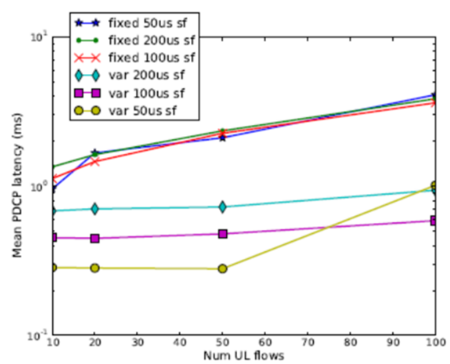
Image from “Single-Carrier FDMA”,
https://en.wikipedia.org/wiki/Single-carrier_FDMA

Frame Structure





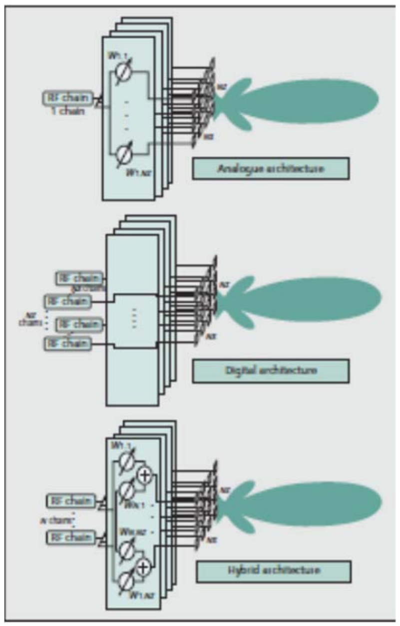
(a)



- Flexible frame structure
  - Scalable TTI
  - Scalable subcarrier spacing (15 kHz x 2^n)
  - Common framework WAN, D2D, Multicast, …
  - Puncturing for short control
- NYU studies
  - Can achieve <1 ms airlink latency
  - Significant benefit control signaling

1. Qualcomm, NYU Talk, Sept 2016
2. Ford et al, Achieving Ultra-Low Latency in 5G Millimeter Wave Cellular Networks, 2016
3. Dutta et al, MAC layer frame design for millimeter wave cellular system, 2016

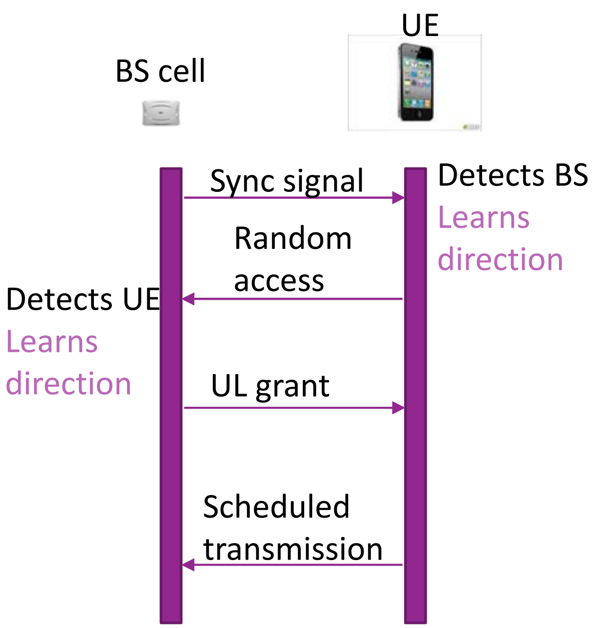
Directionality and MIMO Architectures



Sun, Shu, et al. "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, IEEE ComMag, 2014

- Directional transmissions essential for mmWave
- Need high-dimensional arrays
- Three dominant architectures
  - Analog BF: Low power, but “look” in one direction
  - Digital BF: High power, but most flexible
  - Hybrid: Combination of both
- Significant impact in PHY and MAC
  - Channel tracking,
  - Cell search
  - Control signals

Directional Initial Access

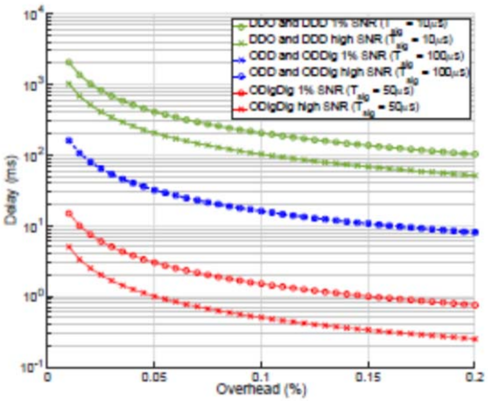


- Initial access:
  - Establish connection from idle mode
- Challenges for mmWave:
  - Must find directions of communications
  - More widely-used
    Radio link failure, handover, idle mode to save power
- Also central problem in massive connection / IoT

Latency	Airlink RTT measurement	Current LTE	Target for 5G
Data plane	UE in connected mode	22 ms	1 to 4 ms
Control	UE begins in idle mode	80 ms	10 ms

Fast Search with Fully Digital

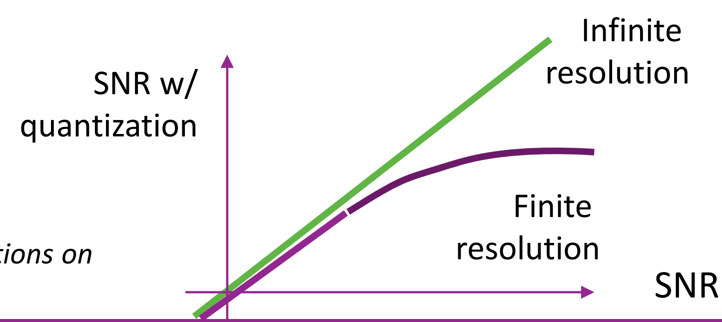
Sync Delay



MIMO	Sync delay	RA delay
Analog BF only	32 ms	128 ms
Low power digital	4 ms	2 ms

C. N. Barati *et al.*, "Initial Access in Millimeter Wave Cellular Systems," *IEEE Transactions on Wireless Communications*, Dec. 2016.

- Low resolution fully digital
  - One ADC per element
  - Compensate power via low resolution (2-3 bits)
- Dramatically better performance
  - Cell search
  - Control signal multiplexing
  - Channel tracking



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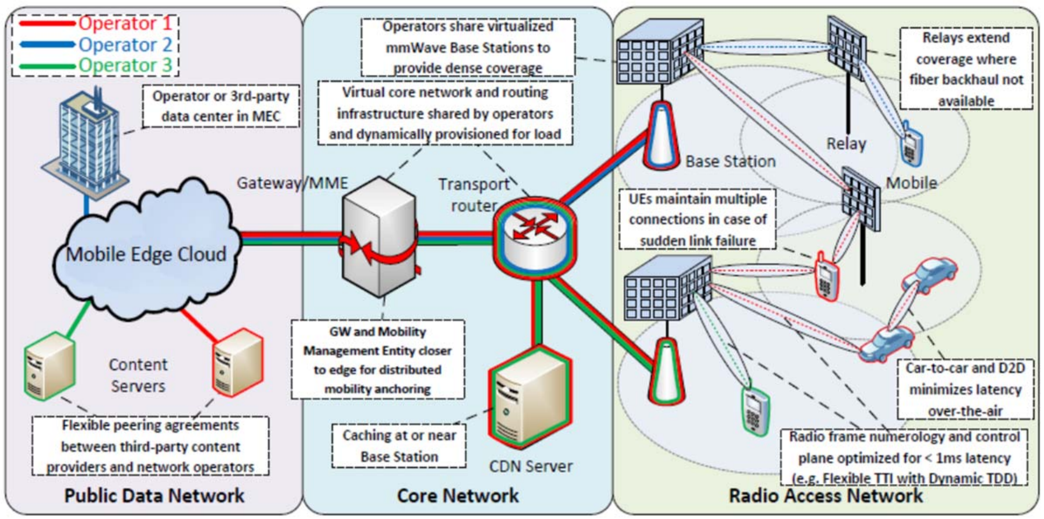
5G Network Architecture

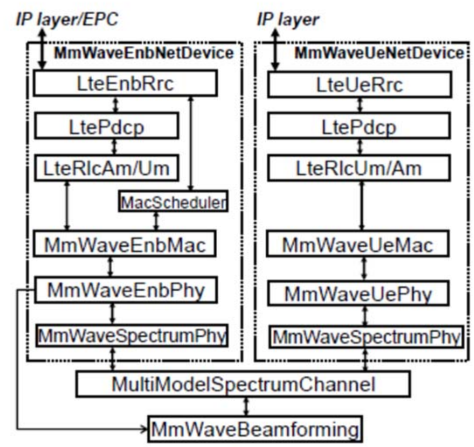


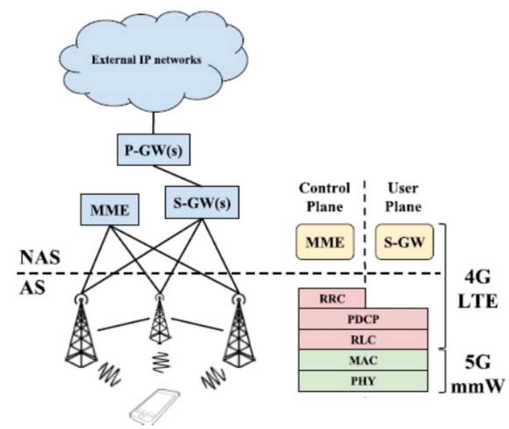
Ford et al, Achieving Ultra-Low Latency in 5G Millimeter Wave Cellular Networks, 2016

- Harmonization across multiple RANs
  - 4G, 5G,…
  - WiFi
- Heterogeneous services
  - Cellular, IoT, …
- Flexible architecture
  - Network virtualization
  - Flexible deployment of services
  - Caching, edge services

MmWave ns3 Module

- ❑ First, open-source mmWave module
- ❑ End-to-end
  - Detailed channel models (statistical, ray tracing, …)
  - Customizable MAC including adaptive HARQ, …
  - RLC, PDCP, realistic RRC
  - Configurable core networking
  - Handover (inter-5G and 4G/5G)
- ❑ https://github.com/mmezzavilla/ns3-mmwave

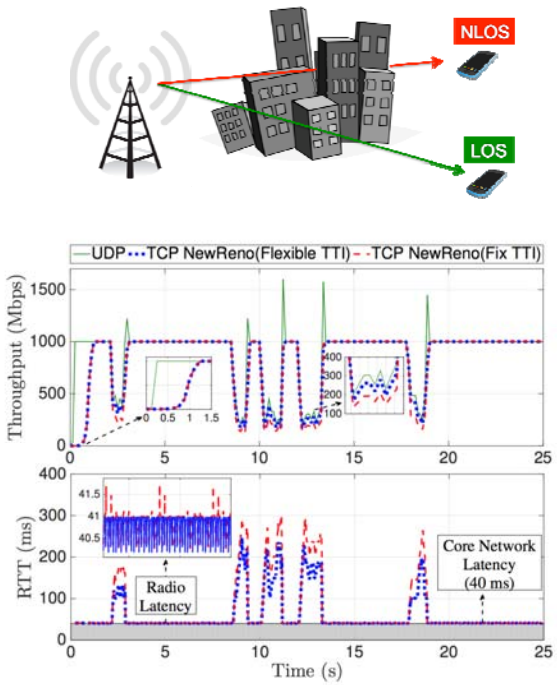




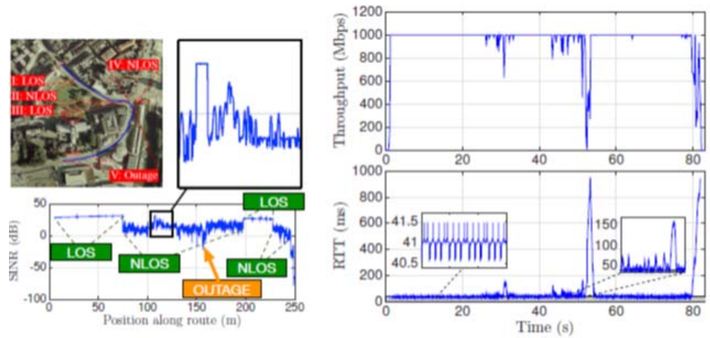
Mezzavilla, Marco, et al. "5G mmwave module for the ns-3 network simulator." *Proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. ACM, 2015.

Insights from Simulations

Statistical Models



Ray Tracing models
Courtesy Andy Nix, U Bristol



(a) SINR (b) TCP performance (3 m/s)

M. Zhang *et al.*, "Transport layer performance in 5G mmWave cellular," *INFOCOM WKSHPS*, April 2016

- Issues for 5G
  - Can TCP adapt in mmWave?
  - Architectures
  - Traffic patterns in new applications
- Simulations reveal several issues
  - Buffer bloat
  - TCP start lag
  - Control / ACK overhead
  - CN delay

Outline

- Motivation and vision
- 3GPP 5G standardization process and activities
- Channel models
- PHY & MAC design
- Networking
- Summary and Perspectives

Summary

- 5G will enable large numbers of use cases:
  - Massive mobile broadband, vehicular, AR/VR
  - But, we still don’t know what will be the killer app
- Builds on the massive success of earlier systems
- Many new technologies
  - Millimeter wave, Massive MIMO, core network evolution, densification
- Significant research but no forseeable show stoppers

People

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  - Michele Zorzi (U Padova)
- Postdocs: Marco Mezzavilla, Aditya Dhananjay
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- U Bristol ray tracing:
  - Evangelos Mellios, Di Kong, Andrew Nix

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