System Level Challenges for mmWave Cellular

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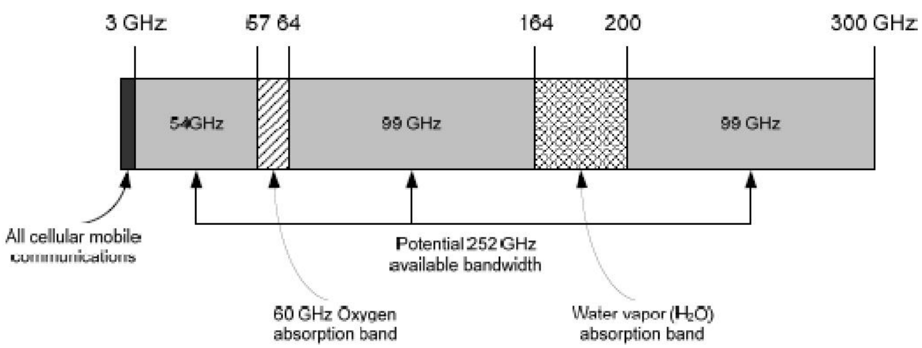
Globecom Workshops, Washington, DC

Outline

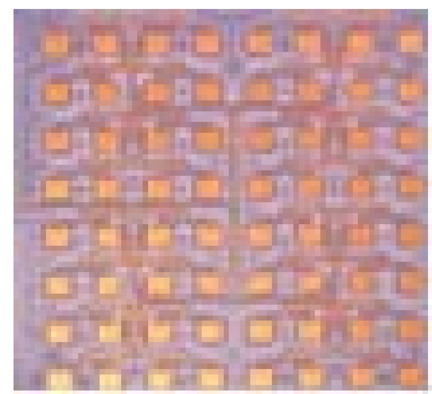
- MmWave cellular: Potential and challenges
- Directional initial access
- Transport performance with intermittent channels
- Future directions

MmWave: The New Frontier for Cellular

- Massive increase in bandwidth
- Spatial degrees of freedom from large antenna arrays

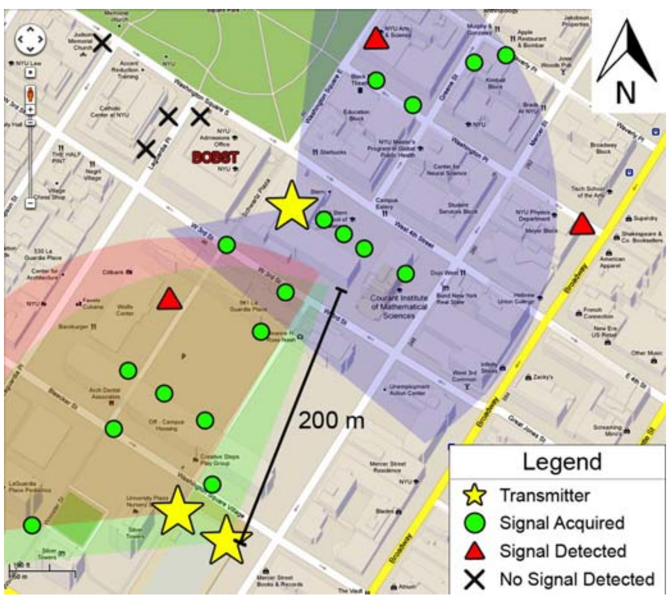


From Khan, Pi "Millimeter Wave Mobile Broadband: Unleashing 3-300 GHz spectrum," 2011



Commercial 64 antenna element array

MmWave: It Can Work!



- First tests in NYC
  - Likely initial use case
  - Mostly NLOS
  - “Worst-case” setting
- Microcell type deployment:
  - Rooftops 2-5 stories to street-level
- Distances up to 200m

All images here from Rappaport’s measurements:

Azar et al, “28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City,” ICC 2013

Comparison to Current LTE

- Initial results show significant gain over LTE
  - Further gains with spatial mux, subband scheduling and wider bandwidths

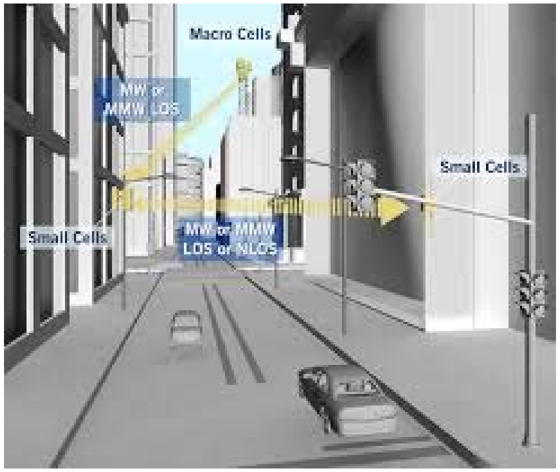
System antenna	Duplex BW	fc (GHz)	Antenna	Cell throughput (Mbps/cell)		Cell edge rate (Mbps/user, 5%)	
				DL	UL	DL	UL
mmW	1 GHz TDD	28	4x4 UE 8x8 eNB	1514	1468	28.5	19.9
		73	8x8 UE 8x8 eNB	1435	1465	24.8	19.8
Current LTE	20+20 MHz FDD	2.5	(2x2 DL, 2x4 UL)	53.8	47.2	1.80	1.94

10 UEs per cell, ISD=200m,
hex cell layout
LTE capacity estimates from 36.814

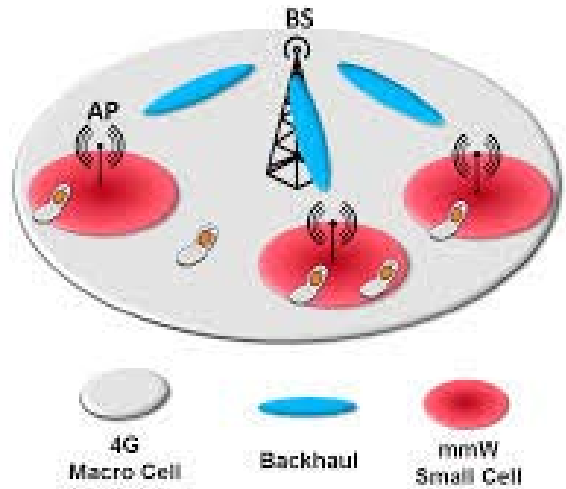
~ 25x gain

~ 10x gain

Challenge 1: Directionality



Uday Mudoi, Electronic Design, 2012

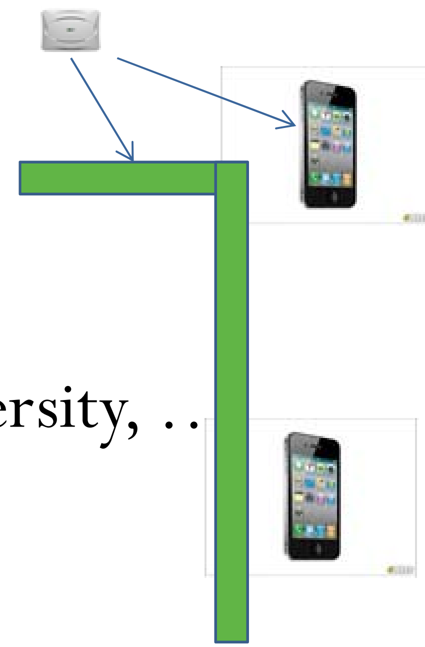


http://www.miwaves.eu/

- Need directionality for power gain, spatial multiplexing
- Challenges:
  - Channel tracking, search, control and multi-access
  - MIMO architectures, power consumption

Challenge 2:
Blockage and Channel Dynamics

- Signals blocked by many common materials
- Brick > 80 dB, human body 20 to 25 dB



- System implications:
  - Highly variable channels
  - Need fast channel tracking, macro-diversity, …

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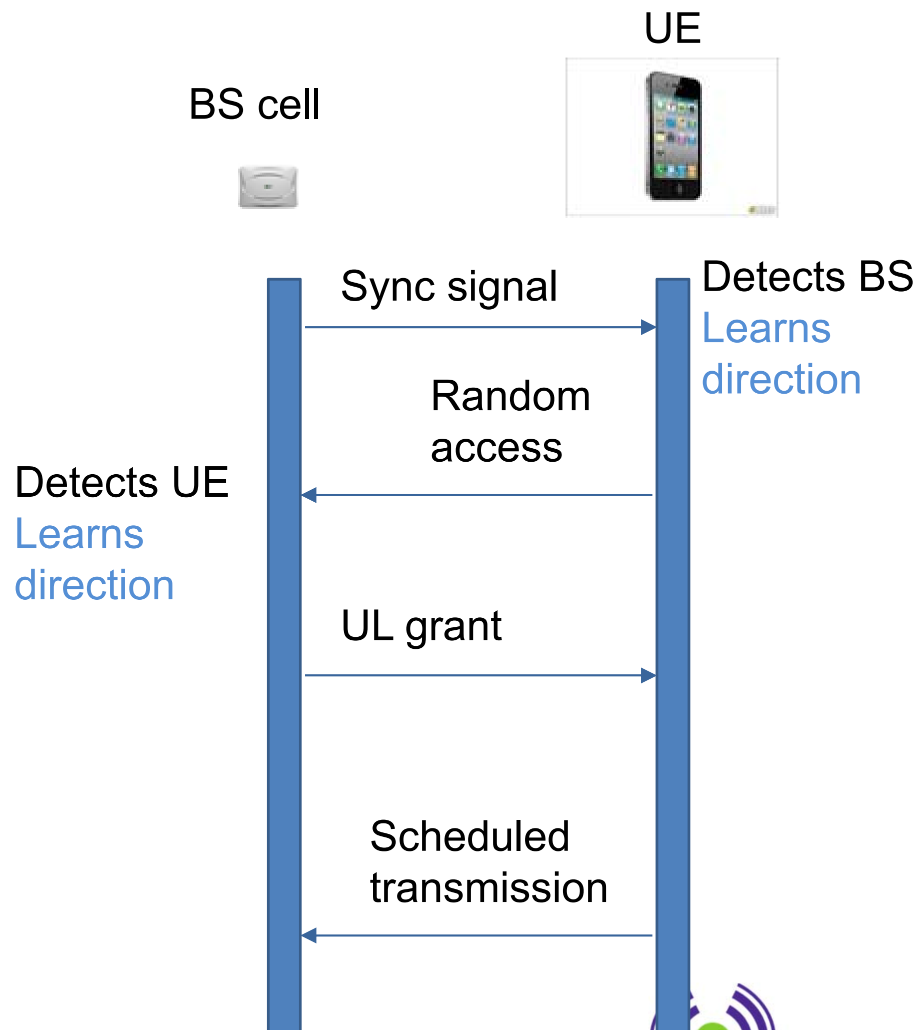
Directional Initial Access

- Initial access in cellular
  - Initial attachment
  - Idle to connected mode
  - 4G to 5G
- Two-way handshake
- Challenge in mmWave:
  - Directional search
  - BS and UE
- Potential for increased delay



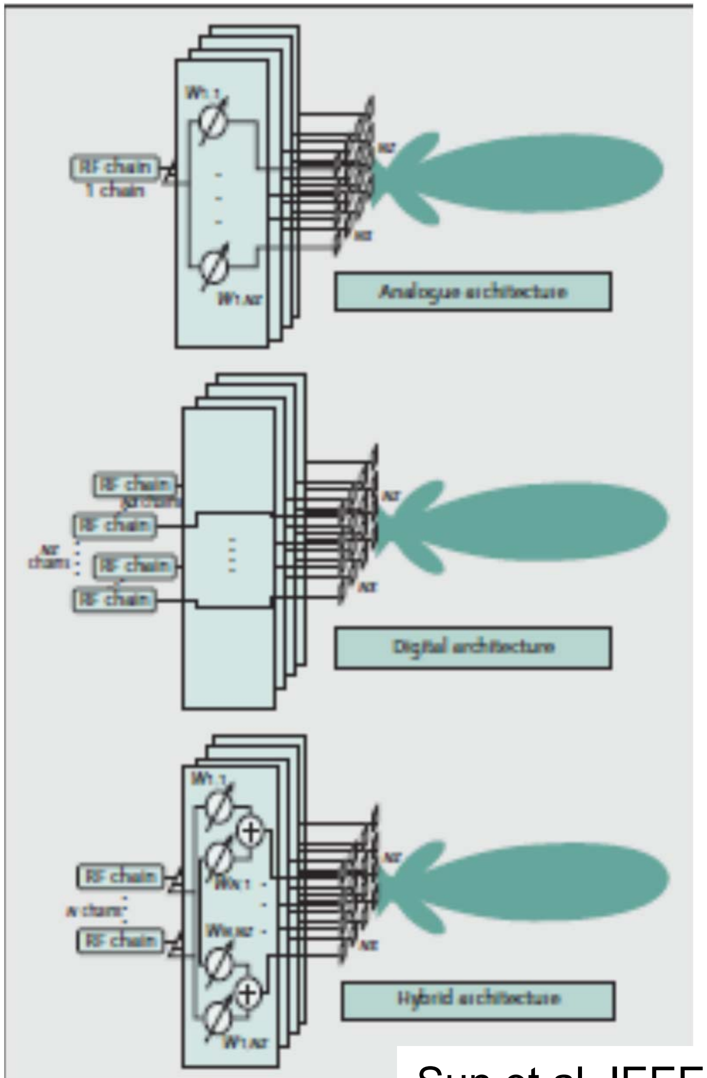
[Barati, Hosseini, Rangan, Zorzi, "Directional Initial Access in mmWave," 2015

Delay Requirements for 5G mmWave

Item	Airlink RTT measurement	Current LTE	Target for 5G
Data plane latency	UE in connected mode	22 ms	< 1 ms
Control plane latency	UE begins in idle mode	80 ms	5 ms?

- Why we need low control plane latency for mmWave?
  - Channels are intermittent, handovers rapid
  - Fast connection re-establishment from link failure
  - 4G to 5G handover
  - Aggressive low power idle mode utilization

MIMO Architectures for mmWave



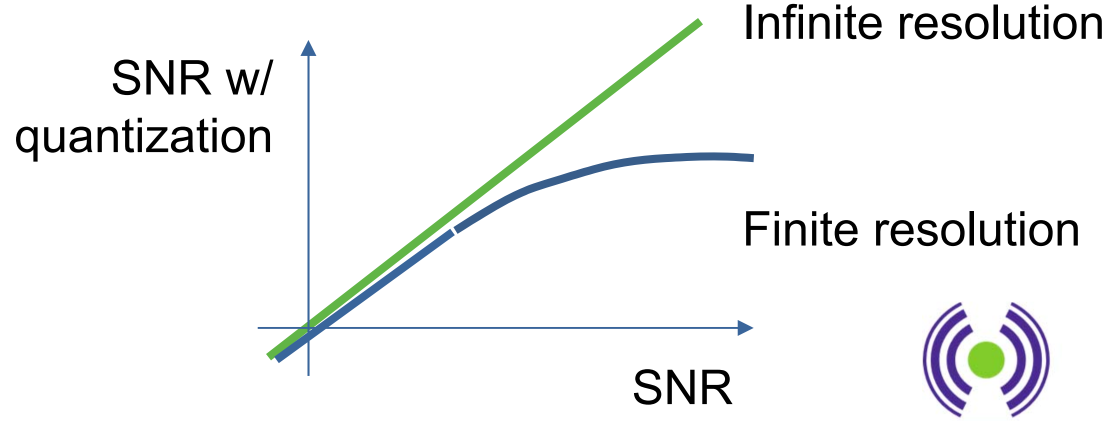
- Analog phased array
  - Lowest power. 1 ADC
  - Looks in only direction at a time
- Fully digital architecture
  - Highest power. N ADCs
  - Looks in multiple directions
- Hybrid architecture
  - Medium power. M < N ADCs

Sun et al, IEEE CommMag, 2014

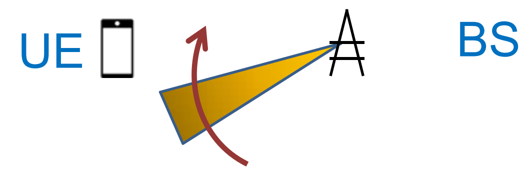
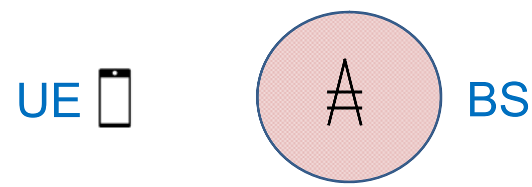
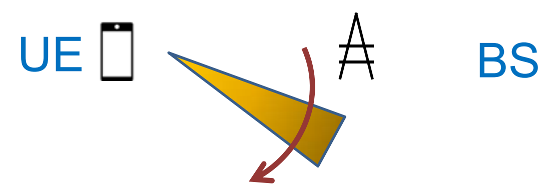
Low Power Fully Digital

- Fully digital architectures
  - Can look in multiple directions at a time
  - But, high power consumption
- Low quantization rates (2-3 bits)
  - Low power solution
- Effect of low resolution is limit on high SNR
  - Many low SNR channels are unaffected

$$SNR_{\text{eff}} = \frac{SNR}{1 + \alpha SNR}$$

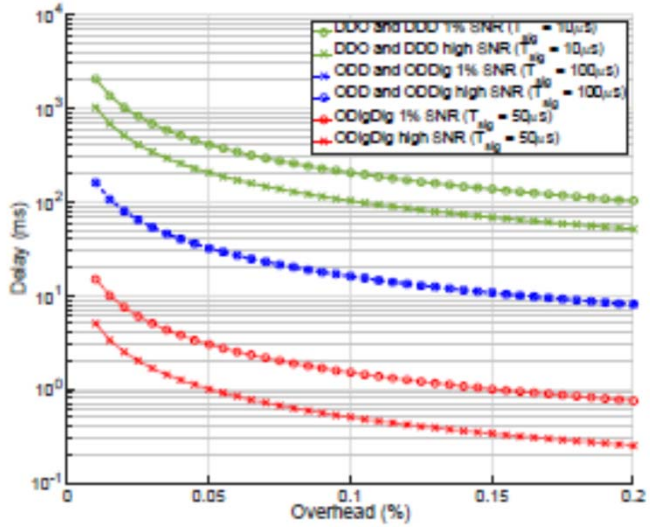


Search Options for Sync

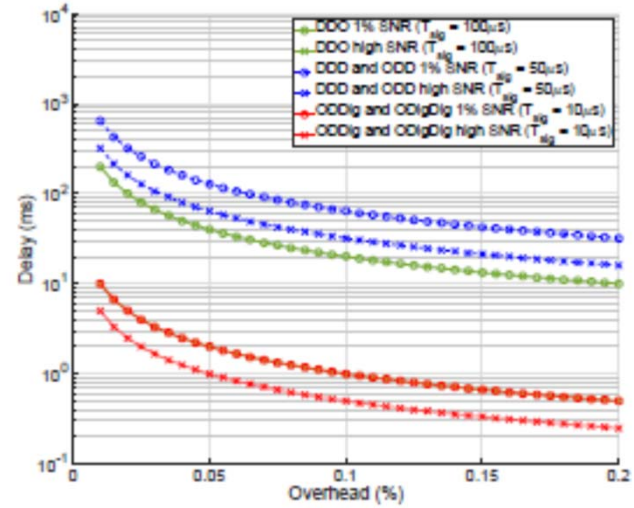
Item	Option	HW	
BS Sync Transmit	Directional TX sequential scan	Analog	
	Omni fixed TX	Analog	
UE Sync receive	Directional RX sequential scan	Analog	
	Digital (all directions at once)	Digital	

Comparison of Options

Sync Delay



Random access delay



MIMO	Best option	Sync delay	RA delay
Analog BF only	ODD	32 ms	128 ms
Low power digital	ODigDig	4 ms	2 ms

Delays for 1% cell edge UE
5% overhead each direction

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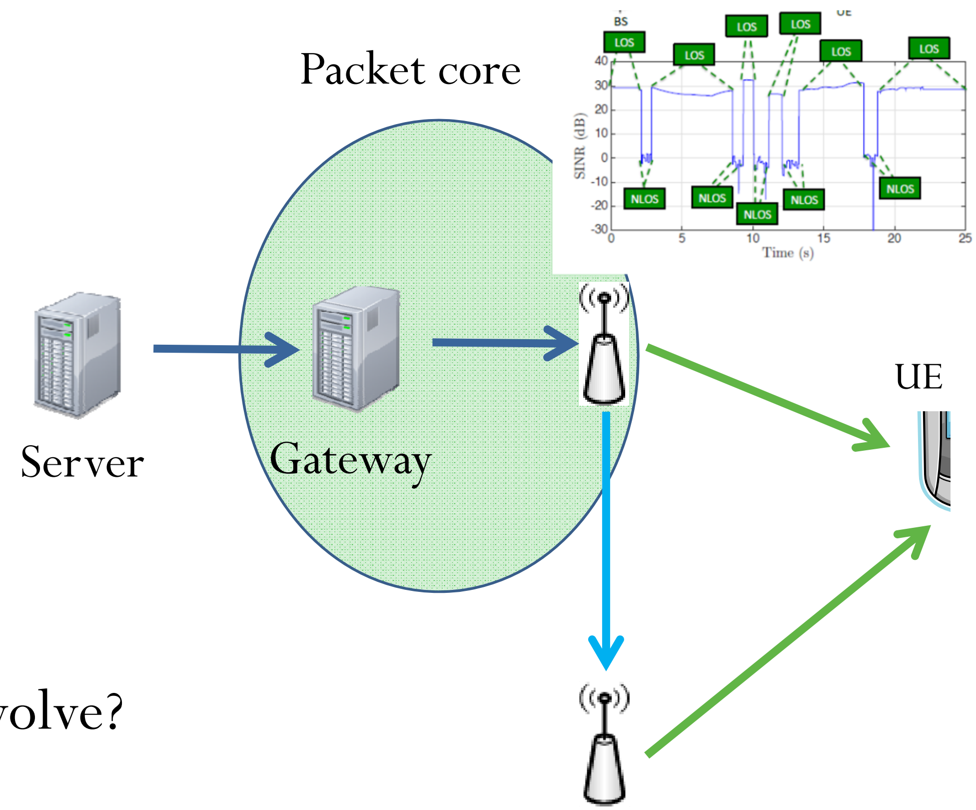
Transport Layer Challenges

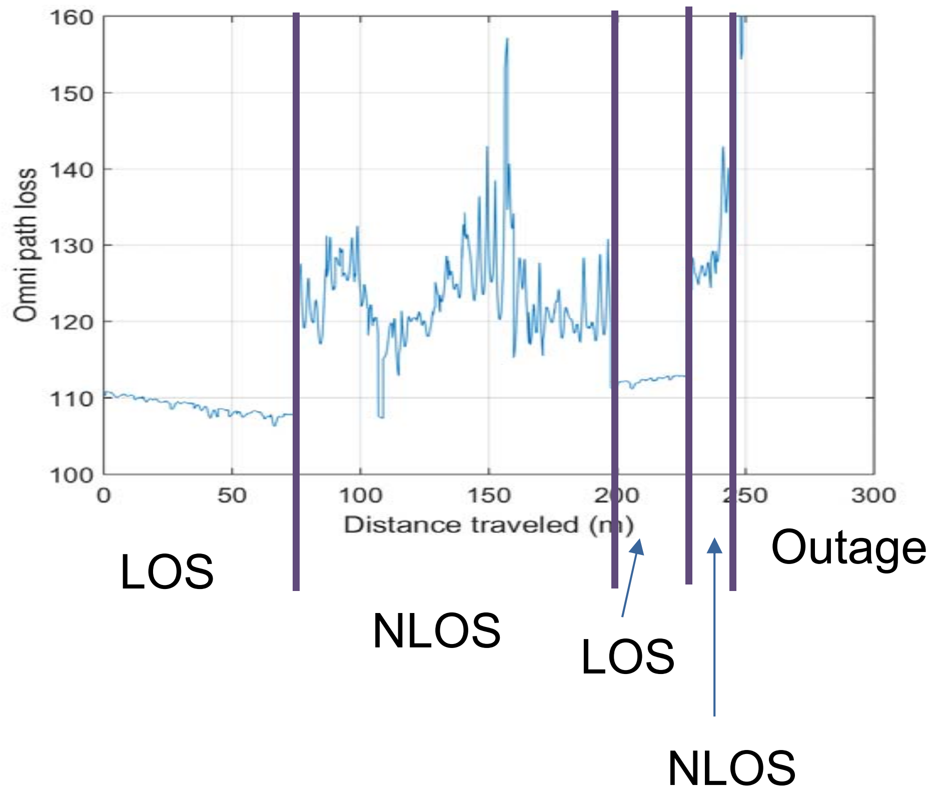
- MmWave links:
  - Intermittent
  - Very high peak rates
- Questions:
  - Can current TCP adapt?
  - If not, how do we fix TCP?
  - Should the core network evolve?



M. Zhang *et al*., "Transport layer performance in 5G mmWave cellular," Infocom workshops, 2016

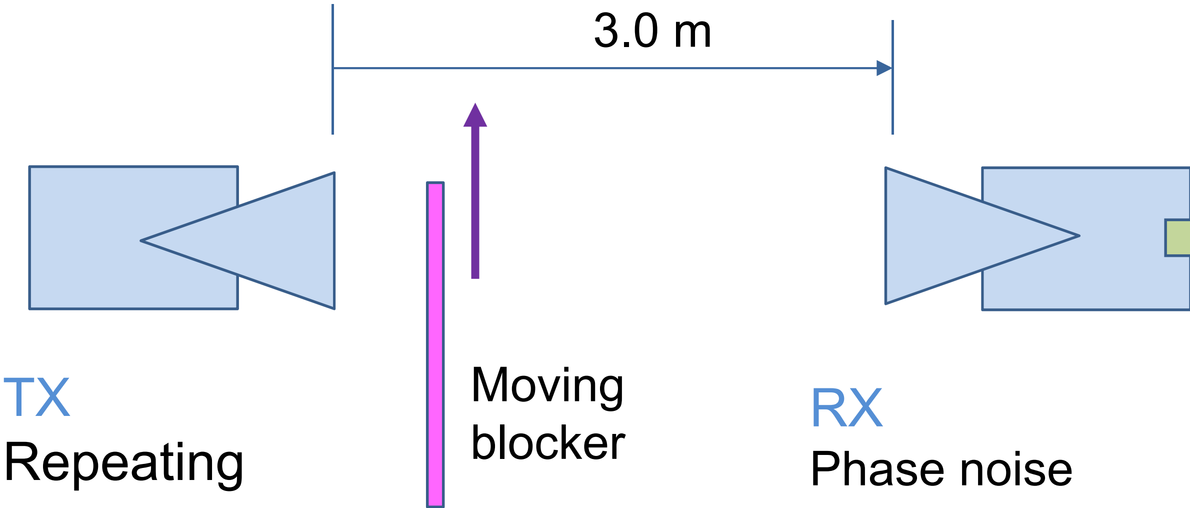
Ray tracing data

Data from Nix, Melios, U Bristol



- Very rapid (< 1m) transitions around buildings
- Diffraction is minimal

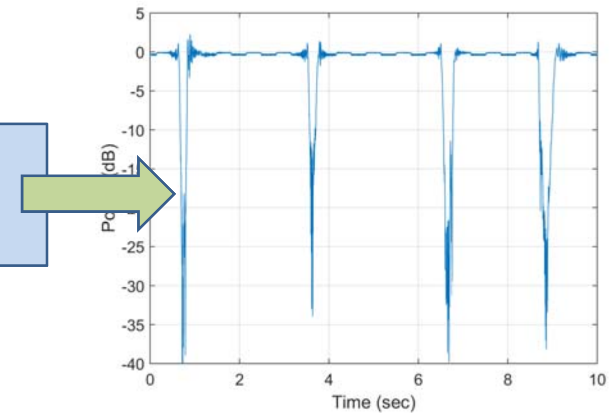
Lab Measurements 60 GHz



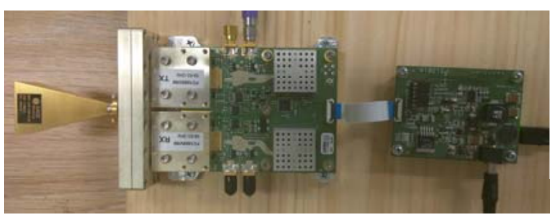
TX
Repeating sequence, 100 MHz bandwidth

Moving blocker

RX
Phase noise correction,
match filter,
capture first path,
128 us sample period



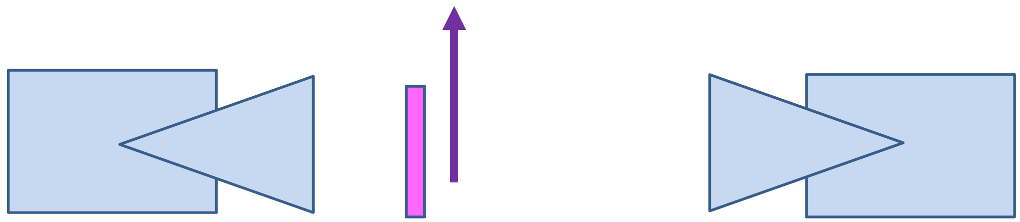
Power vs. time



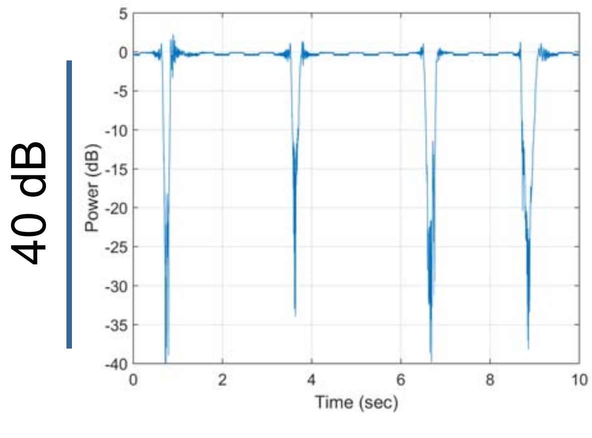
Sivers 60 Hz RF module
Directional horn antenna
23 dBi gain, 9.5 deg beamwidth

Aditya Dhananjay, Millilabs & NYU

Measurement Results

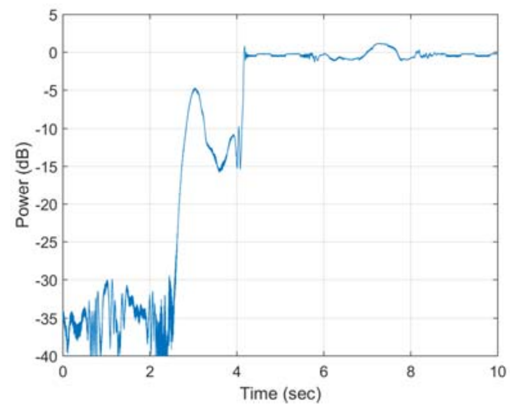


Runner btw TX and RX

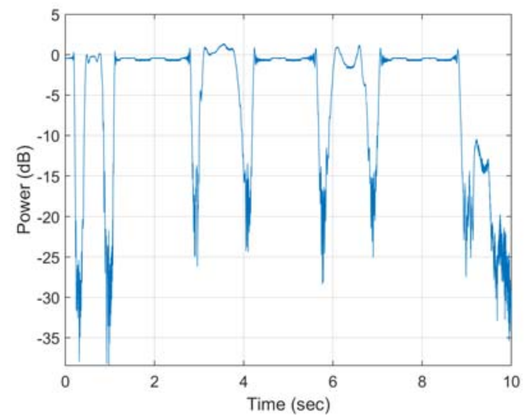


10 seconds

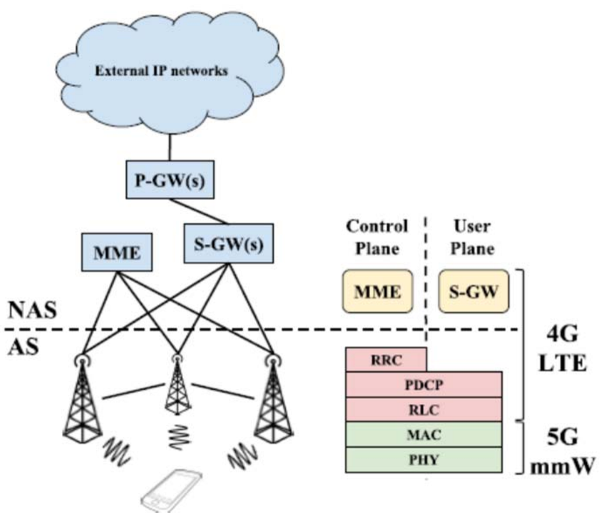
Hand blockage

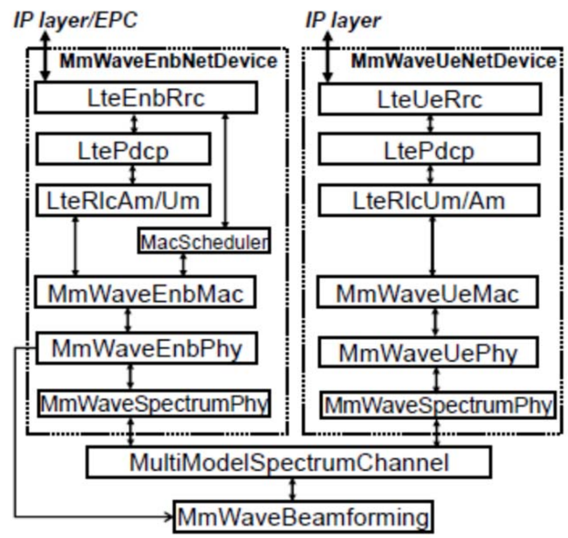


Metal plate



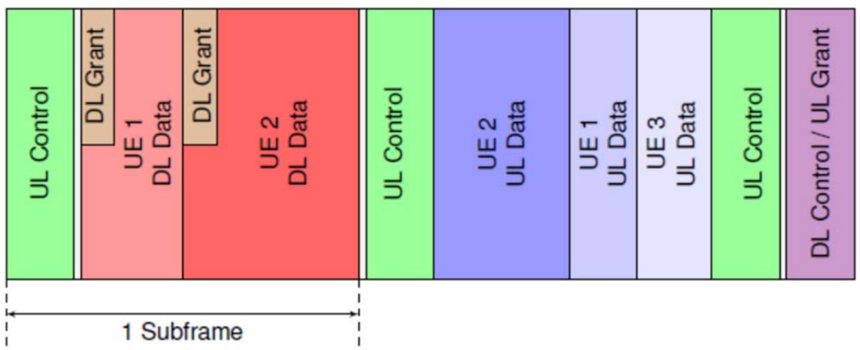
Ns3 End-to-end Simulation

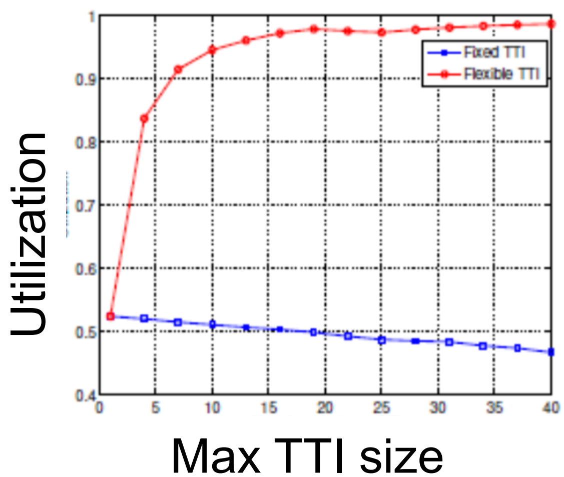




- All code is publicly available

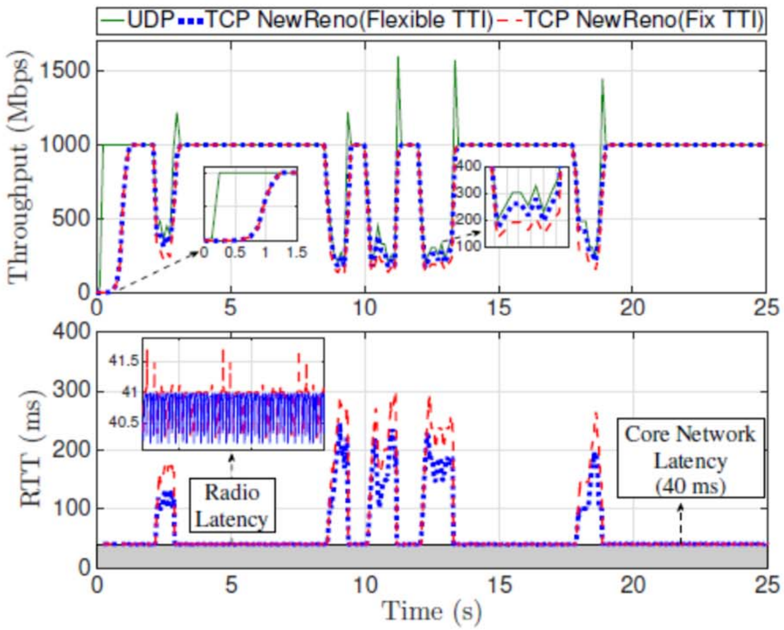
Flexible MAC Layer

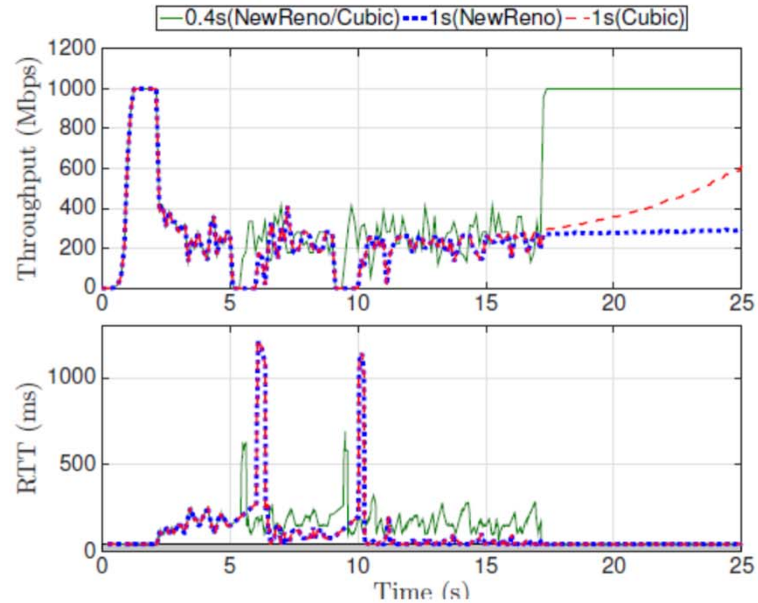




- Flexible frame structure
- Dynamically scheduled ACKs
- Low latency HARQ
  - < 1ms RTT
- Efficiently accommodates:
  - Small packets (e.g. TCP ACKs)
  - Control messages
  - Dynamic duplexing

Insights from Simulations…





- Very low initial ramp up under current TCP slow start
- Bufferbloat during blockage periods
- Very slow recovery from losses (even under TCP cubic)

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Conclusions

- MmWave presents fundamental challenges for system design:
  - Directionality and limits on RF architecture
  - Very high peak rates, but very bursty
- Solutions involve multiple layers
  - RF, MAC, network, …
- Other topics:
  - Distributed core network architecture
  - Applications

NYU WIRELESS Industrial Affiliates

Thanks

- Faculty:
  - Ted Rappaport, Elza Erkip, Shiv Panwar, Pei Liu
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- Students:
  - Sourjya Dutta, Parisa Amir Eliasi, Russell Ford, George McCartney, Oner Orhan, Menglei Zhang
- U Bristol ray tracing:
  Evangelos Mellios, Di Kong, Andrew Nix

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