Beyond 4G: Millimeter Wave Picocellular Wireless Networks

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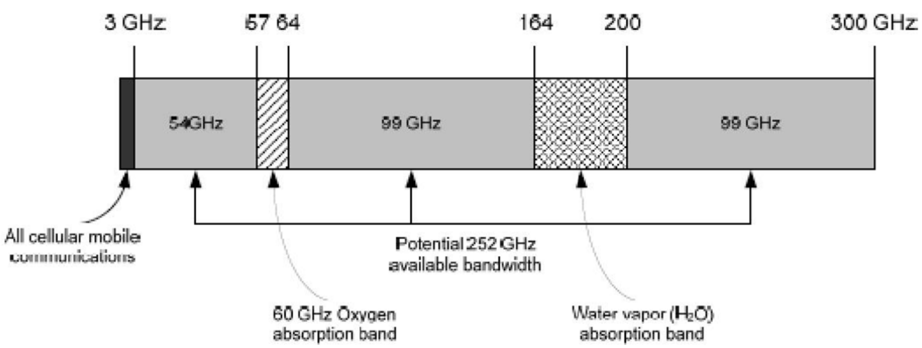
NJ ACS, Hoboken, J

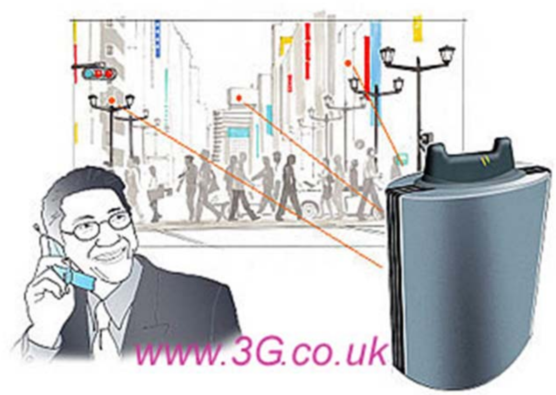
Outline

- Millimeter Wave: Potentials and Challenges
- 28 GHz Measurements in New York City
- Capacity Estimation
- Multiple Access with Limited Streams
- Research Directions

mmW: The New Frontier for Cellular

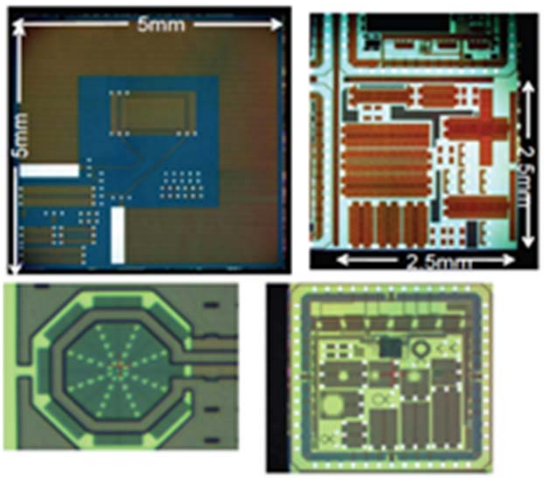
- Potential 1000x increase over current cellular:
  - Massive increase in bandwidth
    - Near term opportunities in LMDS and E-Bands
    - Up to 200x total over long-time
  - Spatial degrees of freedom from large antenna arrays



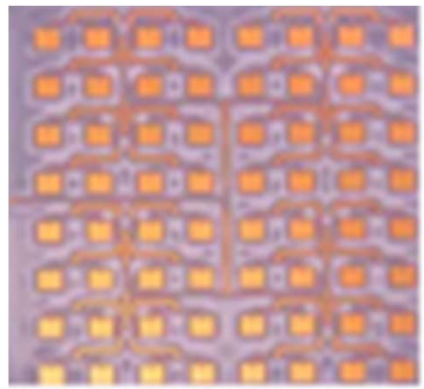


From Khan, Pi "Millimeter Wave Mobile Broadband: Unleashing 3-300 GHz spectrum," 2011

Very High Dimensional Arrays



Test 60 GHz circuits fabricated in Rappaport's lab at NYU wireless



Commercial 64 antenna element array

- 64+ antennas in a single chip
- Standard CMOS
- Beamforming
- Spatial multiplexing
- NYU wireless has unique facilities for fabrication and test

Key Challenges: Range

- Friis' Law: $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda^2}{4\pi r^2}\right)$
  - Free-space path loss $\propto \lambda^{-2}$
  - Increase in 20 dB moving from 3 to 30 GHz
- Shadowing: Significant transmission losses possible:
  - Mortar, brick, concrete > 150 dB
  - Human body: Up to 35 dB
- NLOS propagation relies on reflections

Other Challenges

- Device power consumption
  - High bandwidths, large numbers of antennas
  - Low PA efficiency in CMOS (often $< 10\%$)

- Intermittent connectivity
  - Loss of LOS

- Higher Doppler

mmW Work at NYU Wireless

- Faculty: Ted Rappaport, Sundeep Rangan, Elza Erkip
- 10+ students
- NSF NeTS: $1.2M
- NSF AIR grant: Accelerating cellular technologies
  - $800k NSF grant + $1.2M industry match
  - Targeted to short-term commercial research realization
- Intel Beyond 4G Award (with USC and Princeton)
- Industry partners:
  - Samsung, InterDigital, National Instruments, Verizon, Intel, …

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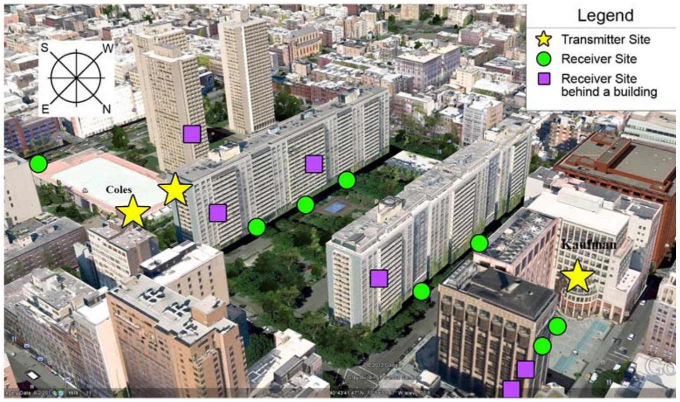
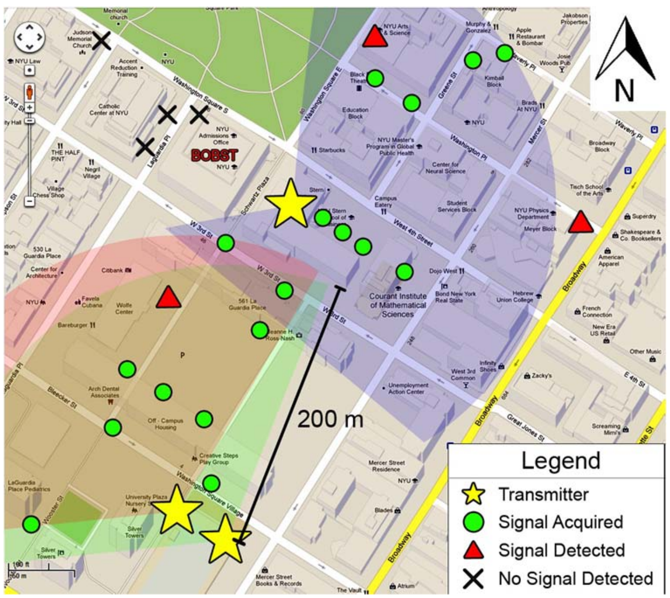
NYC 28 GHz Measurements





- Focus on urban canyon environment
  - Likely initial use case
  - Mostly NLOS
  - "Worst-case" setting
- Measurements mimic 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

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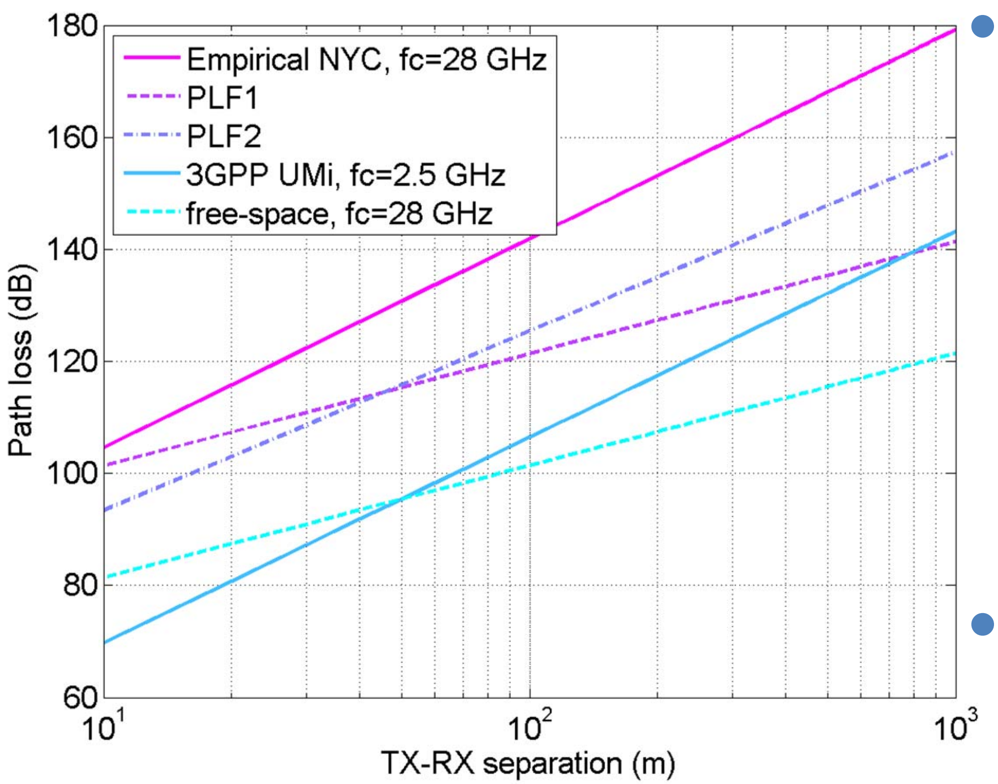
Path Loss Comparison



- Measured NLOS path loss in NYC
  - > 40 dB over free-space
  - > 40 dB worse than 3GPP urban micro model for fc=2.5 GHz
  - > 20 dB over prev. studies
- But, will still see large capacity gain possible

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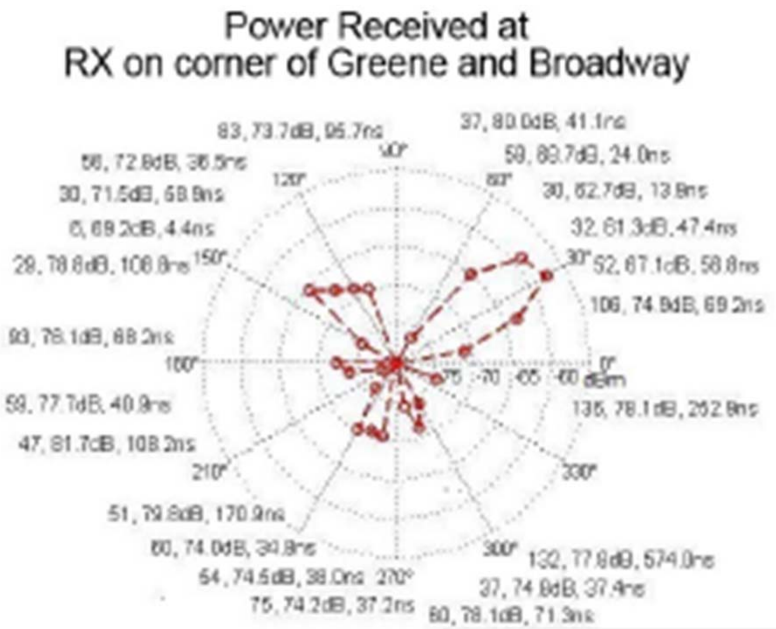
Angular Spread



- Observed significant angular spread:
  - Average 3 clusters
  - 7 degree beamwidth each
- Significant NLOS reflections
- Delay spread mostly < 400ns

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This material was presented at the IEEE North Jersey Advanced Communications Symposium - Hoboken, NJ - Sep. 21, 2013

Future Measurements

- Micro vs. picocellular deployments:
  - Transmitters placed lower heights, below rooftops
  - Lower range but greater LOS links
- Higher frequencies:
  - 72 GHz
- Indoor-outdoor propagation

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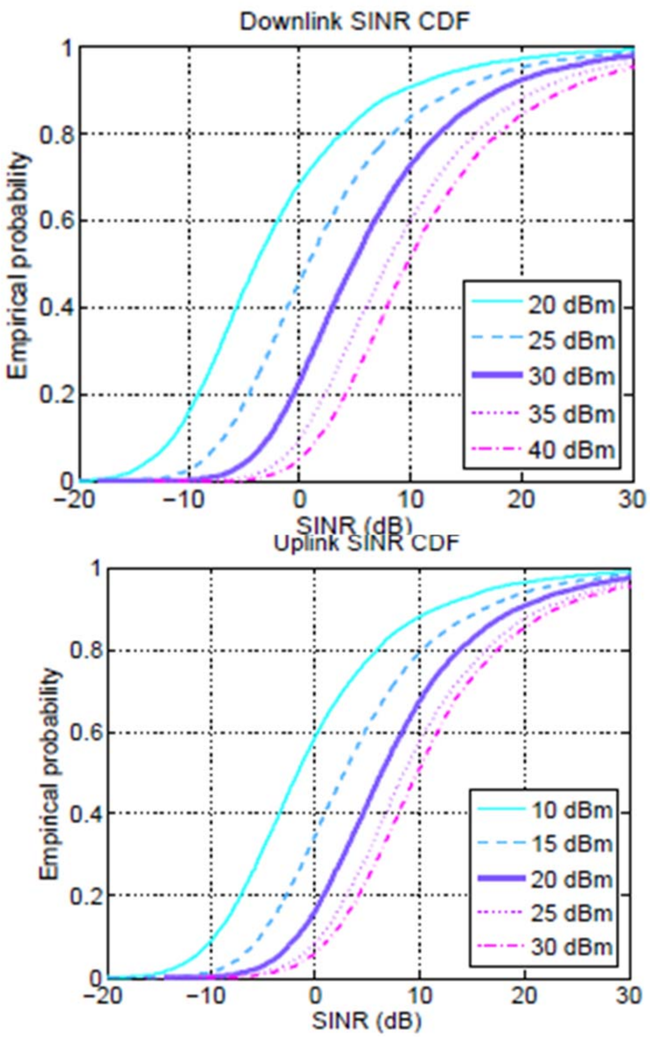
Simulation Parameters

Parameter	Value	Remarks
BS layout	Hex, 3 cells per site, ISD = 200m	Similar to 3GPP Urban Micro (UMi) model (36.814)
UE layout	Uniform, 10 UEs / cell	
Bandwidth	1 GHz	
Duplex	TDD	To support beamforming
Carrier	28 GHz	
Noise figure	7 dB (UE), 5 dB (BS)	
TX power	20 dBm (UE), 30 dBm (BS)	Supportable with 8% PA efficiency
Scheduling	Proportional fair, full buffer traffic	Static simulation corresponds to equal bandwidth
Antenna	8x8 2D uniform array at UE and BS)	Long-term beamforming. Single stream, no SDMA

SNR Distribution



- SNR distribution similar to current macrocellular deployment
- But, depends on:
  - Power
  - Beamforming

Comparison to Current LTE

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

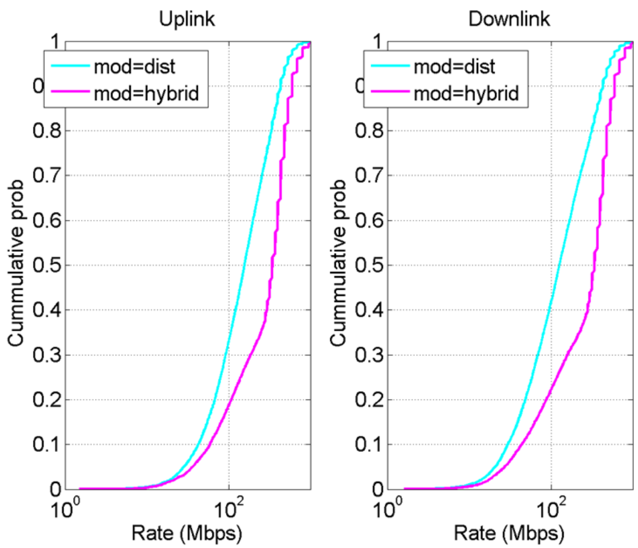
System antenna	Duplex BW	fc (GHz)	Cell throughput (Mbps/cell)		Cell edge rate (Mbps/user, 5%)	
			DL	UL	DL	UL
mmW (64x64)	1 GHz TDD	28	780	850	8.22	11.3
Current LTE (2x2 DL, 2x4 UL)	20+20 MHz FDD	2.5	53.8	47.2	1.80	1.94

~ 15x gain (cell throughput) ~ 5x gain (cell edge rate)

Parameters from previous slide with 50-50 UL/DL split & 20% overhead

LTE capacity estimates from 36.814

Alternate Deployment Models



Rate CDF under hybrid model

LOS/NLOS probability from 36.814 relay case

- Current study considered micro-cell type deployment
  - Rooftop aimed at large coverage
  - Mostly NLOS and power-limited
- Alternate deployment:
  - Street-level, LOS links
  - Much greater capacity in shorter range
- Possible HetNet

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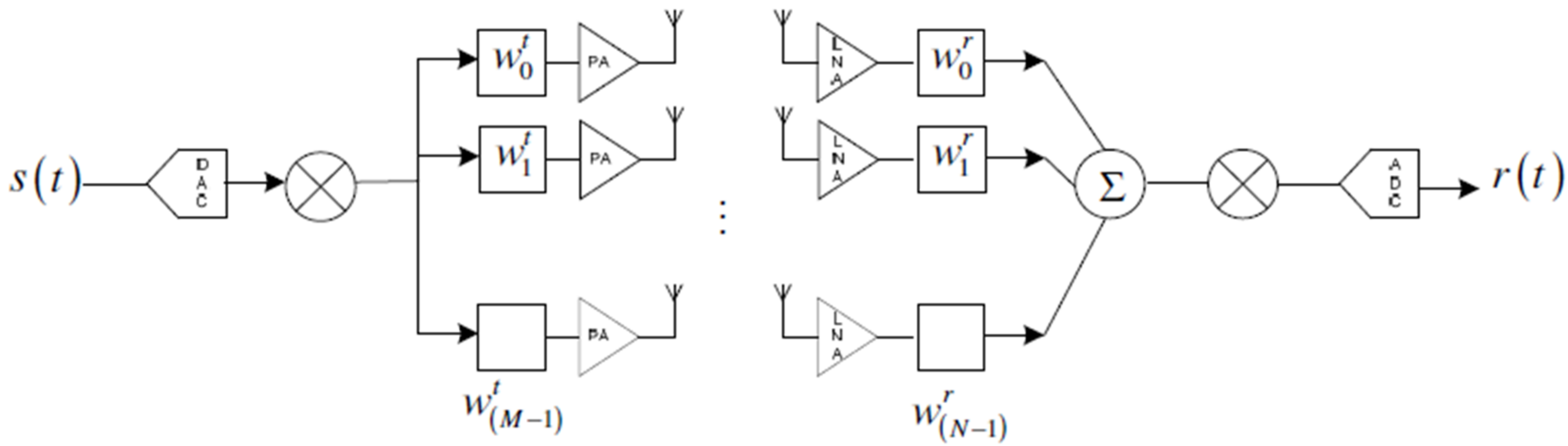
RF Beamforming



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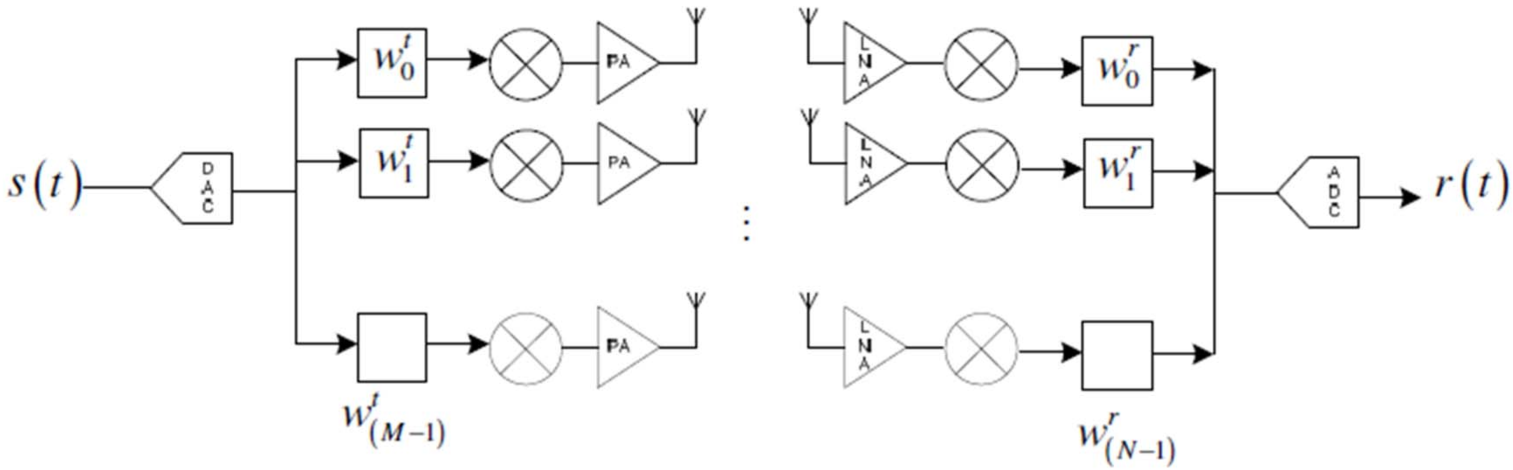
- Low power consumption
  - Single mixer and ADC / DAC per digital stream
  - RF phase shifting may lack accuracy

BB Analog Beamforming



- Intermediate power consumption
  - One mixer per antenna and stream
  - One DAC / ADC + BB amp per stream
  - Lower mixer linearity requirement

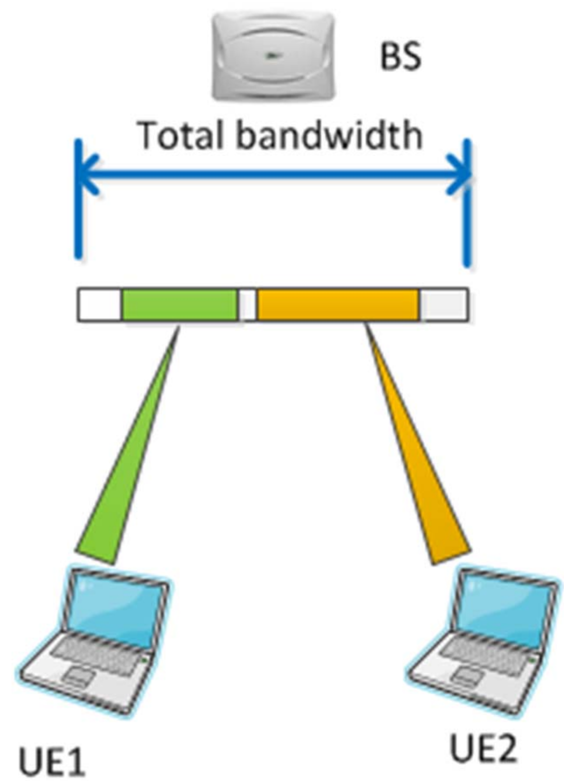
Component Power Consumption

Component	Power (mW)	RF BF	Analog BF	Remarks
PA	*	N	N	Typ efficiency = 8%
LNA	20	N	N	
RF shifter	23	KN	0	
Mixer	19	K	N	
LO buffer	5	K	2N-1	
Filter	14	K	N	
Phase rotator	1.4	0	KN	
BB amp	5	K	K	
ADC	255	K	K	6 bit, 2 Gsps

K=# streams, N=#antennas

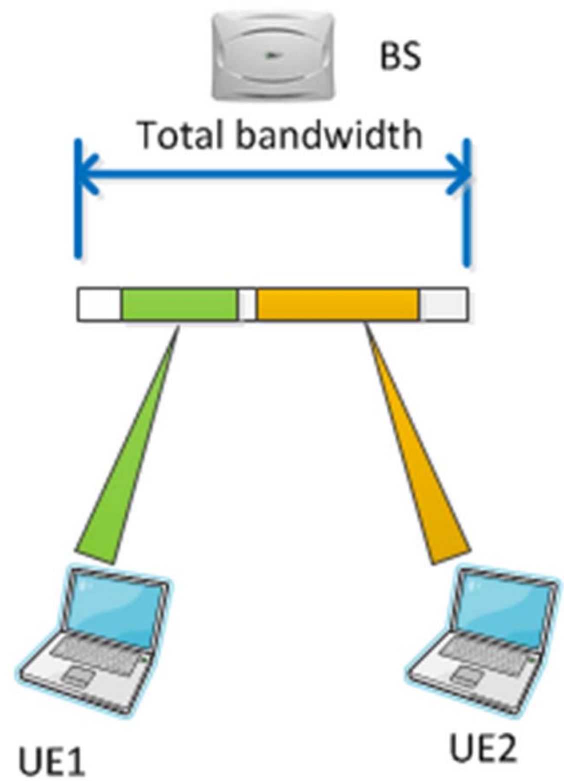
Subband Scheduling

- Reduce UE power consumption
  - A/D power scales linearly with bandwidth
- Reduced peak rate to individual UE
- But, no loss in total capacity in DL
- Improved capacity in UL
- Enables smaller MAC transport blocks.



Beamforming Optimization

- Each UE needs to only support one digital stream
- But, BS ideally uses different beams to each UE
- What is possible with limited number of digital streams?



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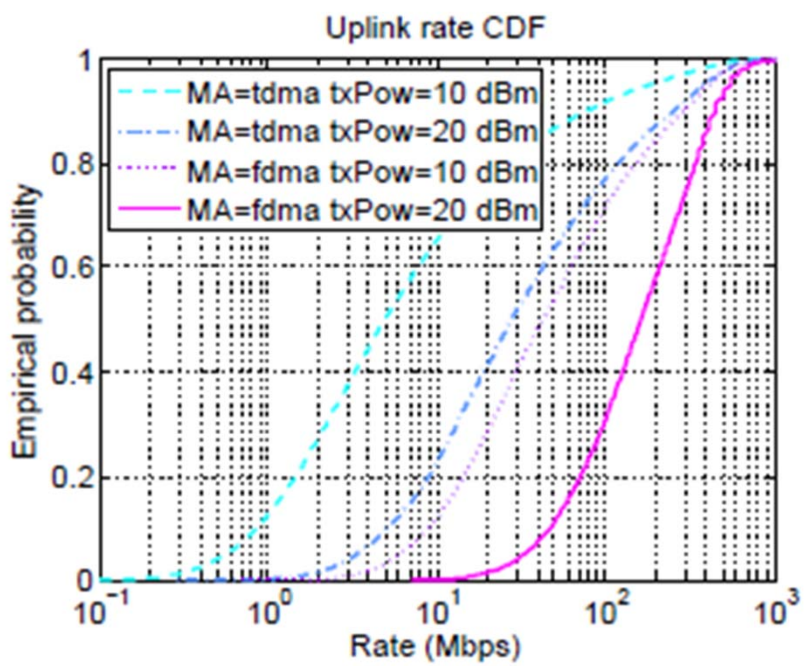
Multiple Access & Other Benefits



- Power saving also possible via TDMA and DRX
- Very inefficient in power-limited regime
  - 10x decrease in UL
- Reduced MAC Transport block
  - Ex: 125 us TTI x 1 GHz x 2 bps/Hz = 250,000 DoF

Beamforming Optimization

- Parameters
  - N = # antennas, K = # streams at BS
  - $W = N \times K$ unitary beamforming matrix
  - $\gamma_i = Tr(W^* Q_i W)$ = long-term SNR of UE i
- Utility optimization:

$$\max_{W} \sum_{i} U_i(\gamma_i)$$

- Non-convex, but can perform local optimization easily
  - Weighted power algorithm.

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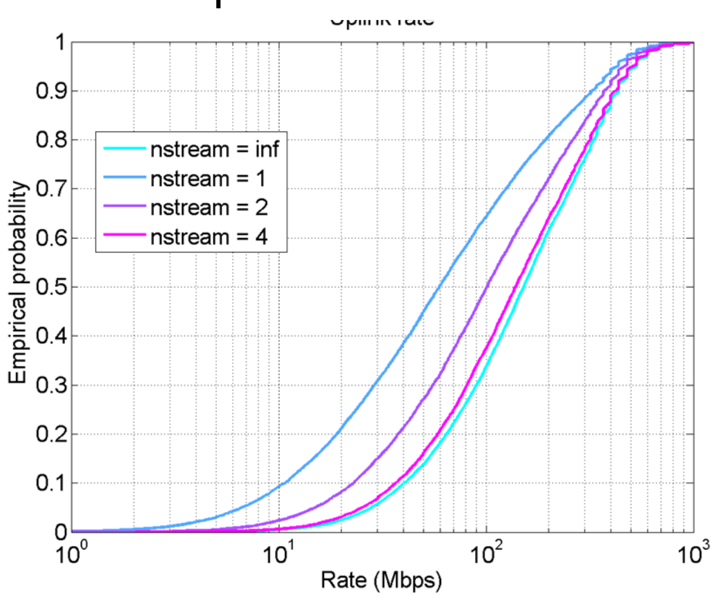
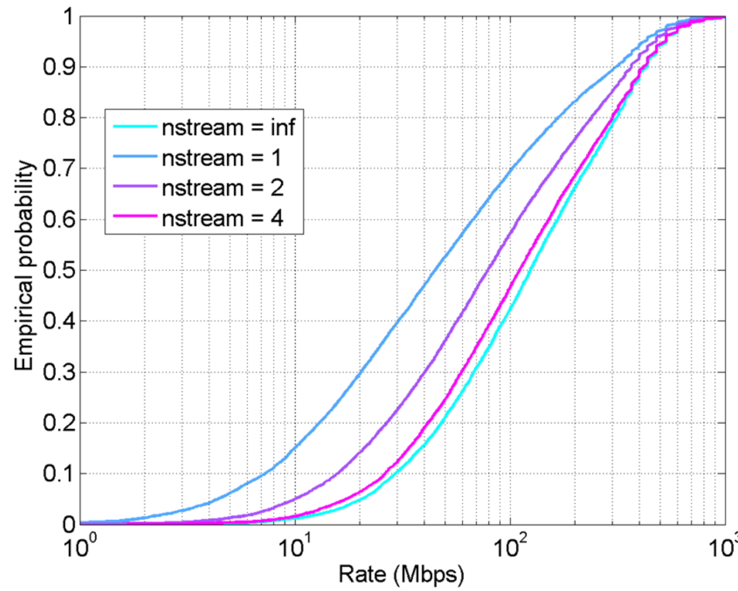
Optimization Results

Uplink Rate CDF



Downlink Rate CDF



- 4 streams is adequate with 10 UEs per cell

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Summary

- Significant potential for capacity increase in mmW
  - 1GHz TDD mmW offers 15x over 20+20 MHz LTE FDD
  - But, throughput gains are not uniform
- Systems appears power-limited:
  - Heavy dependence on dense cells & beamforming
  - Strong difference to current cellular systems
  - Traditional methods for increasing capacity may be limited
- Capacity tied closely with front-end capabilities
  - Number of digital streams, beamforming, …

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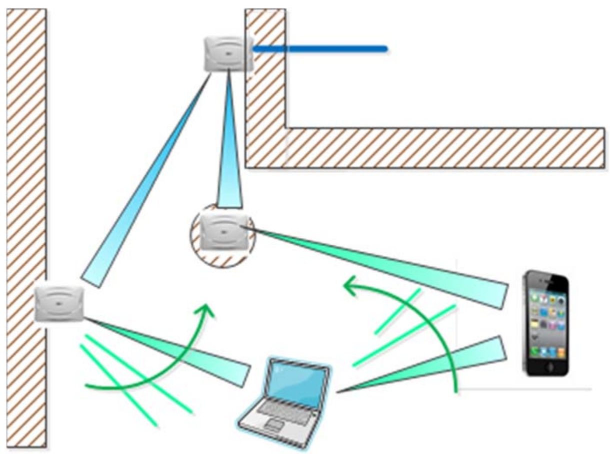
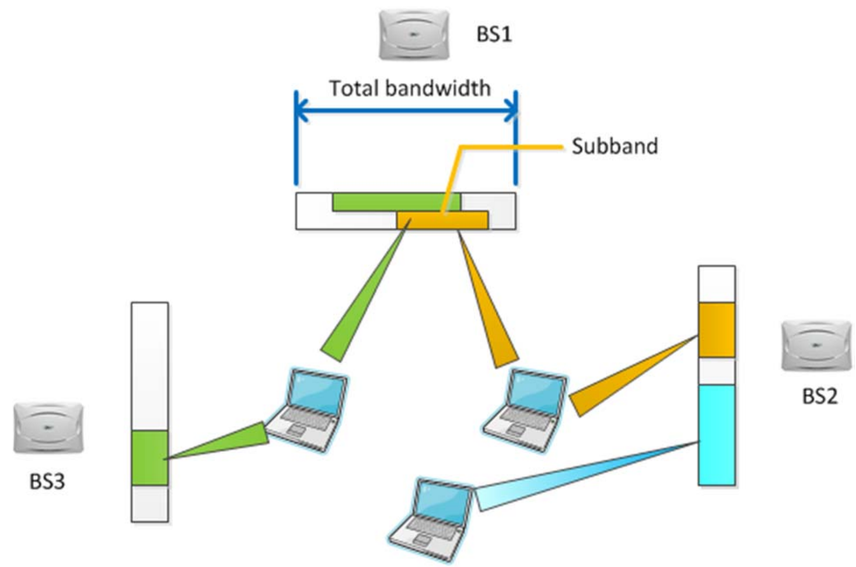
Rethinking LTE for mmW



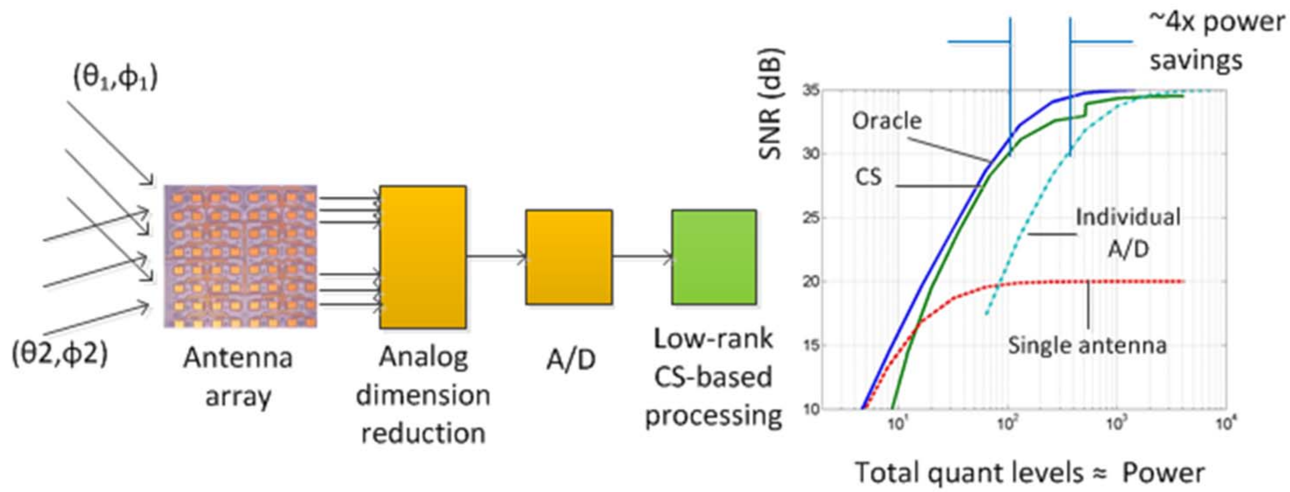
Directional relaying
Mesh networks



Coordinated multi-antenna scheduling with subband allocations

- 5^{th} Generation cellular
- Many innovative technologies

Low-Power Acquisition via Compressed Sensing



- Reduce power through smart A/D conversion
- Enable high spatial degrees of freedom and wide bandwidths

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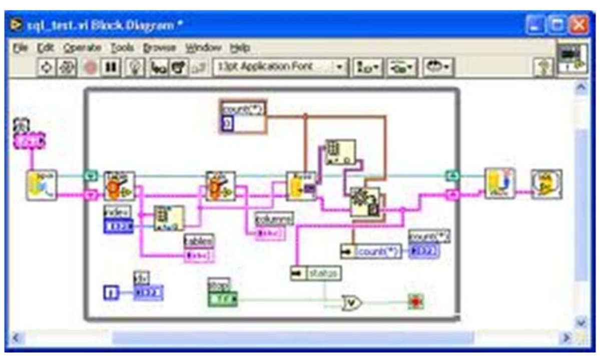
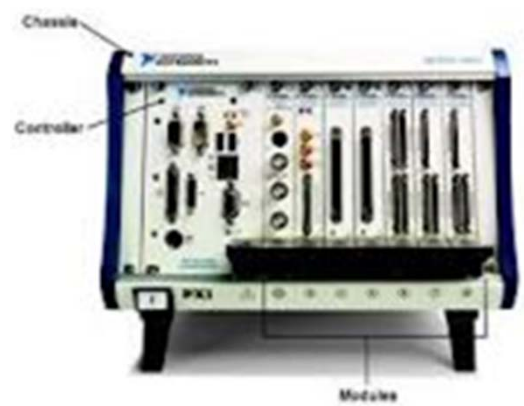
National Instruments Testbed

- Powerful programmable platform
  - Uniquely capable of implementing wideband cellular standards
- NI providing
  - 60 GHz front-end based, possibly with steerable array
  - VM to place Linux for upper-layer software



LabView GUI



NI Chassis

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