USC Viterbi
School of Engineering

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Sub-THz Channels and Communications Systems for 6G

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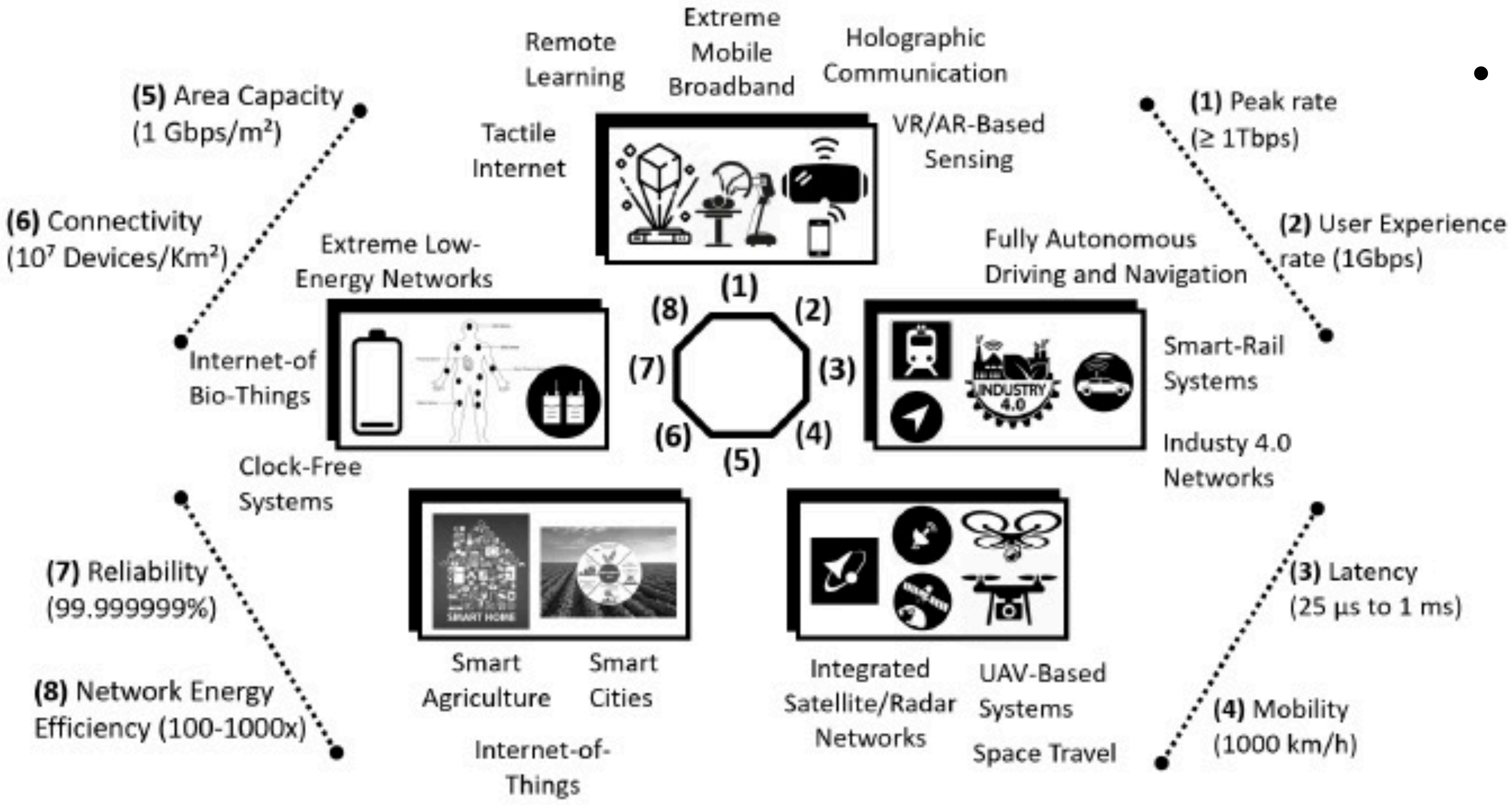
From 5G to 6G

- New applications drive requirements for new physical-layer approaches



- Extreme Mobile Broadband:
  - Holographic communications, XR
  - Peak data rates 1 Tbit/s

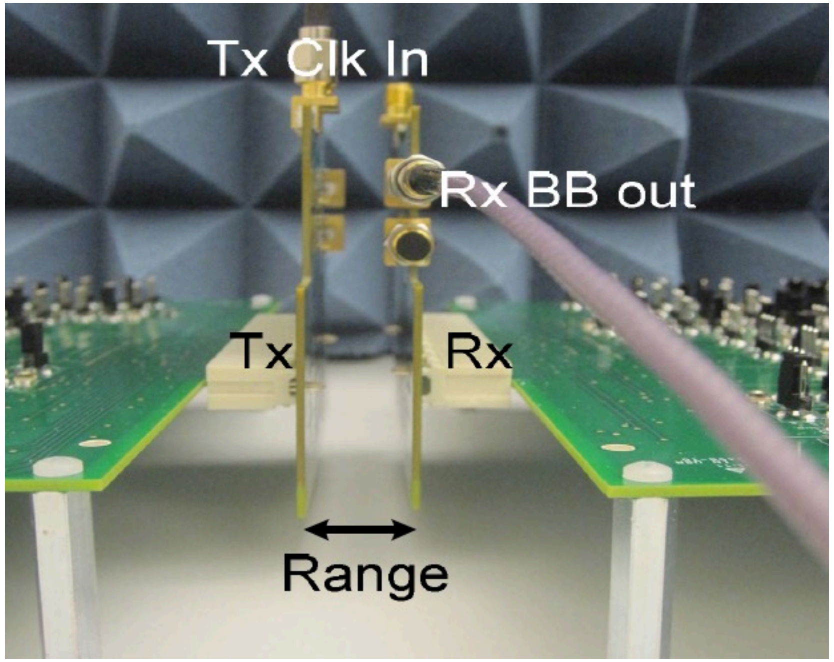
[*with* Tataria et al. 2021]

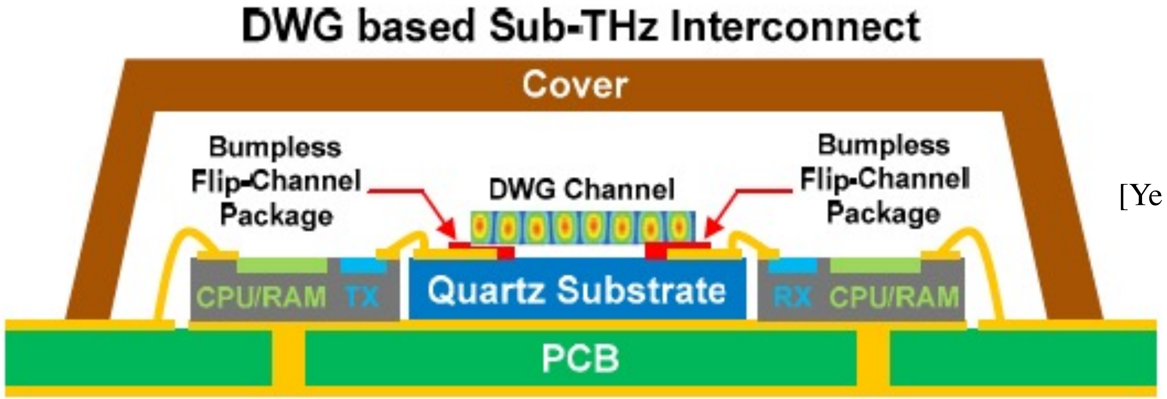
Takeaway message: 6G will use THz band to achieve unprecedented data rates

Applications and environments – in device

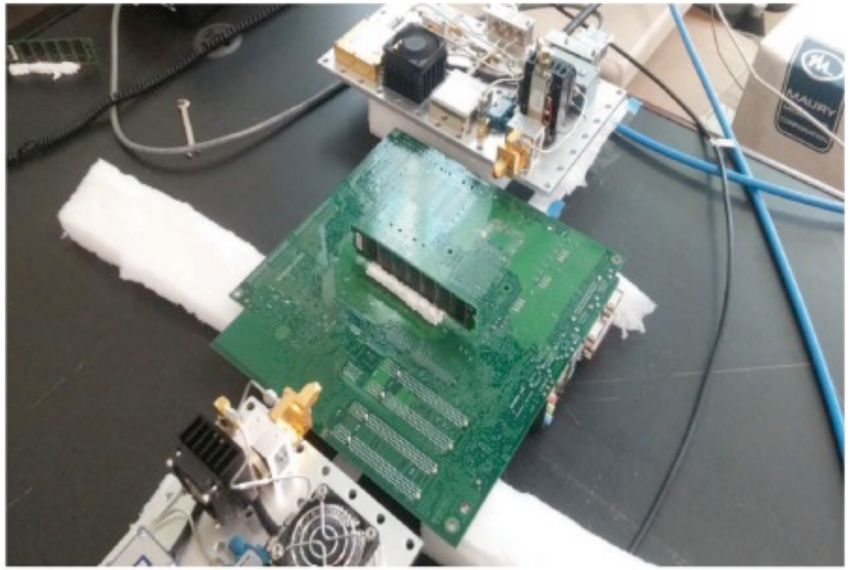
- Inter-chip and inter-board communications

[Park et al. 2012]





[Ye et al. 2017]



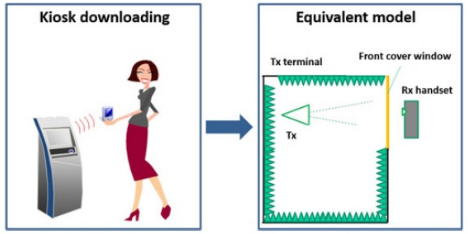
[Kim and Zajic 2016]

Takeaway message: THz will enable wireless between chips and boards

Applications and environments - indoors

- Information kiosk

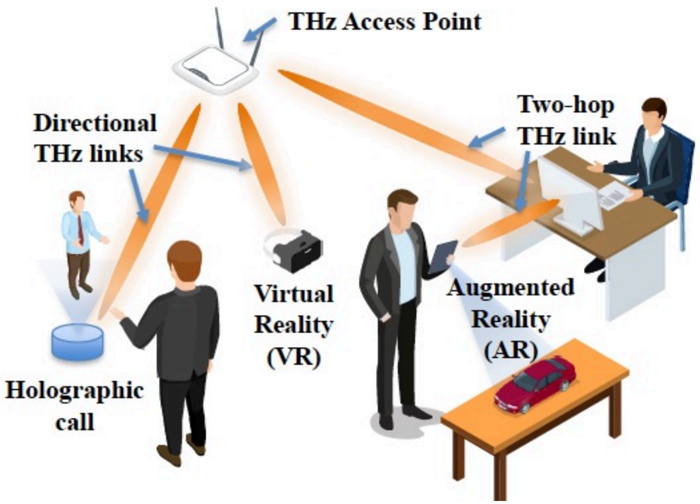
[He et al 2017]



- Virtual Reality headset

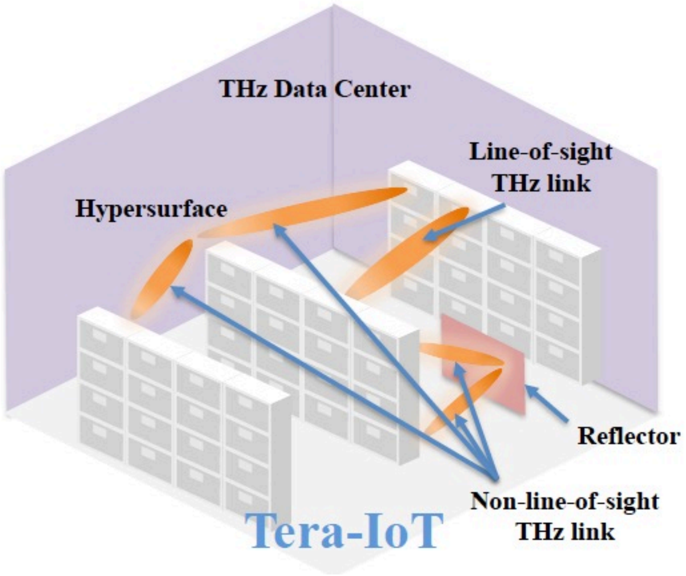
[dw.com, https://p.dw.com/p/3az3F]

Indoor communications



[Han et al 2019]

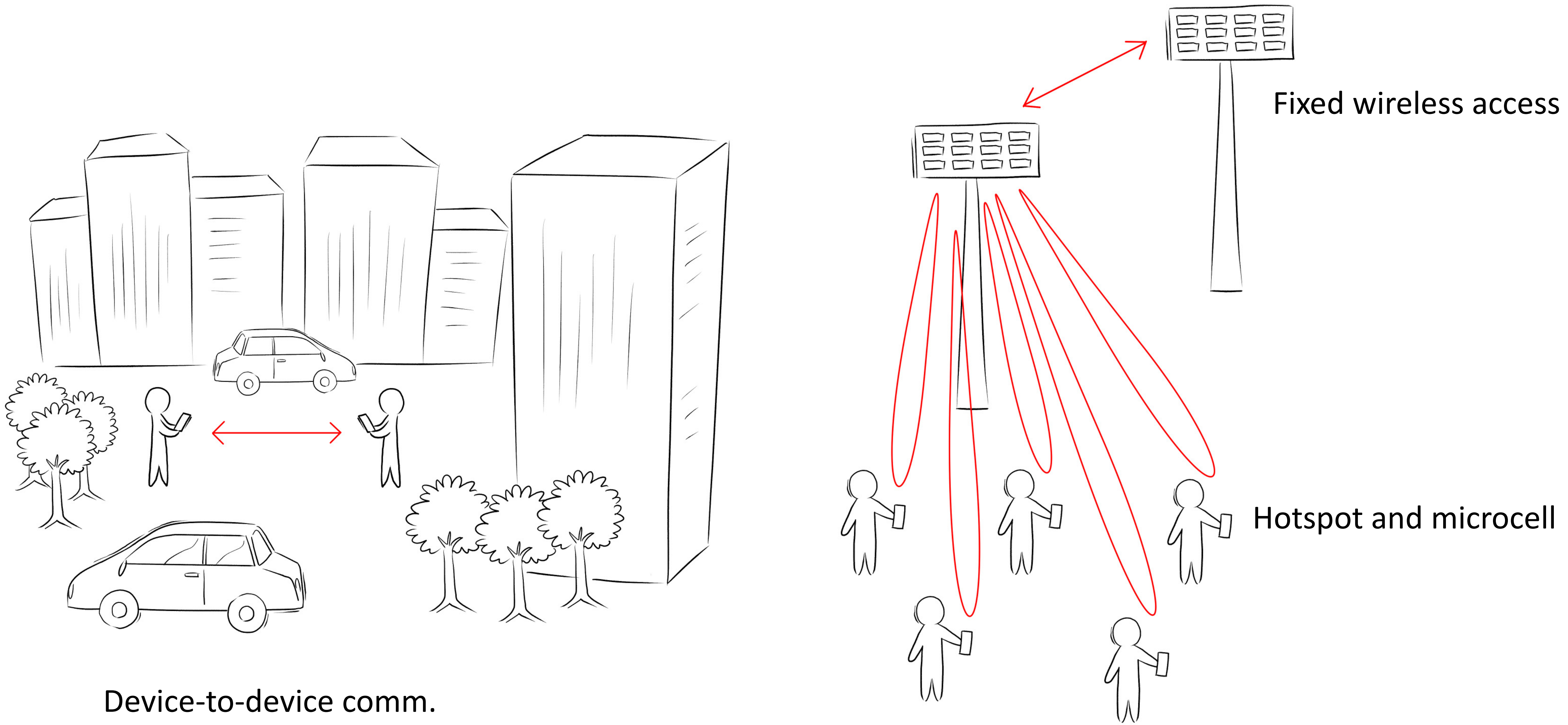
Data centers



[Han et al 2019]

THz will enable ultra-fast connections for office, VR, data centers

Applications and environments - outdoors



THz will enable ultra-fast hotspots and device-to-device communications

THz communication promises and challenges

- Promises
  - Extremely high data rates
  - High user densities

  enabling applications not feasible with other technologies
- Challenges
  - Availability of spectrum
  - Higher attenuation and other difficult propagation channel conditions
  - Low-cost semiconductor technology and transceiver design

THz challenges include (i) spectrum, (ii) channel models, and (iii) adaptive arrays

Contents

- THz spectrum
- THz channel measurements and models
  - Fundamental propagation conditions
  - Measurement technology
  - Recent campaigns and results
  - Ray tracing and modeling
- Semiconductor technology, beamforming, and multiplexing
  - THz arrays
  - Analog, digital, and hybrid beamforming
  - Orbital angular momenta

THz spectrum – regulatory perspective (1)

- Frequencies above 100 GHz *seem* unused
- However: most is allocated to [Marcus 2019]
  - Radio astronomy
  - Passive sensing
  - Satellite communications (satellite-to-earth and inter-satellite)
  - No ITU allocations for >275 GHz
- World Radio Conference
  - Official body of the United Nations for worldwide frequency regulations
  - Very slow reaction times

Internationally, 100-300 GHz spectrum occupied by satellites and radio astronomy

THz spectrum – regulatory perspective (2)

- National regulators have reacted faster
- FCC (USA)
  - Notice of proposed rule making (FCC 19-19): 21.2 GHz of bandwidth available for unlicensed devices
    - 116-123 GHz 174.8-182 GHz 185-190 GHz 244-246 GHz
    - Unlicensed operation
- OFCOM (UK)
  - 116-122 GHz, 174.8-182 GHz and 185-190 GHz
- CEPT (Europe)
  - 122.0–122.25 GHz and 244–246 GHz
- MIC (Japan)
  - 116-134 GHz

National frequency regulators are freeing up spectrum

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Interaction of systems and channels

- First axiom of wireless system design: *In order to design a good wireless system, you have to take into account the channel in which it will operate*
- Fundamental performance limits determined by channel (e.g., Shannon capacity)
- Channel determines which low-complexity solutions work well (e.g., sparsity-based methods)
- Need new channel measurements and models if at least one of the following applies:
  - New frequency band
  - New environment

Design of THz systems needs extensive measurement campaigns and new channel models

Pathloss – closing the link

- Free-space pathloss

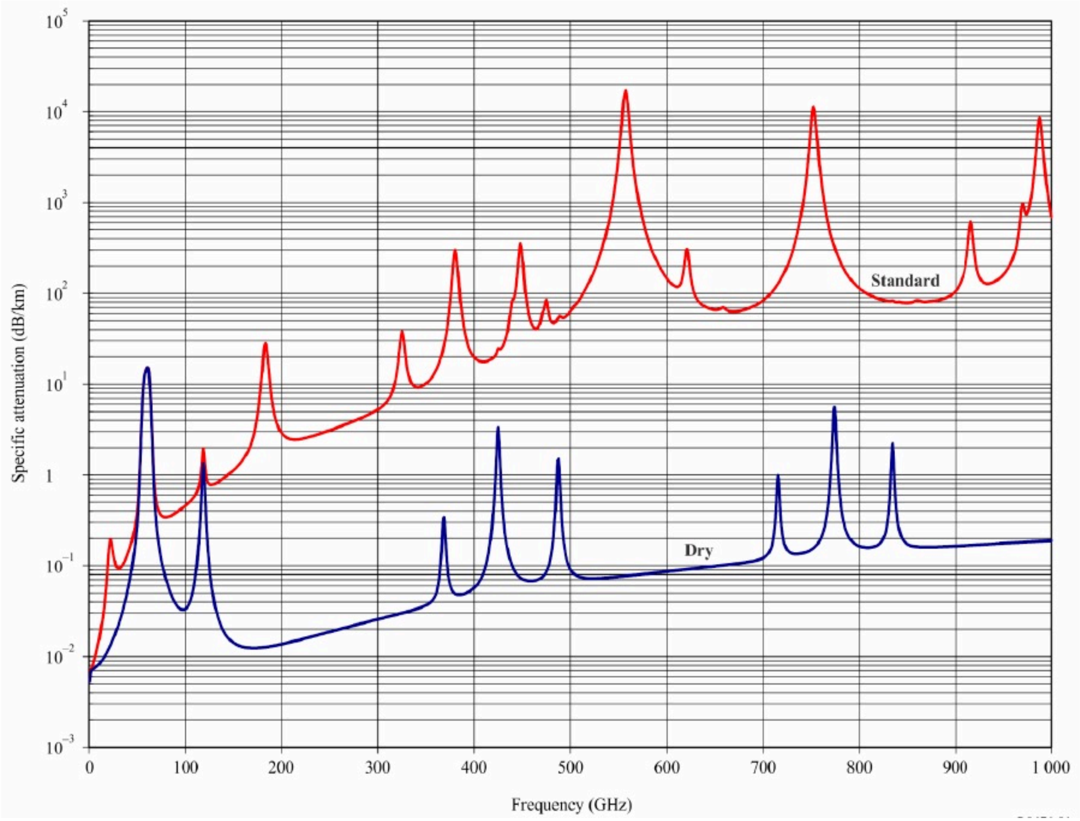
$$PL(d,f) = \frac{1}{G_{\mathrm{TX}} G_{\mathrm{RX}}} \left(\frac{4\pi f d}{c_0} \right)^2 \qquad G_{\mathrm{RX}} = \frac{4\pi f^2}{c_0^2} A_{\mathrm{RX}}$$

  - THz has high pathloss for constant-gain antennas
  - THz has low pathloss for constant-area antennas
- Are we hitting the limits on array sizes?
  - For constant antenna area, number of antenna elements needs to increase
  - For increased bandwidth, noise power increases
  - -> Arrays at THz need many more elements

Adaptive arrays can compensate higher isotropic pathloss, but number of elements very large at THz

Atmospheric attenuation

- Atmospheric attenuation
  - For longer-range applications, only certain windows feasible
  - Strong attenuation can be useful for chip-to-chip communications
- Foliage attenuation
  - Very strong at mm-wave frequencies; anticipated to be even higher at THz

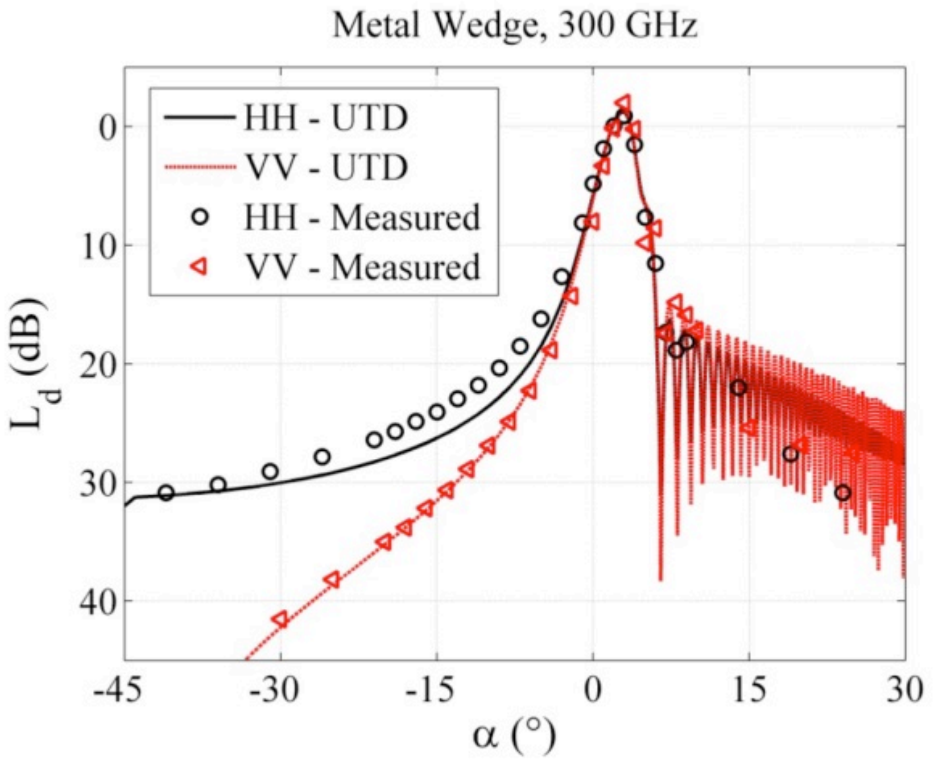


[ITU-R P.676-12]

Some THz bands only suited for short-distance operation

Diffraction and body blockage

- Diffraction efficiency decreases with frequency
- Uniform Theory of Diffraction gives good approximation
- Body shadowing
  - Almost no diffraction around human body
  - Penetration through body is very low
  - ”Super-antenna” concept can be used to emulate impact of human *[with* Harryson et al. 2010]

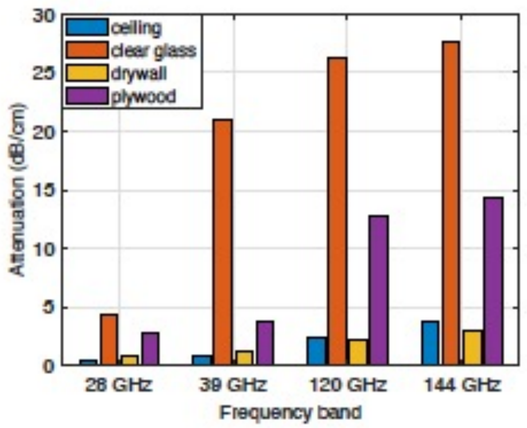


[Kleine et al. 2012]

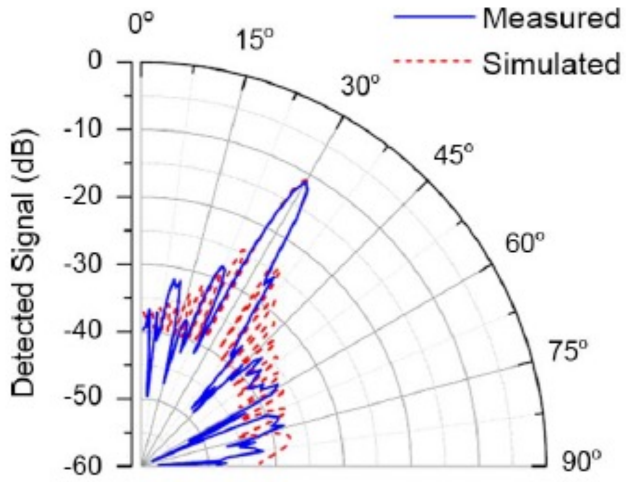
Sharp shadows and severe body shadowing

Other propagation effects

- Penetration loss
  - Stronger attenuation than at mmWave
- Diffuse scattering
  - Surface roughness is on order of wavelength
  - Beckman model or other more advanced models desirable
- Doppler shifts
  - Increase linearly with frequency



[Du et al. 2021]



[Jansen et al. 2011]

Penetation loss through walls very high; diffuse scattering complicated

Overall channel characteristics

- Complete characterization by double-directional impulse response [*with* Steinbauer et al. 2001]
  - For all combinations of delay, TX direction, and RX direction, what is the (complex) signal amplitude
- Receive power:
  - Determines coverage, capacity
  - Distribution and speed of variation impacts temporal diversity and required speed of feedback and adaptation
- Delay dispersion:
  - Determines available frequency diversity,
  - Necessary length of equalizer, length of cyclic prefix
- Angular dispersion:
  - Determines MIMO capacity, suppression of interference
  - Distinguish impact on analog and digital beamforming
- Distinguish omni- vs max dir power and delay spread

Pathloss, delay spread, and angular spread give key summary of channel impact

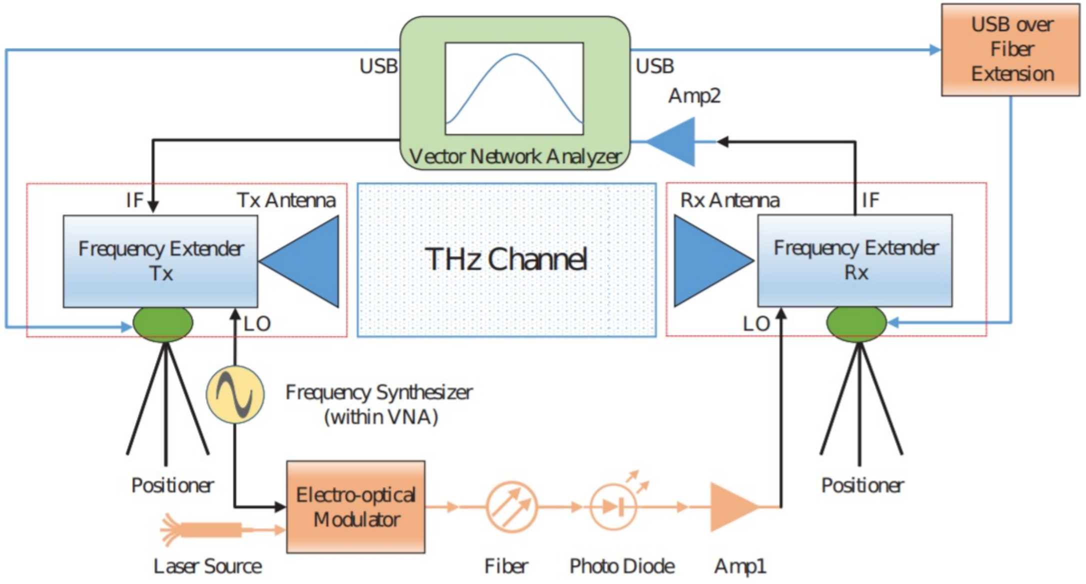
Channel measurements

- Measuring impulse response
  - Correlator, sliding correlator
    - Fast, no cables needed
  - Vector Network Analyzer (VNA)
    - Widely used
    - Slow: complete measurement may take several seconds
    - Phase coherence over multiple measurements can be ensure
- Directionally resolved measurements
  - Rotating horns: widely used, slow
    - Mechanical rotation time dominates overall measurement time
  - Phased arrays would dramatically reduce measurement time (compare [*with* Bas et al. 2017] for mmWave), but are not widely available yet

THz channel measurements are expensive and labor-intensive

USC measurement setup

- Rotating horns with VNA and RoF extensions



USC long-distance frequency domain setup

Parameter	Symbol	Value
Frequency points per sweep	N	1001
Tx/Rx height	$h_{Tx/Rx}$	1.6 m
Start frequency	f_{start}	145 GHz
Stop frequency	f_{stop}	146 GHz
Bandwidth	BW	1 GHz
IF bandwidth	IF_{BW}	10 KHz
THz IF	$f_{THz\,IF}$	279 MHz
Antenna 3 dB beamwidth	$HPBW$	13°
Tx rotation range	ϕ_{Tx}	[0°,360°]
Tx rotation resolution	$\Delta\phi_{Tx}$	10°
Rx Az rotation range	ϕ_{Rx}	[0°,360°]
Rx Az rotation resolution	$\Delta\phi_{Rx}$	10°

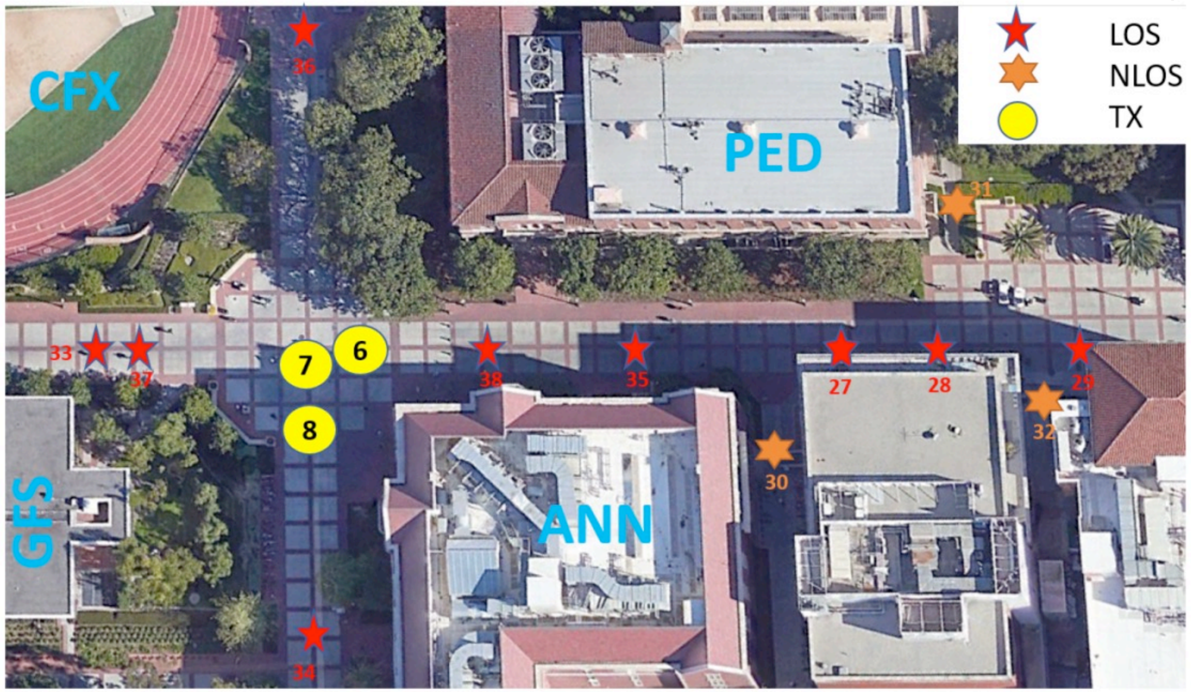
- Used for the first long-distance, double-directional measurements in the THz regime *[with* Abbasi et al. 2019/20]

RF over fiber overcomes range limitation of THz VNA measurements

Device-to-device (D2D) measurement campaign

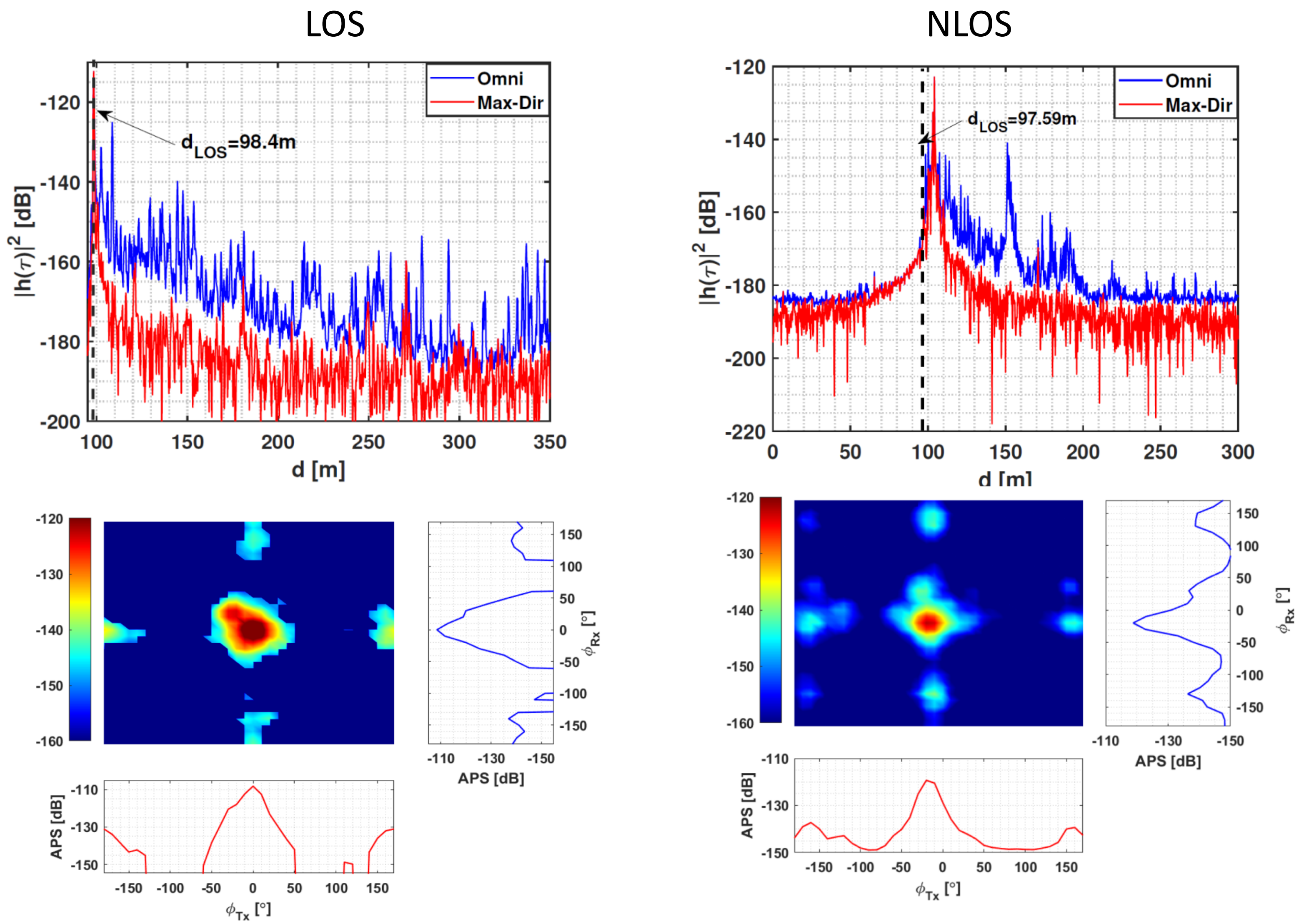
- Urban Environment
  - Quad and Street
  - LoS and NLoS

[*with* Abbasi et al. 2021a]



D2D channel – Sample results

- Sample results PDP
  - Omni and max dir
  - Rich multipath for omni case
- Sample results APS

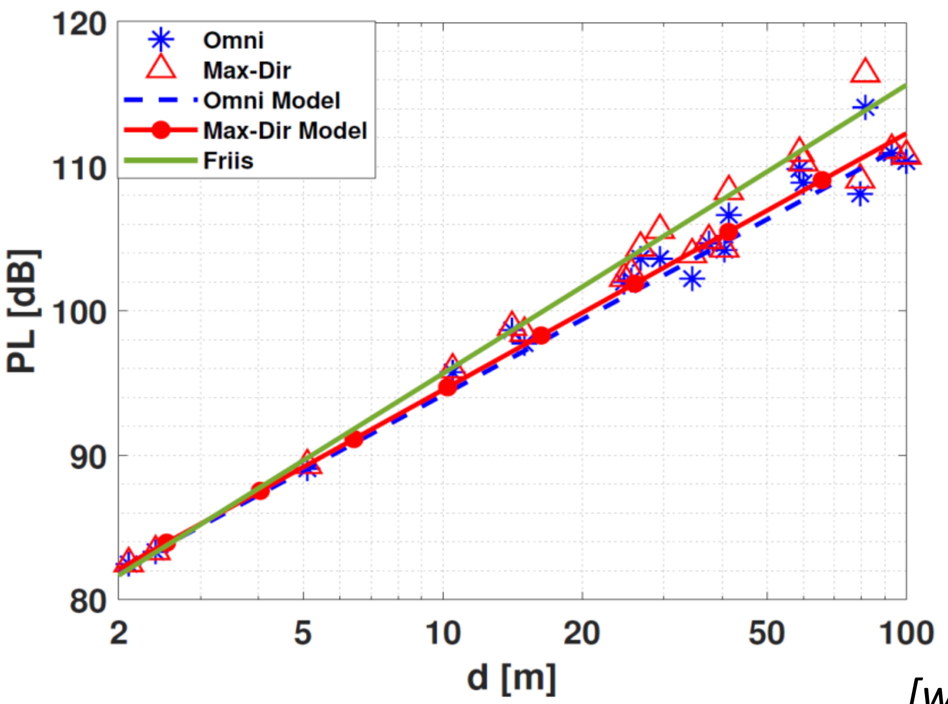


[with Abbasi et al. 2021a]

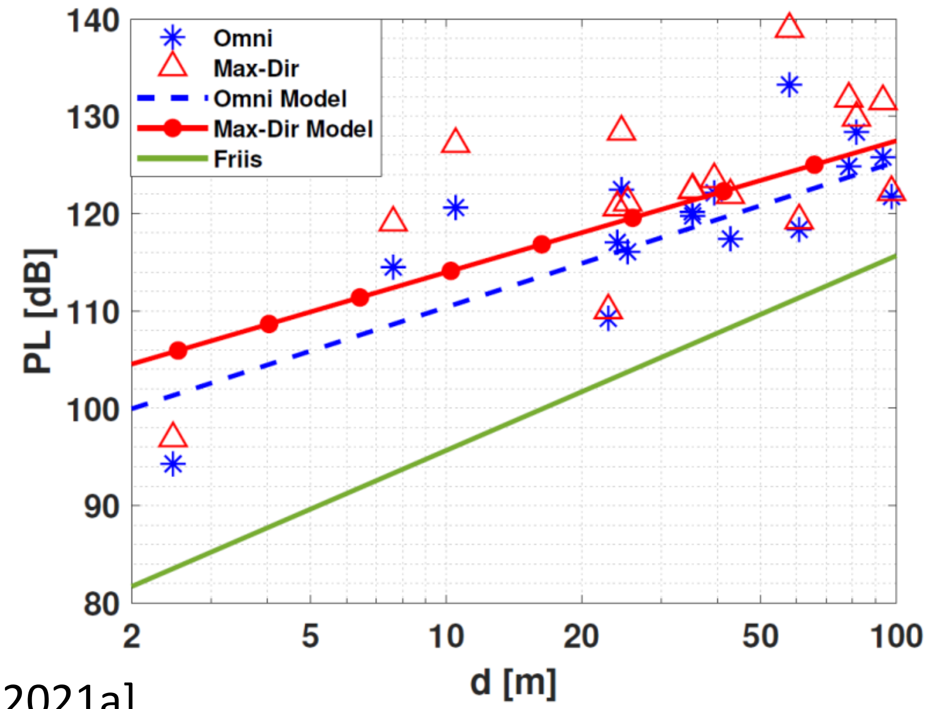
Rich multipath even in LOS, though reduced by directional antennas

D2D: pathloss

LOS pathloss



NLOS pathloss



[*with* Abbasi et al. 2021a]

- LOS: Pathloss coefficient ~1.8 (smaller than Friis)
- Standard deviation: 1.5 dB

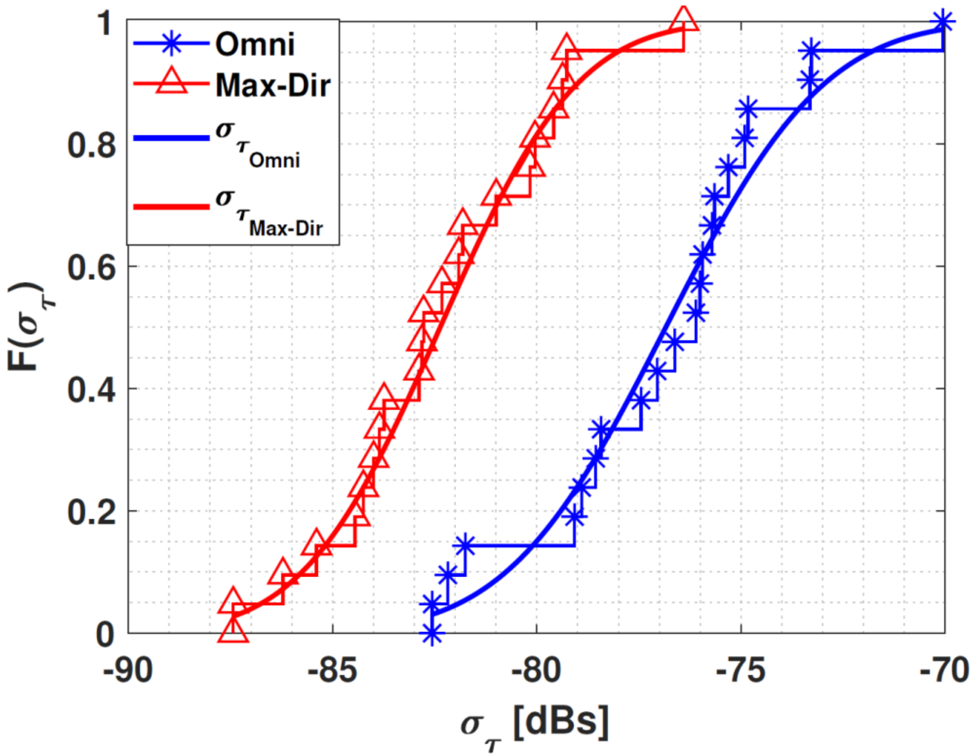
- NLOS
  - Excess pathloss: 10-30 dB
  - Standard deviation
    - 5 dB in NLOS omni
    - 7 dB in NLOS Max-Dir

THz with directional antennas can sustain Gbit/s over 100 m even in NLOS

D2D rms delay spread

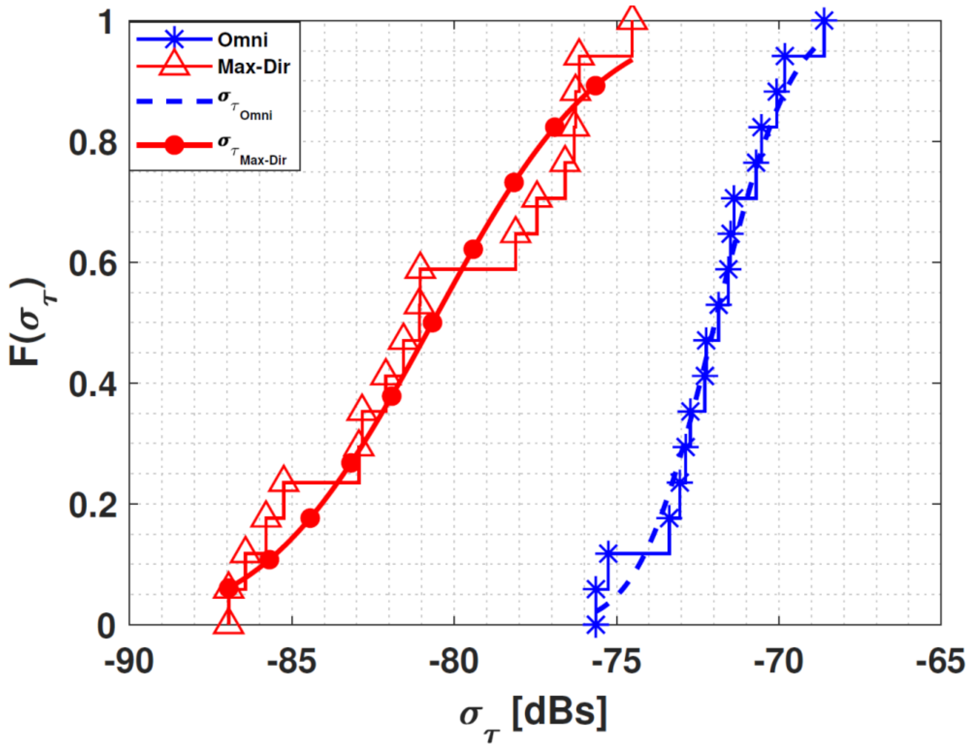
CDF of logarithm of rms delay spread

LOS case



CDF of logarithm of rms delay spread

NOS case



- Delay spread varies with position, can be modeled as random variable
- Lognormal distribution fits well
- Delay spread is large in units of inverse bandwidth

Even with directional antennas, rms delay spread is many ns

D2D angular spread

- Distribution of angular spreads for LoS and NLoS are lognormal
- Mean angular spreads are 17 and 35 degrees

CDF of logarithm of rms angular spread (Fleury definition)

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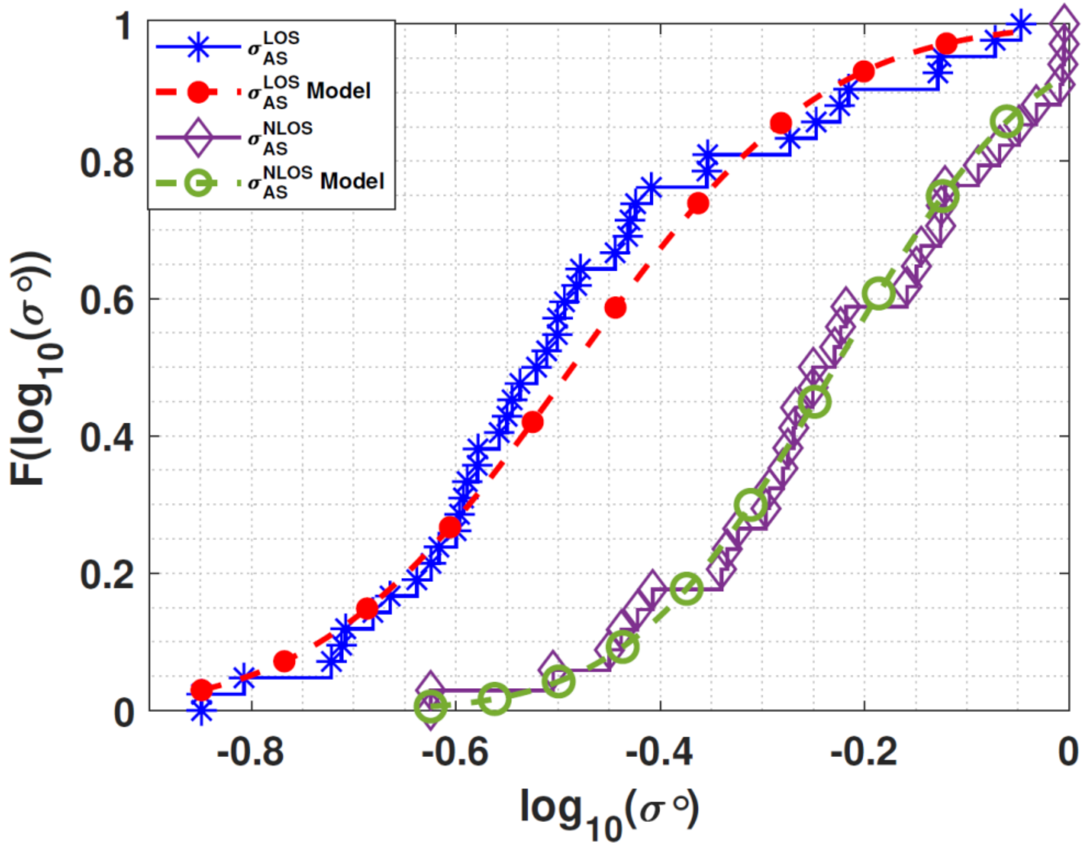


[*with* Abbasi et al. 2021a]

Significant angular dispersion, allowing angle diversity but potentially increasing multi-user interference

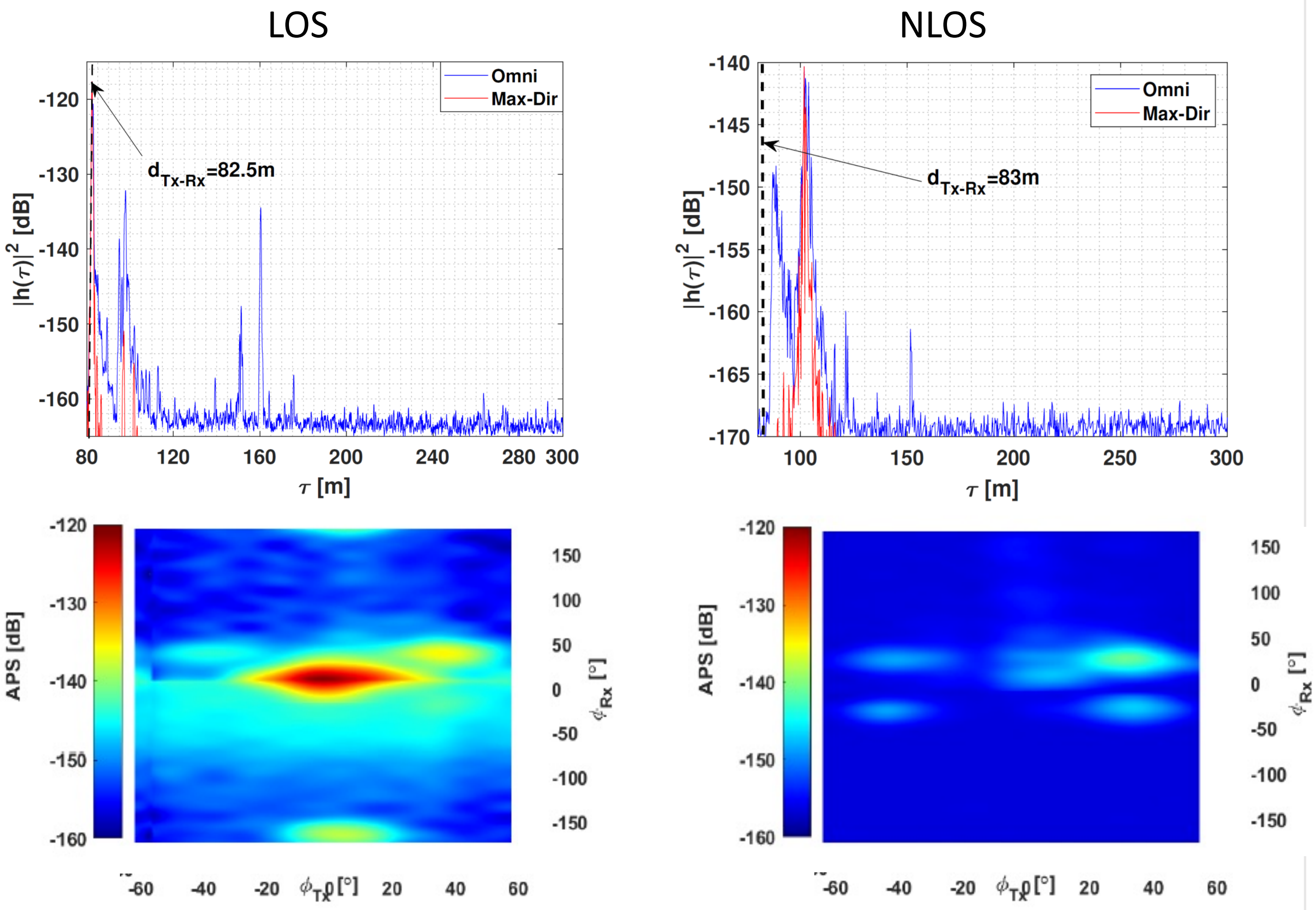
Microcell channel measurement campaign

- Urban environment
  - Street canyons and parking lot
  - LoS and NLoS
  - BS height 11.5m

[*with* Abbasi et al. 2021b]

Microcell channel – Sample results

- LOS:
  - Direct component dominant for maxDir
  - Rich multipath for omni case
- NLOS:
  - Strongest components with large delay
  - Beam directions all different from LOS directions

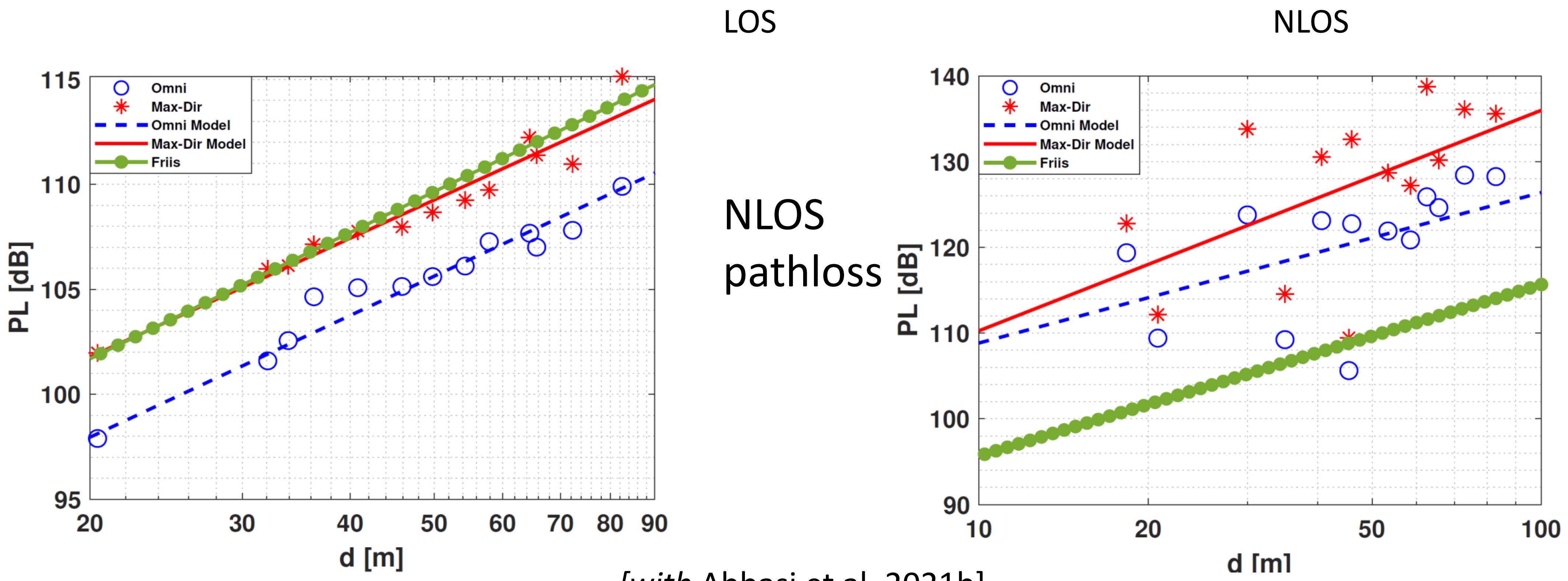


Rich multipath also in microcell scenario; main direction for NLOS often direction of street canyon

Microcell pathloss

LOS pathloss

NLOS pathloss



[with Abbasi et al. 2021b]

- LOS: Pathloss coefficient ~1.9 (smaller than Friis)
- Standard deviation: 1. dB

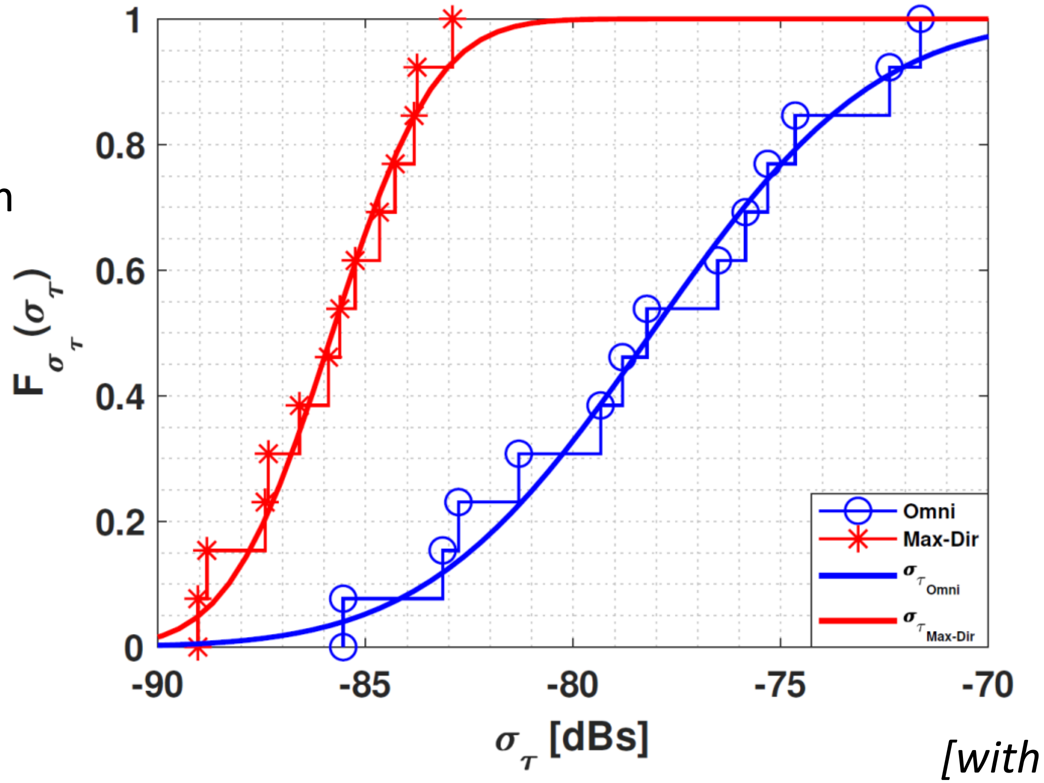
- NLOS
  Excess pathloss: 10-30 dB
  Standard deviation
  8 dB in NLOS omni

Even NLOS links can sustain Gbit/s over 100 m, LOS can sustain hundreds of Gbit

Microcell rms delay spread

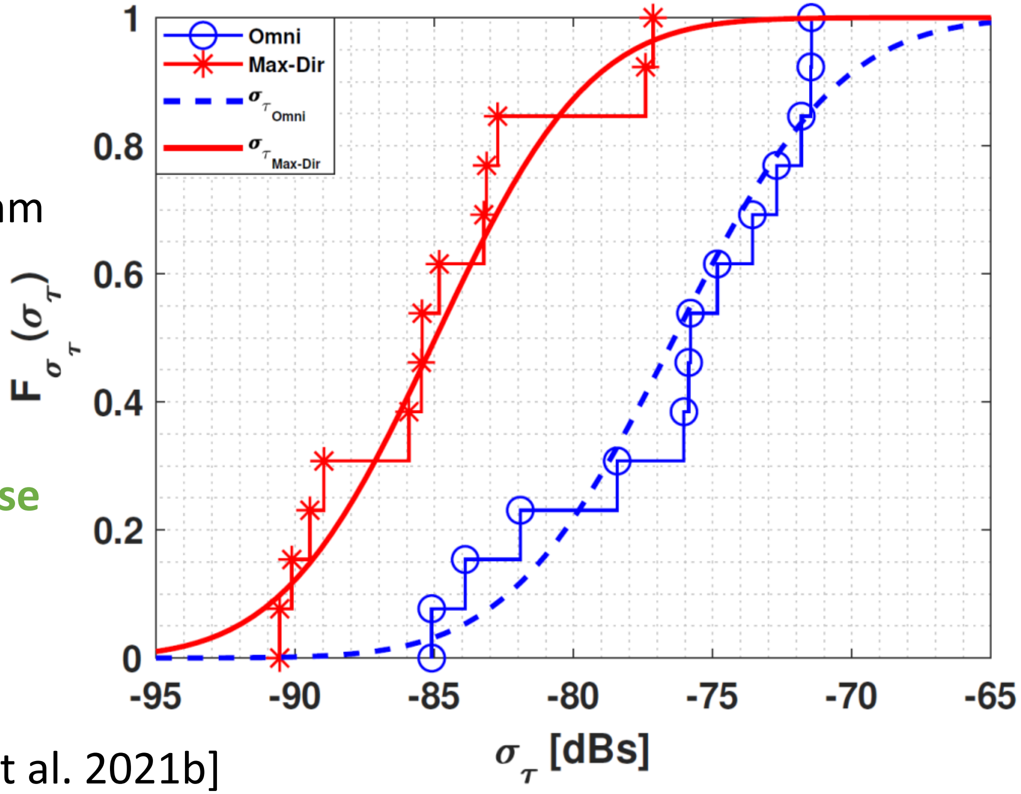
CDF of logarithm of rms delay spread

LOS case



CDF of logarithm of rms delay spread

NOS case



[*with* Abbasi et al. 2021b]

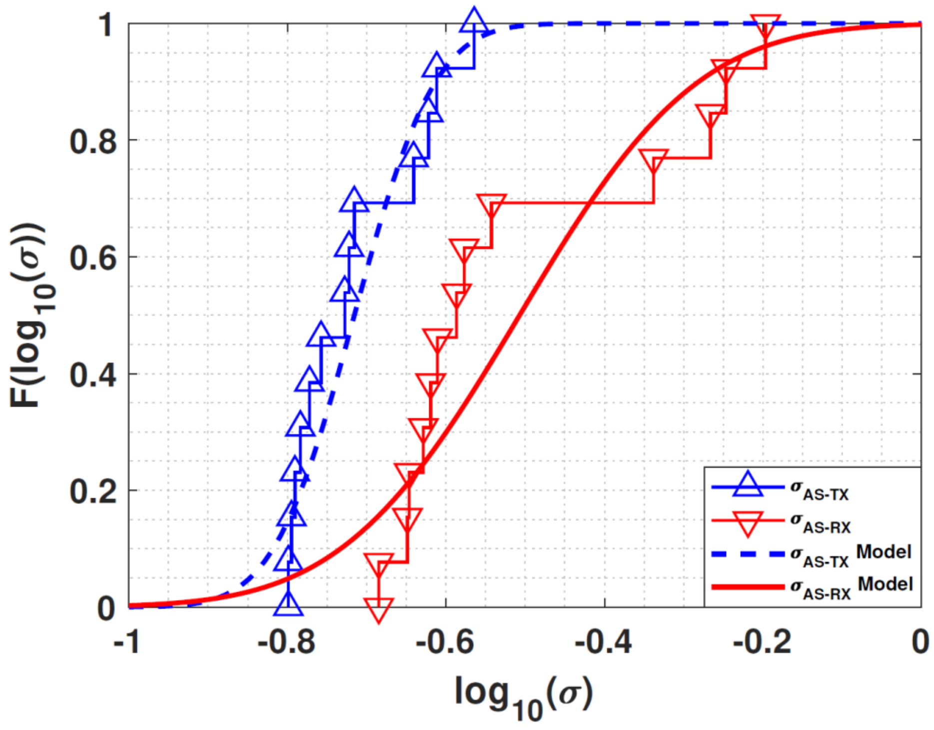
- Lognormal fits well
- Values somewhat smaller than in D2D case

Rms delay spread smaller than for D2D, but still several nanoseconds even with directional antennas

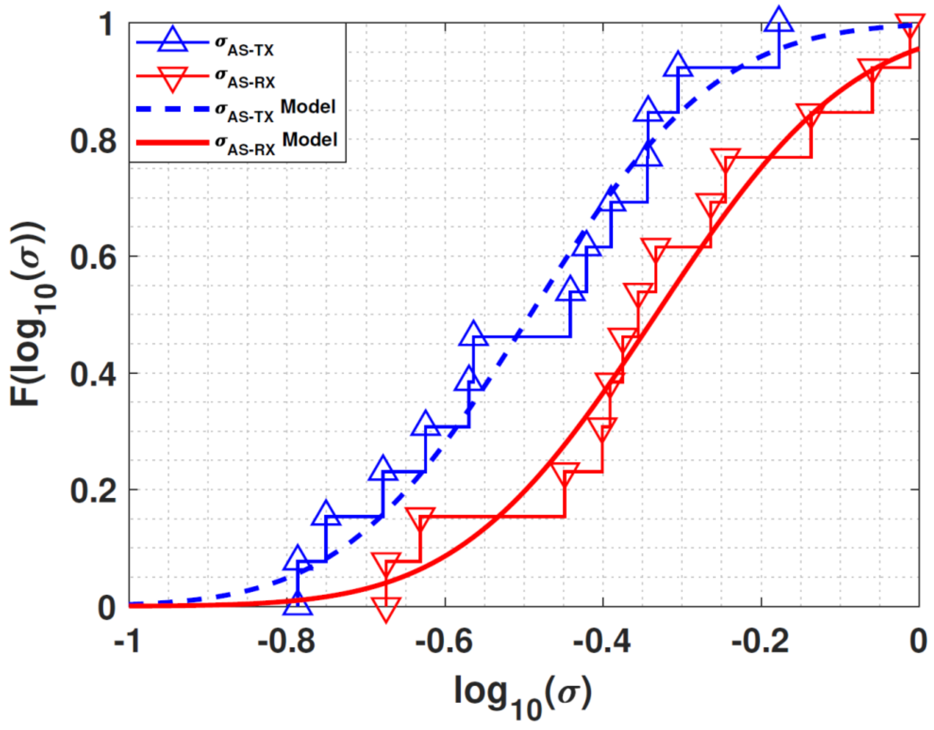
Microcell angular spread

- Angular spreads at BS smaller than at the UE

LOS



NLOS



Angular spread at the BS smaller than at the UE

Example impact of reflecting surface

- Shape propagation environment
- Passive, non-adaptive reflectors


Scenario without and with foil

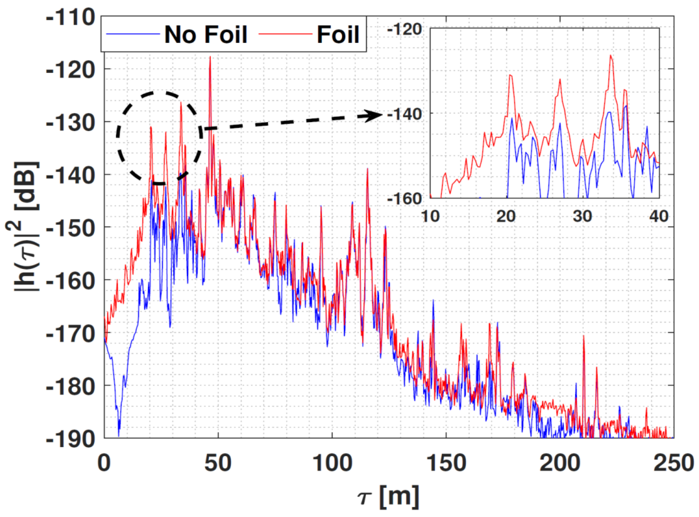
[with Abbasi et al. 2021c]

Passive non-adaptive reflectors easier to implement especially at high frequencies

Example impact of reflecting surface (II)

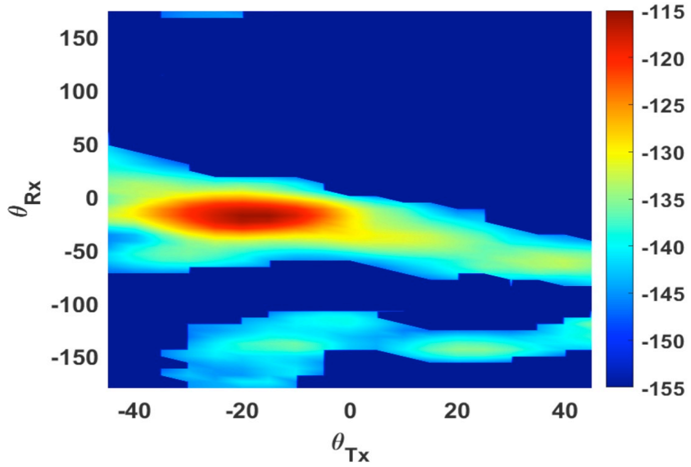
- Addition of foil introduces more multipath
- More frequency selectivity
- Greater beam diversity

Power Delay Profile

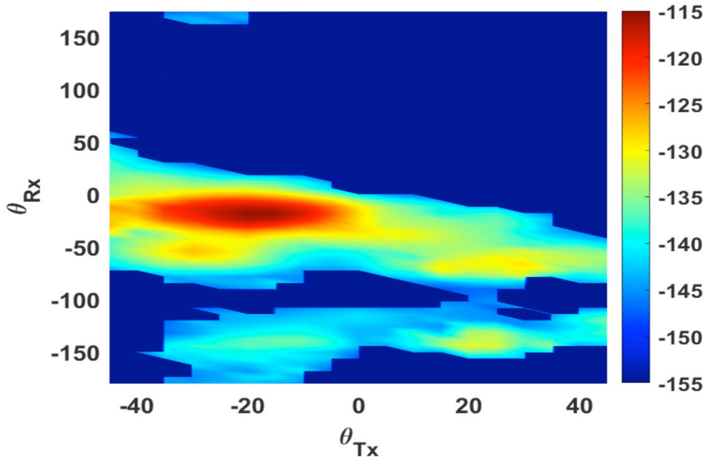


Angular Power Spectrum

No Foil



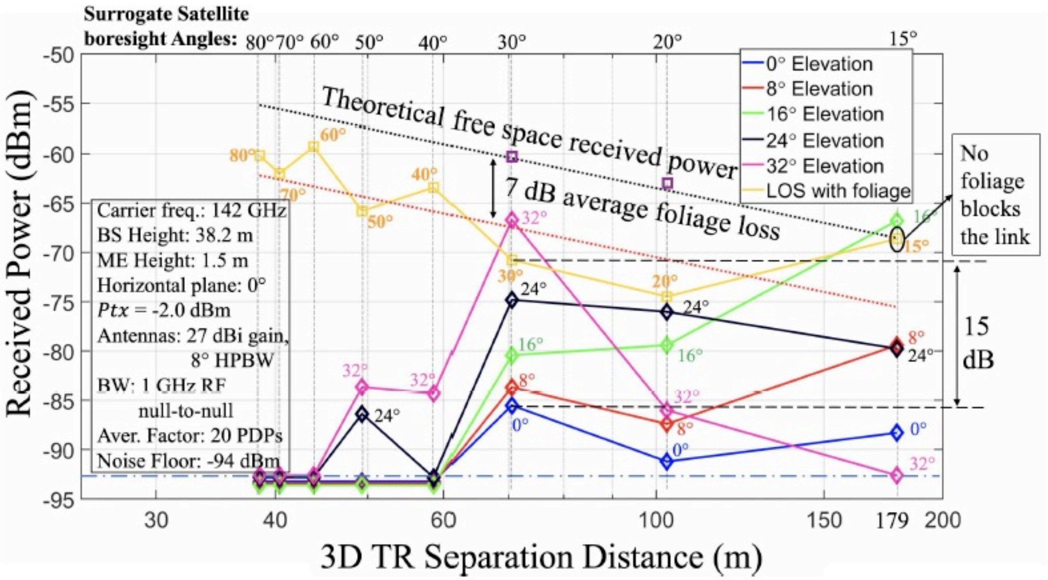
Foil



Passive reflectors enhance some multipath components, increase angular diversity

Other measurements - outdoor

- Survey [*with* Han et al. 2021]
- Outdoor measurements
  - NYU, [Xing and Rappaport 2021ab, Yu and Rappaport 2021]: 140 GHz, BS height 4m
  - HHI, [Undi et al. 2021]: 300 GHz, BS height 2.1m
- Satellite to ground [Xing and Rappaport 2021]

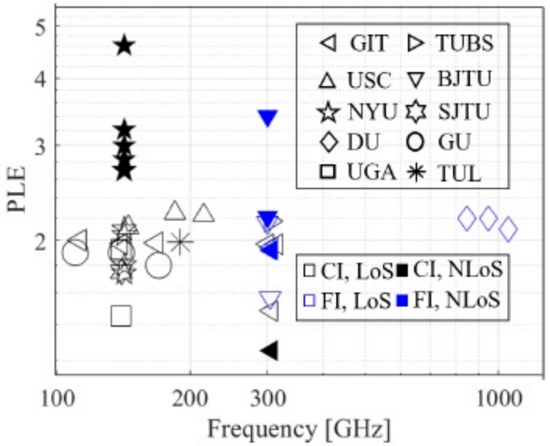


[Xing and Rappaport 2021]

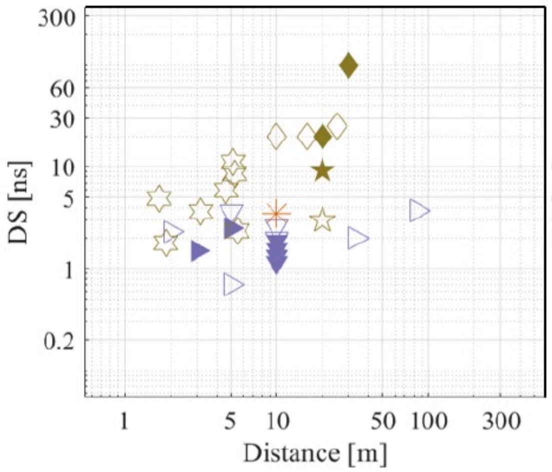
Outdoor with lamppost-height BS, emulated satellite links, have been recently measured

Other measurements - indoor

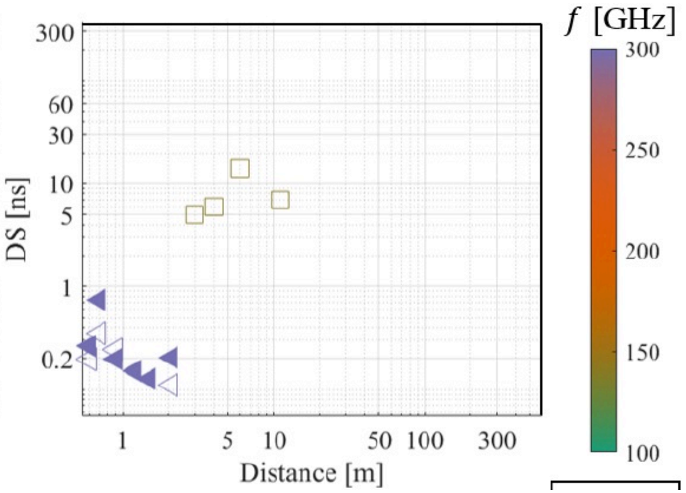
Pathloss



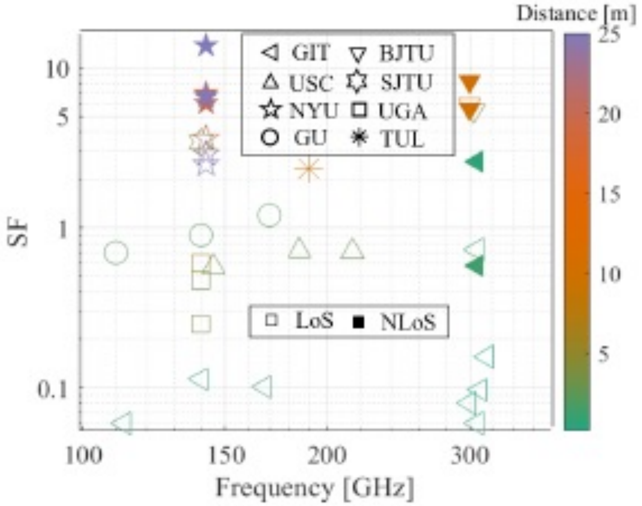
Omni-directional delay spread



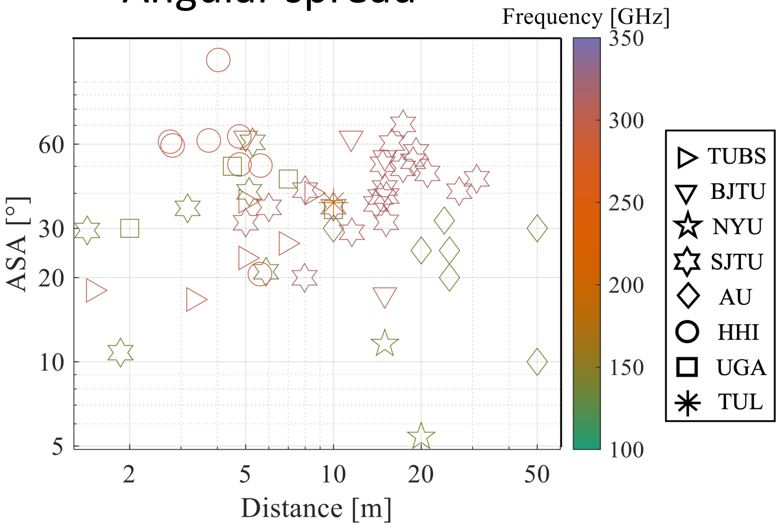
Directional delay spread



Shadowing



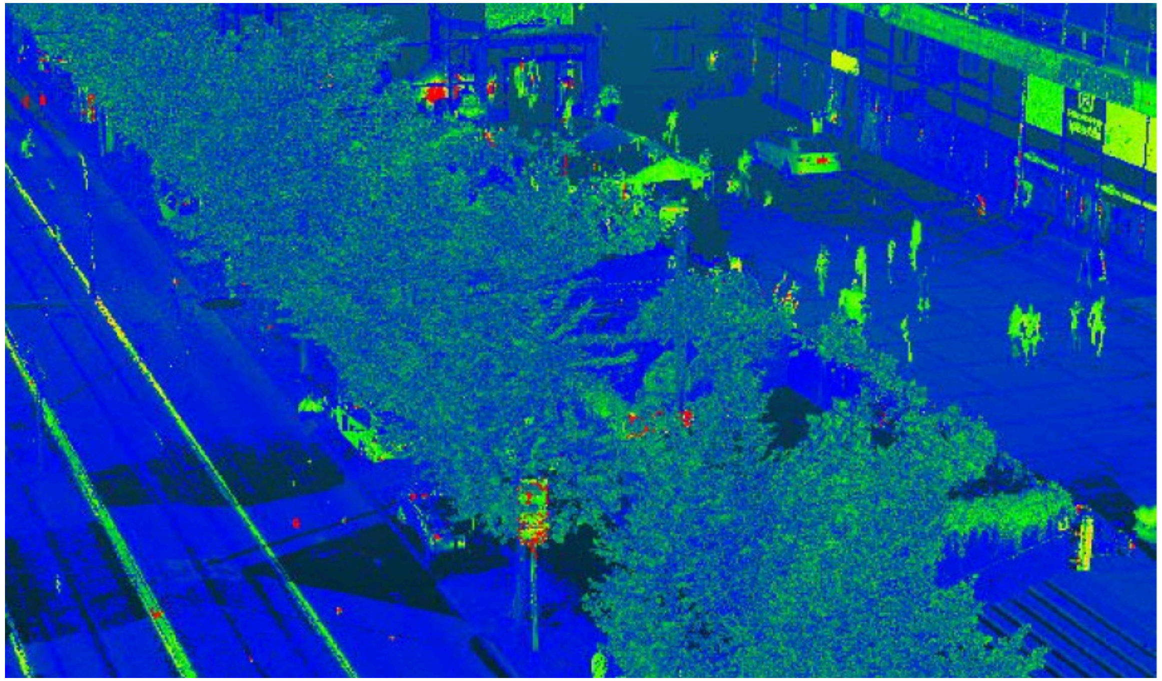
Angular spread



Delay and angular spreads quite high even indoors

Ray tracing/ray launching

- Measurements are gold standard, but too much effort
  - Results often in selection bias
- Principle
  - Quasi-optical approximation of Maxwell's equations
  - Widely used for cellular network planning
  - Very good at predicting power (coverage/interference)
- Accuracy depends on data base, need point cloud (Lidar scan) at high frequencies

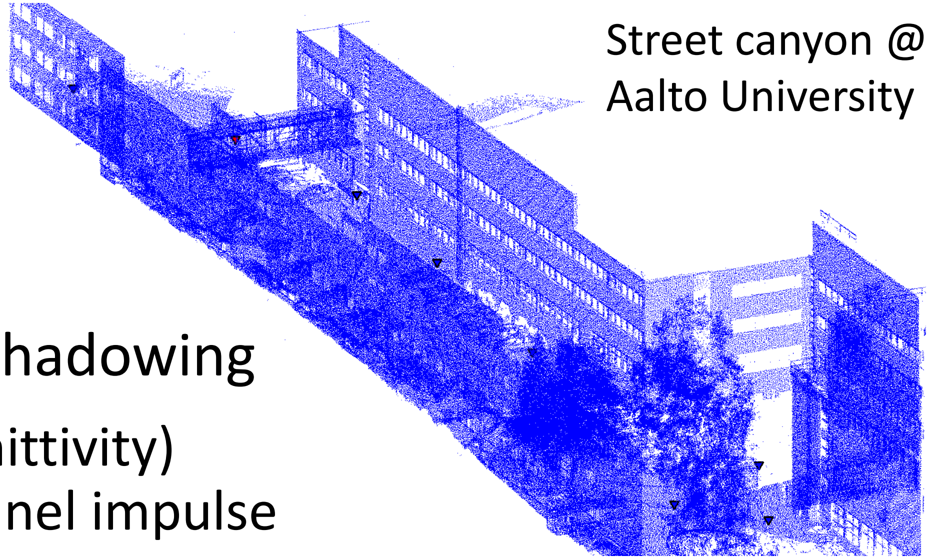


[*with* Koivumaki et al. 2021]

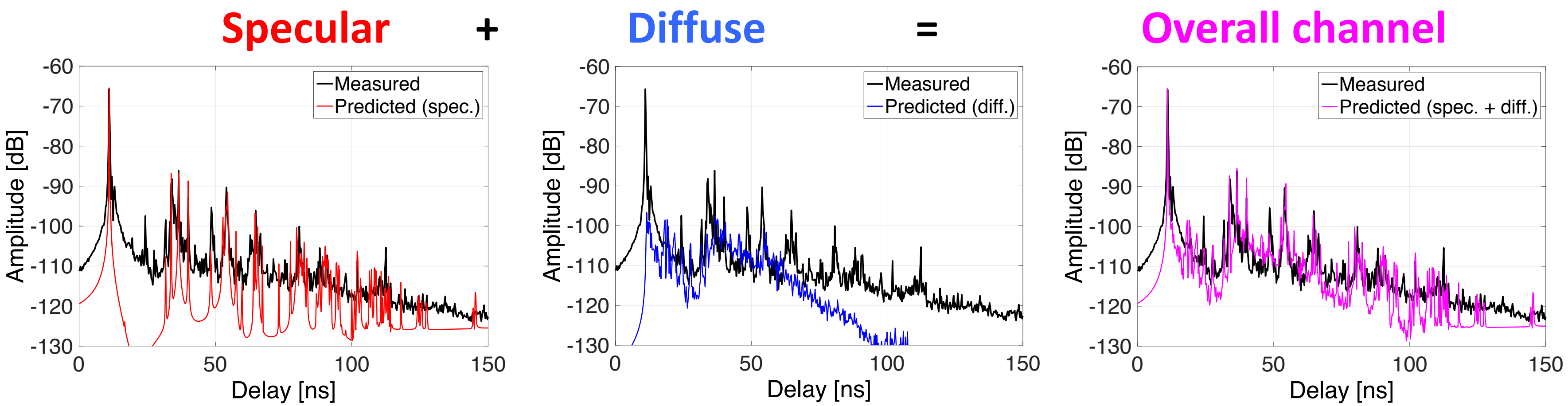
Ray tracing/launching important for large-scale channel data

Examples

- Points in the point cloud produce
  - Specular reflections
  - Diffuse scattering
  - Attenuation loss due to shadowing
- Material parameters (e.g. permittivity) optimized to fit measured channel impulse responses



Street canyon @ Aalto University

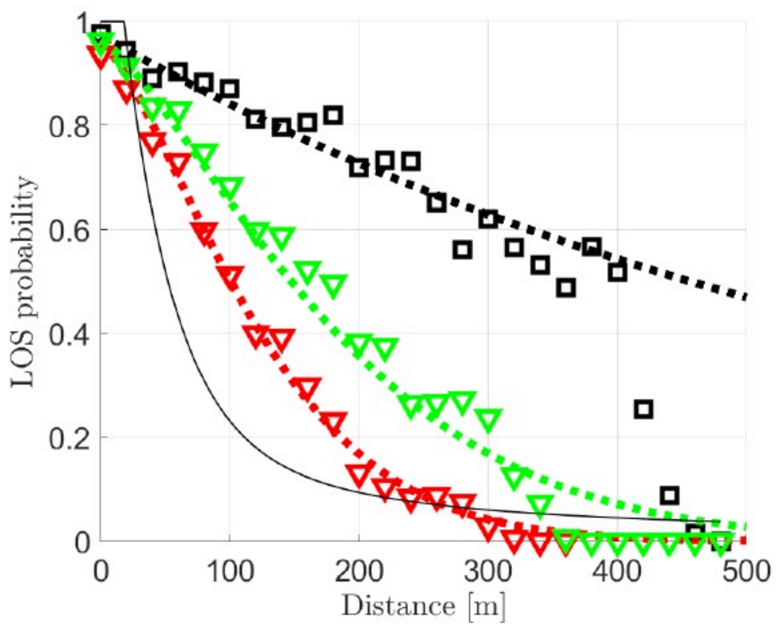


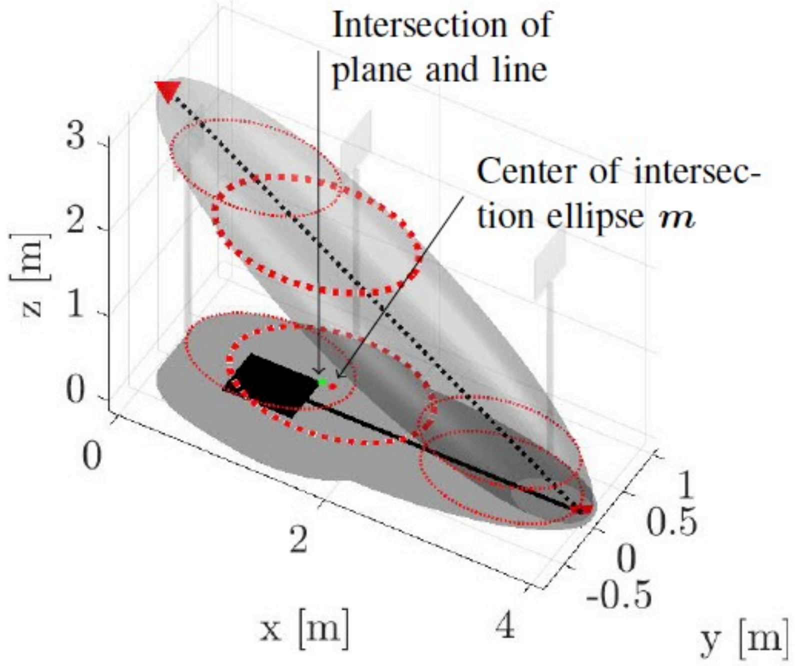
[Haneda et al. 2021]

Point cloud simulations based on Lidar scans give high accuracy

Line of sight probability

LOS probability with point clouds and stochastic modeling



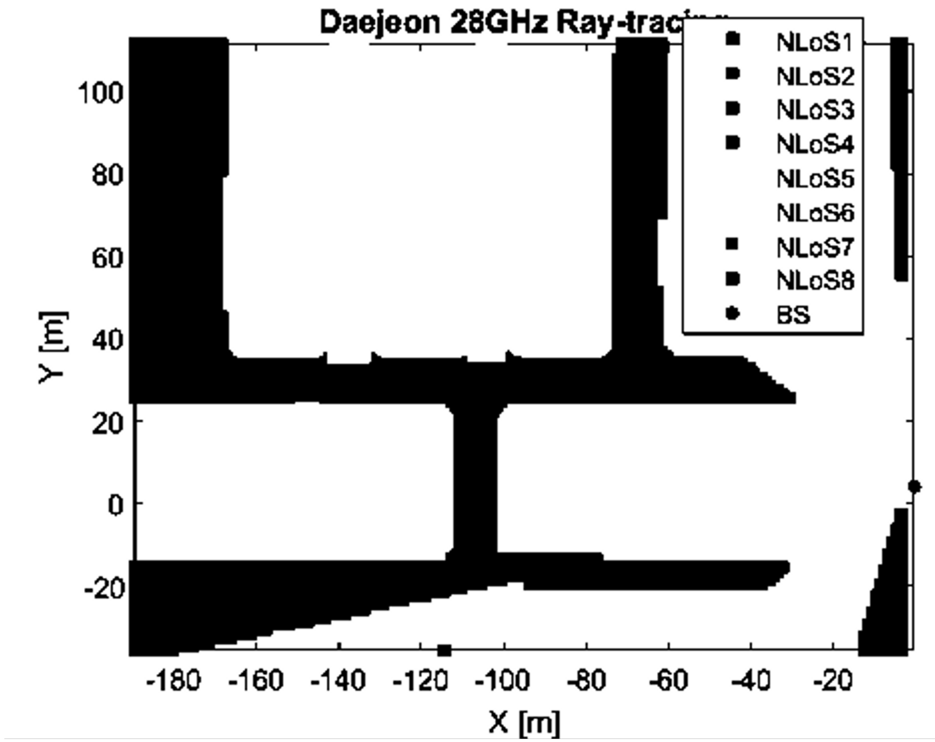


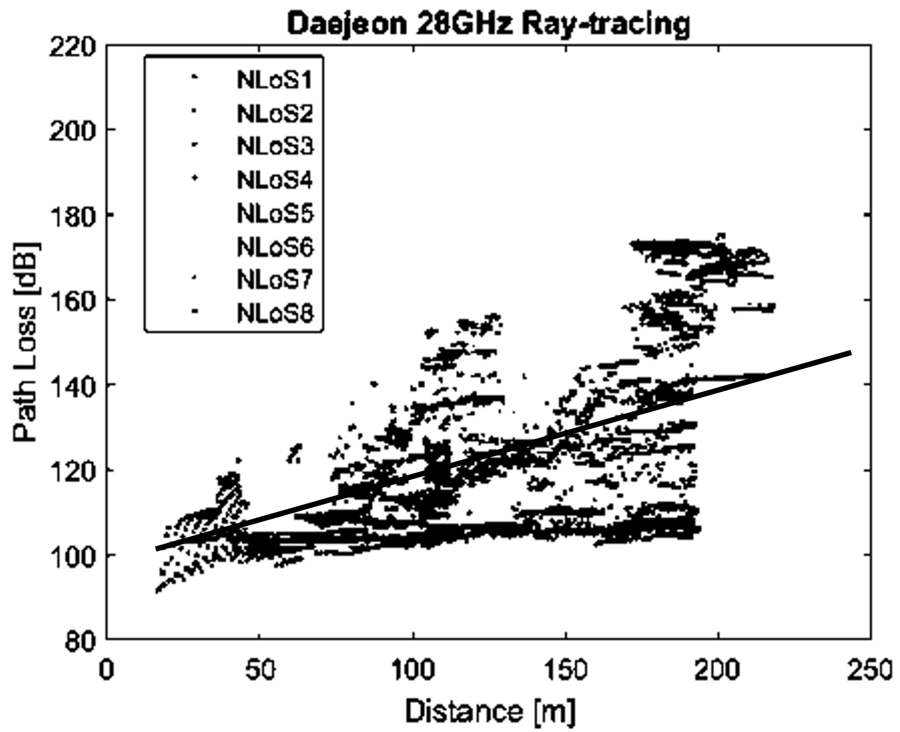
[*with* Koivumaki et al. 2021]

LOS can be blocked even by small objects; blockage of Fresnel zone must be considered

Modeling pathloss in microcells

- Shadowing variance increases with TX-RX distance – why?

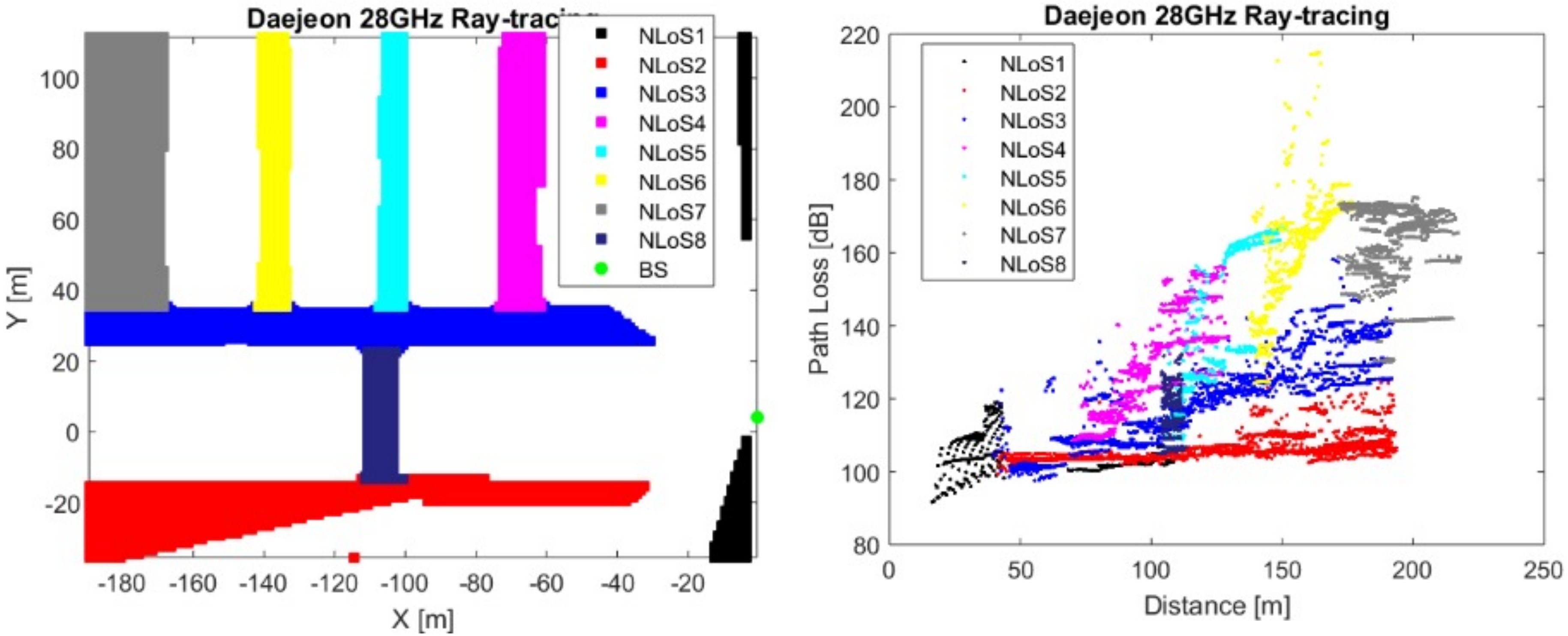




Shadowing variance seems to increase with distance

Modeling pathloss street-by-street

- Street-by-street pathloss



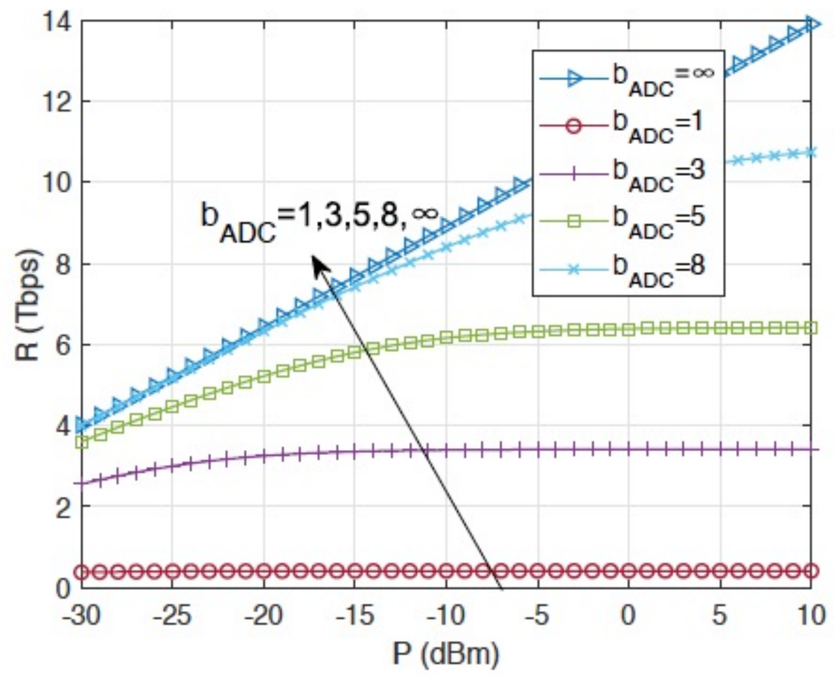
[Molisch et al. 2016; *with* Karttunen et al. 2017]

Different streets have different pathloss coefficients

Contents

Fully digital beamforming

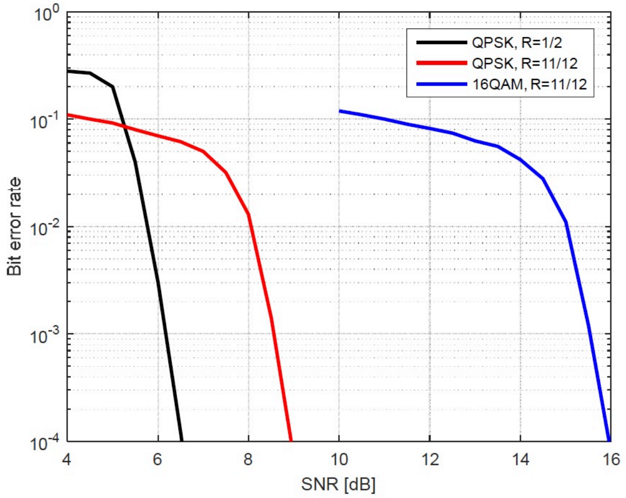
- Flexibility in beamforming per subcarrier
- Higher energy consumption
- For large bandwidth, use low-resolution ADCs to limit energy
- General guideline: quantization noise should be smaller than thermal noise [Roth et al. 2018]
- Advanced signal processing for low-resolution ADC

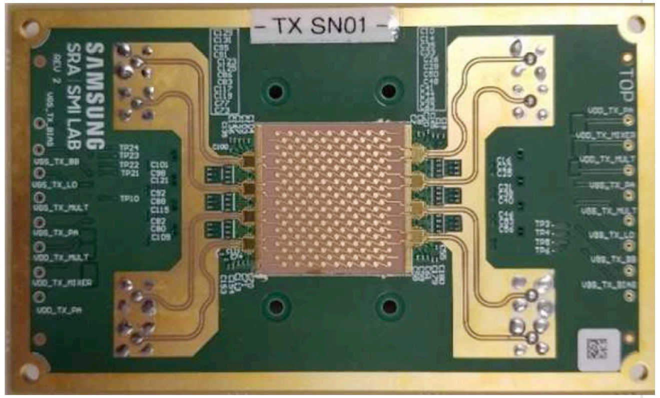


[Zhang et al. 2021]

Fully digital beamforming must use low-resolution ADCs

End-to-end system



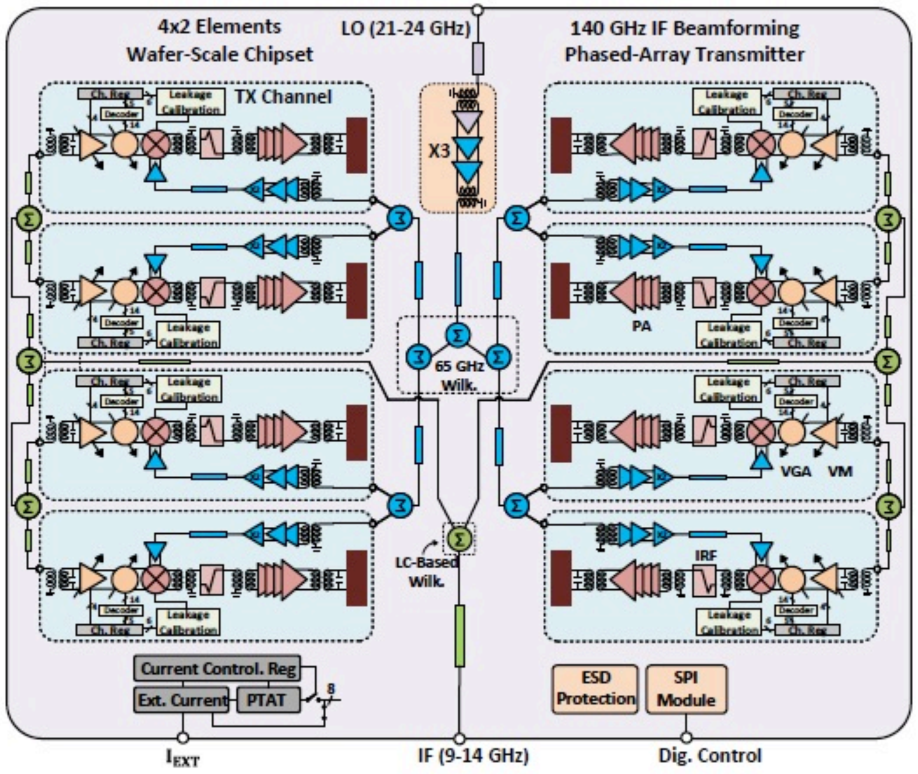


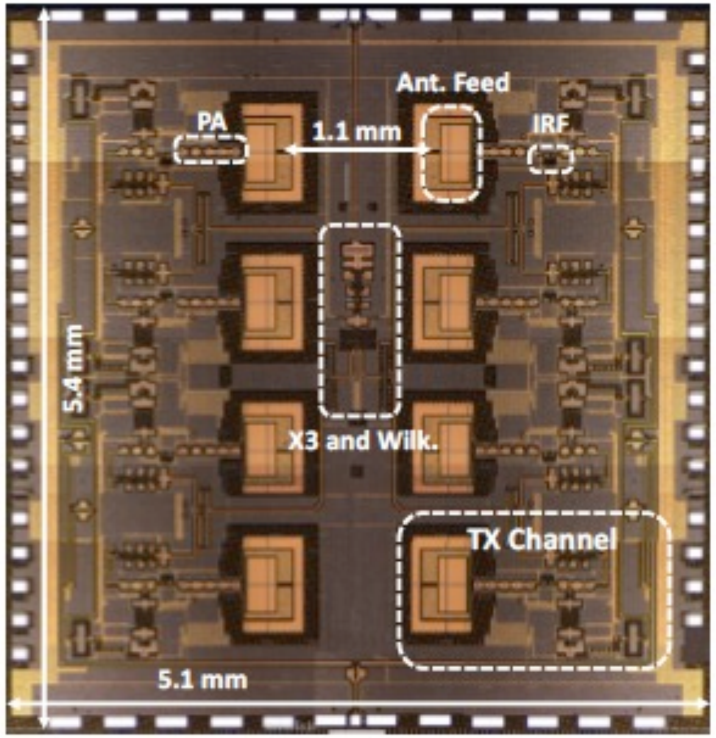
[Abu-Surra et al. 2021]

THz system with fully digital beamforming demonstrated

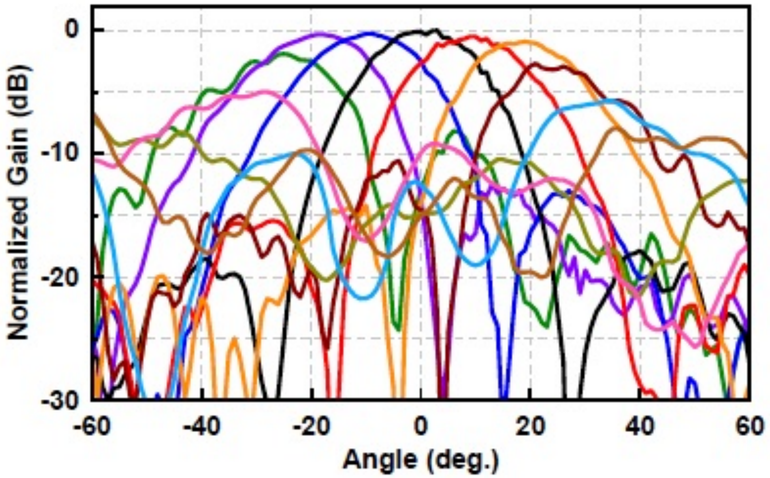
Phased array technology

- High-EIRP CMOS is arriving





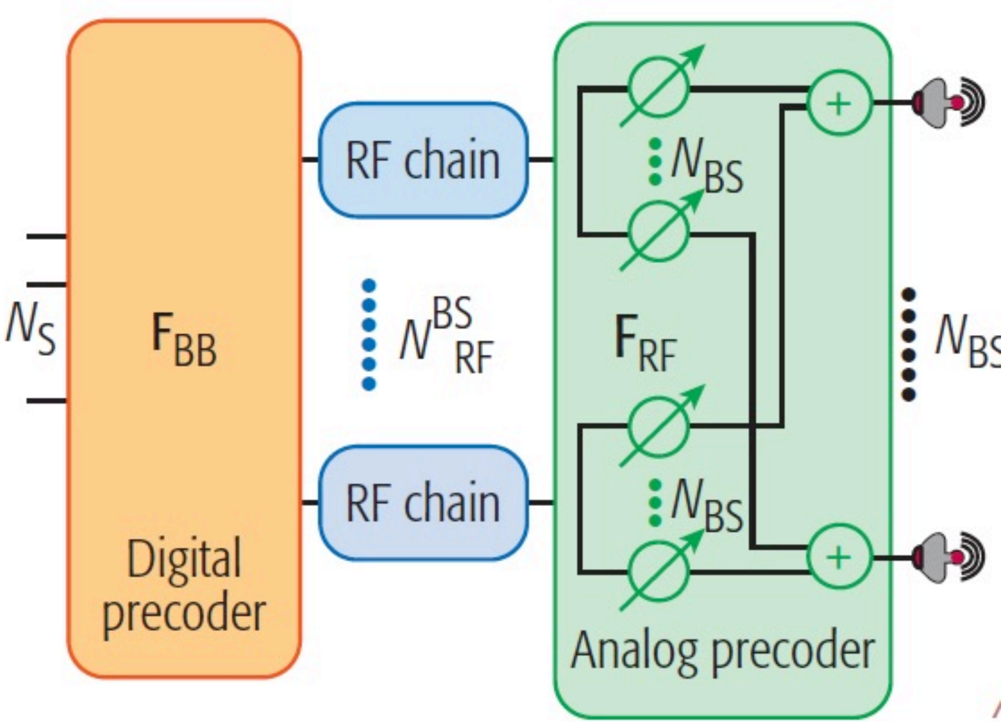
[Li et al. 2021]



CMOS phased arrays at 140 GHz with high EIRP are here, but not yet commercial

Hybrid beamforming

- Combine analog with digital beamforming to reduce number of RF chains

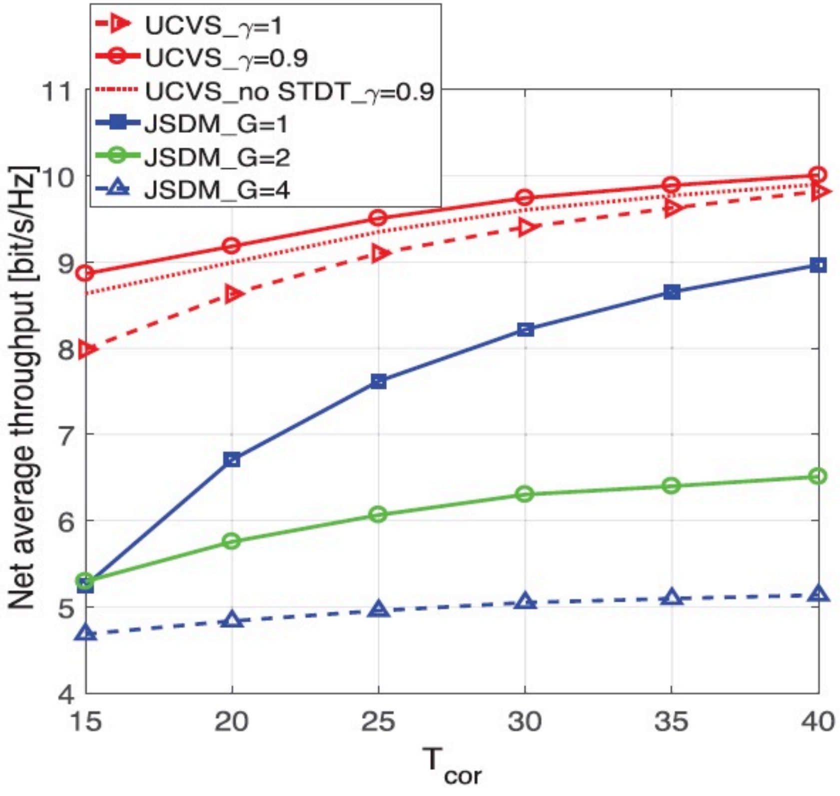


- Invented in early 2000s at MERL: [Molisch and Zhang 2004], [*with* Zhang et al 2005] (using instantaneous CSI), [*with* Sudarshan et al. 2006] (using average CSI).

Hybrid beamforming allows drastic reduction of RF chains without significant performance loss

Hybrid beamforming with second-order statistics

- Use of second-order (statistical) channel state information, CSI:
  - Use for analog beamformer, together with instantaneous CSI for digital beamformer
  - Large reduction of channel estimation effort
- Grouping/scheduling of UEs critically impacts performance

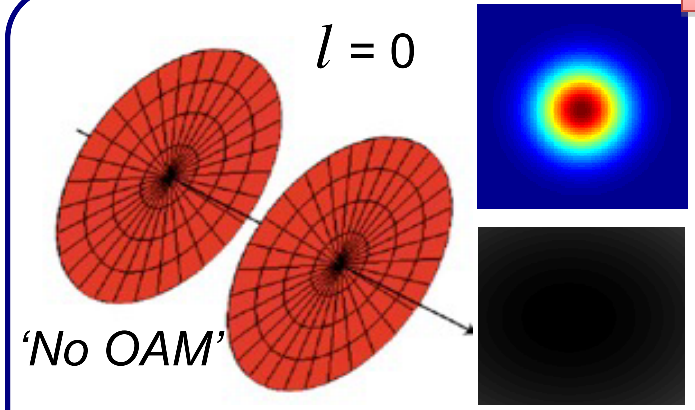


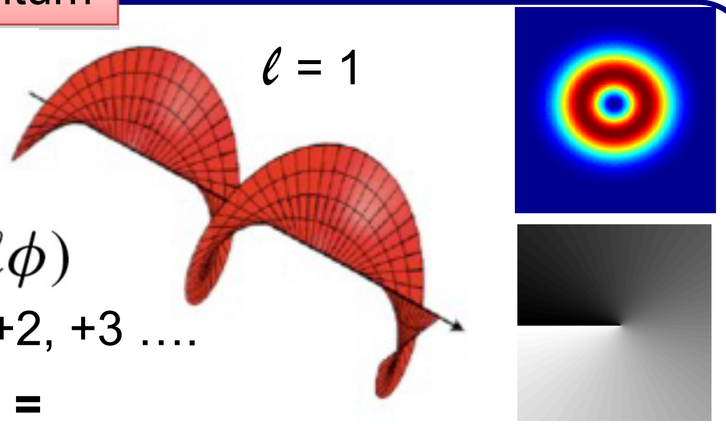
[*with* Li et al. 2018]

Analog beamformer in hybrid beamforming system best based on second-order channel state information; User grouping/scheduling is critical

Orbital Angular Momenta Multiplexing

Orbital Angular Momentum

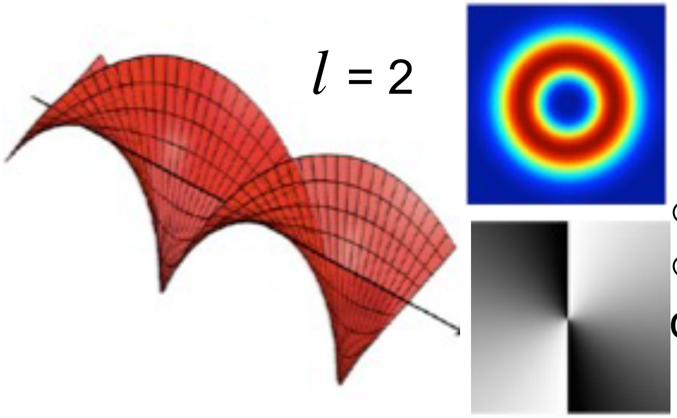


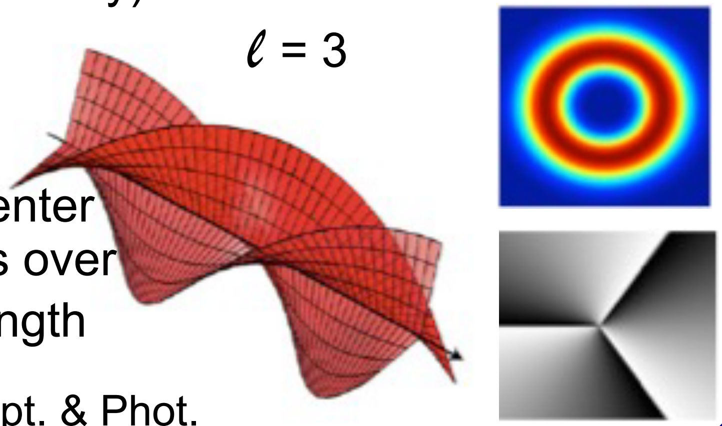


$$\phi(r, \phi) = \exp(i\ell\phi)$$

ℓ = …. -3, -2, -1 ,+1, +2, +3 ….

# of states possible = infinite , …. (theoretically)





- Intensity null at the center
- Phase spirals 'l' times over distance of one wavelength

[Yao, et al. 2011 Adv. in Opt. & Phot.

OAM well suited for multiple data streams on point-to-point LOS links

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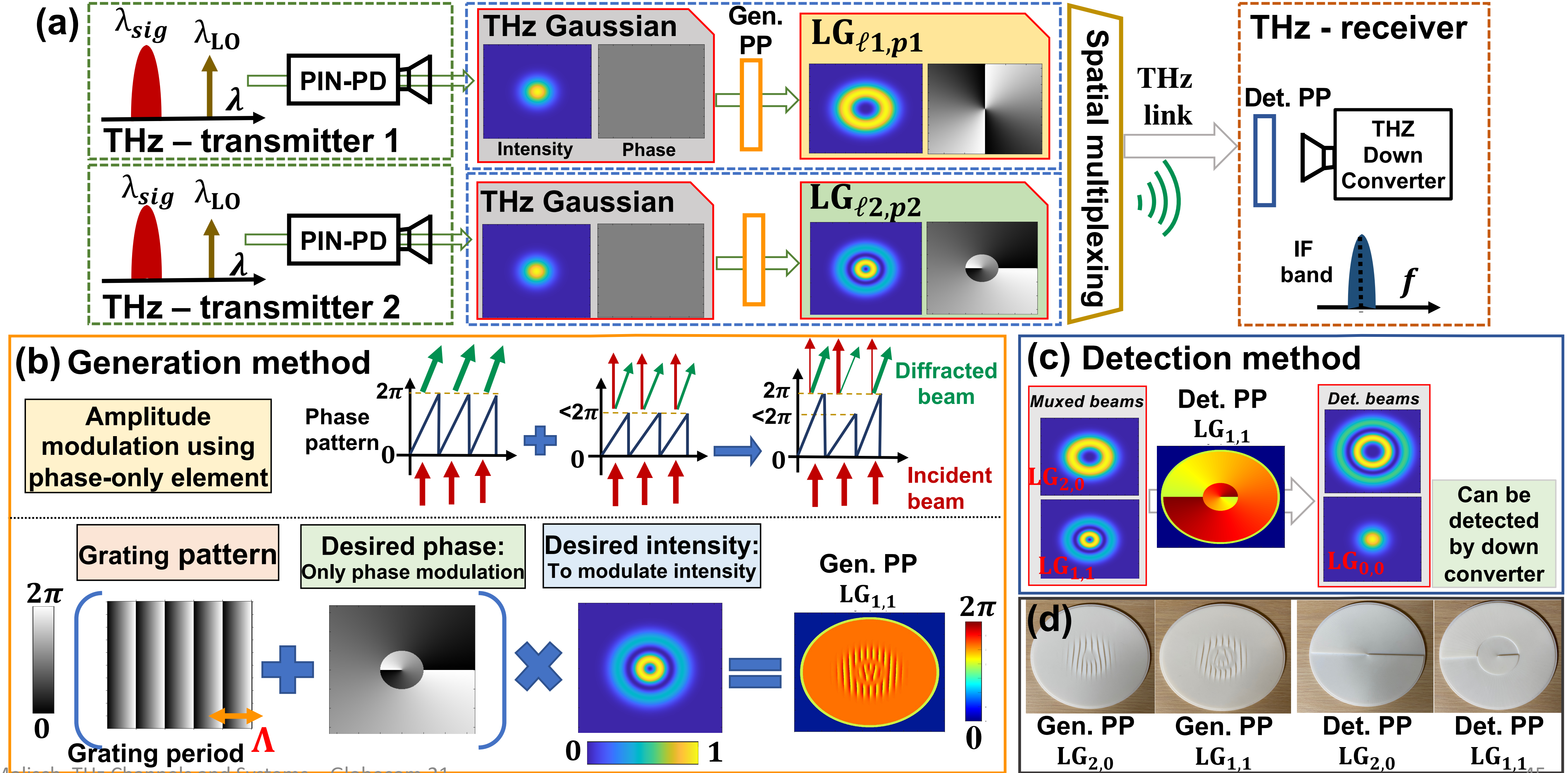
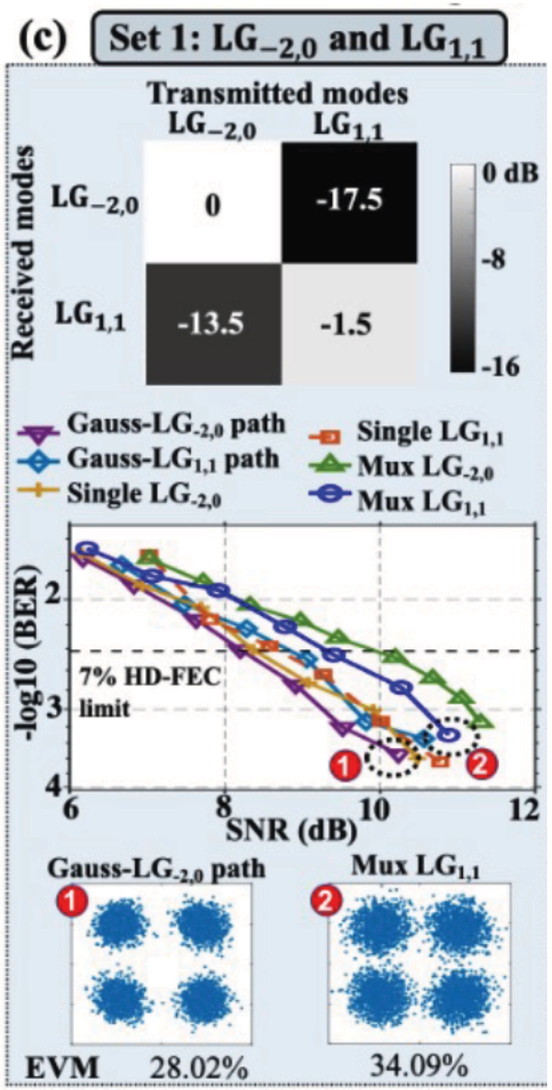
Sample results from OAM (I)

[*with* Minoofar, et al., 2021].



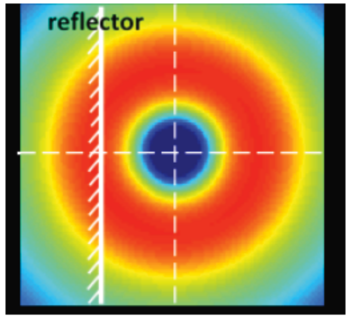
Sample results from OAM (II)

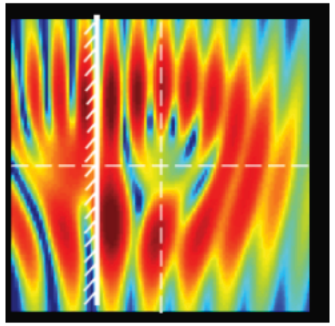


	$LG_{-2,0}$	$LG_{1,1}$
$LG_{-2,0}$	0	-17.5
$LG_{1,1}$	-13.5	-1.5

- Sources of intermodal interference
  - Imperfect phase plates/detectors
  - Radial offset
  - Finite aperture
  - Turbulence
  - Multi-path
  - Blockers in path

[*with* Minoofar, et al., 2021].





[*with* Yan et al., 2016].

Multipath leads to inter-modal interference, reducing OAM capacity

Summary and conclusions

- THz expected to be an important part of 6G
- Need new measurements and channel models for THz
- Both cellular and D2D communications are possible outdoors
  - distances of 100+ m possible,
  - Max distance depends on LOS/NLOS, and particularities of environment
- Passive reflectors can enhance coverage and beam diversity
- Hybrid beamforming allows energy-efficient combination of large arrays with smaller number of RF-chains and ADCs
- OAM at THz well suited for backhaul and LOS links
- Still a lot of exciting research to be done !

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(use filter: THz)

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