Millimeter wave & Terahertz channels – and their implication on 6G

FREDRIK TUFVESSON, LUND UNIVERSITY, SWEDEN

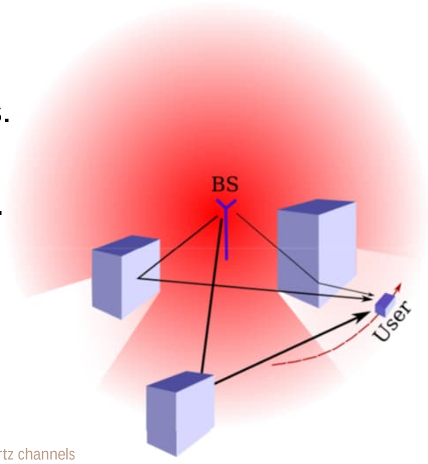
1

mm-wave and Teraherz communication channels

Propagation challenges for mm-wave and (sub-) THz frequencies:

- The path loss is large.
- Shadowing due to objects and humans.
- User-effects for hand-held devices.
- Transmission losses through buildings.

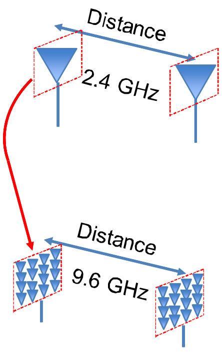
Beamforming/array gain is needed to overcome the increased losses.

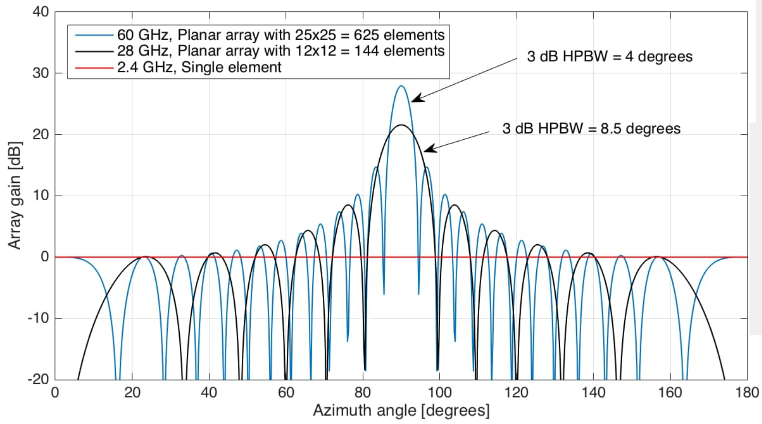


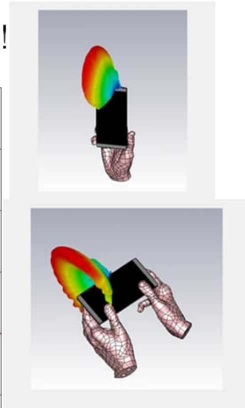
2

Beamforming with tracking of users

Large array => high directivity. Beamforming with tracking needed!





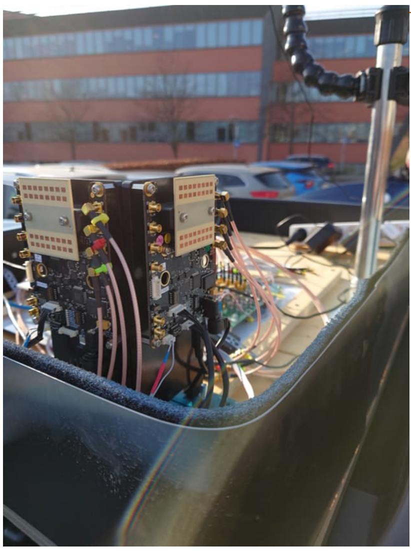


Ying Zhinong, Sony Europe

LUND UNIVERSITY

3

Antennas have limited angular view, at both ends



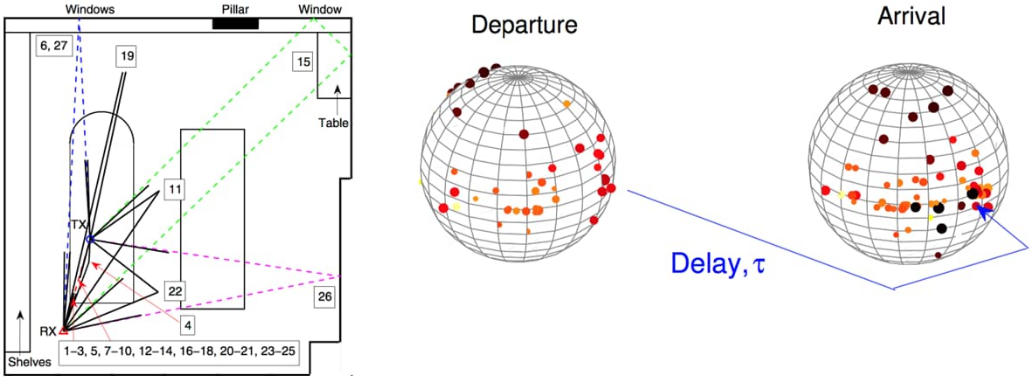
Two examples at 28 GHz:
a Sivers semiconductor development kit
a commercial Ericsson base station

LUND UNIVERSITY

4

For antenna independent modeling, a double directional representation should be used

Delays, arrival and departure angles & complex amplitudes of individual paths at 60 GHz.



C. Gustafson, et. al., "On mm-wave multi-path clustering and channel modeling", IEEE TAP, 2014.
C. Gustafson, F. Tufvesson, S. Wyne, K. Haneda, A. F. Molisch: "Directional analysis of measured 60 GHz indoor radio channels using SAGE", IEEE (VTC Spring), Budapest, Hungary, 2011

Double-directional channel model

Using the double-directional model, the mm-wave radio channel can be described as a sum of *L* different multi-path components (MPCs):

$$h_{m,n} = \sum_{l=1}^{L} \mathbf{G}_{\mathrm{rx}}^{\top}(\phi_l^{\mathrm{rx}}, \theta_l^{\mathrm{rx}})\ \boldsymbol{\alpha}_l\ \mathbf{G}_{\mathrm{tx}}(\phi_l^{\mathrm{tx}}, \theta_l^{\mathrm{tx}}) \mathrm{e}^{-\mathrm{j}2\pi\Delta f \tau_l k}$$

$$\mathbf{G}(\phi,\theta) = \begin{pmatrix} G_V(\phi,\theta) \\ G_H(\phi,\theta) \end{pmatrix}$$

Polarimetric antenna response at the Tx and Rx sides.

$$\boldsymbol{\alpha}_l = \begin{pmatrix} \alpha_l^{VV} & \alpha_l^{VH} \\ \alpha_l^{HV} & \alpha_l^{HH} \end{pmatrix}$$

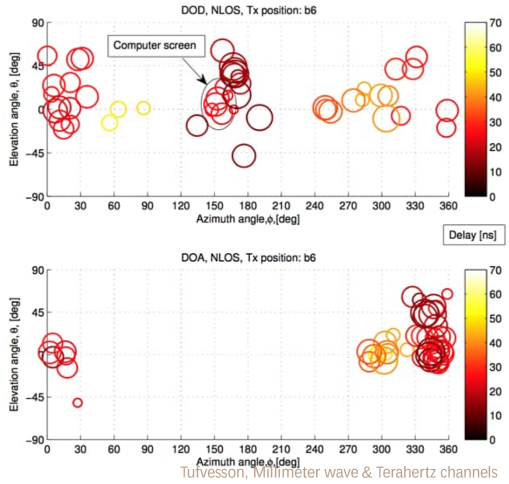
Polarimetric matrix for the complex amplitude of the *l*th MPC.

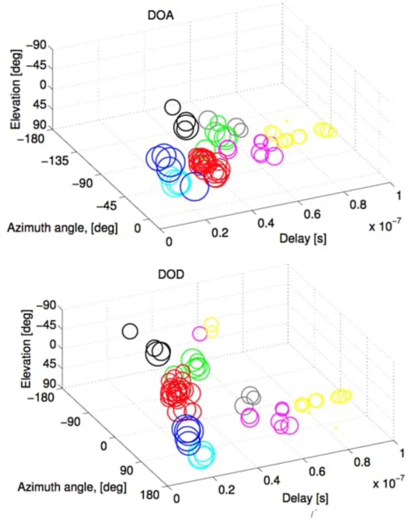
Antenna responses are de-embedded from the measurements.

Polarimetric matrix describing the complex amplitudes of the MPCs.

Multipath components appear in clusters

Measured (N)LOS 60 GHz MPCs and clusters:





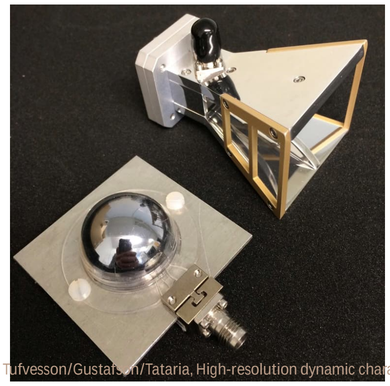
Propagation challenges for mm-wave frequencies

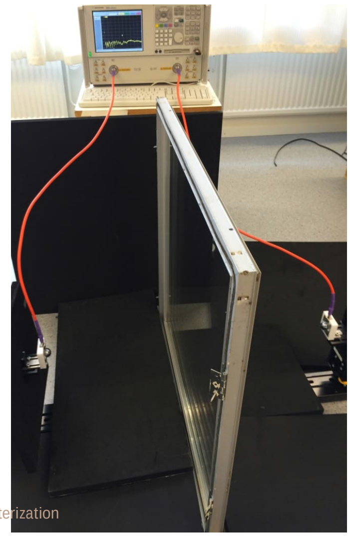
- Shadowing due to objects and humans.
- User-effects for hand-held devices.
- Transmission losses through buildings.
- The path loss is large.

LUND UNIVERSITY

Transmission loss: Windows and walls

Measurements from 5-67 GHz
Horn antenna (5-50 GHz) and
lens antenna (20-67 GHz):

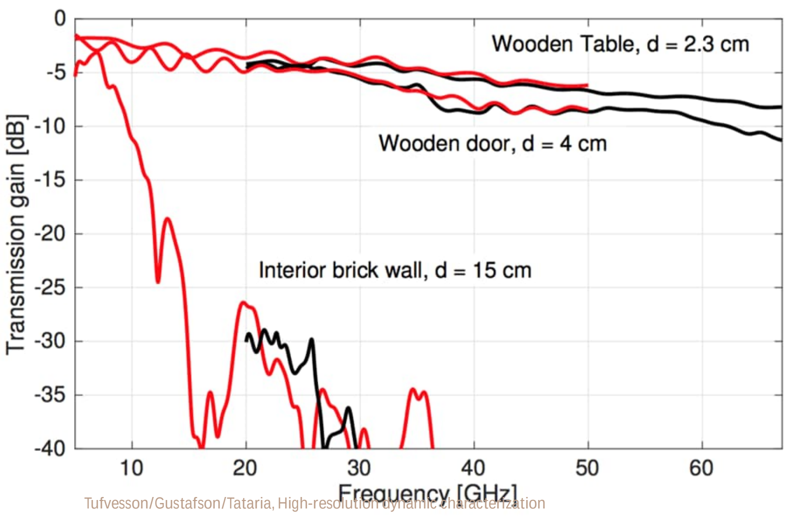




LUND UNIVERSITY

9

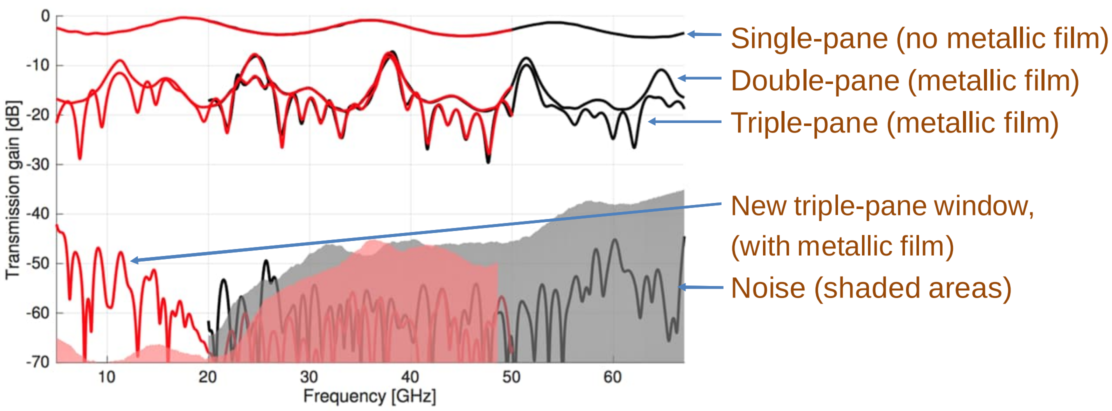
Transmission loss measurements



LUND UNIVERSITY

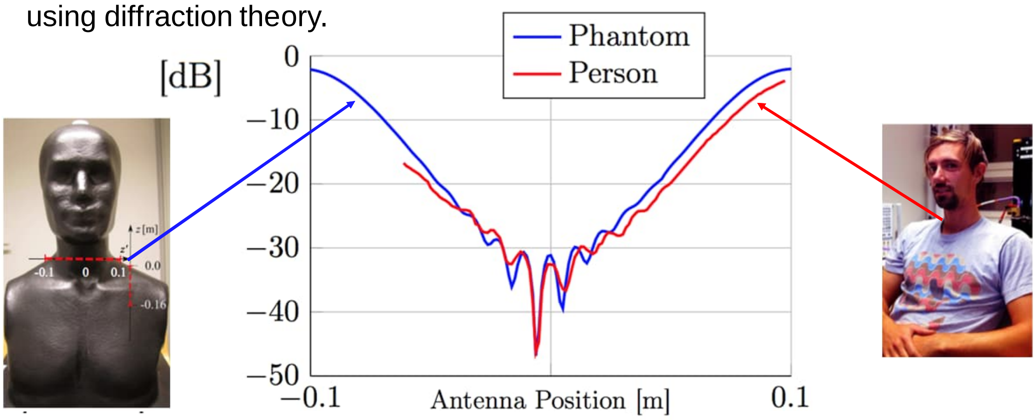
10

Transmission loss: Windows



Human shadowing creates large losses

Human body mm-wave shadowing causes severe power losses, can be modelled using diffraction theory.



C. Gustafson and F.Tufvesson,"Characterization of 60 GHz Shadowing by Human Bodies and Simple Phantoms" *Radioengineering*, 2012.

Dynamic behavior is not well understood

- For reliable beamforming we need to understand the dynamic behavior and the multipath structure in detail
  - Dynamic characterization means that we can not use rotational horns or virtual arrays.
  - Double directional characterization is needed.
  - Large bandwidths enable good delay resolution.
  - High resolution processing is preferred to understand the detailed multipath structure.

- Sometimes incompatible requirements, especially for (sub-) THz frequencies

LUND UNIVERSITY

13

LUND UNIVERSITY | 350

Dynamic mm wave channel sounding

14

Dynamic Channel Sounding at mmWave Frequencies

- ❑ Requirements from a propagation viewpoint:
  - ❑ Dynamic measurements implies the use of rotating horn antennas or virtual arrays are not effective.
  - ❑ Double directional treatment with high resolution processing to understand the multipath structure.
- ❑ Common channel sounding techniques:
  - ❑ Rotational horn (or other directional elements) to get a direction-specific description of the channel.
  - ❑ Virtual antenna arrays (antenna elements mechanically moved to form an array with single RF chain).
- ❑ Limitations: (1) Only static channels/environments measured. (2) Highly time consuming. (3) Limited amount of measurement data. (4) Unable to capture Doppler or dynamic behavior of channels.
- ❑ Need for antenna array implementations:
  - ❑ Analog or digital processing with single or multiple RF chains.
  - ❑ Switched antenna arrays (fast electronic switch routing paths from elements to RF chains)

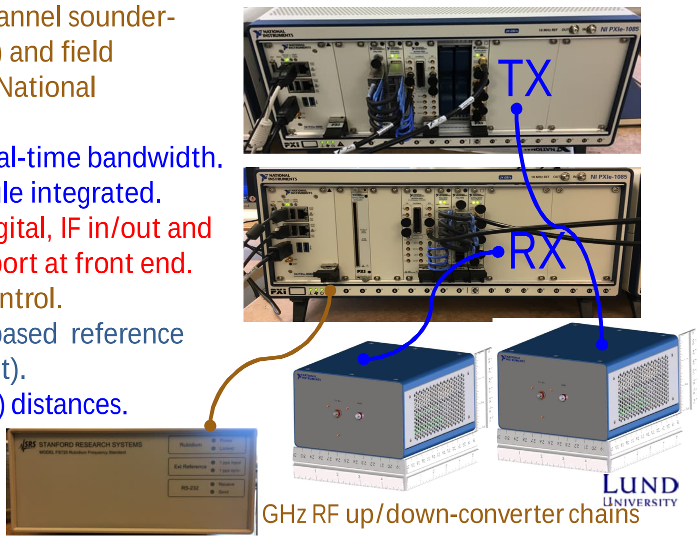
LUND UNIVERSITY

15

Lund University mmWave Channel Sounder

- ❑ A 28 GHz mmWave multiple antenna channel sounder- based on software defined radios (SDRs) and field programmable gate arrays (FPGA) from National Instruments (NI).
- ❑ Up to 32 dBm TX power and 2 GHz of real-time bandwidth. 12 bit ADC/DAC, LO/IF, and timing module integrated.
- ❑ 28 GHz RF heads at TX/RX supporting digital, IF in/out and LO in/out at rear, as well as TX/RX TDD port at front end.
- ❑ Scheduler support for TX/RX antenna control.
- ❑ Timing synchronization with Rubidium-based reference clocks (10 MHz and pulse per-second out).
- ❑ TX and RX can be separated over large(r) distances.

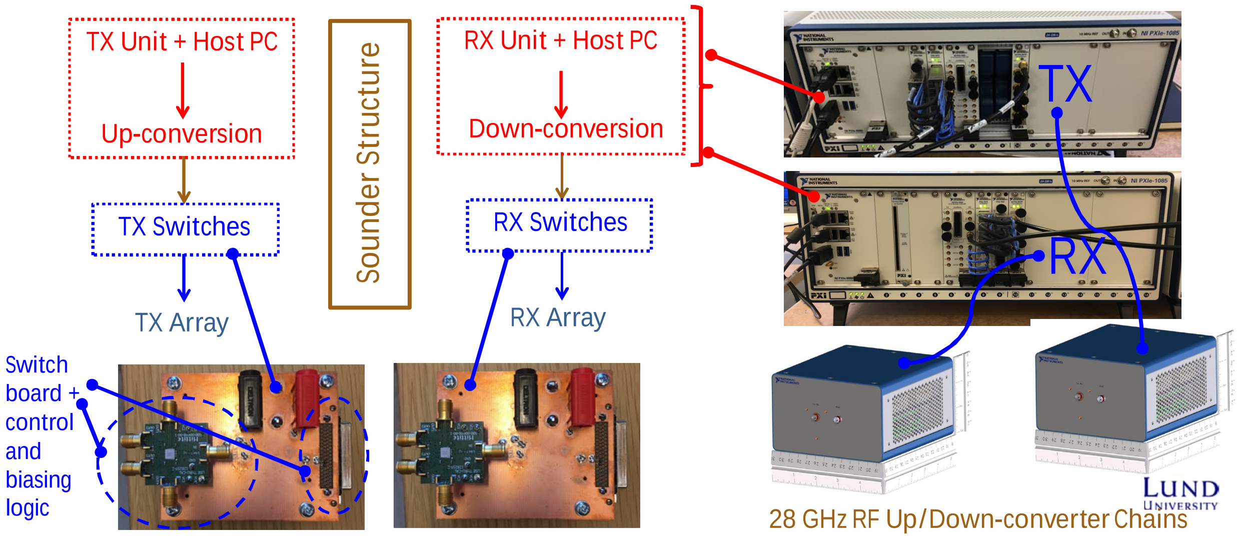
Rubidium reference



LUND UNIVERSITY

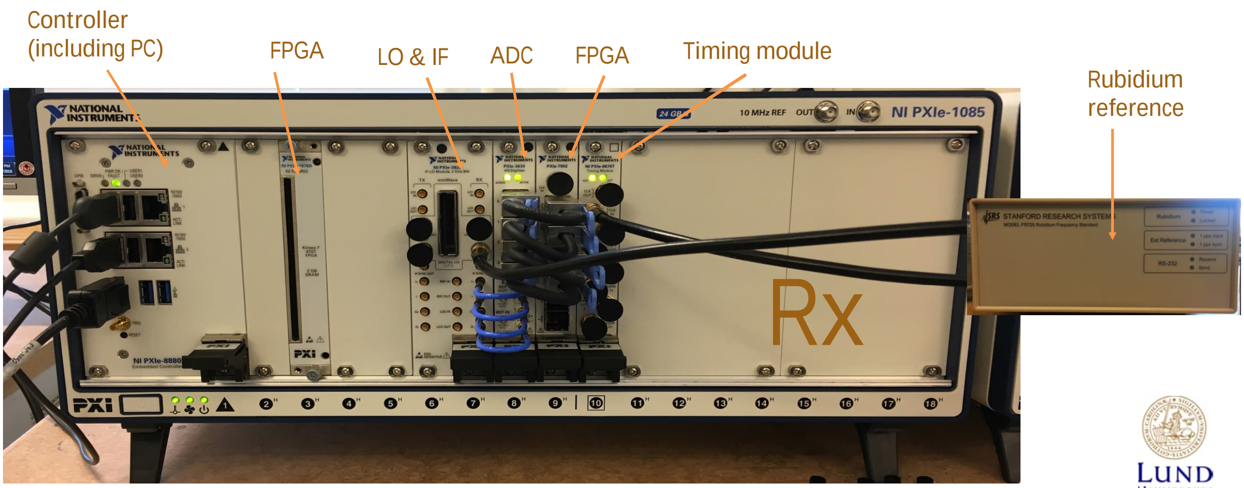
16

Lund University mmWave Switched Channel Sounder



17

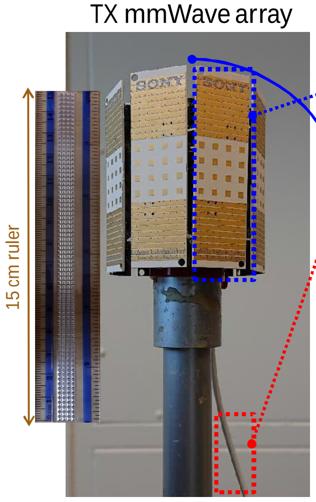
Lund University mmWave Channel Sounder



18

MmWave TX Antenna Array Design and Parameters

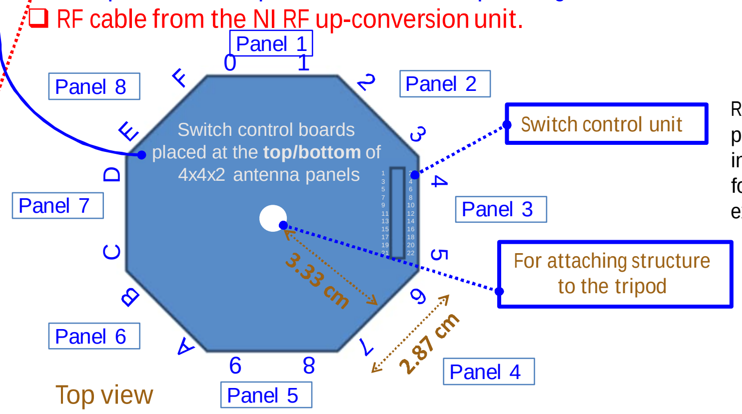
TX mmWave array



Front view

8 panels: each with 4 (rows) x 4 (columns) x 2 (polarizations) = 32 patch antennas.

- 256 elements in total across the octagonal structure (6 dBi gain per-element).
- Backplane of each panel has the corresponding antenna control board.
- RF cable from the NI RF up-conversion unit.

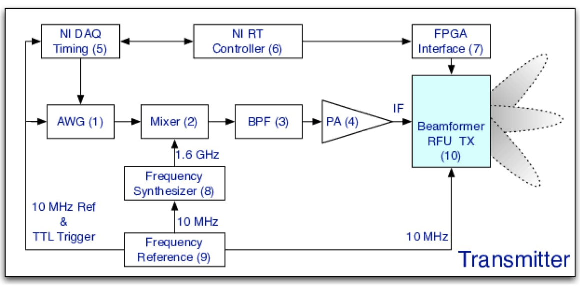


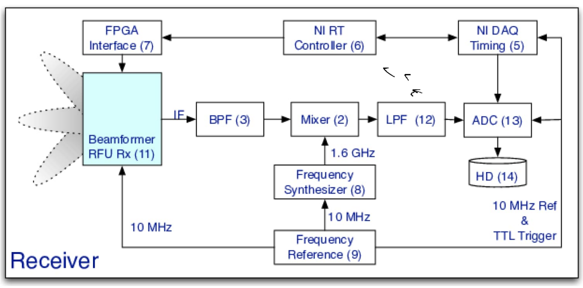
Top view

Rx array: 128 cross-polarized elements in rectangular form, i.e., 4 panels extracted.

LUND UNIVERSITY

USC: Beamformed real time mm wave MIMO channel sounder

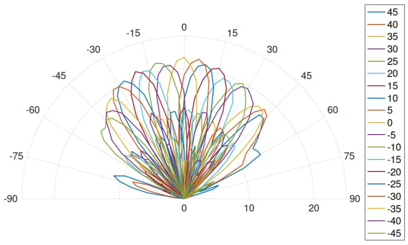




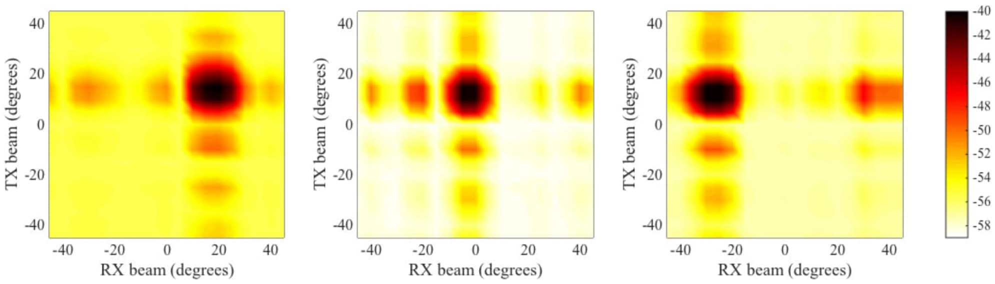
Bas, C. Umit, et al. "Real-time millimeter-wave MIMO channel sounder for dynamic directional measurements." *arXiv preprint arXiv:1807.11921* (2018).

LUND UNIVERSITY

USC: switch through all beam combinations

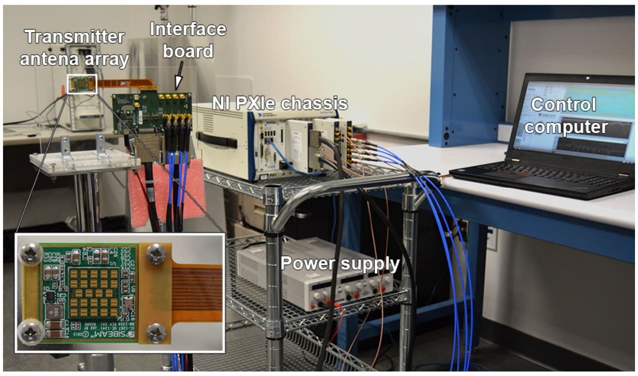


Bas, C. Umit, et al. "Real-time millimeter-wave MIMO channel sounder for dynamic directional measurements." *arXiv preprint arXiv:1807.11921* (2018).



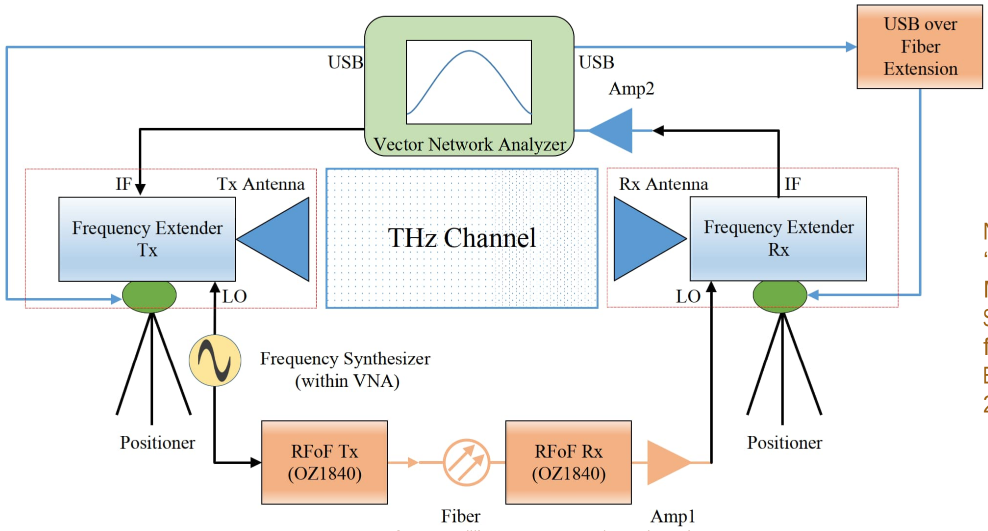
NYU: 60 GHz dynamic beamswitching sounder

- Based on SiBeam 60 GHz phased arrays and NI sampling and control units
- 12 steerable beams at both ends, +/- 45 deg



Slezak, Christopher, et al. "Empirical Effects of Dynamic Human-Body Blockage in 60 GHz Communications." *arXiv preprint arXiv:1811.06139* (2018).

USC 140 GHz sounder



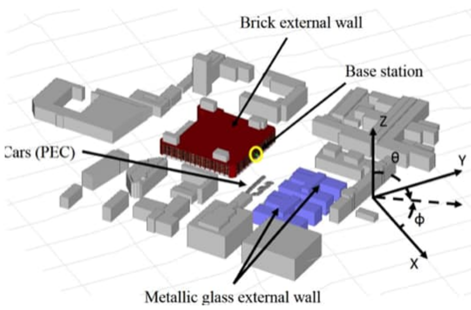
N.A. Abbasi et al "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", Arxiv, 2022

USC 140 GHz sounder

N.A. Abbasi et al "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", Arxiv 2022

mm wave characteristics

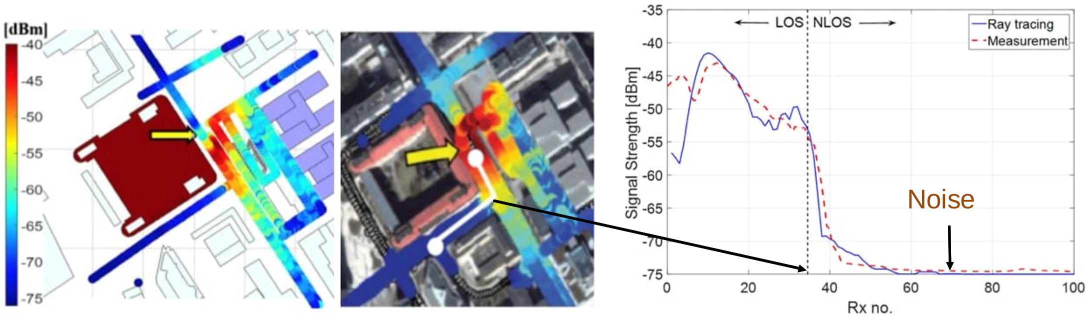
Blocking by buildings, Kista, Sweden



Measurements vs ray tracing, 15 GHz vs 28 GHz.

[1] P. Ökvist, et. al., "15 GHz Progatation Properties Assessed with 5G Radio Access Prototype", PIMRC 2015.
[2] K. Zhao, **C. Gustafson**, et. al., “Channel Characteristics and User Body Effects in an Outdoor Urban Scenario at 15 and 28 GHz”, IEEE Transactions on Antennas and Propagation, 2017

Shadowing by buildings at 15 GHz



Ray tracing results | Measurements | LOS/NLOS transition around corner

Ray tracing results includes fine details in the environment (cars, windows, etc.). Antenna configurations are also included.

LUND UNIVERSITY

27

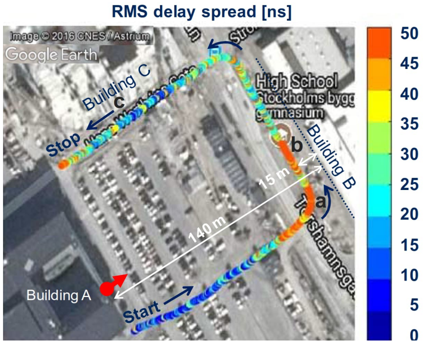
Shadowing by buildings at 15 and 28 GHz

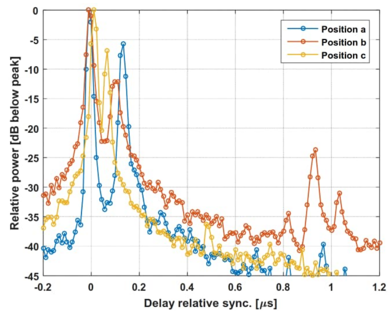
The shadowing effect due to buildings increases with frequency.

LUND UNIVERSITY

28

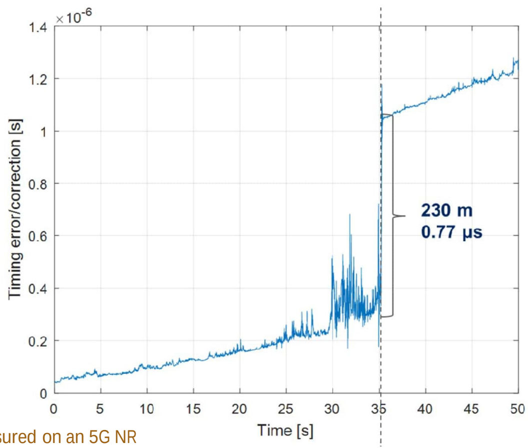
Channel characteristics depend on beam selection





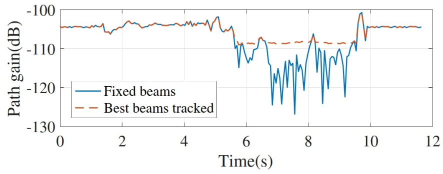
Thurfjell, Magnus, et al. "Narrow Beam Channel Characteristics Measured on an 5G NR Grid-of-Beam Test-Bed." *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE, 2018.

Blocking causes not only changes in power levels

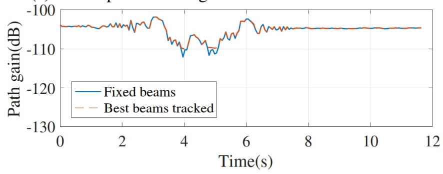


Thurfjell, Magnus, et al. "Narrow Beam Channel Characteristics Measured on an 5G NR Grid-of-Beam Test-Bed." *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE, 2018.

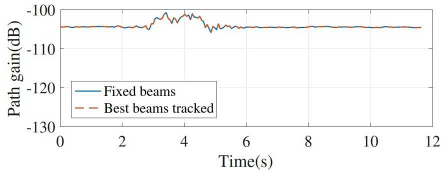
Vehicle blocking



(a) Truck passes through LOS between 5 s and 9 s



(b) Van passes through LOS between 2 s and 7 s

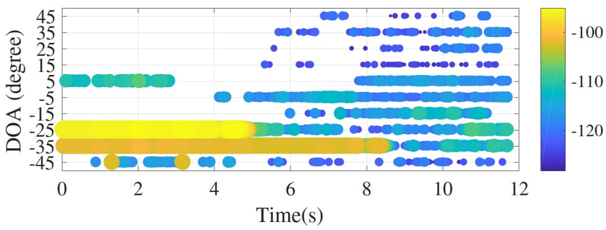


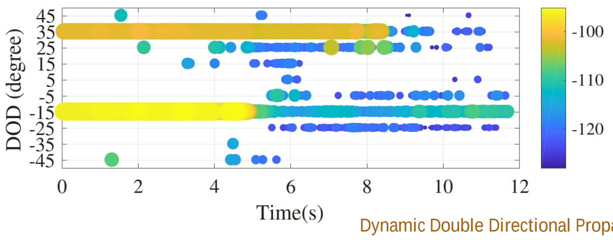
(c) Car passes through LOS between 3 s and 5 s

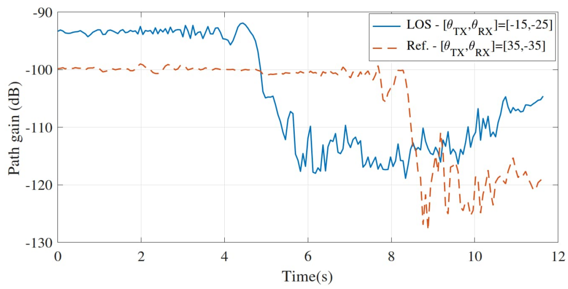
Bas, C. Umit, et al. "Real-time millimeter-wave MIMO channel sounder for dynamic directional measurements." *arXiv:1807.11921*, 2018.

LUND UNIVERSITY

Blocking, appearance and disappearance of MPCs





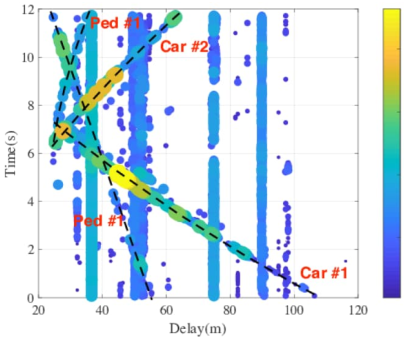


Dynamic Double Directional Propagation Channel Measurements at 28 GHz
CU Bas, R Wang, S Sangodoyin, S Hur, K Whang... arXiv:1711.00169, 2017

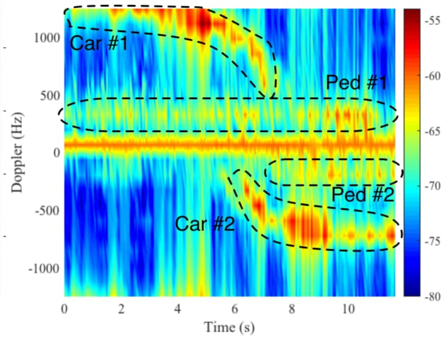
LUND UNIVERSITY

Moving scatterers create large Doppler

Antennas parallel to each other



Delay of MPCs



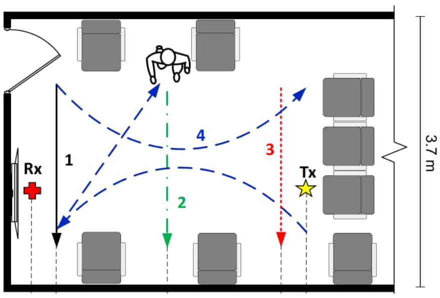
Doppler spectrum

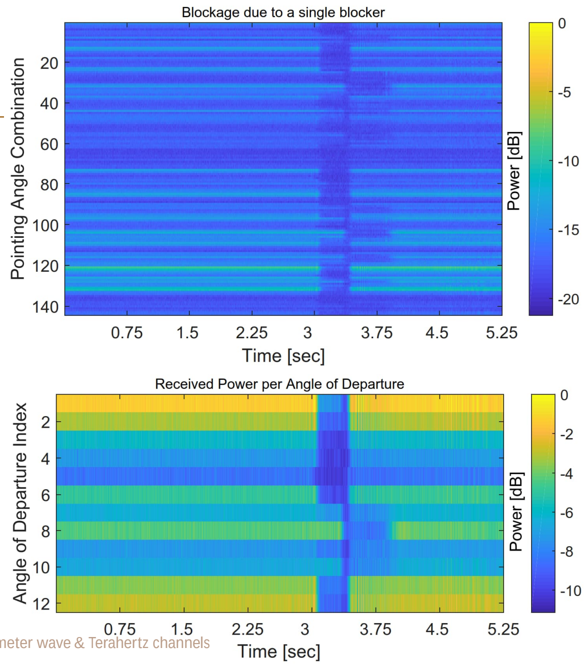
Dynamic Double Directional Propagation Channel Measurements at 28 GHz
CU Bas, R Wang, S Sangodoyin, S Hur, K Whang... arXiv:1711.00169, 2017

LUND UNIVERSITY

33

Human blocking



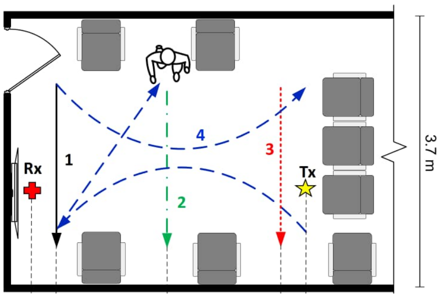


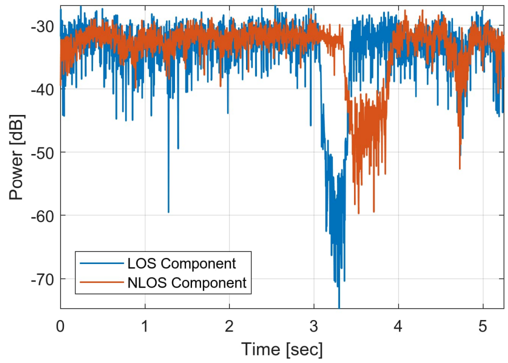
Slezak, Christopher, et al. "Empirical Effects of Dynamic Human-Body Blockage in 60 GHz Communications." *arXiv:1811.06139*, 2018.

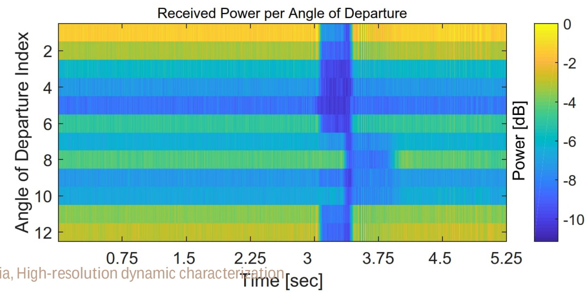
LUND UNIVERSITY

34

Human blocking







Slezak, Christopher, et al. "Empirical Effects of Dynamic Human-Body Blockage in 60 GHz Communications." *arXiv:1811.06139*, 2018.

Tufvesson/Gustafson/Tataria, High-resolution dynamic characterization 35

LUND UNIVERSITY

35

LUND UNIVERSITY

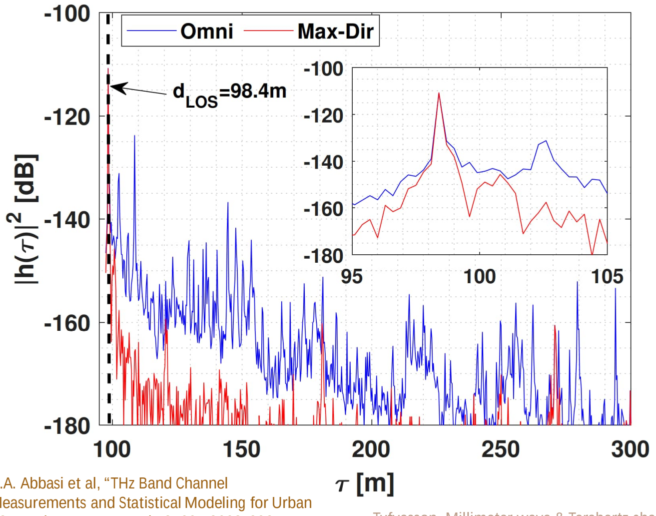
140 GHz outdoor channels

BASED ON MEASUREMENTS FROM USC BY ABBASSI ET AL

Tufvesson, Millimeter wave & Terahertz channels 36

36

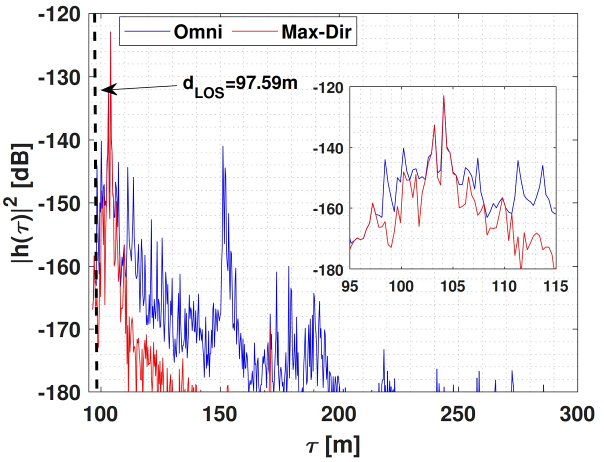
Urban LOS impulse response



- Big difference whether beast beam pair or "omni-directional" results are considered
- In LOS one clear main component, but others exist
- You cannot rely on spatial suppression
- There is still some excess delay
- LOS dominance decreases with distance

N.A. Abbasi et al, "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", arXiv:2109.13693, 2021

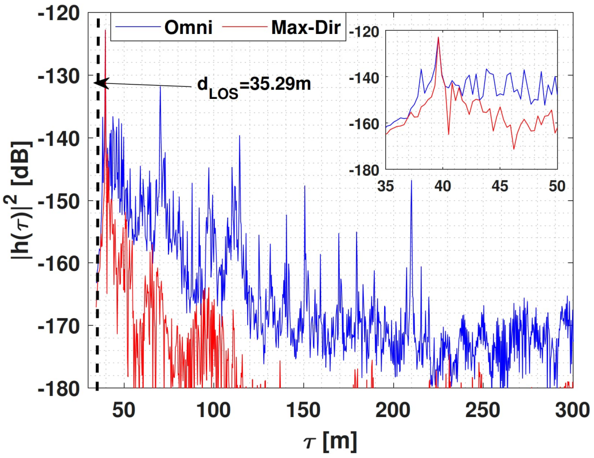
Urban NLOS impulse response (street intersection)



- Few dominating clusters
- Alternative beam pairs exist
- Buildings create good reflection/scattering

N.A. Abbasi et al, "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", arXiv:2109.13693, 2021

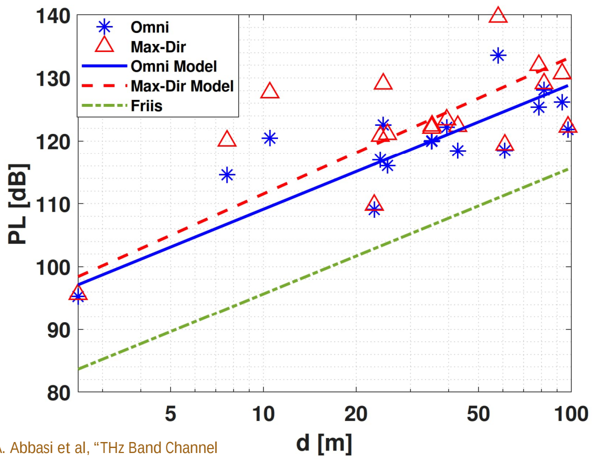
Urban NLOS impulse response (court yard)



- Significant excess delay
- Many MPCs with similar strengths
- Large angular spread, no dominating cluster
- Smaller reflectors play a large role

N.A. Abbasi et al, "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", arXiv:2109.13693, 2021

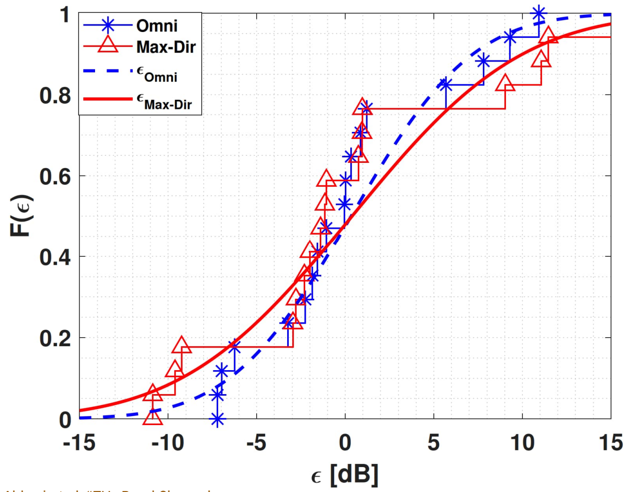
NLOS path loss



- NLOS gives 15-20 dB loss compared to LOS
- Again, antenna dependent
- Losses can be large also for short distances
- The path loss exponent is slightly below 2

N.A. Abbasi et al, "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", arXiv:2109.13693, 2021

Large scale fading (shadowing effects) in NLOS



- Large scale fading 10-15 dB
- Given that you find optimum direction
- More critical for narrow beam antennas
- Significantly smaller large sclae fading in LOS

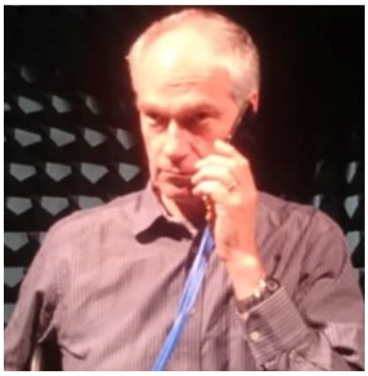
N.A. Abbasi et al, "THz Band Channel Measurements and Statistical Modeling for Urban D2D Environments", arXiv:2109.13693, 2021

LUND UNIVERSITY

Influence of the user

Hand-held devices and user-effects

The user will have a large influence on the experienced channel forhand-held devices.

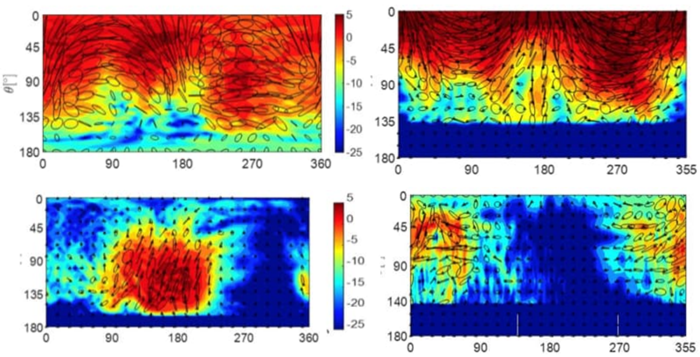


Measured user-effects for hand held devices

15 GHz

28 GHz

Free space
(in mock-up)



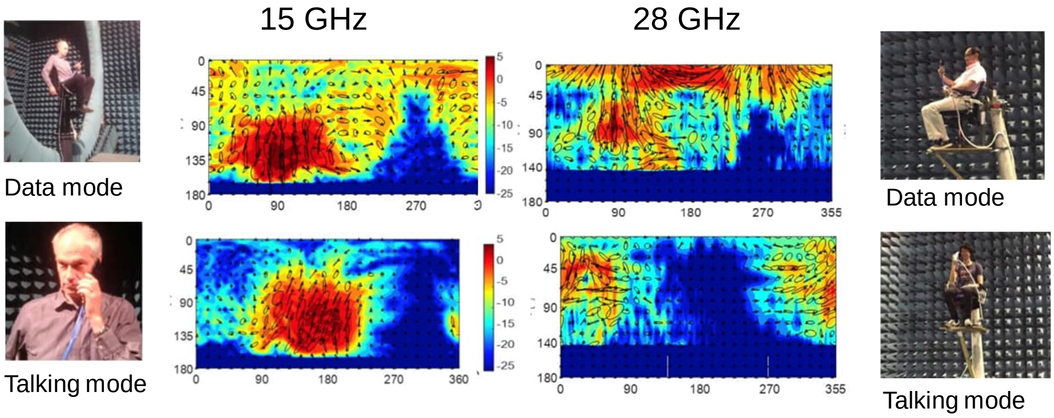
Free space
(in mock-up)

Talking mode

Talking mode

K. Zhao, **C. Gustafson**, et. al., “Channel Characteristics and User Body Effects in an Outdoor Urban Scenario at 15 and 28 GHz”, IEEE TAP, 2017.
Zhinong Ying et al., "Study of phased array in UE for 5G mm wave communication system with consideration of user body effect," EuCAP 2016.

Measured user-effects for hand held devices

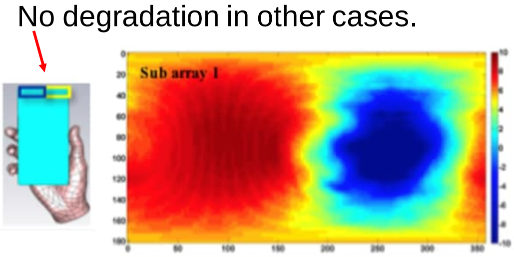


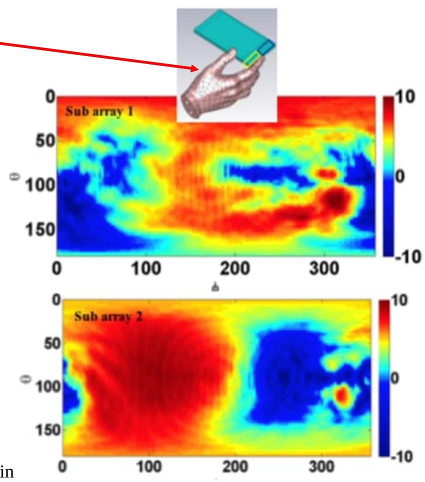
The effective antenna pattern depends on the user interaction!

Hand-effects at mm-wave frequencies

Significant degradation of the pattern when in close proximity to the element.

No degradation in other cases.





Distributed antennas needed?

K. Zhao, J. Helander, Z. Ying, D. Sjöberg, M. Gustafsson, S. He, "mmWave Phased Array in Mobile Terminal for 5G Mobile System with Consideration of Hand Effect", VTC Spring 2015.

Sub-6 GHz Massive MIMO, mmWave , sub-THz

	Sub-6 GHz Massive-MIMO	mmWave	Sub-THz
Propagation conditions	Rich multi-path environment, tolerable propagation losses.	Few strong multi-paths, large propagation losses.	Few strong multi-paths, severe propagation losses.
Deployment scenario	Macro cells with high user mobility.	Small cells with limited user mobility, fixed links	Very small cells with low user mobility, fixed links
Base station array architecture	Fully digital processing, with >100 BS antennas, each with an individual RF chain.	Hybrid analog and digital processing or fully digital	Not clear yet
Main reason for having a massive number of antennas	Efficient spatial multiplexing for multi-user MIMO.	Beamforming to ensure sufficient link budget. Some spatial multiplexing capabilities.	Beamforming to ensure sufficient link budget.
Number of simultaneous users	>10	Initially just a few.	Very few
Spectral efficiency & bandwidth	High spectral efficiency, with low BW	Moderate spectral efficiency, high BW	Very large BW

Conclusions

- A lot of research done, but further results are needed:
- Characterizing and modeling dynamic mmWave and sub-THz channels.
- Channel models need to be antenna independent and reflect the fine details of the channel
- Trade-offs between *spectral efficiency, cost* and *energy-efficiency.*
- LOS sub-THz communication is possible for medium distances as long as you can track the beam properly, NLOS is harder but still possible.
- Large scale fading can be severe, excess delays large
- To achieve reliable communication, parallel paths are necessary.
- Antenna diversity in form of multiple arrays might be necessary.
- Do not forget the influence of the user, has to be included.
- The antenna limits what you see, and influences channel characteristics

LUND UNIVERSITY

Selected references

[1] P. Ökvist, H. Asplund, A. Simonsson, B. Halvarsson, J. Medbo, N. Seifi, "15 GHz Progatation Properties Assessed with 5G Radio Access Prototype", PIMRC 2015.

[2] C. Gustafson and F.Tufvesson,"Characterization of 60 GHz Shadowing by Human Bodies and Simple Phantoms" *Radioengineering*, 2012.

[3] K. Zhao, C. Gustafson, et. al., "Channel Characteristics and User Body Effects in an Outdoor Urban Scenario at 15 and 28 GHz", IEEE Tr. on Antennas and Propagation, 2017.

[4] Zhinong Ying et al., "Study of phased array in UE for 5G mm wave communication system with consideration of user body effect," EuCAP 2016.

[5] K. Zhao, J. Helander, Z. Ying, D. Sjöberg, M. Gustafsson, S. He, "mmWave Phased Array in Mobile Terminal for 5G Mobile System with Consideration of Hand Effect", VTC Spring 2015.

[6] J. Hansryd, et. al., "Non-line-of-sight microwave backhaul for small cells", Ericsson Review, 2013.

[7] M. Marcus, B. Pattan, "Millimeter-wave Propagation: Spectrum Management Implications", IEEE Microw. Mag., 2005.

[8] C. Gustafson, et. al., "On mm-wave multi-path clustering and channel modeling", IEEE TAP, 2014.

[9] C. Gustafson, F. Tufvesson, S. Wyne, K. Haneda, A. F. Molisch: "Directional analysis of measured 60 GHz indoor radio channels using SAGE", IEEE (VTC Spring), Budapest, Hungary, 2011

[10] C. Gustafson, D. Bolin, and F. Tufvesson, "Modeling the cluster decay in mm-wave channels," IEEE *(EuCAP)*, 2014.

Selected references

[11] K. Haneda, K. Afroza, C. Gustafson, S. Wyne: "Spatial Degrees-of-Freedom of 60 GHz Multiple-Antenna Channels", IEEE Vehicular Technology Conference (VTC Spring), 2013

[12] K. Haneda, C. Gustafson, S. Wyne: "60 GHz Spatial Radio Transmission: Multiplexing or Beamforming?" IEEE Transactions on Antennas and Propagation, 2013.

[13] A. Karttunen, C. Gustafson, A.F. Molisch, J. Järvelainen, K. Haneda, "Censored Multipath Component Cross-Polarization Ratio Modeling", IEEE Wireless Communication Letters, 2016.

[14] K. Witrisal, P. Meissner, E. Leitinger, Y. Shen, C. Gustafson, F. Tufvesson, K. Haneda, D. Dardari, A. F. Molisch, A. Conti and M. Z. Win: "High-Accuracy Localization for Assisted Living: 5G systems will turn multipath channels from foe to friend", IEEE Signal Processing Magazine, 2016.

[15] C. Gustafson, T. Abbas, D. Bolin, F. Tufvesson, "Statistical Modeling and Estimation of Censored Pathloss Data", IEEE Wireless Communications Letters, 2015.

[16] K. Sakaguchi, et. al., "Where, When, and How mmWave is Used in 5G and Beyond", ArXiV, 2017.

[17] Q. Liao, Z. Ying, C. Gustafson: "Simulations and Measurements of 15 and 28 GHz Indoor Channels with Different Array Configurations", (iWAT), Athens, Greece, Mar. 2017.

[18] R. Wang, C.U. Bas, S. Sangodoyin, S. Hur, J. Park, J. Zhang, A.F. Molisch "Stationarity Region of mm-Wave Channel Based on Outdoor Microcellular Measurements at 28 GHz ", ArXiV preprint, 2017.

[19] A. Karttunen, C. Gustafson, A.F. Molisch, R. Wang, S. Hur, "Path loss models with distance-dependent weighted fitting and estimation of censored path loss data", IET Microwaves, Antennas & Propagation, 2016.

Thanks to former and current colleagues and project partners for contribution to this presentation: Carl Gustafson, Harsh Tataria, Meifang Zhu, Hedieh Khorsravi, Xuesong Cai, Erik Bengtsson,

LUND UNIVERSITY

SONY

ERICSSON

TAKING YOU FORWARD

51