6GNC

NC STATE UNIVERSITY

Multidevice Localization with mmWave Signals in Factory Environments

Prof. Nuria González Prelcic

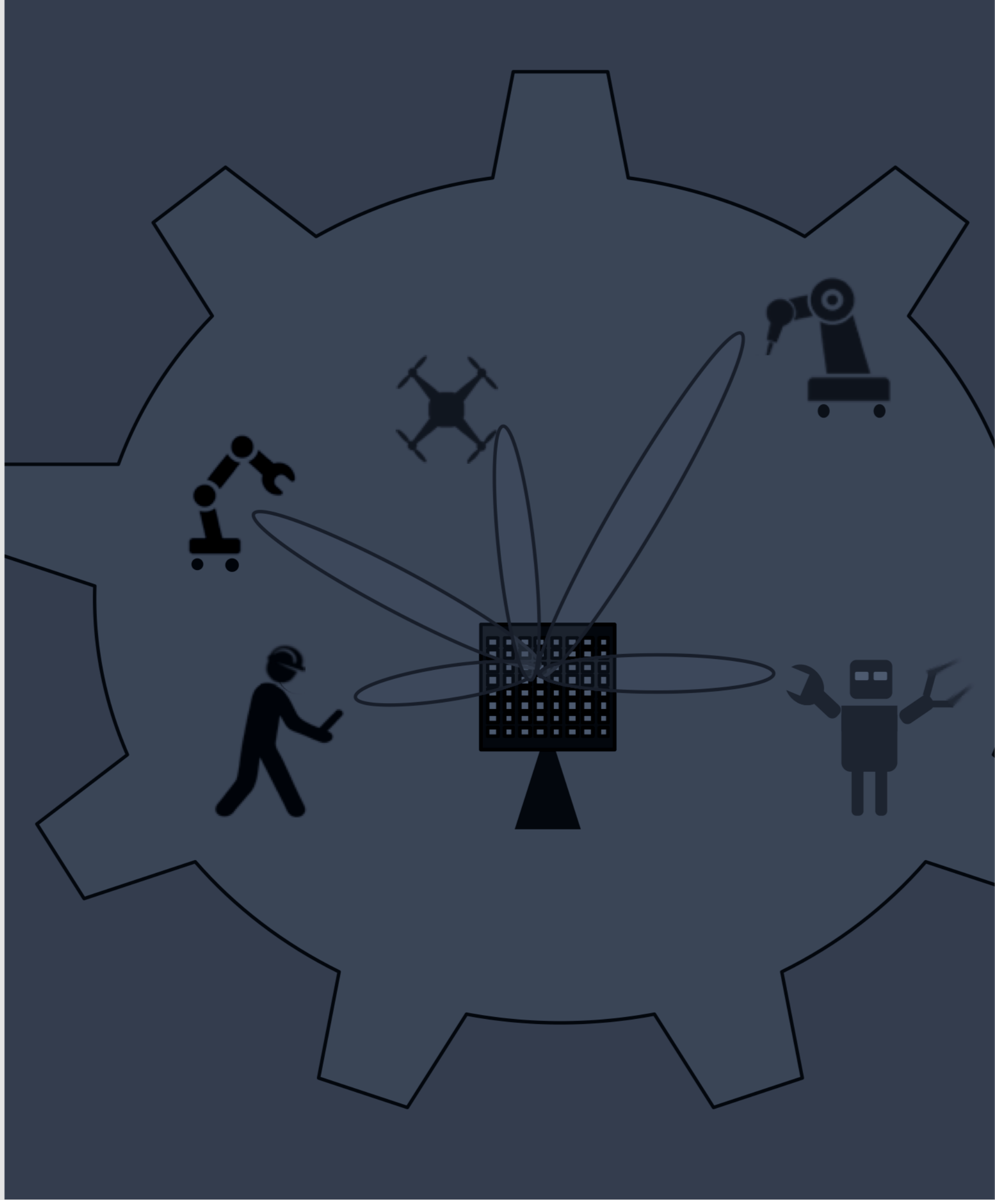
with input from Dr. Joan Palacios

Department of Electrical and Computer Engineering

North Carolina State University

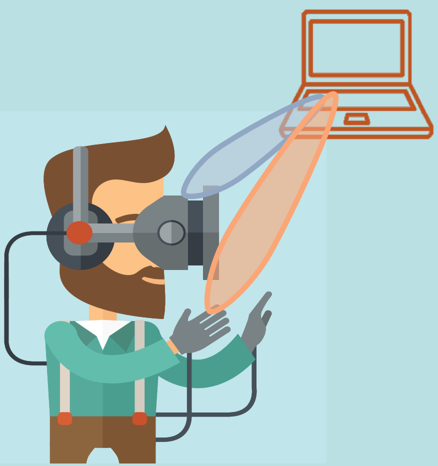
http://www.6gnc.org

Motivation

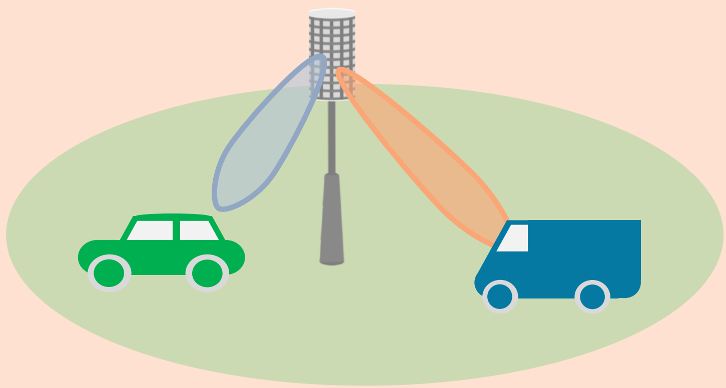


Interesting use cases for mmWave communications and positioning

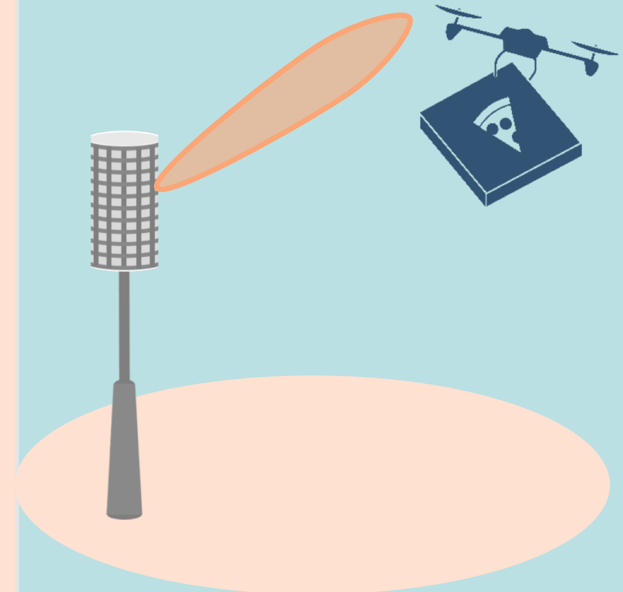
Indoor positioning (factories, gaming, …)



MmWave cellular for vehicular communication and positioning



Cellular network supporting UAVs



High accuracy positioning and communication at mmWave is a key technology for different use cases in indoor and outdoor scenarios

MmWave communication based positioning: use cases defined by 3GPP

Accurate positioning supporting AR/VR devices for gaming

Accurate positioning for emergency services

Accurate positioning for first responders

Person location in hospitals (psychiatry, geriatrics)

Passenger flow management in airports

Cellular/WiFi supported indoor

Accurate positioning to support traffic monitoring/management

Accurate positioning to support automated vehicles

Accurate positioning supporting AR/VR devices (sports and leisure activities, ...)

Accurate positioning to support UAV missions and operations

Accurate positioning for shared bikes

Location based advertising push

Patient location outside hospitals

Cellular supported outdoor

High accuracy positioning based on communication at mmWave is a key technology for different use cases [1]

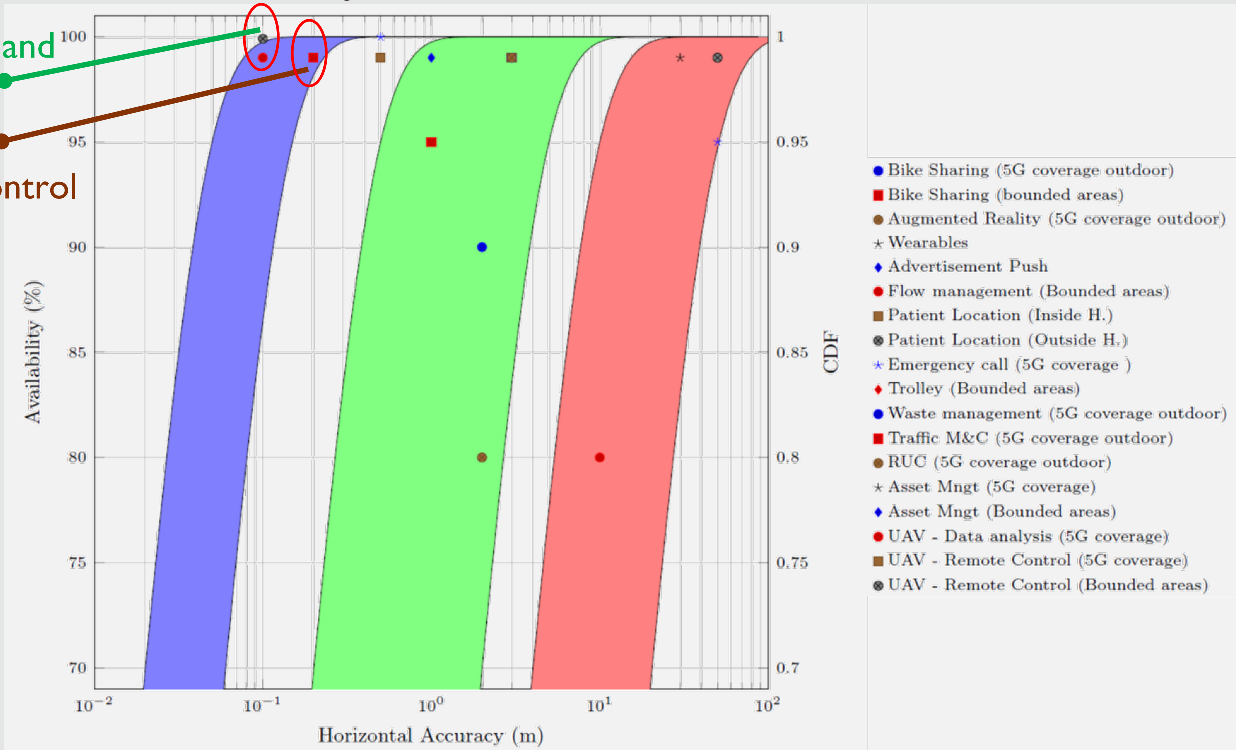
[1] 3GPP TR 22.872 V16.0.0, Technical Specification Group Services and System Aspects; Study on positioning use cases; Stage 1 (Release 16), June 2018

Accuracy and availability: potential requirements

Figure taken from [1]

UAV control and data analysis

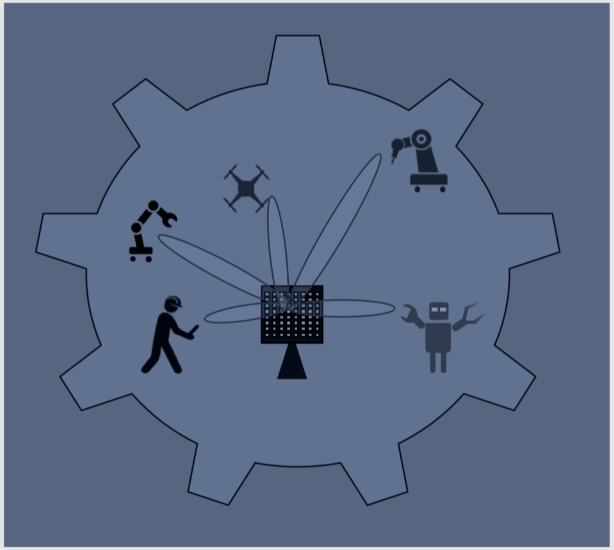
Traffic Monitoring, Management and Control Bike sharing



Some key use cases need of very high accuracy and high availability

[1] 3GPP TR 22.872 V16.0.0, Technical Specification Group Services and System Aspects; Study on positioning use cases; Stage 1 (Release 16), June 2018

Positioning in 5G industrial use cases (IIOT)



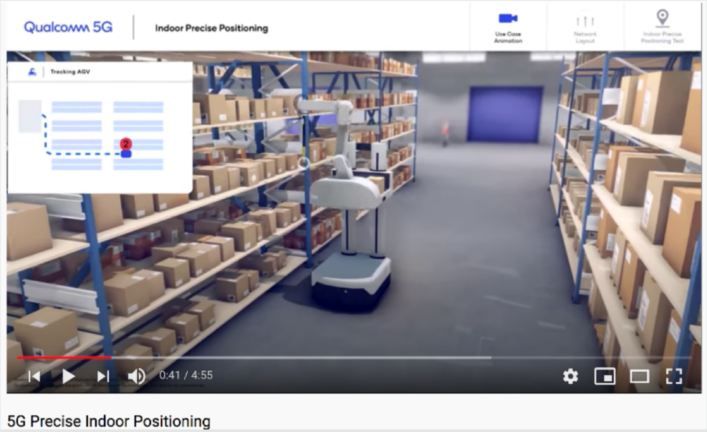


Image from [1]

Horizontal positioning accuracy better than 3 meters (indoors) for 80% of the UEs

Vertical positioning accuracy better than 3 meters (indoors and outdoors) for 80% of the UEs

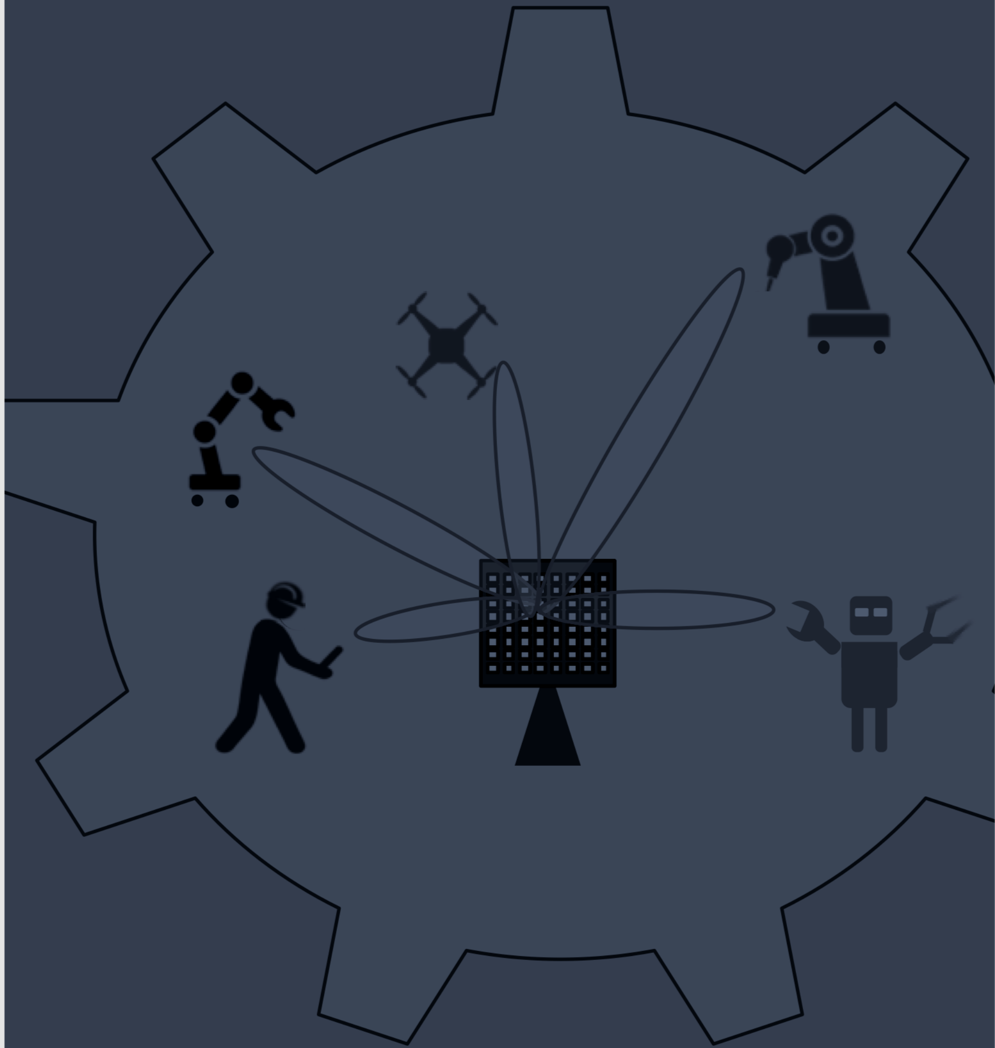
End-to-end latency less than 1 second.

Downlink and uplink based solutions possible [2]

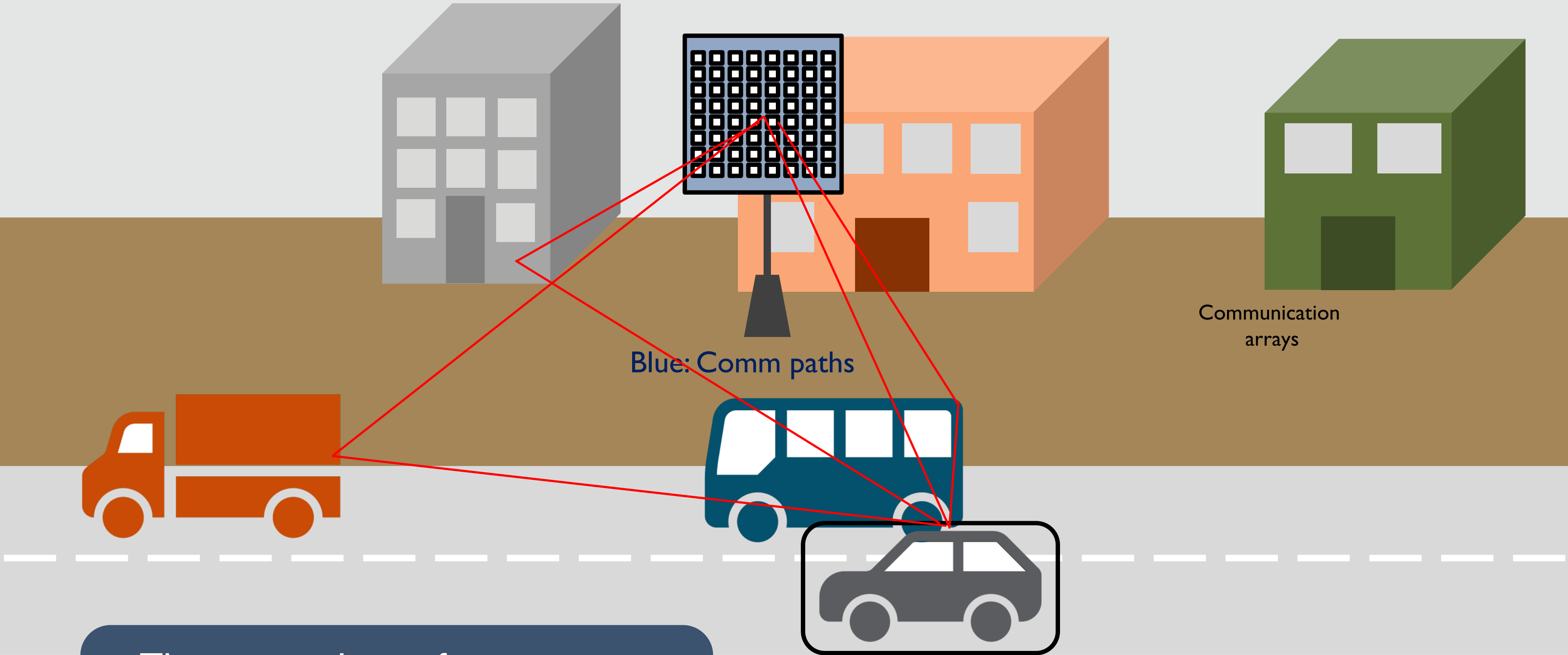
Higher accuracies being defined for release 17, specially for IIOT use cases

[1] https://www.youtube.com/watch?v=pTdsAuwZPFI&list=PLADNcabi-P9Z-ntSevtC_AFWSxLpl-2af&index=8
[2] 3GPP TR 38.855 V16.0.0, Technical Specification Group Radio Access Network; Study on NR positioning support (Release 16), March 2019

Overview of mmWave localization



Main idea

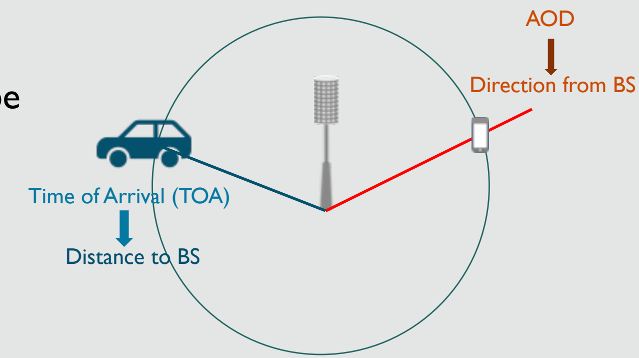


The received waveform contains information about the geometry of the propagation environment

How can we determine the UE position and orientation? Why mmWave waveform?

Measurements for localization: geometric intuition

-All methods assume LoS, asingle measurement per AP and the AP locations known.
-Alternative measurements like NLoS or measurements over time can be used to improve the location system.
-ADoA is AoA without orientation.
-TDoA is ToA without a synchronized timestamp
-ADoD is useless with only LoS
-There’s no benefit on using TDoA+AoA



Measurement	Estimate
(AoA or AoD)	Location if $N_{\mathrm{AP}} \geq 2$ (triangulation), also Orientation if AoA or ADoA available
ToA	Location if $N_{\mathrm{AP}} \geq 3$ (trilateration)
ADoA	Location and Orientation if $N_{\mathrm{AP}} \geq 3$ (isoptical arcs)
TDoA	Location if $N_{\mathrm{AP}} \geq 4$ (hyperbolic intersection)
ToA + (AoA or AoD)	Location if $N_{\mathrm{AP}} \geq 1$ (direct calculation), also Orientation if AoA
ToA + ADoA	Location and Orientation if $N_{\mathrm{AP}} \geq 2$ (isoptical arc + circumferences)
TDoA + ADoA	Location and Orientation if $N_{\mathrm{AP}} \geq 2$ (isoptical arc + hyperbole)

Results obtained in3GPP

Baseline Channel Model based on common assumptions defined related to the channel models of 3GPP TRs 38.901 / 38.802 / 37.857.
30 GHz
120 KHz
Interference from 4 UEs
TOA estimation without oversampling with TOA pruning before the positioning engine using the ratio of the estimated TOA peak over the median of the Channel Energy Response (CER).
For UL-TDOA Pick the best between Taylor series*, and Chan's Algorithm**.
Perfect Sync and Realistic Sync with T1 = 50 nsec
Kronecker product between vertical and horizontal weight vectors taken from DFT, with oversampling factor 2

Percentile	50	67	80	90	95
UL-TDOA, FR2, 400 MHz, Perfect Sync	0.4	0.7	1.5	4.2	9.5
UL-TDOA, FR2, 400 MHz, Realistic Sync	12.2	17.3	25.3	41	56
UL-TDOA, FR2, 100 MHz, Perfect Sync	1.2	1.9	3	5.6	10.2
UL-TDOA, FR2, 100 MHz, Realistic Sync	12.3	17,5	25.3	41.1	56.8
UL-TDOA+AoD, FR2, 400 MHz, Perfect Sync	0.3	0.4	1	2.5	6.5
UL-TDOA+AoD, FR2, 400 MHz, Realistic Sync	10.5	15.8	23.4	36	47.7
UL-TDOA+AoD, FR2, 100 MHz, Perfect Sync	0.7	1	1.5	2.8	5.1
UL-TDOA+AoD, FR2, 100 MHz, Realistic Sync	11.9	18	26.3	41.1	53.3

*Chan's Algorithm according to: Y. T. Chan, K. C. Ho, " A Simple and Efficient Estimator for Hyperbolic Location", IEEE Transactions on Signal Processing, vol. 42, pp. 1905-1915, Aug. 1994.
**Taylor Series Algorithm: W. H. Foy, " Position-Location Solutions by Taylor-Series Estimation", IEEE Transactions on Aerospace and Electronic Systems, vol. AES-12, pp. 187-194, March 1976.
***For UL-TDOA+AoA, the algorithm presented in the following paper is used: Chunhua Yang, Yi Huang and Xu Zhu, 'HYBRID TDOA/AOA METHOD FOR INDOOR POSITIONING SYSTEMS', IEEE Sig. Proc. Letters, Vol23, issue 1, 2016 Equal weight is used in the TOA covariance matrix

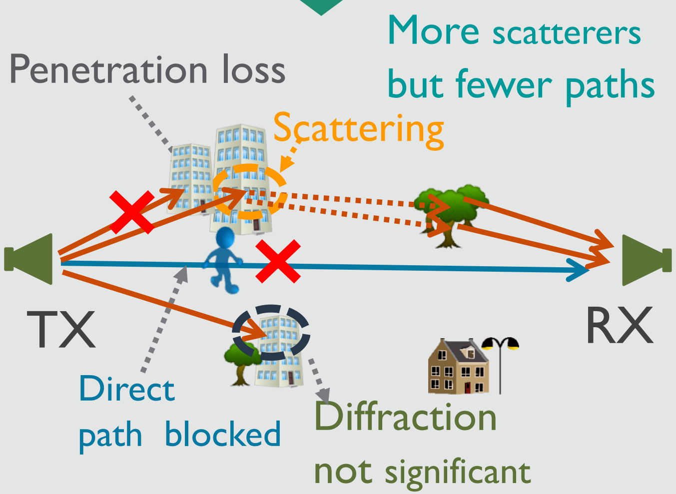
[1] 3GPP TR 38.855 V16.0.0, Technical Specification Group Radio Access Network; Study on NR positioning support (Release 16), March 2019

Why mmWave positioning?

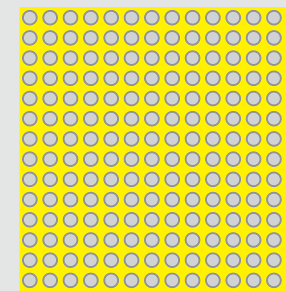
High carrier frequencies

Large bandwidth

Large arrays



$$\boxed{|\tau_1-\tau_2|B>>1}$$



Sparse channel, easier to relate to propagation environment

Large bandwidth provides better estimation accuracy and more paths are resolvable

Large N_{RX} provides better AoA resolvability

Large N_{TX} provides better AoD resolvability

Approaches and assumptions for mmWave localization

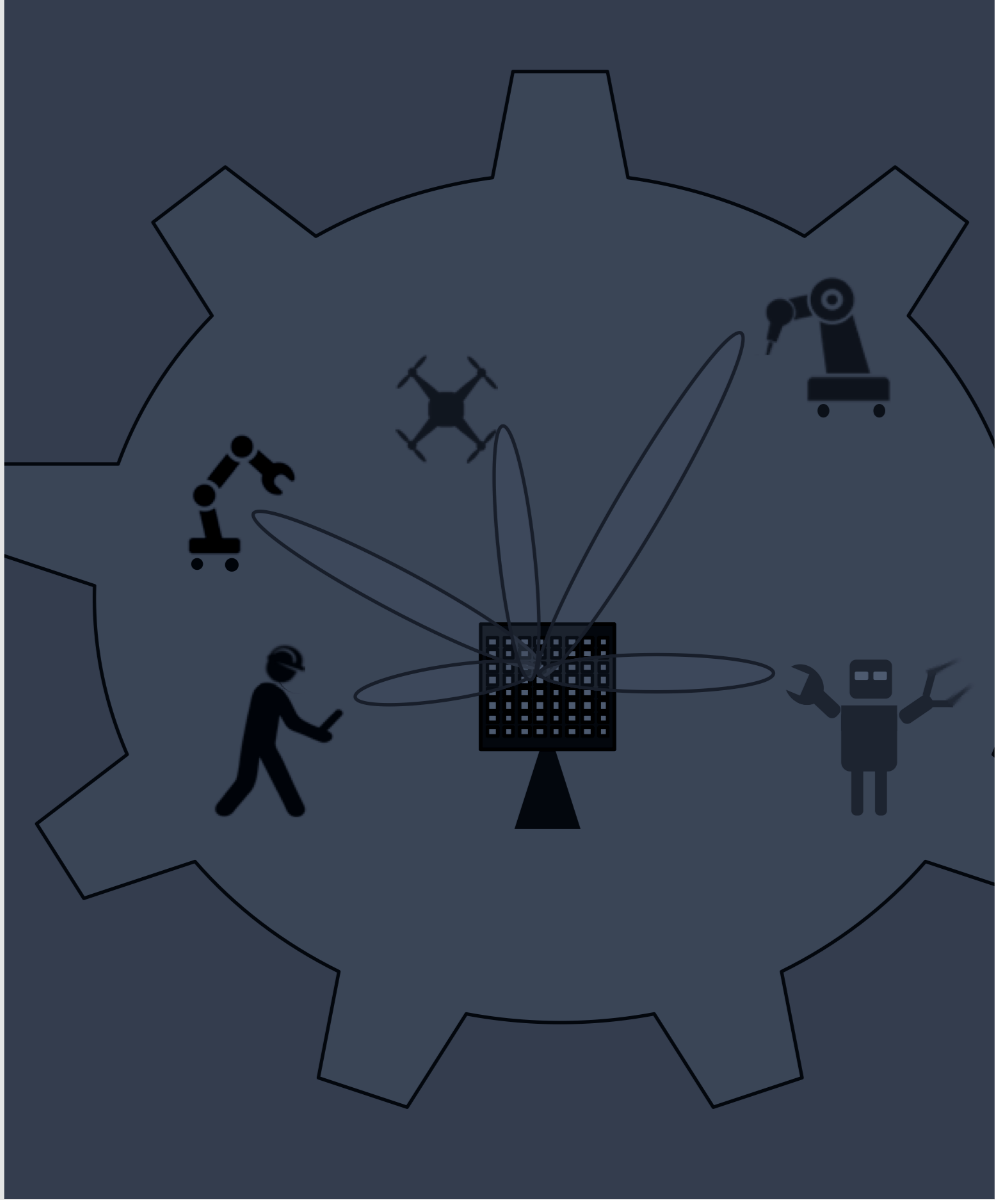
Zero knowledge vs. some PO info of anchors

Model driven vs. data driven approaches

Layered vs. direct approaches

Delay domain vs. angle domain or combined approaches

A ML approach to mmWave localization



Positioning based Beamformed Fingerprints

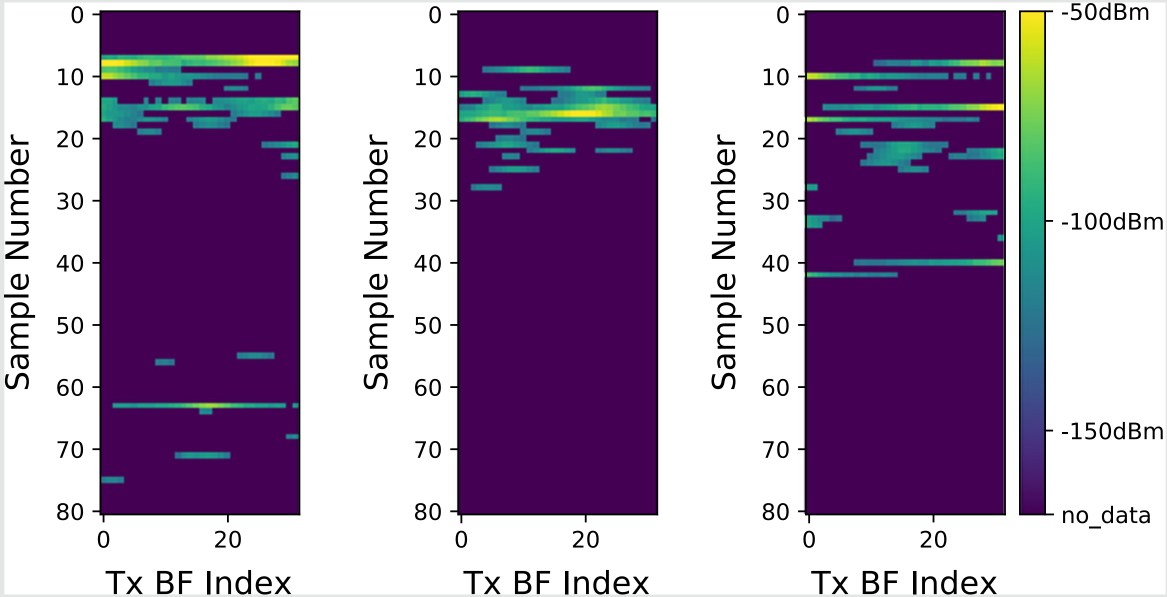


Image taken from [1]

Example of noiseless fingerprints

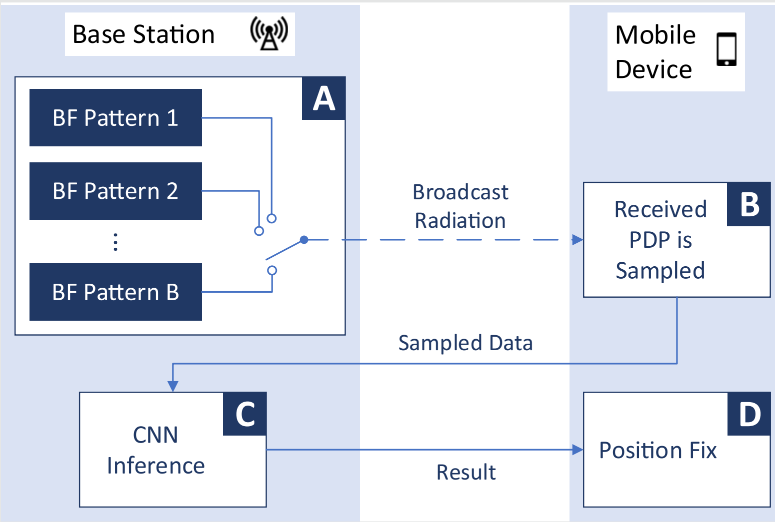
Each propagation path provides a unique power attenuation and delay

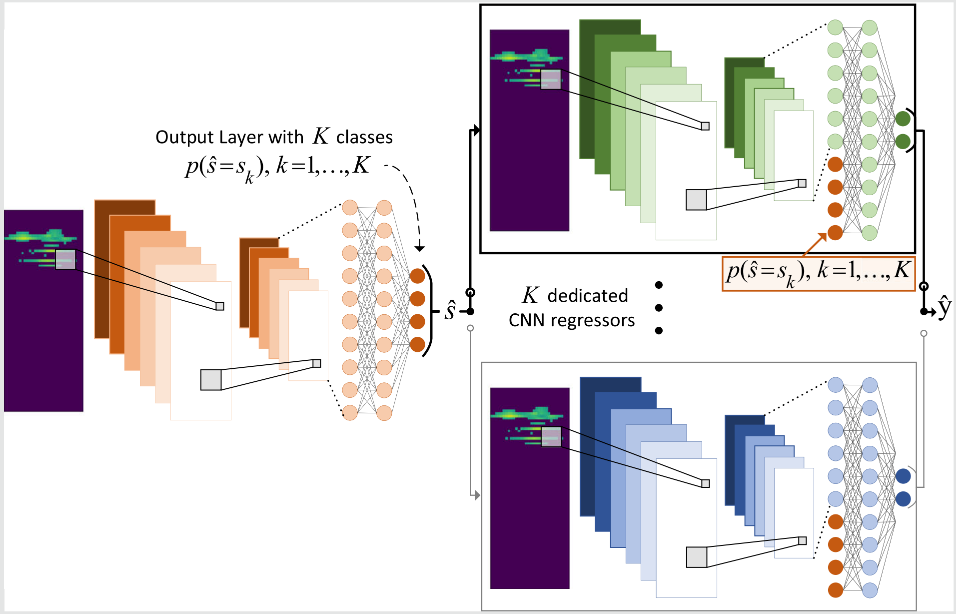
A collection of PDPs obtained with different transmit beampatterns provides position information

Requires a single anchor

[1] J. Gante, G. Falcão, L. Sousa, "Deep Learning Architectures for Accurate Millimeter Wave Positioning in 5G", Neural Processing Letters (2020) 51:487–514

Proposed scheme and DNN





Images taken from [1]

Position estimation at the BS to avoid weights downloads from each BS

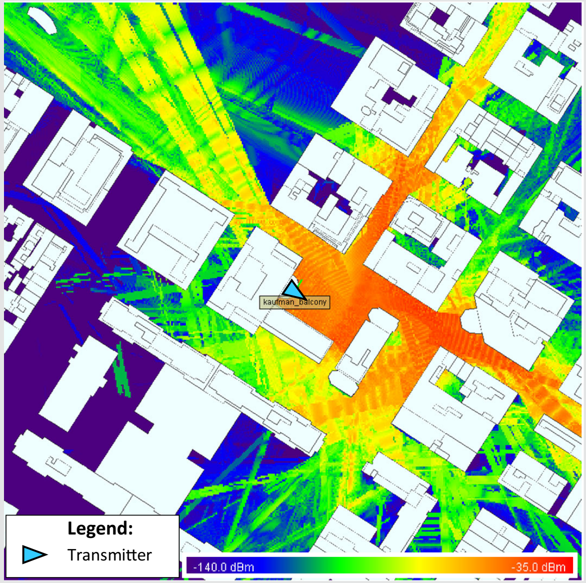
Orientation estimation not available

K dedicated CNNs to cover K subregions in the coverage area

CNN training is guided by a loss function based on MSE in position estimate

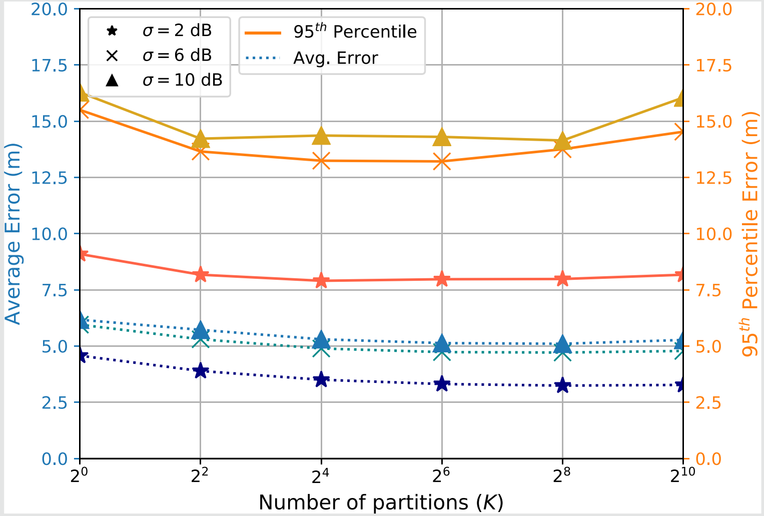
[1] J. Gante, G. Falcão, L. Sousa, "Deep Learning Architectures for Accurate Millimeter Wave Positioning in 5G", Neural Processing Letters (2020) 51:487–514

Simulation results



Images taken from [1]

Parameter name	Value
Carrier frequency	28 GHz
Transmit power	45 dBm
Tx. antenna gain	24.5 dBi (horn antenna)
HPBW	10.9°
Transmitter downtilt	10°
Codebook size	32 (155° arc with 5° between entries)
Receiver grid size	160801 (400 × 400 m, 1 m between Rx, 1 m above the ground)
Samples per Tx. BF	82 (4.1 µs @ 20 MHz)
Assumed Rx. Gain	10 dBi (as in [36])
Detection threshold	−100 dBm
Added noise	σ = [2, 10] dB (Log-Normal)

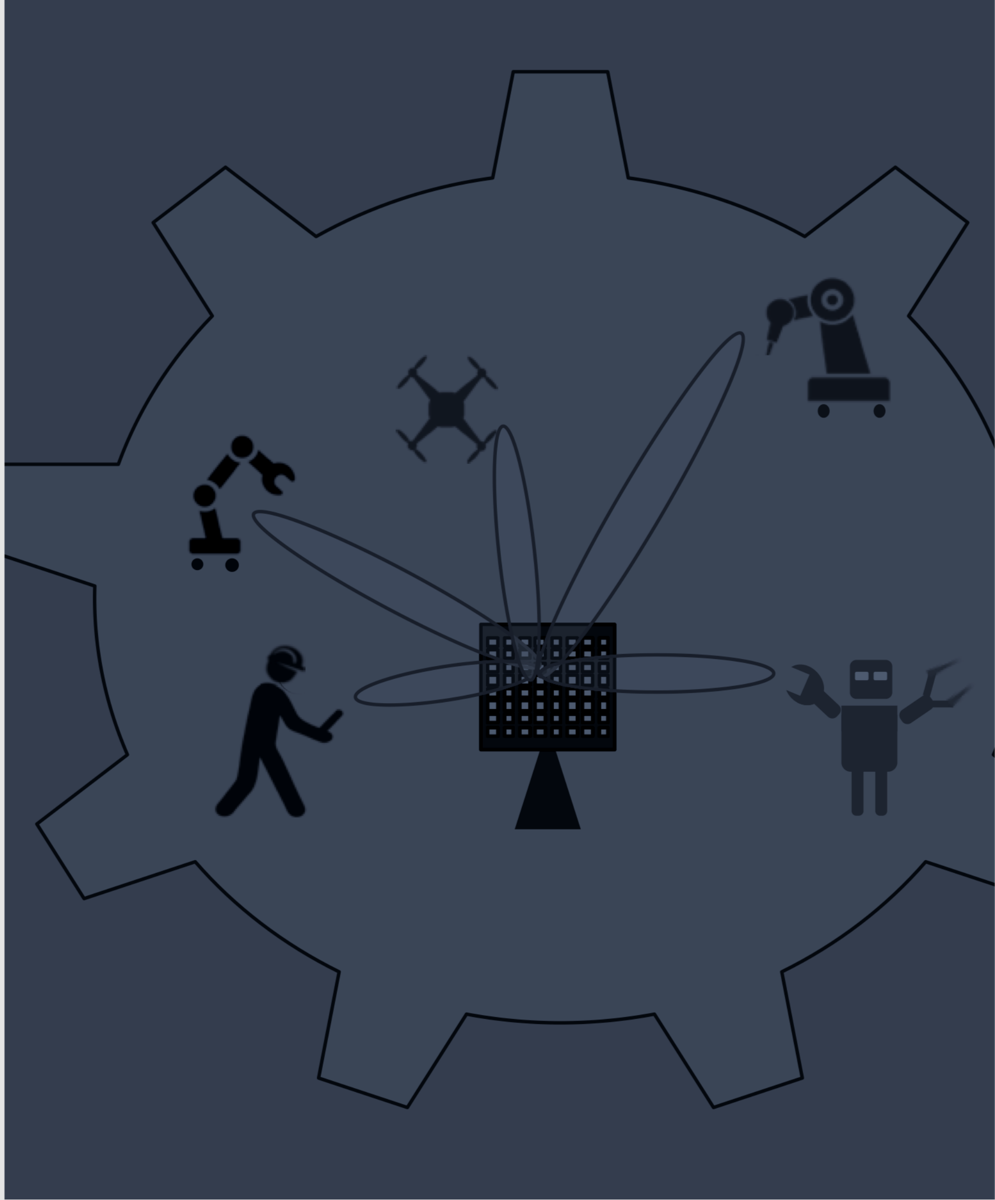


Dataset using mmWave ray-tracing simulations in the New York University area is used, containing BFF data from 160801 different bidimensional positions

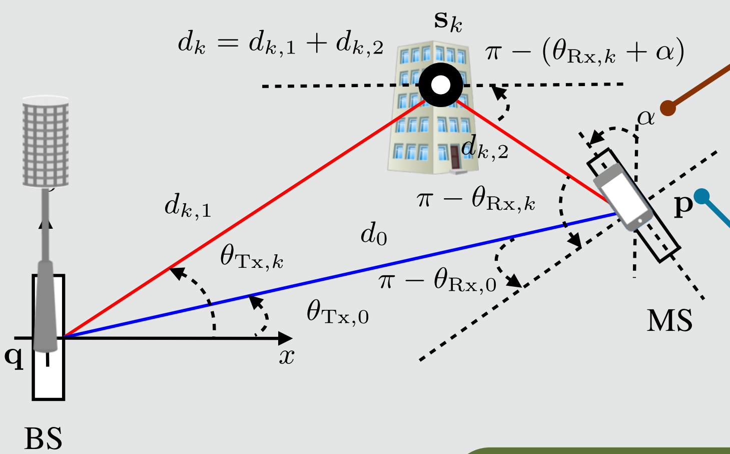
Estimation accuracy in the order of 3 m for sigma=2

[1] J. Gante, G. Falcão, L. Sousa, "Deep Learning Architectures for Accurate Millimeter Wave Positioning in 5G", Neural Processing Letters (2020) 51:487–514

A layered approach to mmWave localization



A layered approach to mmWave positioning



Orientation of the device

Position of the device

Tx location and orientation are known

Single bound reflections

Smart device position can be obtained from the distance to the BS and AoD/AoD information

Frequency-selective MIMO channel

N_c is the delay tap length

$$\sum_{d=0}^{N_c-1} p_{\mathrm{rc}}(dT_s - \tau_\ell) e^{-\mathrm{j}\frac{2\pi k d}{K}}$$

$$\boldsymbol{H}[k] = \sqrt{\frac{N_\mathrm{r} N_\mathrm{t}}{L}} \sum_{\ell=1}^{L} \alpha_\ell \beta_{k,\ell} \mathbf{a}_\mathrm{R}(\phi_\ell) \mathbf{a}_\mathrm{T}^*(\theta_\ell)$$

Channel estimate provides gains, delays and AoA/AoD info

Delays depend on distance

MmWave RX signal → Channel estimation → Convert to distance/bearing →

Estimate MS position in the presence of unknown scatterers locations from channel estimate

Wideband channel model in the frequency domain

Frequency domain MIMO channel matrix in the *kth* subcarrier at time t_n

# of rays

# of clusters

Delay for r_l ray in l cluster

TX and RX array response vectors

AoA

AoD

$$\mathbf{H}^{(n)}[k] = \sum_{l=1}^{L}\sum_{r_l=1}^{R} \alpha_{l,r_l}^{(n)} \exp\left(\frac{-j2\pi k \tau_{l,r_l}^{(n)}}{K T_{\mathrm{s}}}\right) \mathbf{a}_{\mathrm{r}}\left(\phi_{l,r_l}^{(n)}\right) \mathbf{a}_{\mathrm{t}}^{\mathrm{H}}\left(\theta_{l,r_l}^{(n)}\right)$$

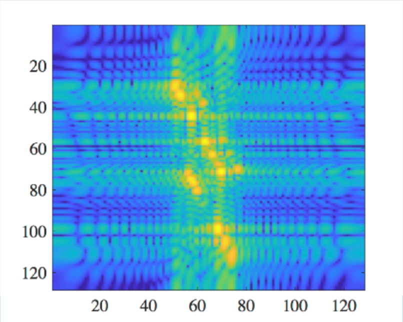
Incorporates effect of channel gains and pulse shaping and analog filtering evaluated at the delays of each cluster

$$\mathbf{H}[k] = \mathbf{A}_{\mathrm{R}}\left(\boldsymbol{\phi}^{(n)}\right)\mathbf{G}^{(n)}[k]\mathbf{A}_{\mathrm{T}}^{*}\left(\boldsymbol{\theta}^{(n)}\right)$$

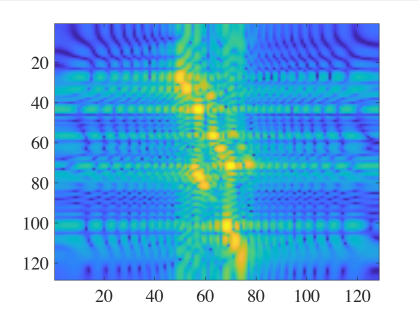
For a wideband model there is a sparse virtual matrix for every subcarrier [1]

256 subcarriers, 500 MHz bandwidth

Subcarrier 1



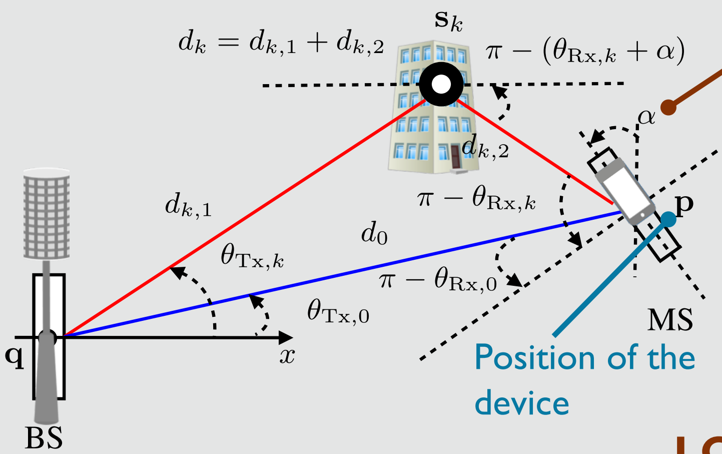
Subcarrier 128



Common support between subcarriers can be exploited [2] to estimate the channel

[1] P- Schniter and A. Sayeed, "Channel estimation and precoder design for millimter wave communication:s: the sparse way", Asilomar 2014
[2] Javier Rodríguez-Fernández, Nuria González-Prelcic, Kiran Venugopal, and Robert W. Heath Jr., "Frequency-domain Compressive Channel Estimation for Wideband Hybrid Millimeter Wave Systems", IEEE Trans. On Wireless Communications, 2018,.

Conversion from channel parameters to position and orientation



Orientation of the device

Equations taken from [1]

Use AOA, DOA, TOA

$$\tau_0 = \|\mathbf{p} - \mathbf{q}\|_2 / c,$$

$$\theta_{\mathrm{Tx},0} = \arccos((p_x - q_x)/\|\mathbf{p} - \mathbf{q}\|_2)$$

$$\theta_{\mathrm{Rx},0} = \pi + \arccos((p_x - q_x)/\|\mathbf{p} - \mathbf{q}\|_2) - \alpha.$$

Geometry of the problem

LOS case

Single path, line-of-sight

Delay for LOS path

AoD for LOS path

$$\hat{\mathbf{p}} = \mathbf{q} + c\hat{\tau}_0[\cos(\hat{\theta}_{\mathrm{Tx},0}), \sin(\hat{\theta}_{\mathrm{Tx},0})]^{\mathrm{T}}$$

$$\hat{\alpha} = \pi + \hat{\theta}_{\mathrm{Tx},0} - \hat{\theta}_{\mathrm{Rx},0}.$$

AoA for LOS path

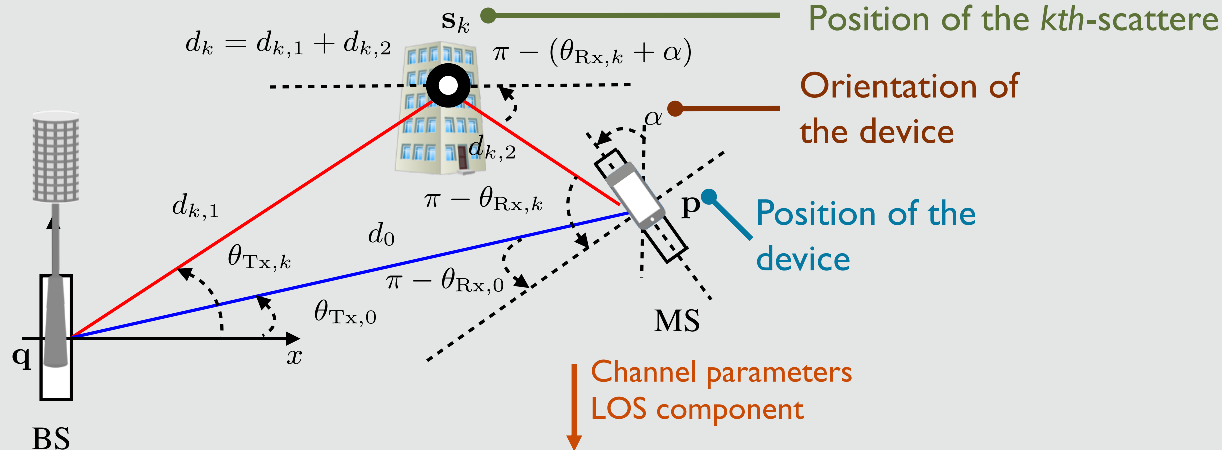
For the LOS case, there is a simple mapping between position and channel parameters

[1] A. Shahmansoori et al., "Position and Orientation Estimation through Millimeter Wave MIMO in 5G Systems," IEEE Trans. Wireless Commun. , March 2018.

Conversion from channel parameters to position/orientation

NLOS case

$\hat{K}$ scatterers and a line-of-sight path



- Initial estimation of $\mathbf{p}$ and α from LOS path
- For the first order reflection estimate the position of the scatterer $\hat{\mathbf{s}}_k$, at the intersection of the lines:

$$\tan(\pi - (\hat{\theta}_{\mathrm{Rx},k} + \hat{\alpha})) = (\hat{p}_y - s_{1,y})/(\hat{p}_x - s_{1,x})$$
$$\tan(\hat{\theta}_{\mathrm{Tx},k}) = (s_{1,y} - q_y)/(s_{1,x} - q_x).$$

- Consider the geometric relationships between $\hat{\mathbf{s}}_k$ and the estimated channel parameters

$$\tau_k = \|\mathbf{q} - \mathbf{s}_k\|_2/c + \|\mathbf{p} - \mathbf{s}_k\|_2/c, \quad k > 0$$
$$\theta_{\mathrm{Tx},k} = \arccos((s_{k,x} - q_x)/\|\mathbf{s}_k - \mathbf{q}\|_2), \quad k > 0$$
$$\theta_{\mathrm{Rx},k} = \pi - \arccos((p_x - s_{k,x})/\|\mathbf{p} - \mathbf{s}_k\|_2) - \alpha, \quad k > 0$$

Channel parameters LOS component

→ **Initial estimation of $\mathbf{p}$ and α**

→ AoA/AoD first reflection → **Estimate position of first scatterer**

→ Delay, AoA/AoD first reflection → **Refine estimation of $\mathbf{p}$ and α**

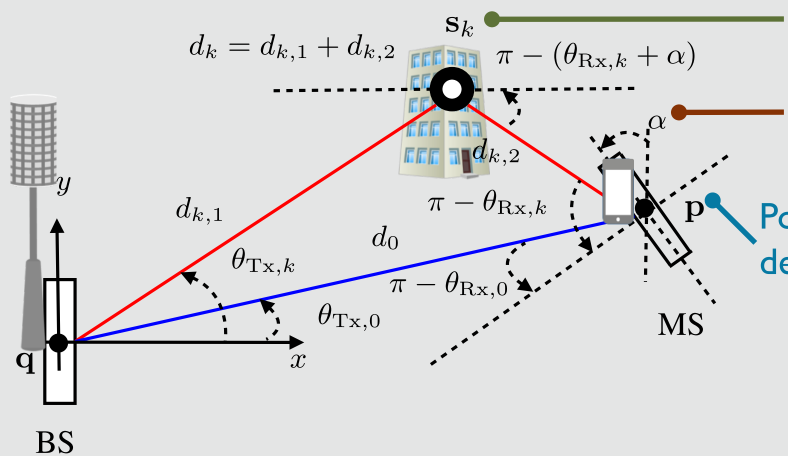
When only a first order reflection is considered, there is a unique relationship between the channel parameters and position/orientation

[1] A. Shahmansoori et al., "Position and Orientation Estimation through Millimeter Wave MIMO in 5G Systems," IEEE Trans. Wireless Commun. , March 2018.

Conversion from channel parameters to position/orientation

NLOS case

$\hat{K}$ scatterers and a line-of-sight path



Position of the *kth*-scatterer

Orientation of the device

Position of the device

How to find $\hat{\mathbf{p}}$ and $\hat{\alpha}$ that better fits the measurements from all the $\hat{K}$ scatterers?

Formulate and solve an optimization problem

$$\tilde{\boldsymbol{\eta}} = \begin{pmatrix} \hat{\mathbf{p}} \\ \hat{\alpha} \\ \hat{\mathbf{s}}_1 \\ \hat{\mathbf{s}}_2 \\ \dots \end{pmatrix} = \underset{\tilde{\eta}}{\operatorname{argmin}} \sum \left| \begin{pmatrix} \hat{\boldsymbol{\theta}}_k \\ \hat{\tau}_k \end{pmatrix} - f\begin{pmatrix} \mathbf{p} \\ \mathbf{s}_k \end{pmatrix} \right|^2$$

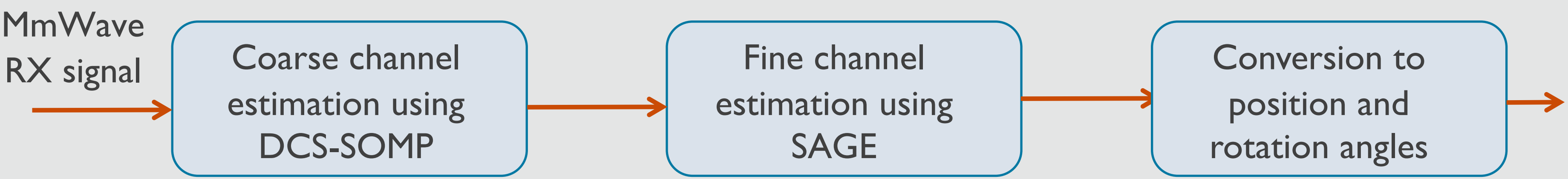
mapping position-channel

If there is prior knowledge about the statistics of the channel parameters and/or the received signal, it could also be exploited using a different cost function

Conversion strategies for OLOS, and unknown case can also be derived

[1] A. Shahmansoori et al., "Position and Orientation Estimation through Millimeter Wave MIMO in 5G Systems," IEEE Trans. Wireless Commun. , March 2018.

Summary of this approach

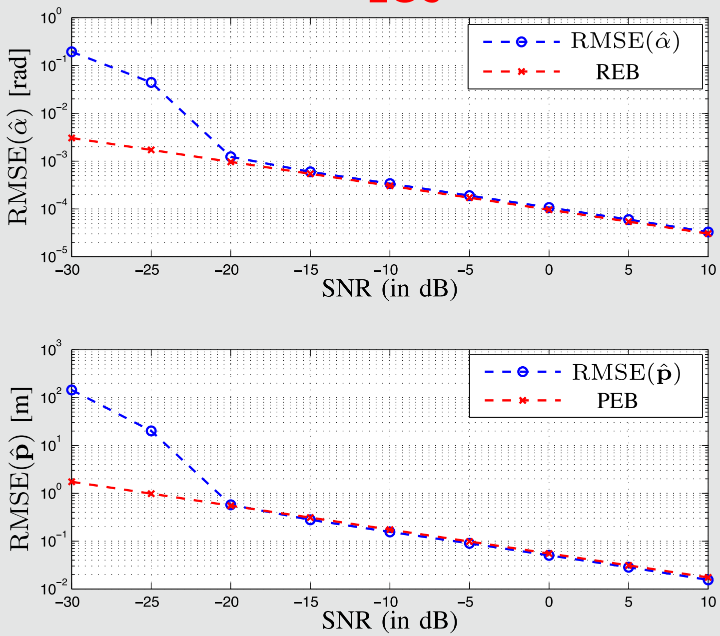


- Non band-limited channel
- Fully digital architecture at the RX (65 antennas at the device)
- High complexity
- Evaluation with an indoor localization, only short distance (4m), static channel

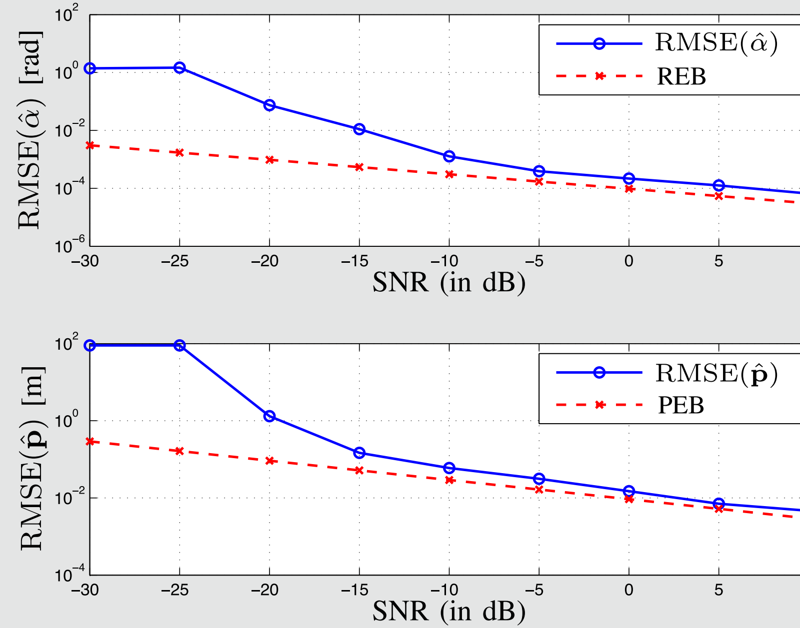
[1] A. Shahmansoori et al., "Position and Orientation Estimation through Millimeter Wave MIMO in 5G Systems," IEEE Trans. Wireless Commun. , March 2018.

Results in an indoor scenario

LOS



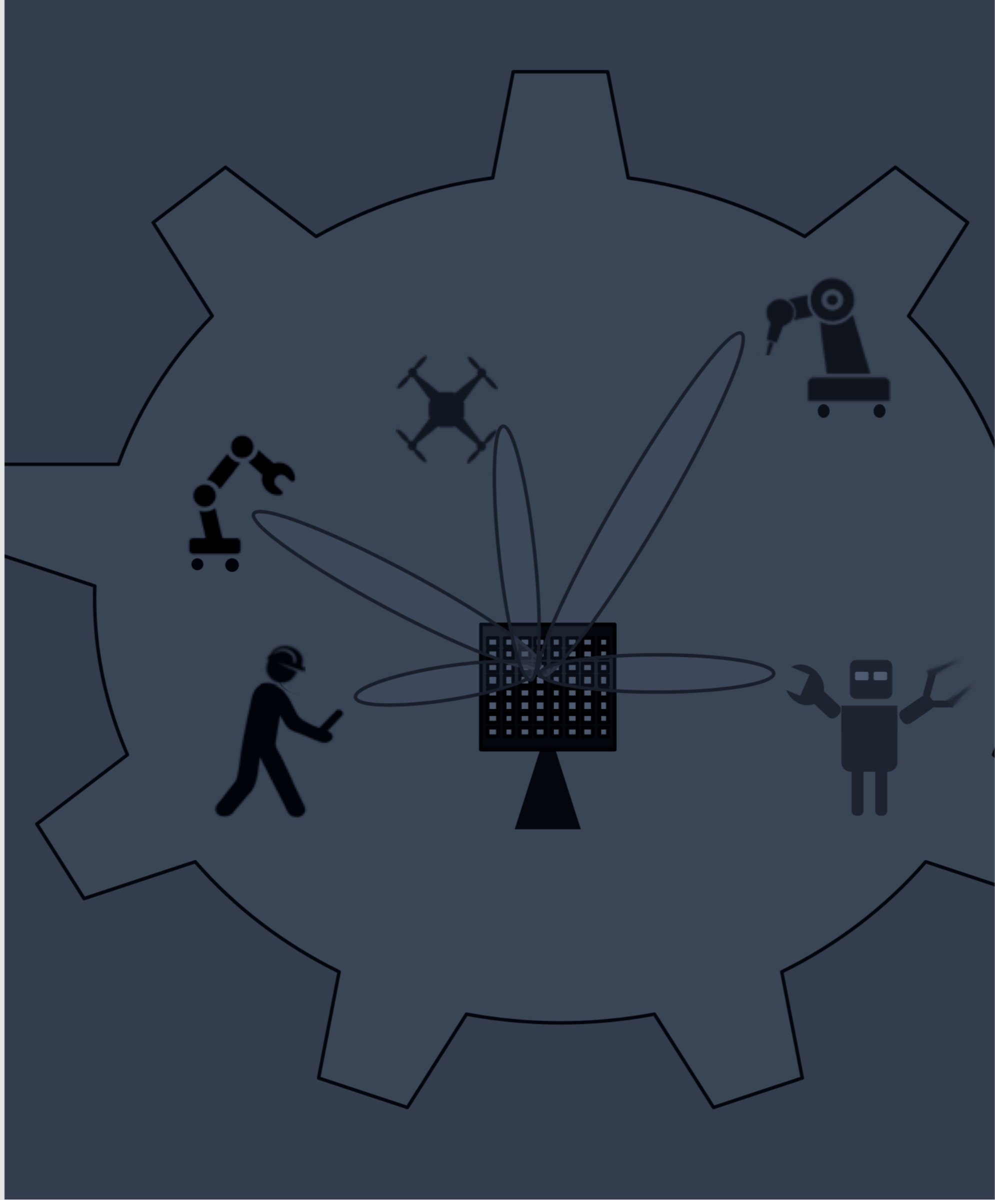
NLOS



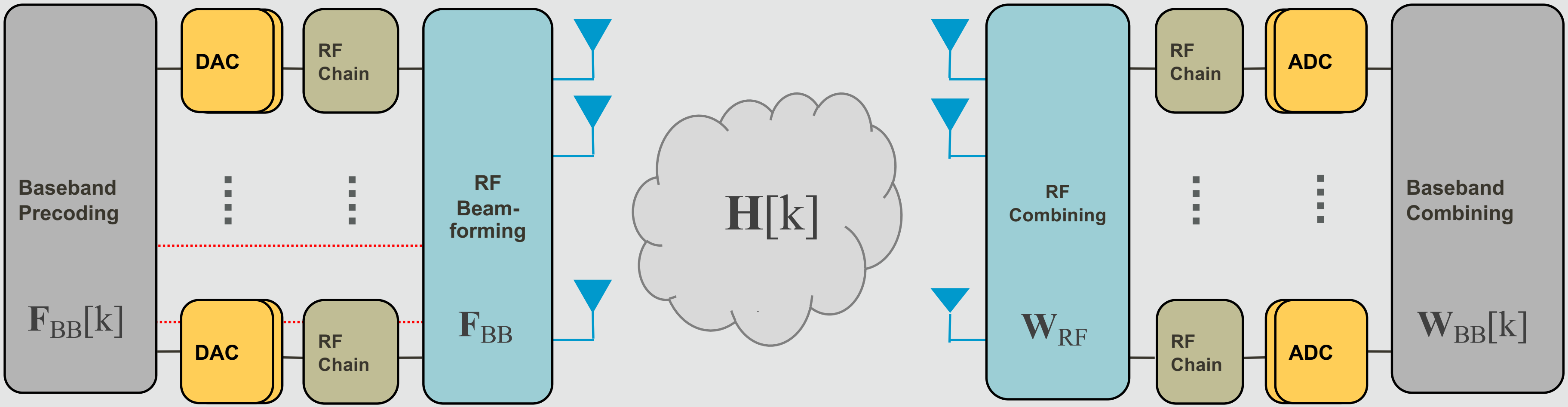
Maximum distance between BS and device of 4 m, B=100 MHz, f_c=60 GHz, N=20 subcarriers, N_t=65 antennas, N_r=65 antennas, up to 3 scatterers

For SNR=0 dB, position estimation error in the order of 5 cm for LOS and 1cm for NLOS

The challenge



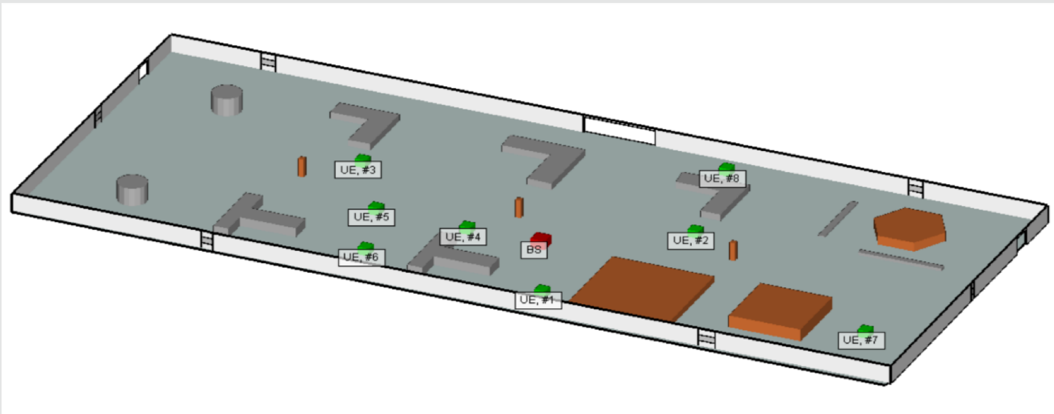
A realistic mmWave MIMO architecture



We consider a hybrid mmWave MIMO architecture operating at mmWave to reduce power consumption

Position and orientation has to be estimated from the received signal in a multidevice case

The data set

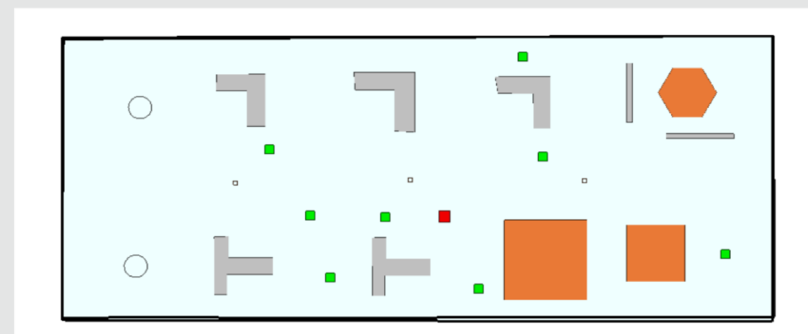


Access points on the ceiling:
6 x 3 grid (20 m spacing),
4 x 2 grid (30m spacing)

Room Size: 120 m x 60 m x 10 m
6 Windows (glass), 2 Doors
Objects:
7 boxes made of metal, 6 boxes made of wood, with sizes around 2m x 2m x2m

Ray tracing set up (Wireless Insite) already developed to generate a data base of channel realization and associated P/O of devices in an emulated factory environment

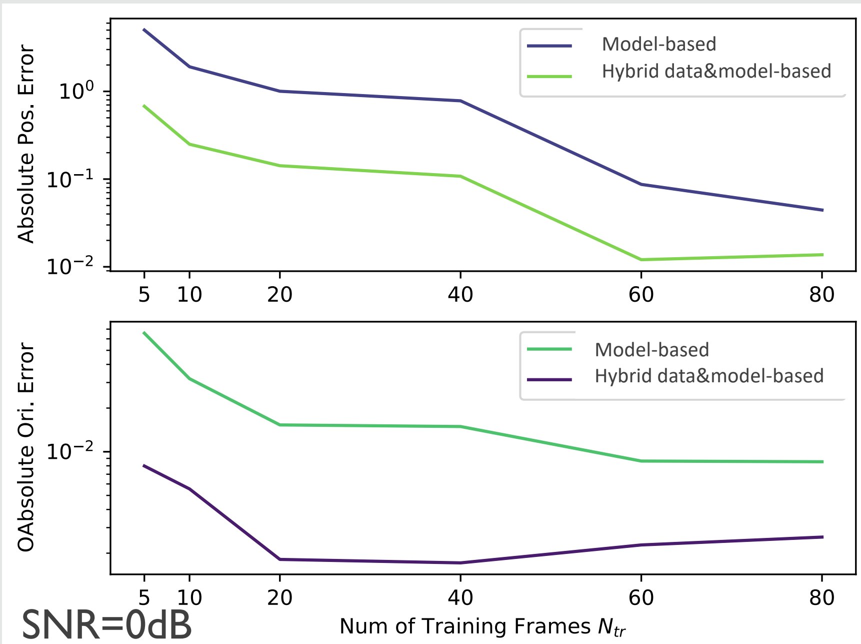
fc=60GHz, Bandwidth= 1GHz

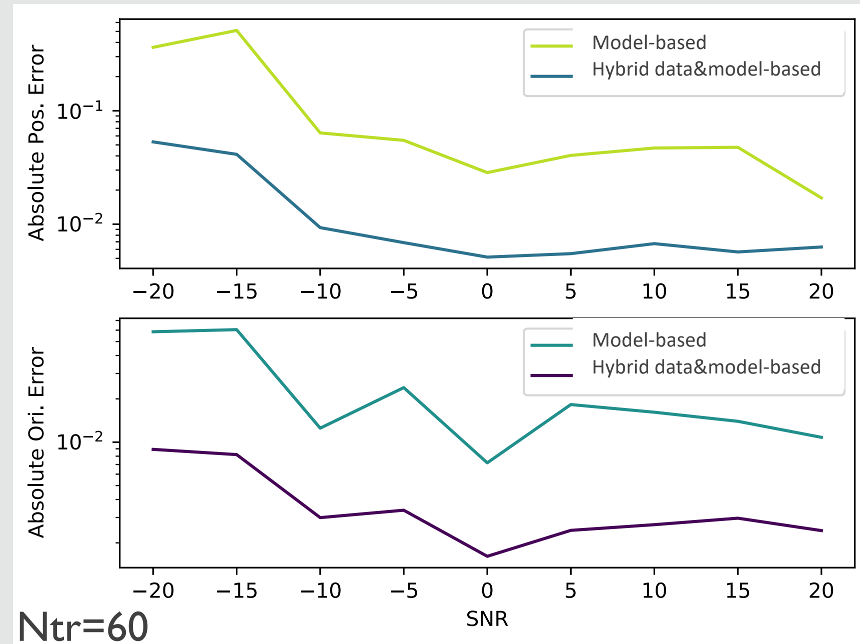


Test: we will provide a set of received signals and corresponding precoders and combiners

Our preliminary results

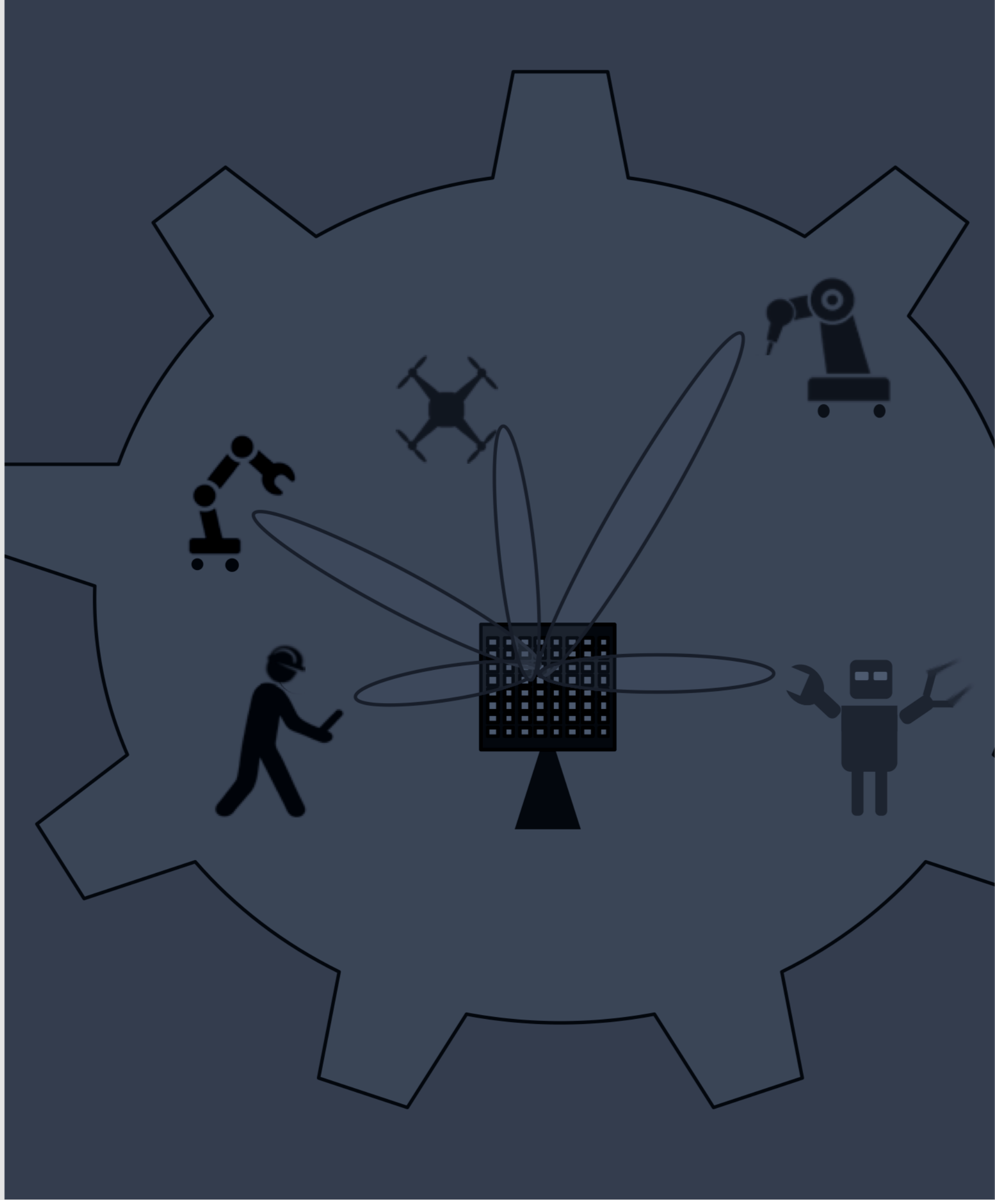
Nt=16, Nr=64, RF chains: $L_{rf}=L_{rf}=2$





[1] W. Zheng and N. González-Prelcic, "Joint Position, Orientation AND Channel Estimation in Hybrid mmWave MIMO Systems," 2019 53rd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2019, pp. 1453-1458.
[2] W. Zheng and N. Gonzalez Prelcic, “Multidevice mmWave localization in a factory environment: a hybrid data and model driven approach”, under preparation, 2021.

Thanks!



http://www.6gnc.org
ngprelcic@ncsu.edu