Deep Learning for THz Channel Estimation and Beamforming Prediction via Sub-6GHz Channel

MODERN WIRELESS NETWORKS GROUP

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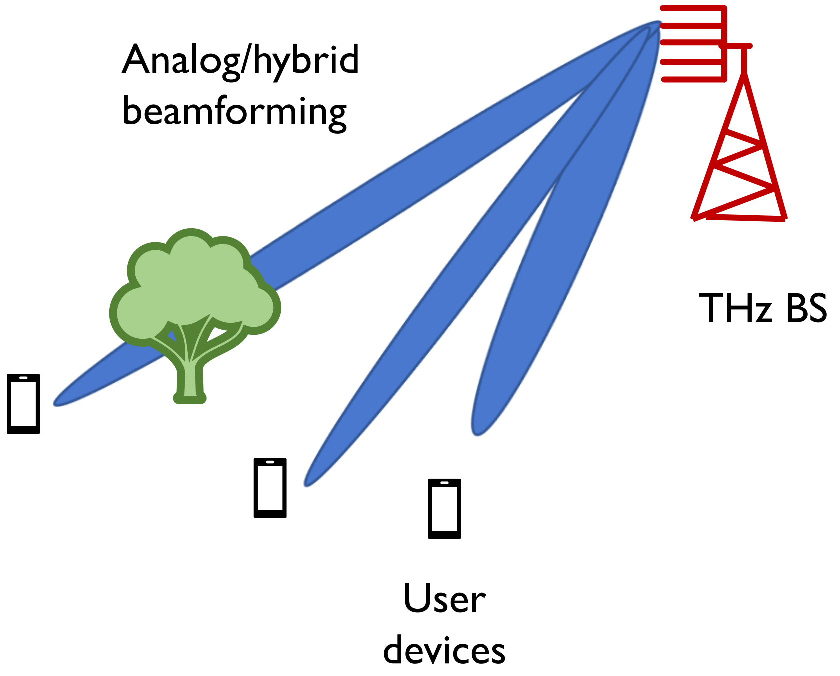
Communications at Terahertz (THz) Frequencies

- Emerging wireless applications
  - Augmented reality, ultra-low latency video conferencing.
- Requiring data rates in Tb/s.
- Even mmWave assisted 5G may fall short of requirement.
- Use of THz spectrum is inevitable.
- Challenges of THz signals
  - Exponential pathloss decay due to atmospheric attenuation,
  - High blockage and penetration losses.
- Implications
  - Ultra dense base station (BS) deployment
  - Large antenna arrays with analog/hybrid beamforming.



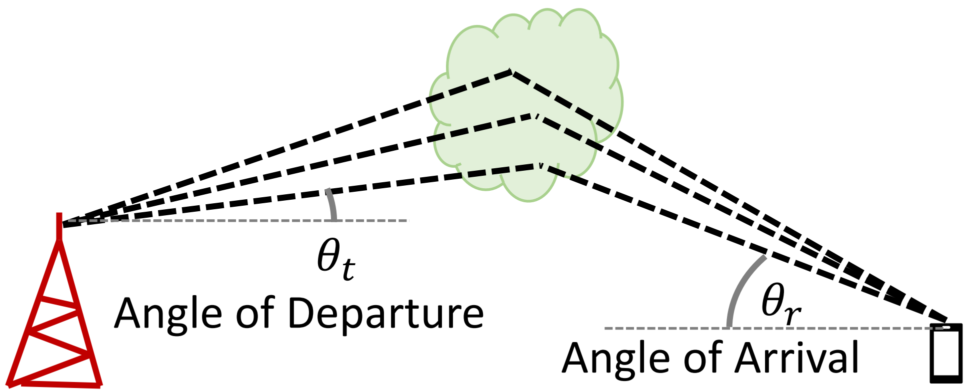
S. Tripathi, N. V. Sabu, A. K. Gupta and H. S. Dhillon, ''Millimeter-wave and Terahertz Spectrum for 6G Wireless,'' in 6G Mobile Wireless Networks, Springer. 2021

THz Channel Estimation

- Real-time and reasonably accurate THz channel estimation is required.

- Conventional channel estimation methods, e.g. least square (LS) or linear minimum mean squared (LMMS) estimation, require large number of uplink pilot signals due to large antenna array at THz
  - Significant overhead considering real-time applications.
  - Not viable.

- Sub-6GHz channel, on the other hand, can be estimated with a smaller number of uplink pilots
  - Relatively low overhead.



Can we estimate THz channel from Sub-6GHz channel values?

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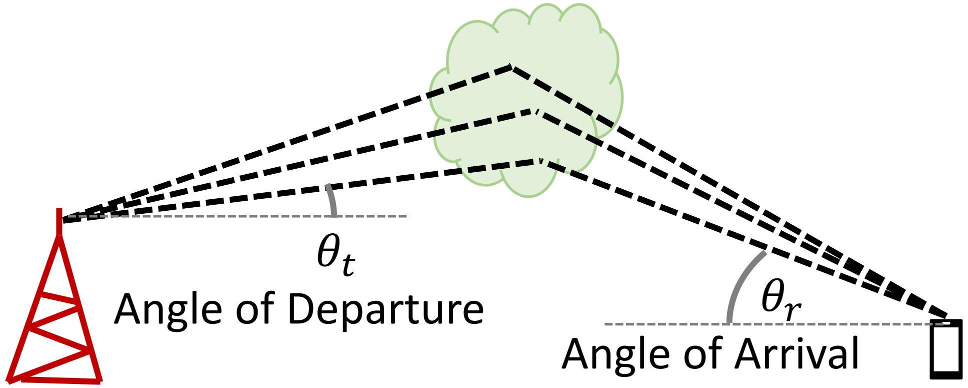
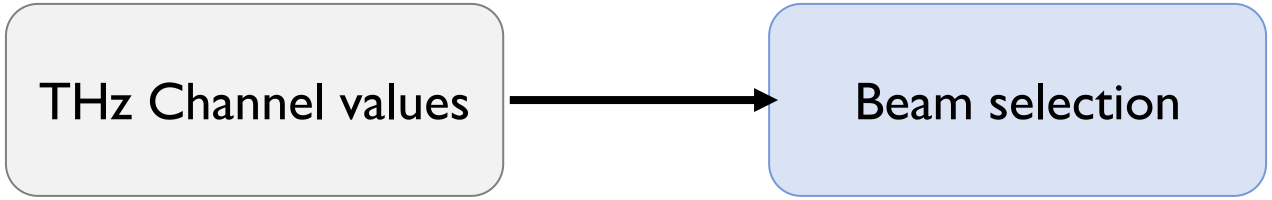


Can we estimate THz channel from Sub-6GHz channel values?

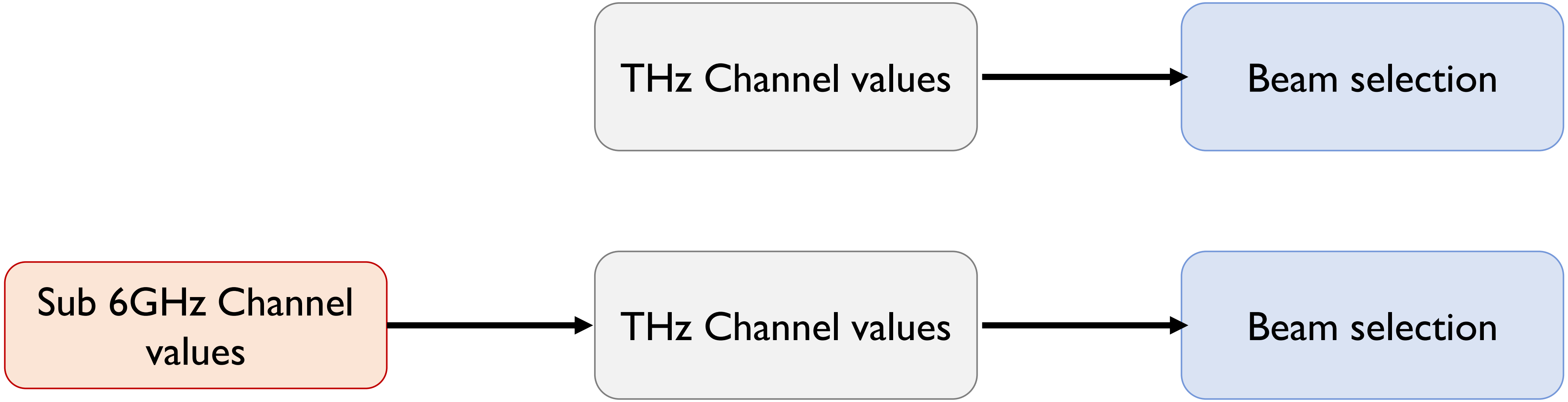
Can we take transmitter side decision from Sub-6GHz channel values?

Beam selection
BS selection
Blockage prediction

Cascaded Architecture

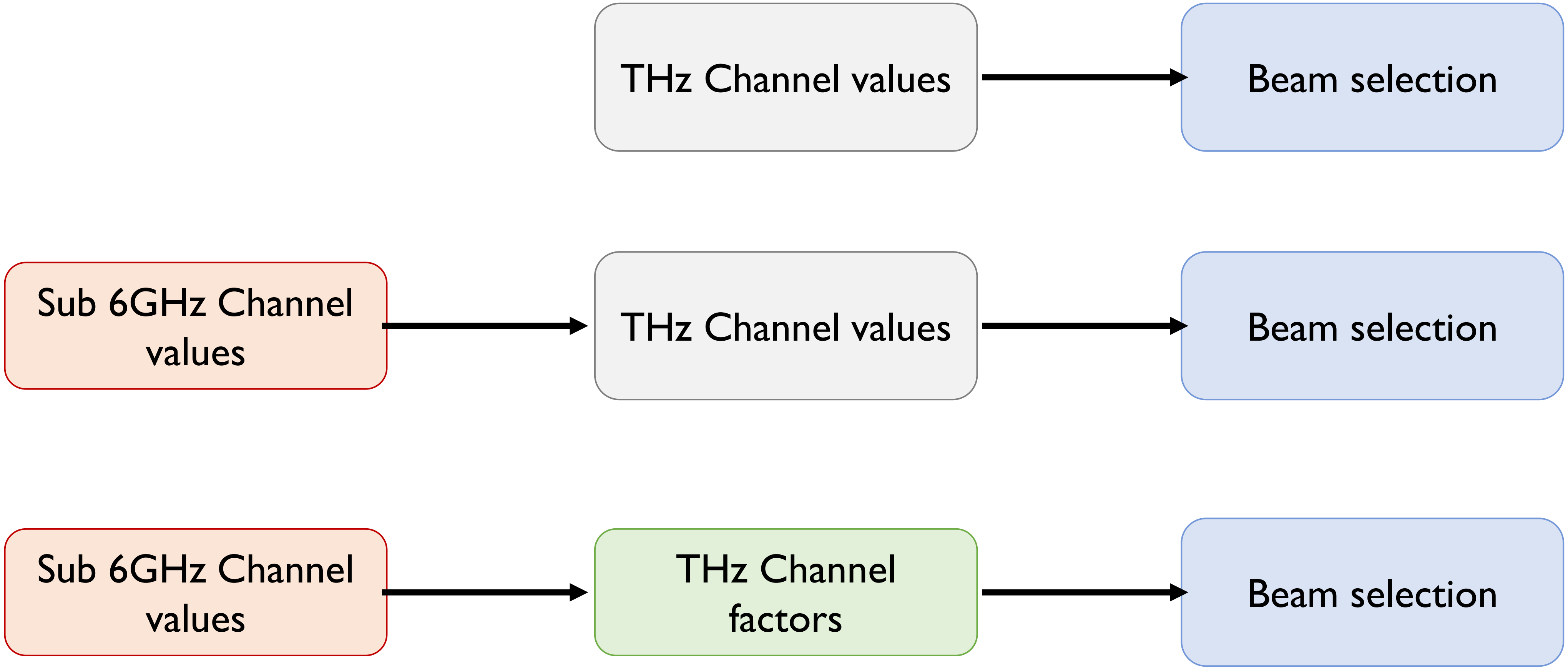


Cascaded Architecture



Direct estimation of THz channel matrix computationally expensive

Cascaded Architecture



Direct estimation of THz channel matrix computationally expensive

Angles of arrival and departure,
Time of arrival,
phase change on arrival

Computationally expensive THz channel matrix estimation and exhaustive codebook search bypassed.

Cascaded Architecture

Sub 6GHz Channel values → THz Channel factors → Beam selection

Cascaded Architecture

Sub 6GHz Channel values → THz Channel factors → Beam selection

Given the uplink Sub-6GHz channel matrix

- Estimate the channel factors for N strongest THz channel paths between BS and user in a computationally efficient manner
- N is a pre-specified constant.

Phase I

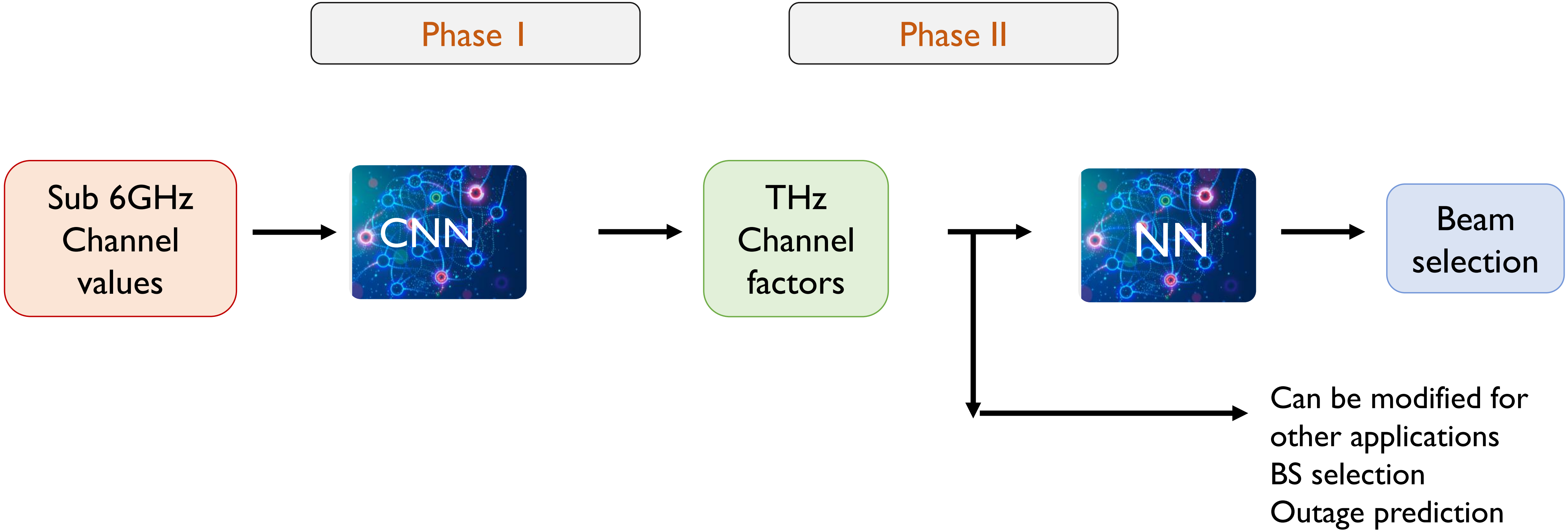
Given the estimated THz channel factors between a BS and a user,

- Predict the optimal analog beamformer from a pre-specified codebook, in a computationally efficient manner

Phase II

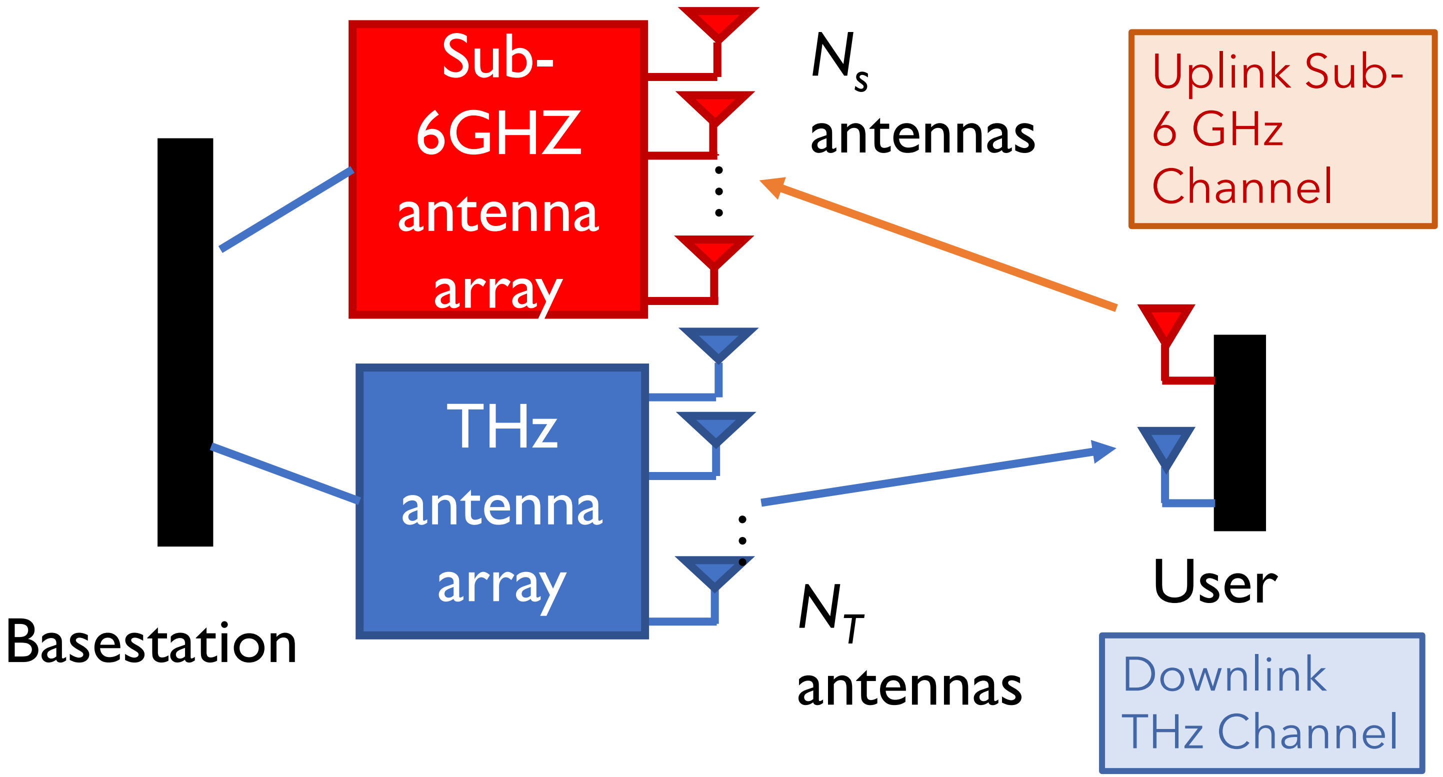
- Deep Learning algorithms efficiently map otherwise intractable functions, using training data.
- Convolutional Neural Networks (CNN) - suitable for extracting spatial/temporal features directly from raw data.

Cascaded Architecture

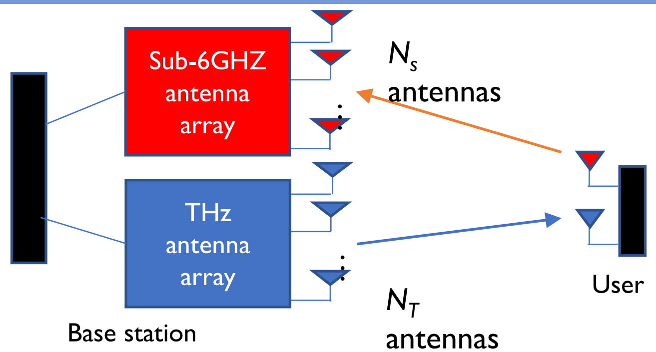


- Deep Learning algorithms efficiently map otherwise intractable functions, using training data.
- Convolutional Neural Networks (CNN) - extremely successful at extracting spatial/temporal features directly from raw data.

System Model



Channel Model



Uplink Sub-6 GHz Channel

$$y_s[k] = h_s[k]\ x_s[k] + n_s[k]$$

received uplink sub-6 symbol vector

sub-6 channel vector from UE to BS $\mathbb{C}^{Ns\times 1}$

input symbol

received noise $\mathcal{N}_{\mathbb{C}}(0, \sigma_s^2 I)$

- OFDM with K subcarriers
- Let $k \in \{1, 2, \dots, K\}$ be the OFDM subcarrier index.
- N_S small enough for fully digital beamforming.

Downlink THz Channel

$$y_{\mathrm{T}}[k] = h_{\mathrm{T}}^H[k]\ p\ x_{\mathrm{T}}[k] + n_{\mathrm{T}}[k]$$

downlink received symbol at THz

THz channel vector from BS to UE

chosen beam former from P $\mathbb{C}^{N_T\times 1}$

transmit symbol

received noise $\mathcal{N}_{\mathbb{C}}(0, \sigma_T^2)$

- Fully analog beamforming adopted for THz scenario, single RF chain with N_T quantized phase shifters.
- Pre-supplied codebook P comprises all candidate beamformers.

Channel Model

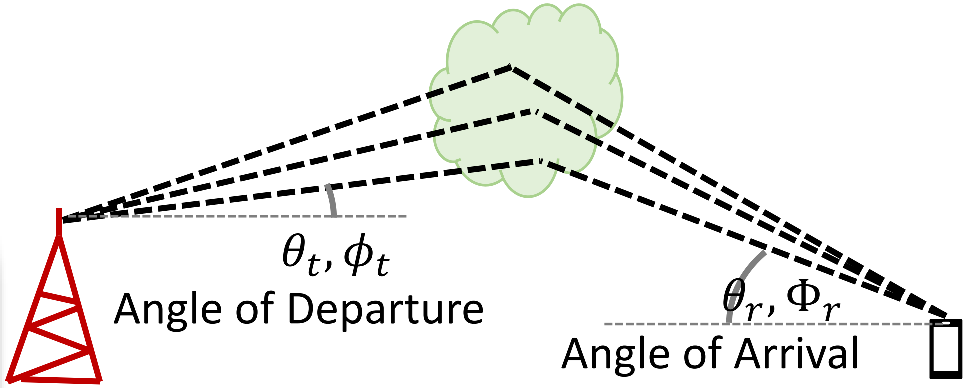
- Geometric channel model (both Sub-6GHz and THz)

Sub-6GHz channel :

$$h_s[k] = \sum_{m=0}^{M-1} \lambda_m \, \alpha_{r,m}(\phi_{r,m}, \theta_{r,m}) \, \alpha^*_{t,m}(\phi_{t,m}\theta_{t,m})$$

k = OFDM subcarrier index
M = number of channel paths
λ_m = path gain
$\phi_{r,m}$ and $\theta_{r,m}$ = azimuth and elevation angles of arrival
$\phi_{t,m}$ and $\theta_{t,m}$ = azimuth and elevation angles of departure

for *M*th channel path



Channel Model for THz

- Significant molecular absorption, exponentially dependent on the link distance r: $\delta(r)$
- THz path gain contains additional absorption term.

$$p_{\mathrm{rx}} = p_{\mathrm{tx}}\, \ell'(r)\, \delta(r)$$

where r is the distance between receiver and transmitter, $\ell'(r)$ is the power law path gain

- $\ell(r) = \ell'(r)\delta(r)$ is the effective path gain for THz channel.
- THz channel model can be obtained from the Sub-6GHz channel equation by replacing corresponding terms with their THz channel counterparts.
- **Channel factors for a channel path : (effective) pathloss, azimuth and elevation angles of arrival and departure, time of arrival, and phase difference on arrival**.
- Given the channel factors for *M* channel paths, the channel can be determined completely.

Phase I: THz Channel Factors Estimation

- Input : Sub-6GHz channel matrix $h_s \in \mathbb{C}^{K \times N_s}$ - estimated using uplink pilot signals.
  Each element of h_s is separated into magnitude and phase angle - resulting in a 3D matrix $h_s' \in \mathbb{C}^{K \times N_s \times 2}$

- Output : THz channel factors for the first (strongest) *N* channel paths, where *N* is a pre-specified hyperparameter – $S_T \in \mathbb{R}^{N \times 7}$

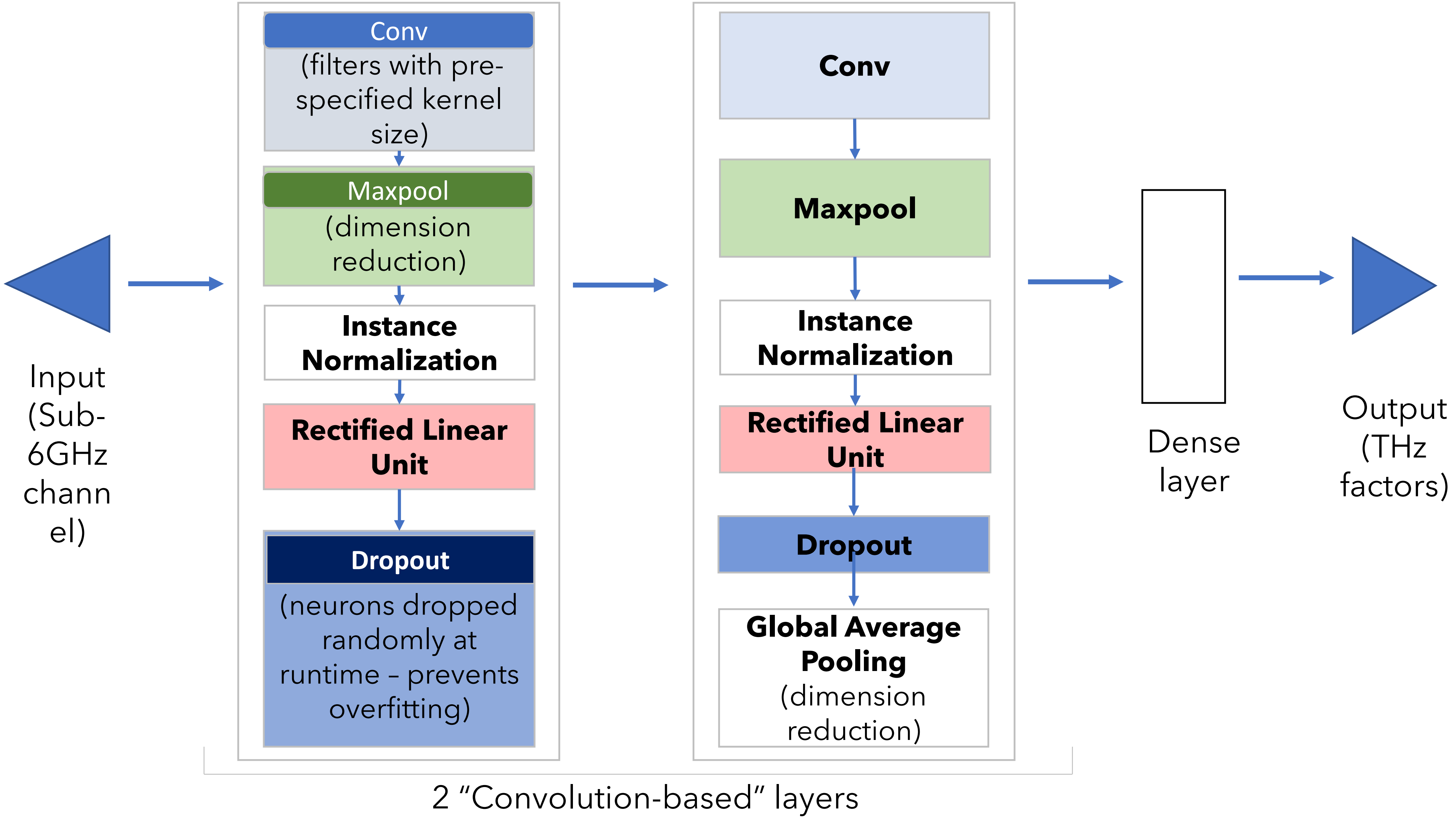
- CNN based model to estimate THz channel factors.

- Training Phase :
  - Raytracing data obtained for both Sub-6GHz and THz channels, from multiple users - training samples (h_s', S_T)

- Deployment Phase :
  - Sub-6GHz channel matrix estimated from uplink signals – used by model to estimate THz channel factors.

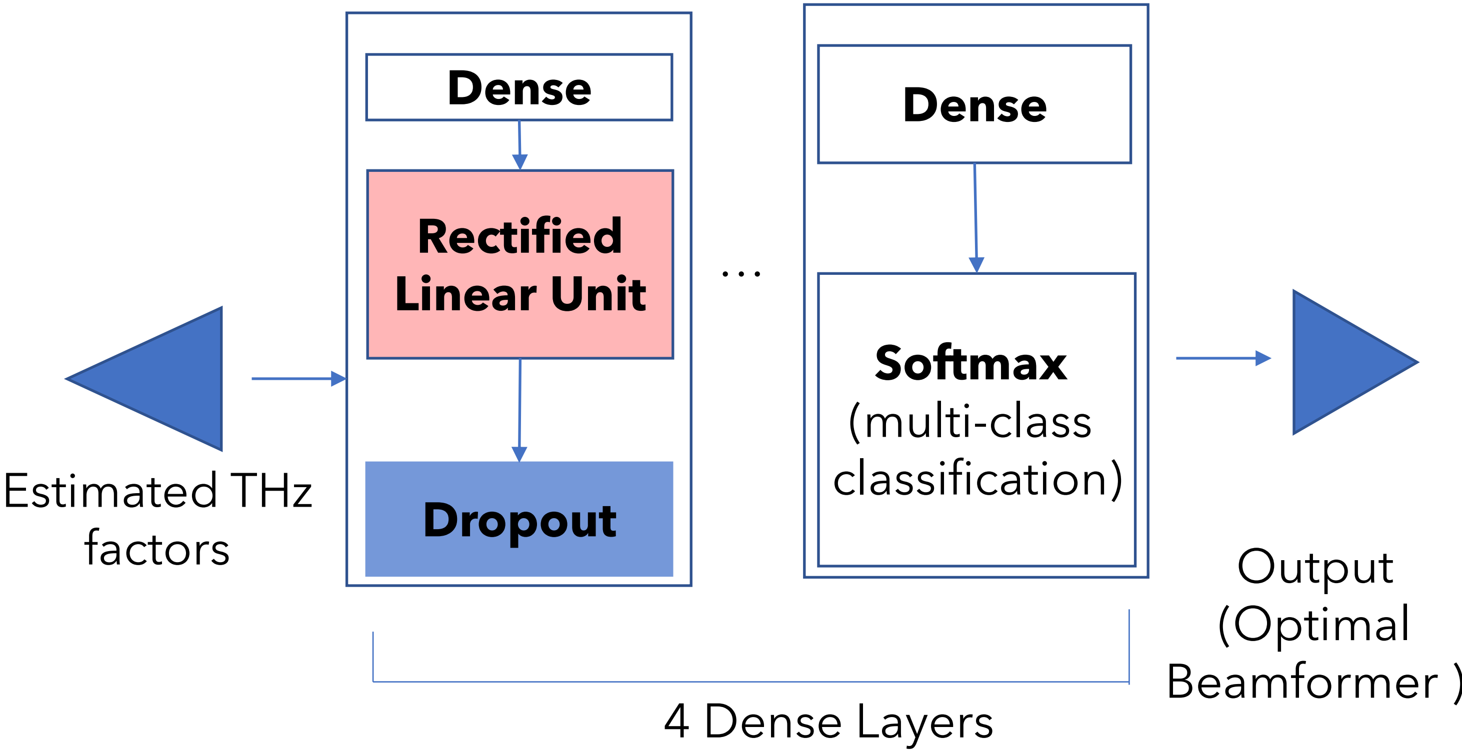
  - We considered the ray trace data for sub-6GHz channel as the input.

Phase I: Proposed Learning Network's Architecture



Phase II: Optimal Analog Beamformer Prediction

- Input : S_T - Estimated THz channel factors from CNN model
- Output : Optimal beamformer index
- Deep neural network to directly predict the optimal beamformer index from the estimated THz factors.



Phase II: Optimal Analog Beamformer Prediction

Training Phase :

- THz raytracing data (S_T) obtained for multiple users –
  - Used to compute THz channel matrix h_T.
- Exhaustive beam search is conducted from entire codebook *P*
  - Optimal beamformer index $\hat{p}$, providing the highest spectral efficiency is selected.

$$\hat{p} = \underset{p \in P}{\operatorname{argmax}} \left(\sum_{k=1}^{K} \log_2 \left(1 + \mathrm{SNR} \left| h_T^H[k]\, p \right|^2 \right) \right)$$

- Neural network input samples are (S_T, p_{ind}), where p_{ind} is the categorical variable representing index of $\hat{p}$ in *P*.

Deployment Phase :

- CNN estimated THz channel factors provided as input - output is p_{ind} .

Performance Evaluation

Baseline Algorithm :

1. THz channel matrix, computed from raytracing, passed into a deep learning model to output optimal beamformer index.
2. Model comprises a convolutional layer, followed by GAP, ReLU, and 4 dense layers, each followed by ReLU and dropout layers. Softmax function at the end outputs beamformer index.

Upper Bound :

- Exhaustive codebook search using raytracing derived THz channel matrix – to find the optimal beamformer by brute force.
- Computationally prohibitive for real-time applications

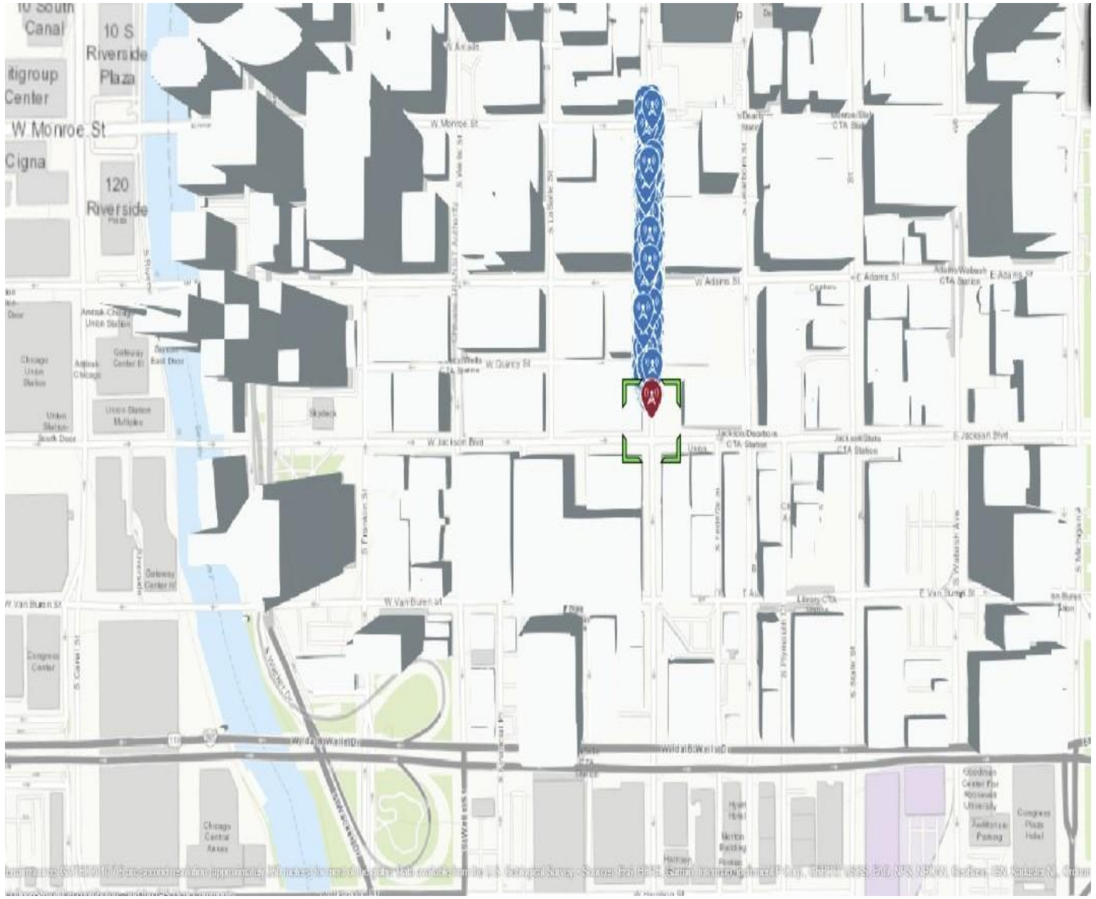
Neural Network Hyperparameters

- The neural network hyperparameters for the CNN based THz factors estimation, and the beamformer prediction models are the following:

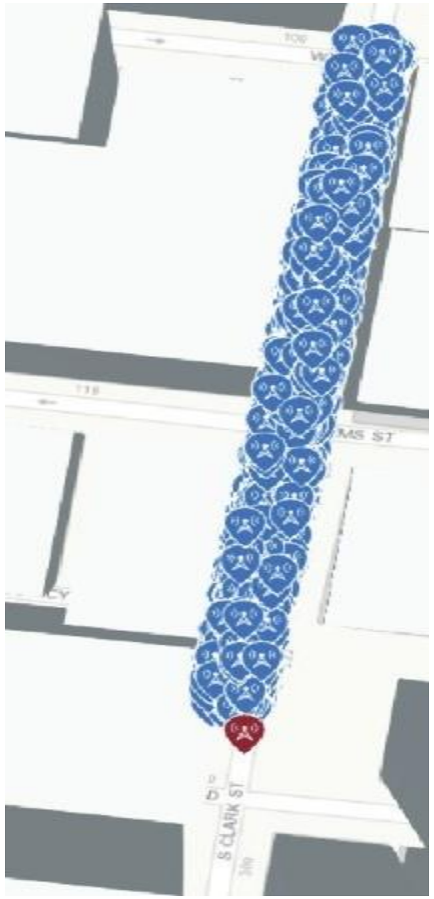
Hyperparameter	THz Estimation	Beamformer Prediction
Conv kernel size	(2,2)	-
Conv no. of filters	64	-
Maxpool kernel size	(2,2)	-
Maxpool stride length	2	-
Dense layer dimension	-	64
No. of training samples	80,000	80,000
No. of test samples	20,000	20,000
No. of epochs	100	100
Task objective	Regression	Classification
Optimizer	Stochastic gradient descent	Adam
Initial learning rate (LR)	10^{-3}	10^{-2}
LR decay factor	0.1	-
LR decay schedule	80 epochs	-
Momentum	0.8	-
Dropout	0.2	0.2

Simulation

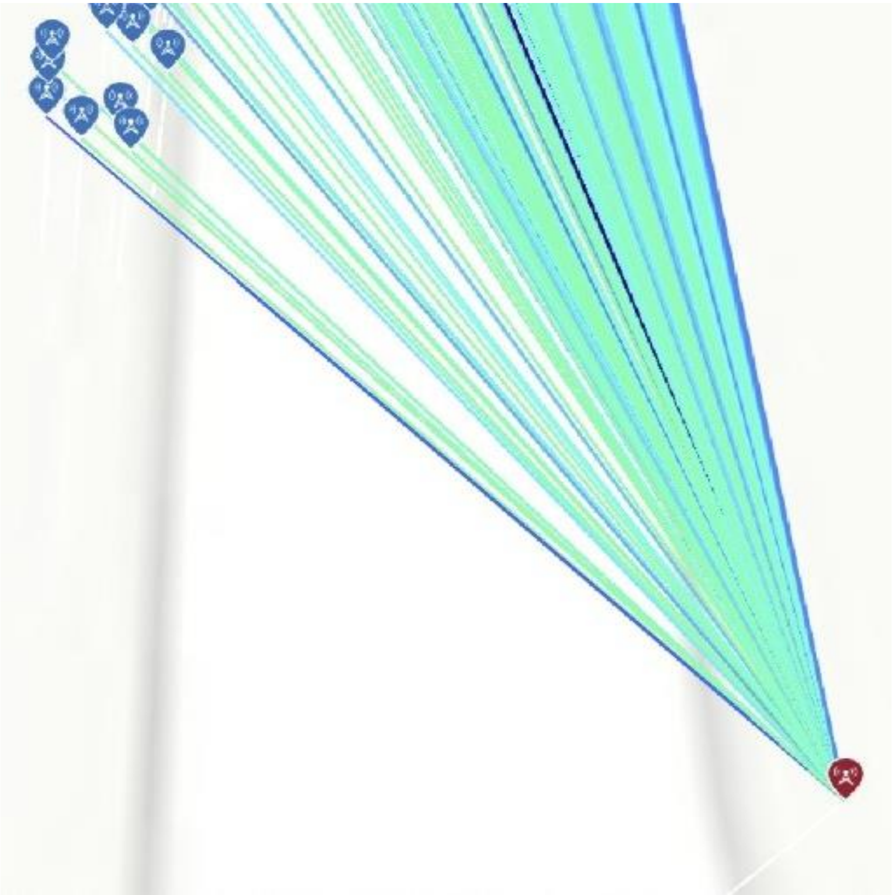
- Raytracing Scenario is generated using MATLAB raytrace function from Communications Toolbox.
- Outdoor environment, rectangular block of dimensions (*400m × 30m*) in S Clarke St., Chicago downtown area.
- BS at one corner of rectangular block, user locations randomly generated inside block – raytracing data gathered.



Location of BS (red) and users (blue) in Chicago



Zoomed in scenario – S Clarke St.



Raytracing – highly zoomed in

Simulation Parameters

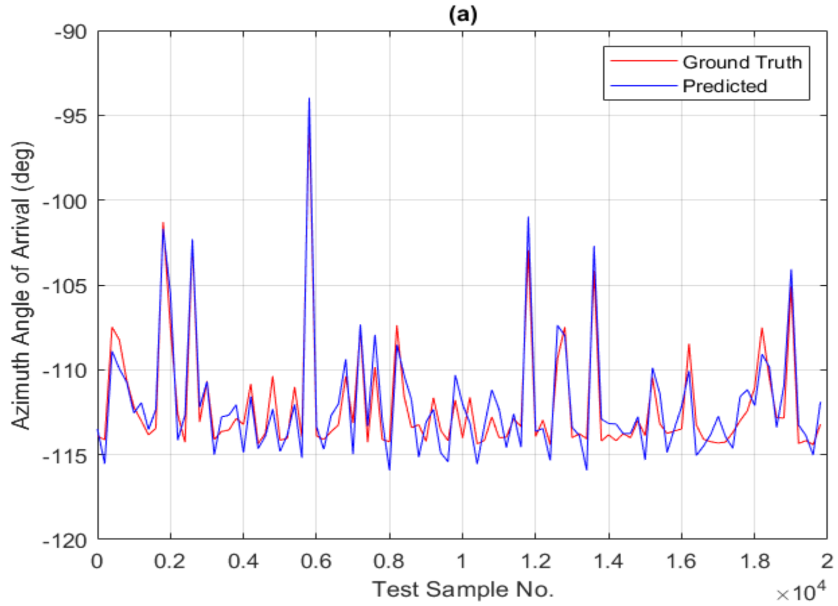
Scenario Parameter	Sub-6GHz	THz
No. of users	100,000	100,000
BS antenna array length	4	128
BS antenna height (m)	8	8
User antenna height (m)	2	2
Center frequency (GHz)	2.4	100
Propagation model	sbr*+gas+cloud	sbr*+gas+cloud
Max no. of channel paths	8	4
Bandwidth (MHz)	20	500
No. of OFDM subcarriers	64	64
Codebook size (X, Y, Z)	$4 \times 64 \times 4$	$4 \times 128 \times 4$

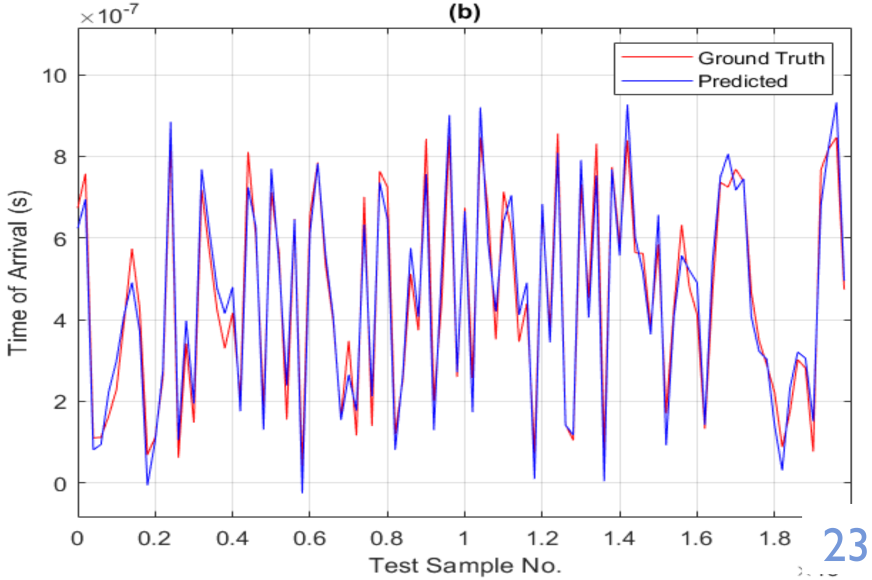
* - sbr = shooting and bouncing rays propagation model

Performance Evaluation: THz Channel Factors Estimation

- Table shows mean and standard deviation absolute errors of proposed algorithm's THz channel factors predictions.
- Error values show high estimation accuracy (<6 degree for AoA, AoD, and Phase Change estimates; and very low errors on ToA and Pathloss as well).
- Figures show the graph of two THz channel factors as examples - Azimuth Angle of Arrival and Time of Arrival versus No. of samples.

Factors	Average Absolute Error	Standard Deviation
AoD ϕ (deg)	5.67	1.23
AoD θ (deg)	2.36	0.47
AoA ϕ (deg)	2.22	0.63
AoA θ (deg)	4.43	0.91
Phase Change (deg)	5.93	1.08
ToA (10^{-18}s)	3.80	0.67
Pathloss (10^{-19})	5.70	0.35





Performance Evaluation: Beamformer Prediction

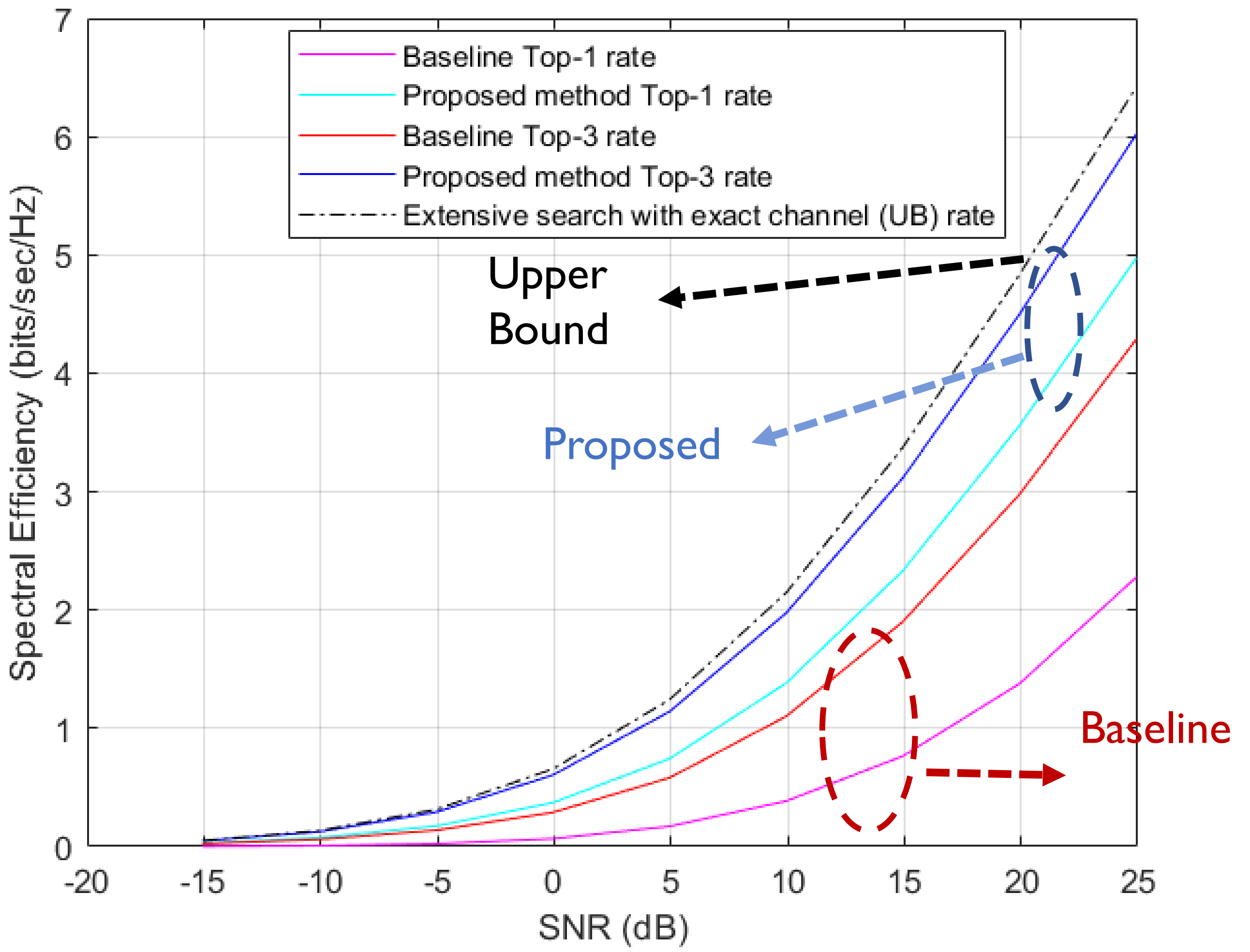
- Top-3 rate – 3 best beams predicted by model
  Top-1 rate – best beam predicted by model

- Wide range of SNR values (-17dB to 25dB) considered.

- Proposed algorithm Top-3 rate approaches computationally prohibitive upper bound spectral efficiency – **proving the accuracy of estimated THz channel factors.**

- Proposed algorithm Top-1 rate outperforms Baseline Top-1 and Top-3 rates - **validating our Sub-6GHz based approach.**

- Baseline method **inefficient** because of THz channel matrix input (high dimensionality).



- Baseline model is **underperforming** compared to our Sub-6GHz based proposed algorithm – because severe THz attenuation renders the THz channel matrix highly noisy; not suitable for deep learning.