Low-Complexity Digital Twin for CSI Acquisition in MIMO Communications

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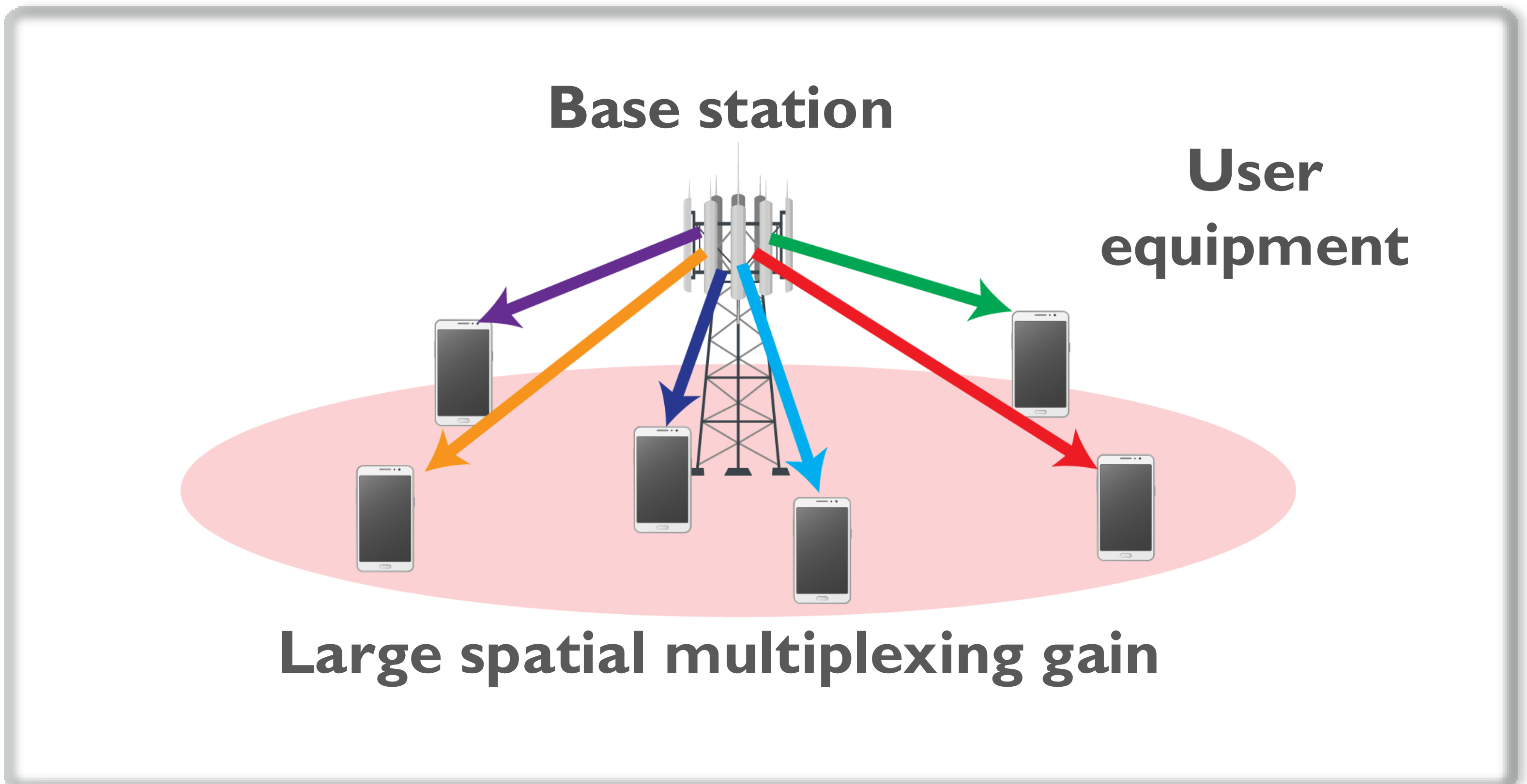
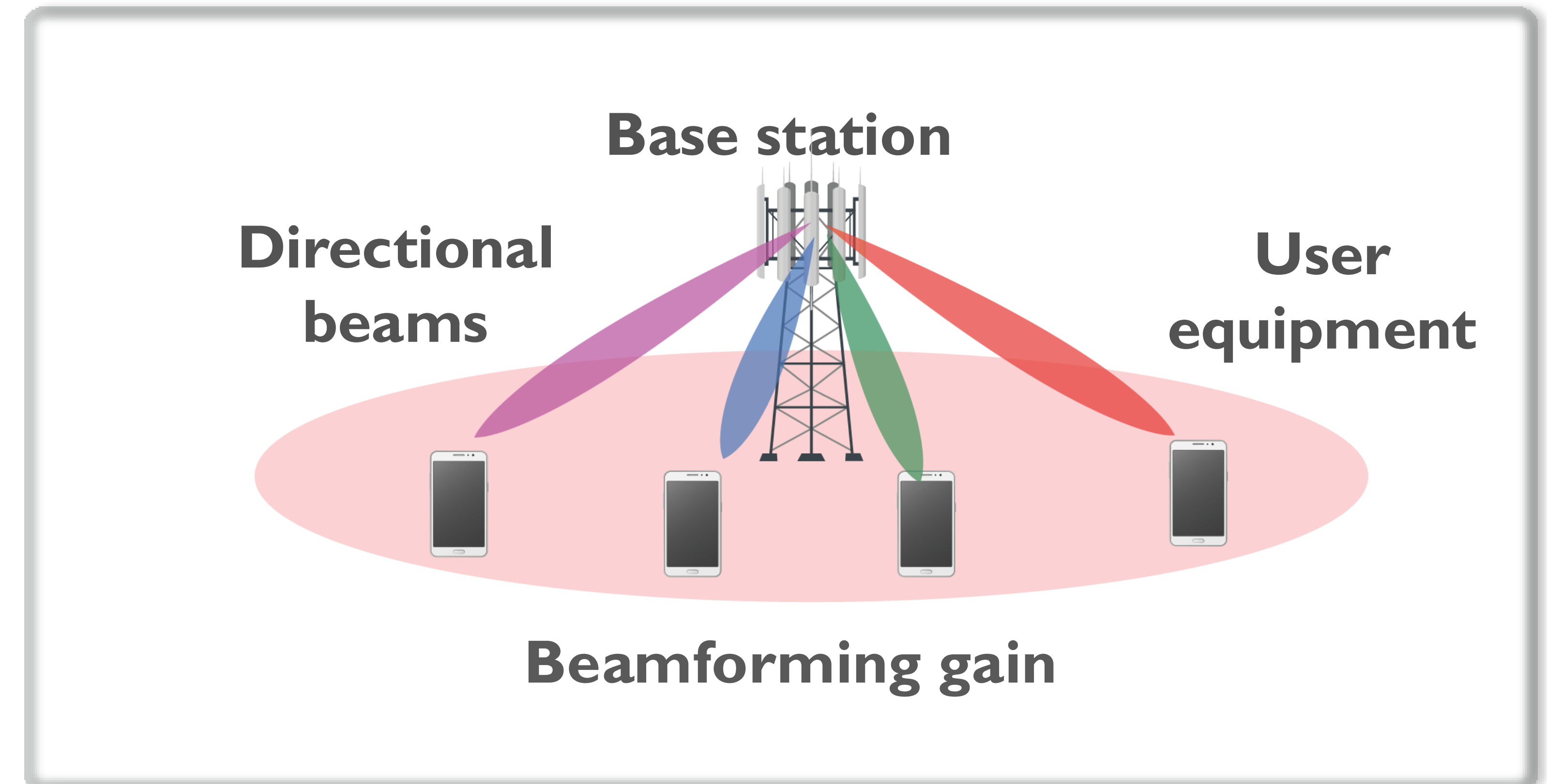
Challenges in MIMO systems

- Large-scale MIMO is a key enabler for next-generation wireless systems

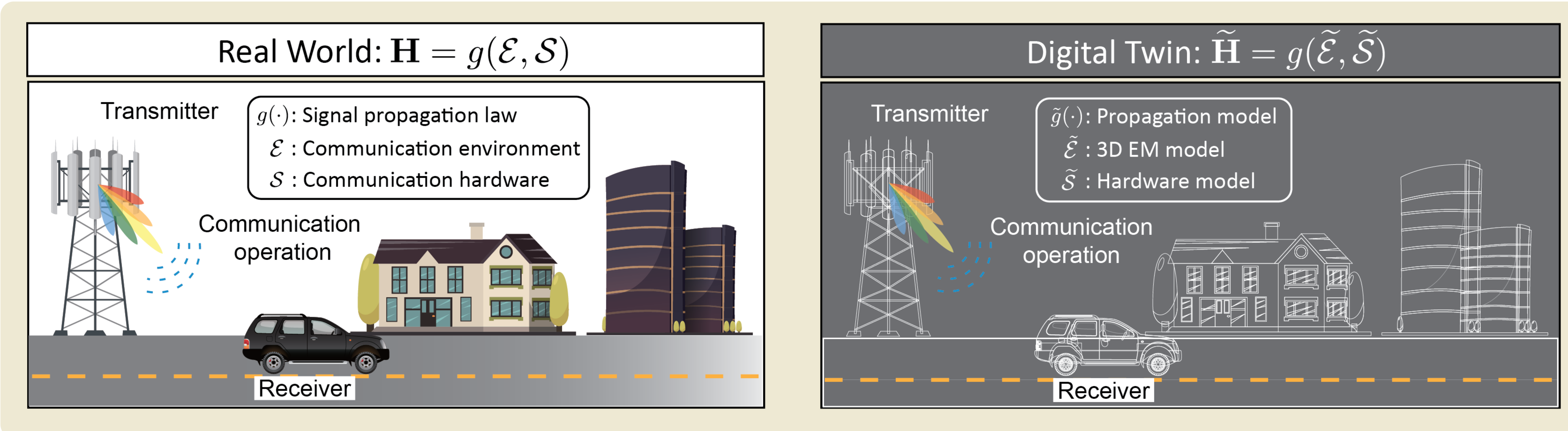




- However, the channel acquisition overhead grows with the number of antennas
  - Pilot/beam training overhead
  - Feedback overhead
  - Control signaling overhead

Channel acquisition overhead hinders large-scale MIMO from scaling gains

Wireless digital twins

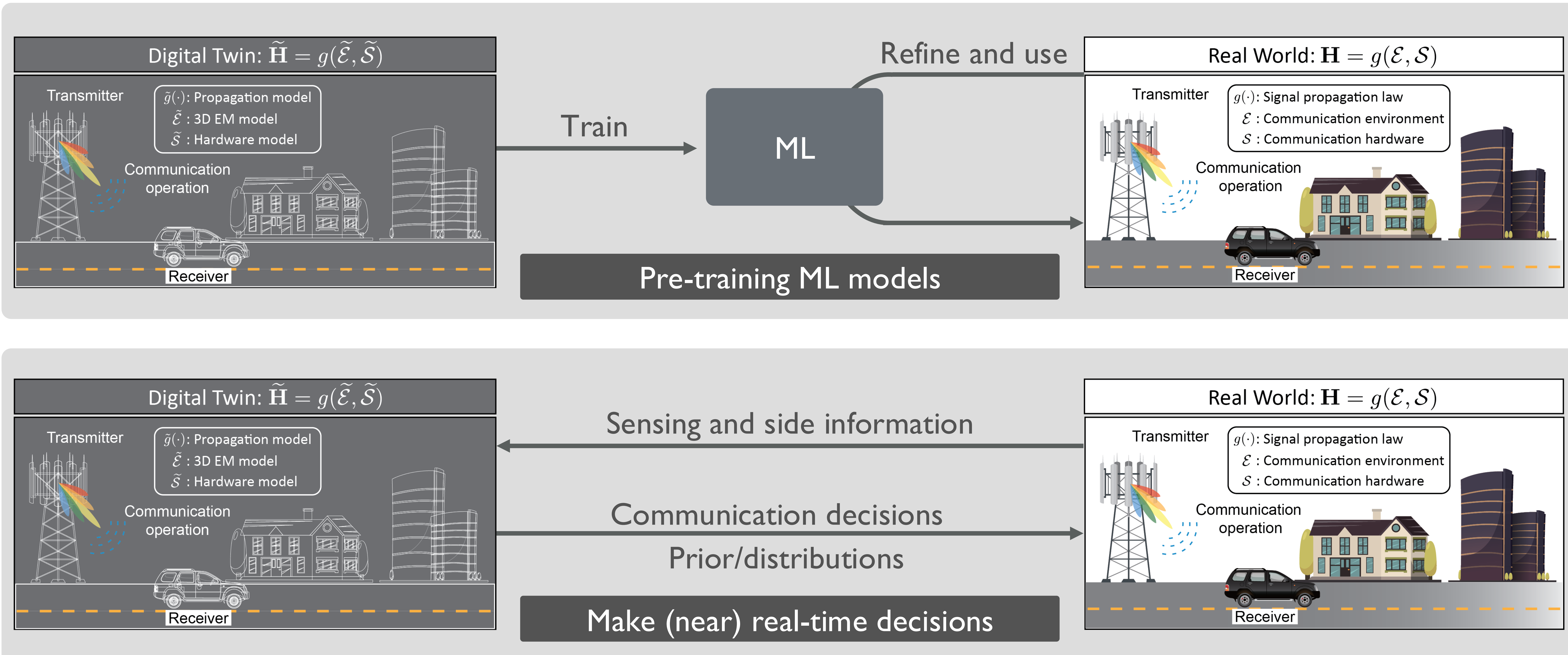


- Real-world channels are determined by
  - Environment model
  - Signal propagation law
  - Communication hardware
- Digital replica approximates real world with
  - 3D EM environment model
  - Signal propagation model
  - Communication hardware model

Wireless digital twins can emulate the wirelss environment with high-fidelity

[Alkhateeb'23] A. Alkhateeb, S. Jiang and G. Charan, "Real-Time Digital Twins: Vision and Research Directions for 6G and Beyond," IEEE Communications Magazine

How to use wireless digital twins?



In real-time operation, digital tiwn can provide prior information for a specific user

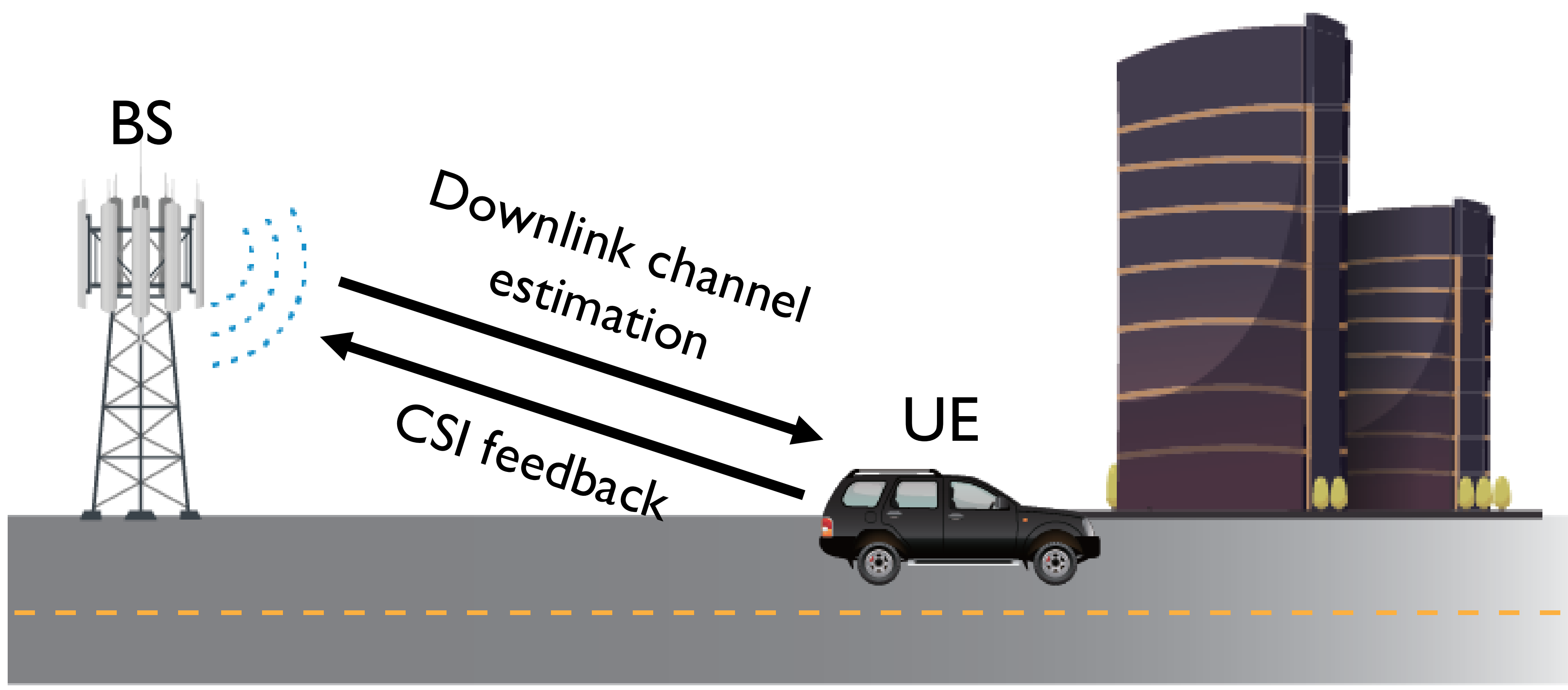
[Alkhateeb'23] A. Alkhateeb, S. Jiang and G. Charan, "Real-Time Digital Twins: Vision and Research Directions for 6G and Beyond," IEEE Communications Magazine

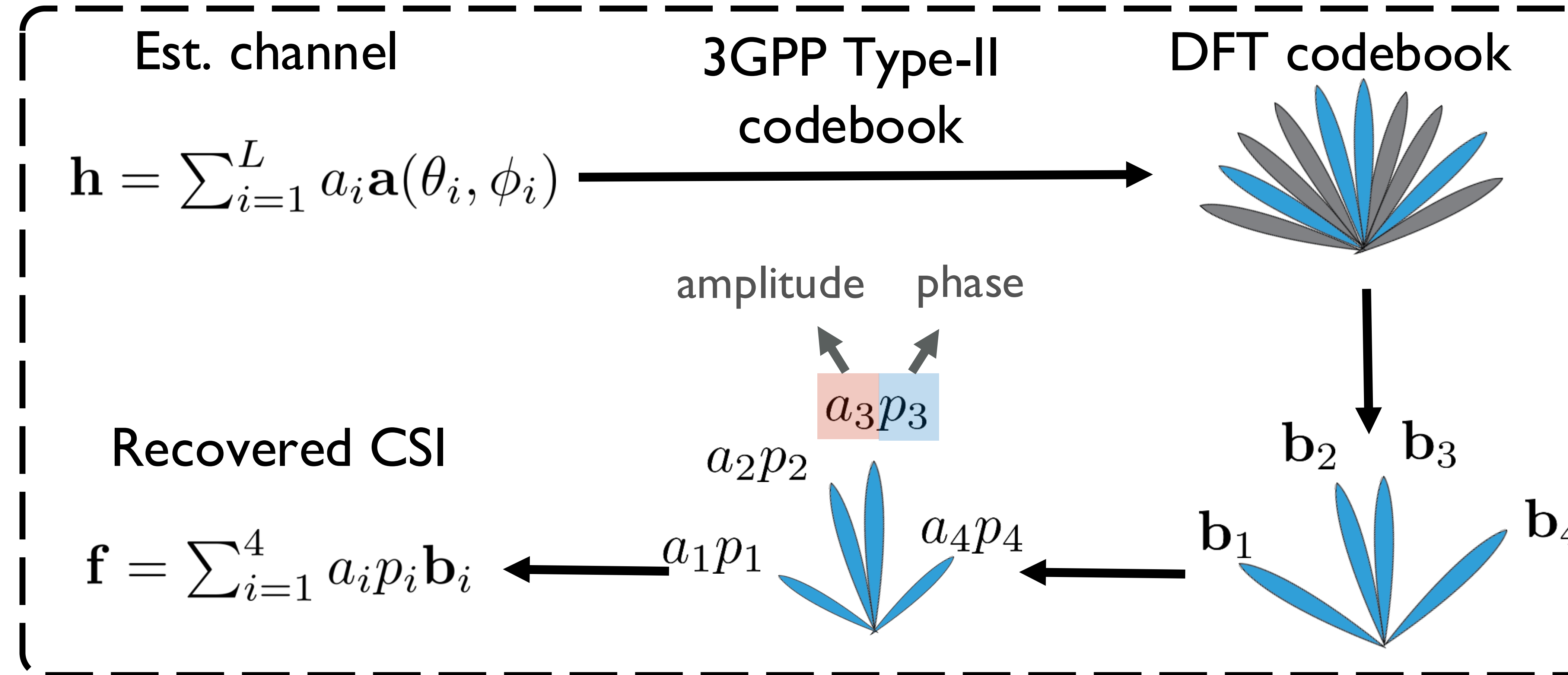
CSI feedback in multi-antenna systems

- In different frequency, the channel state information (CSI) feedback is different

Sub-6 GHz

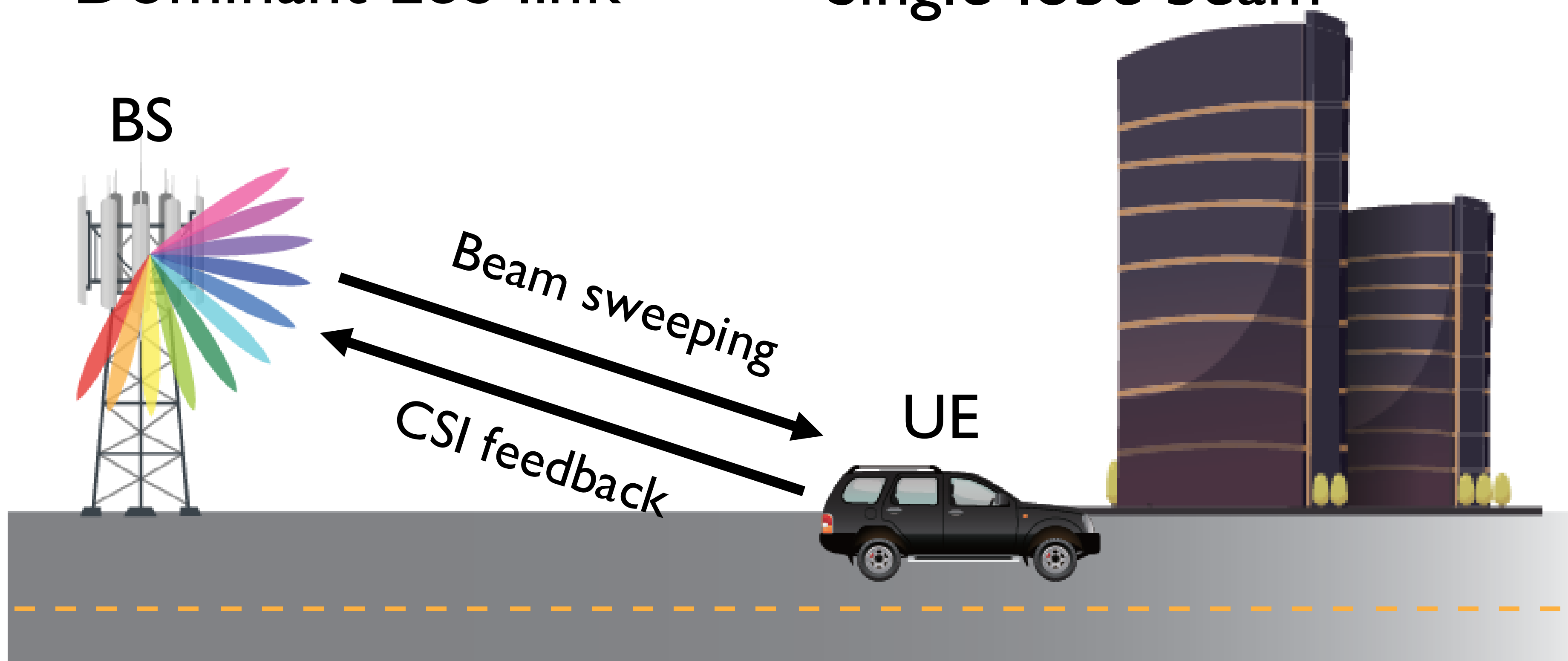
Rich scattering → Multi-path components





mmWave

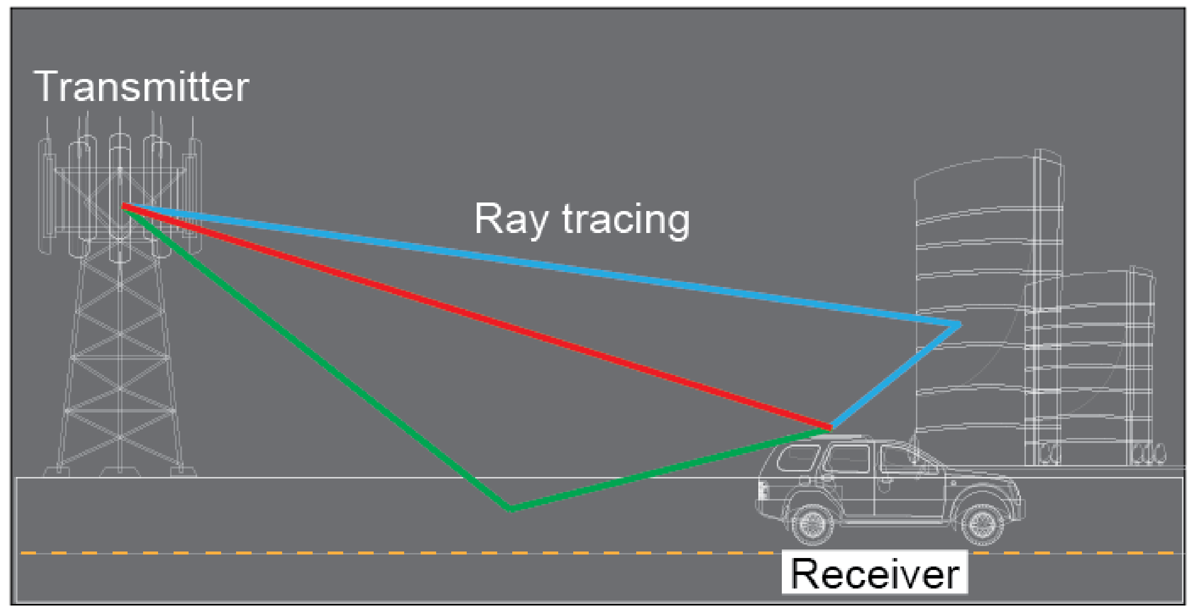
Dominant LoS link → Single-lobe beam



The overhead of CSI acquisition increases with larger antenna arrays

Digital twin aided CSI feedback

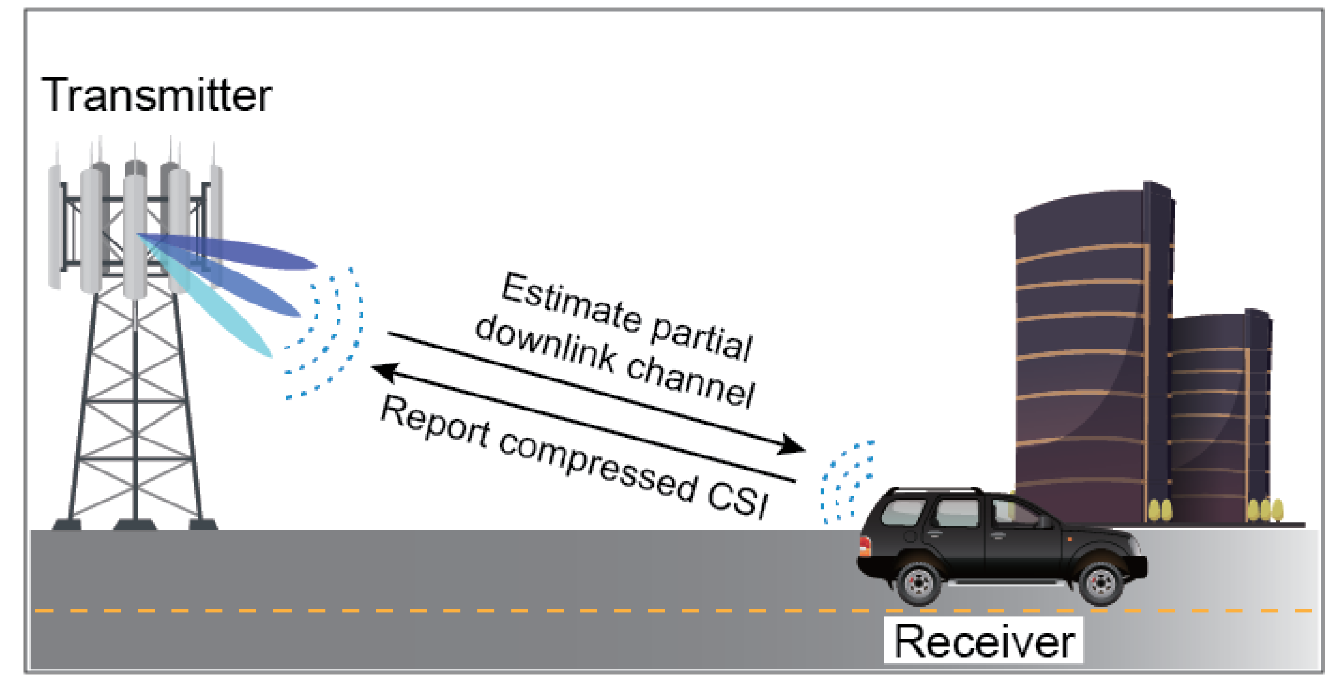
Digital Twin



Synthetic channel $\hat{\mathbf{h}}$

BS only picks the most relevant DFT beams for CSI acquisition

Sub-6 GHz



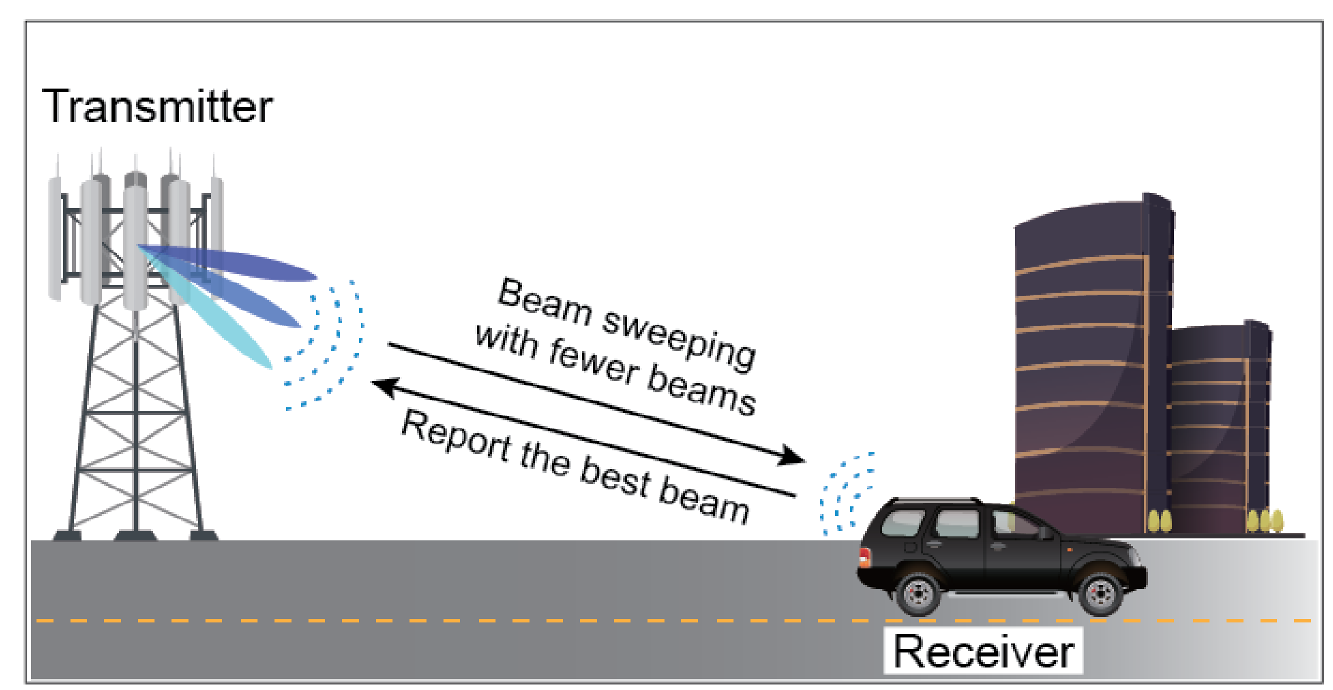
Effective channel of DFT beam

Pilot

$$y = \mathbf{h}^H \mathbf{f} s + n$$

- **Downlink signaling overhead** can be reduced
- **Complexity at the UE side** can be reduced

mmWave



- **Beam training overhead** can be reduced

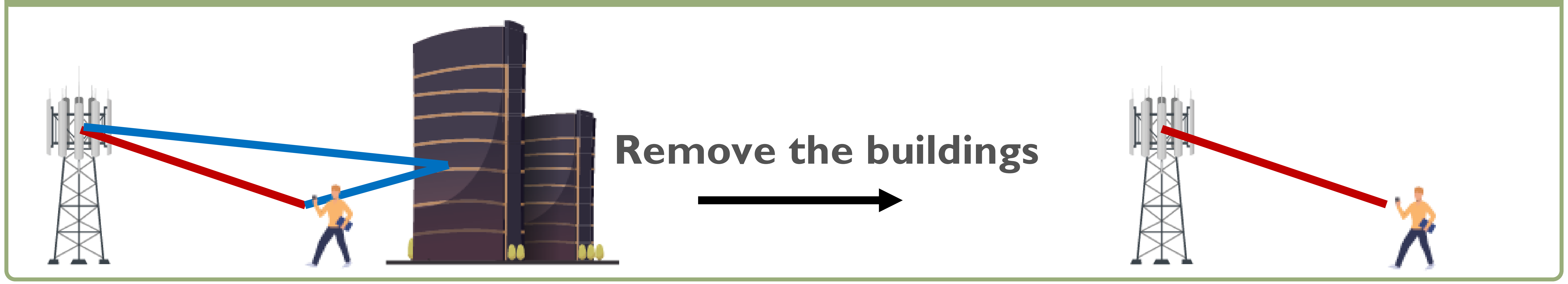
Digital twin can help the BS reduce the overhead of channel acquisition

However, the computational complexity of digital twin is crucial for real-time operation

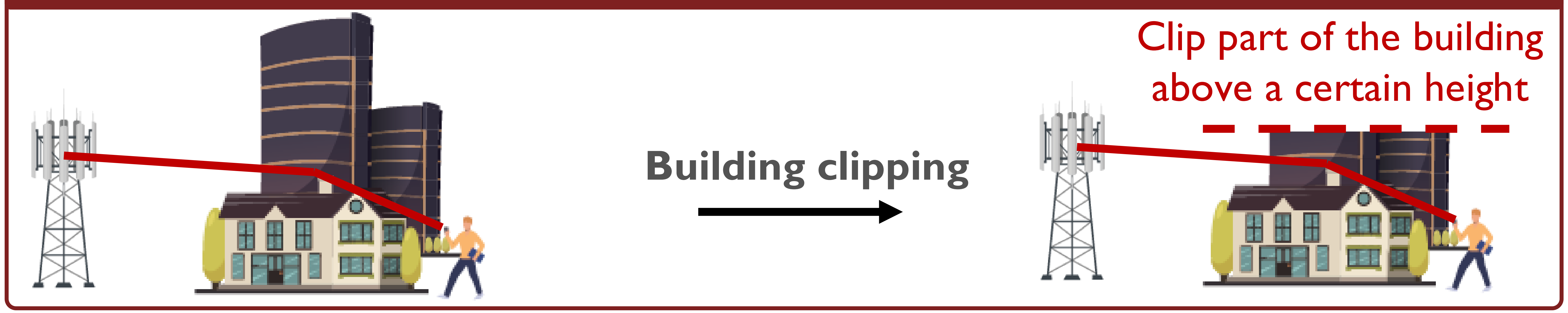
Can we reduce computational complexity in digital twin?

- Ray tracing is the most time-consuming step (determined by geometry and ray-tracing alg.)
- We investigate the approaches to reduce complexity from both perspectives
- First, we propose to simplify the geometry according to different user types

LoS users



NLoS users

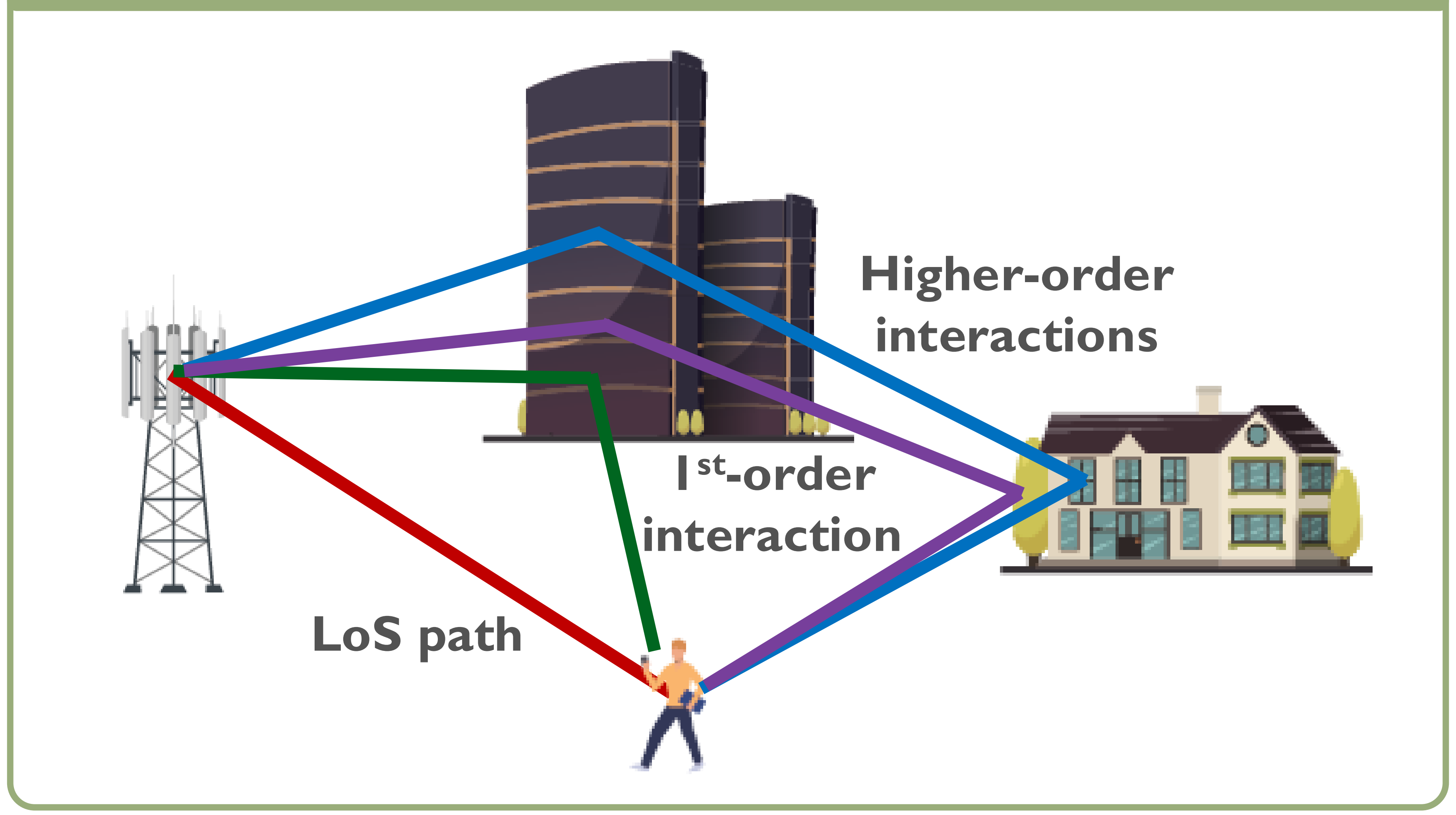


What is the trade-off between performance and imperfect geometry?

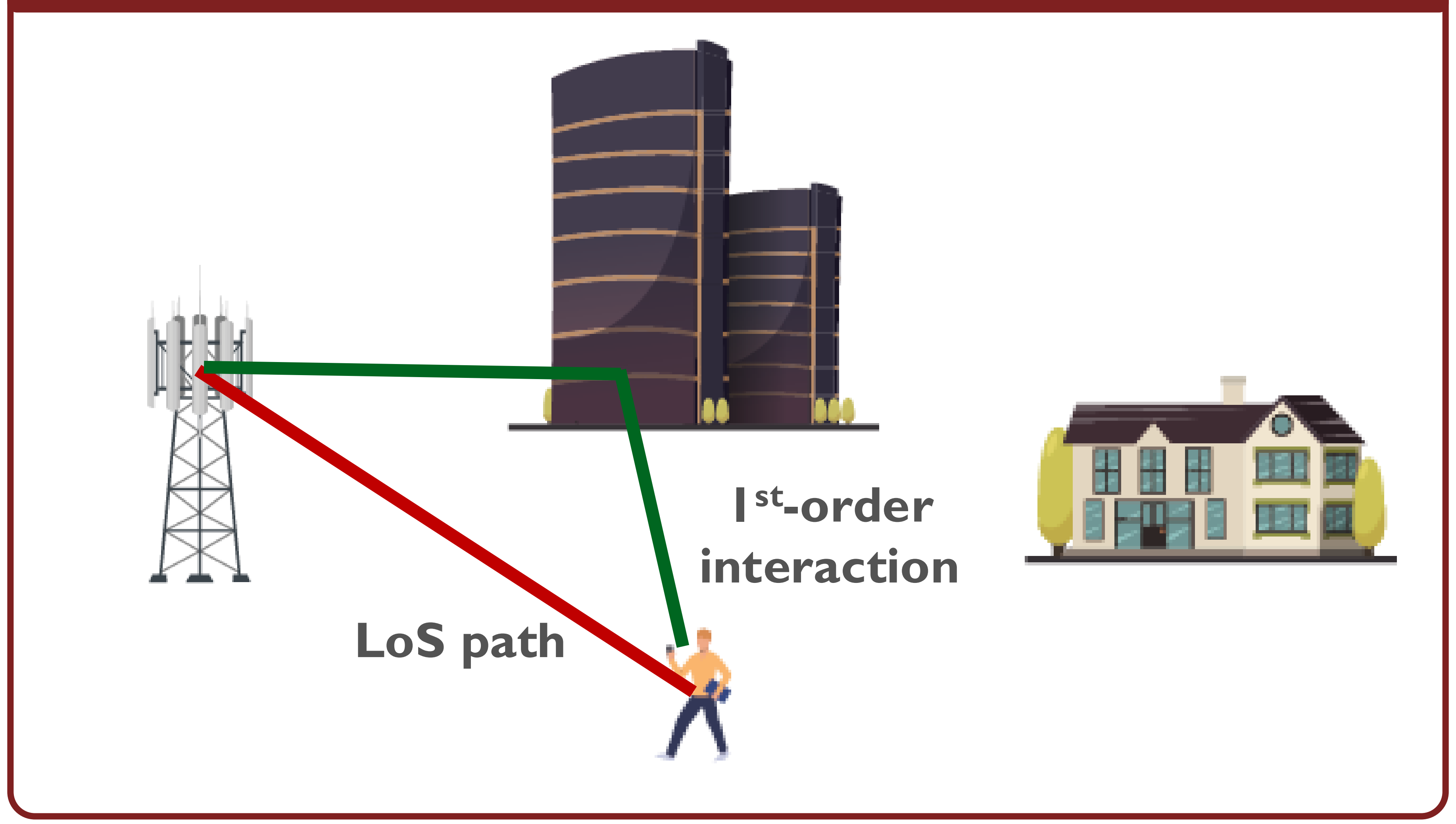
Can we reduce computational complexity in digital twin? (cont'd)

- Next, we investigate the impact of ray-tracing configurations
- Lower-fidelity ray tracing has reduced complexity but may compromise the accuracy

Higher fidelity



Lower fidelity



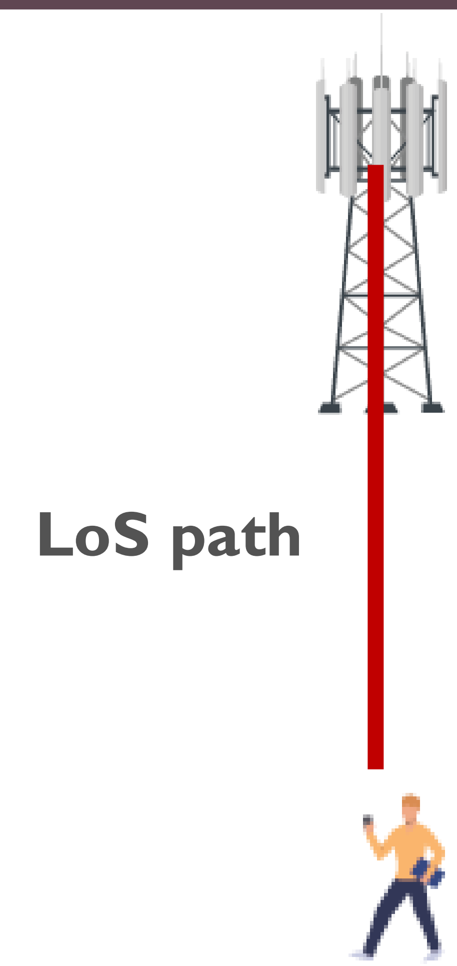
For NLoS users, the multi-path effect may be affected by lower-fidelity ray tracing

What is the trade-off between performance and simpler ray tracing?

A digital twin with various fidelity levels

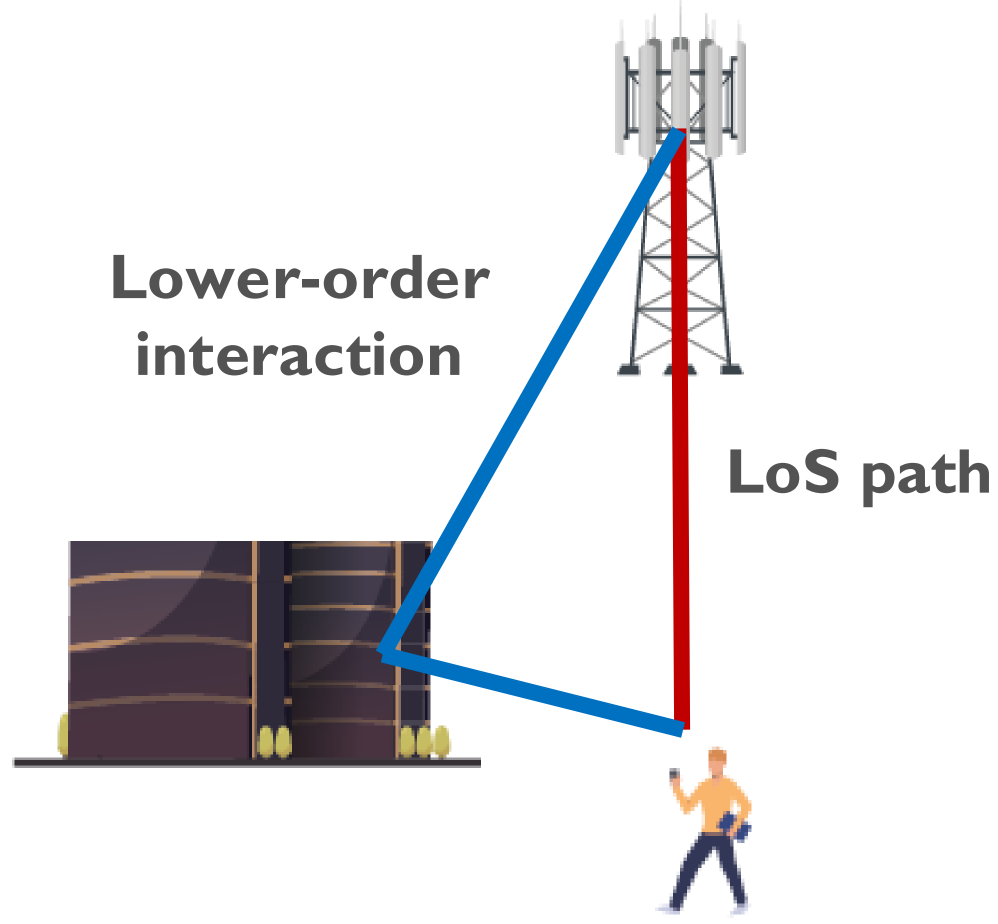
- We envision a digital twin with multi-fidelity levels that adapts to diff. channel conditions
- This multi-tier structure helps us achieve better efficiency in saving computation time

Fidelity level 1



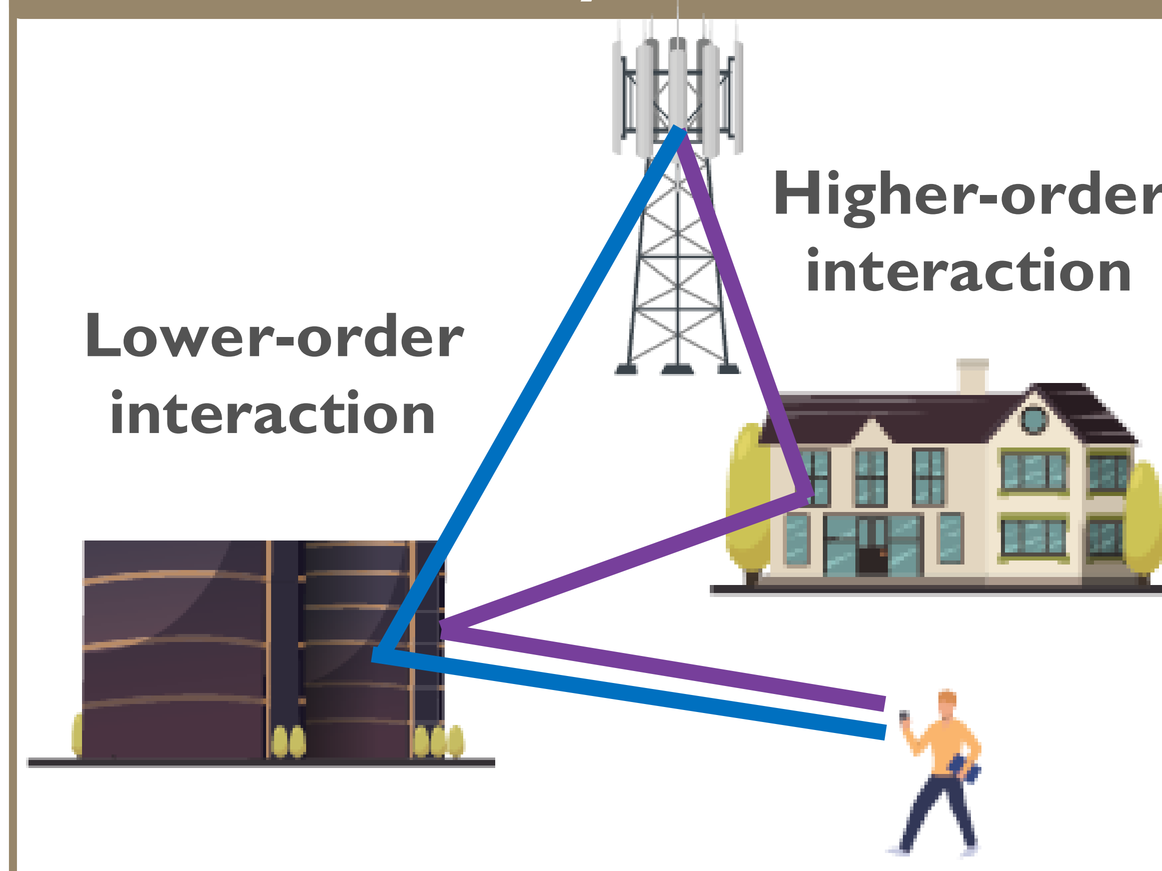
- Remove all buildings

Fidelity level 2



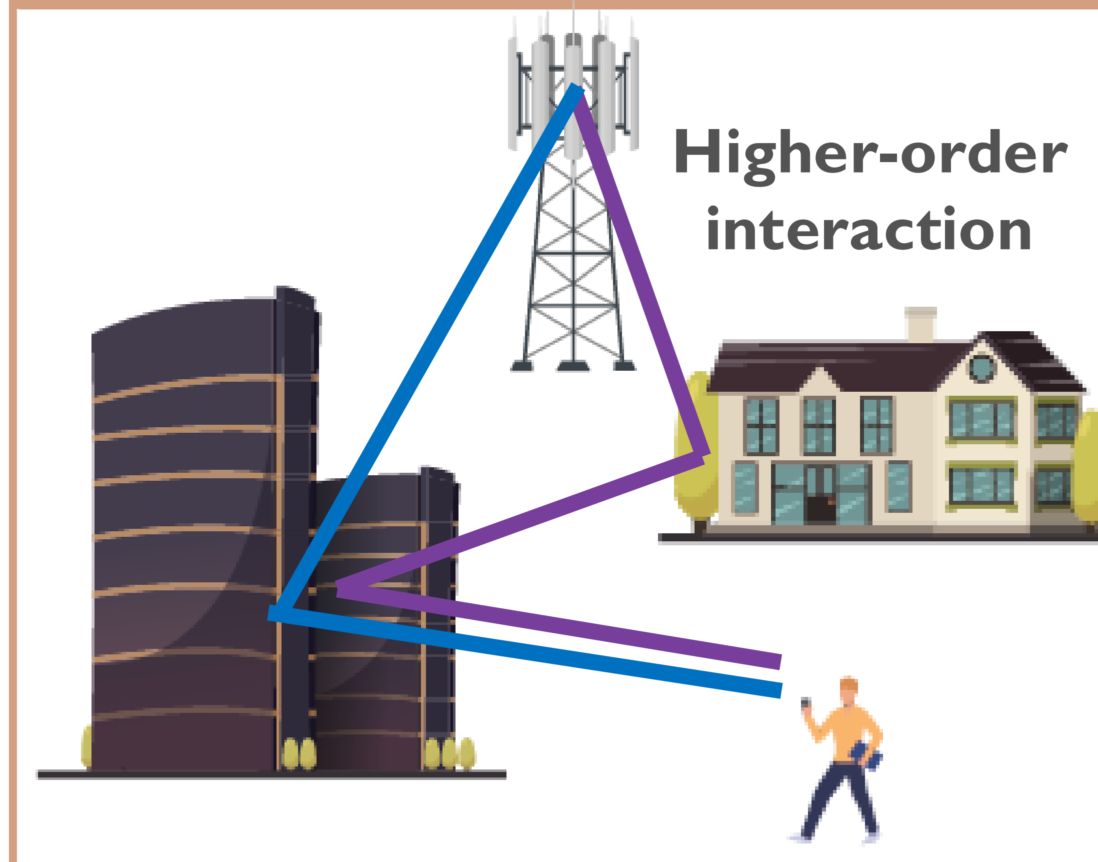
- Building clipping
- Low-fidelity ray tracing

Fidelity level 3



- Building clipping
- High-fidelity ray tracing

Fidelity level 4

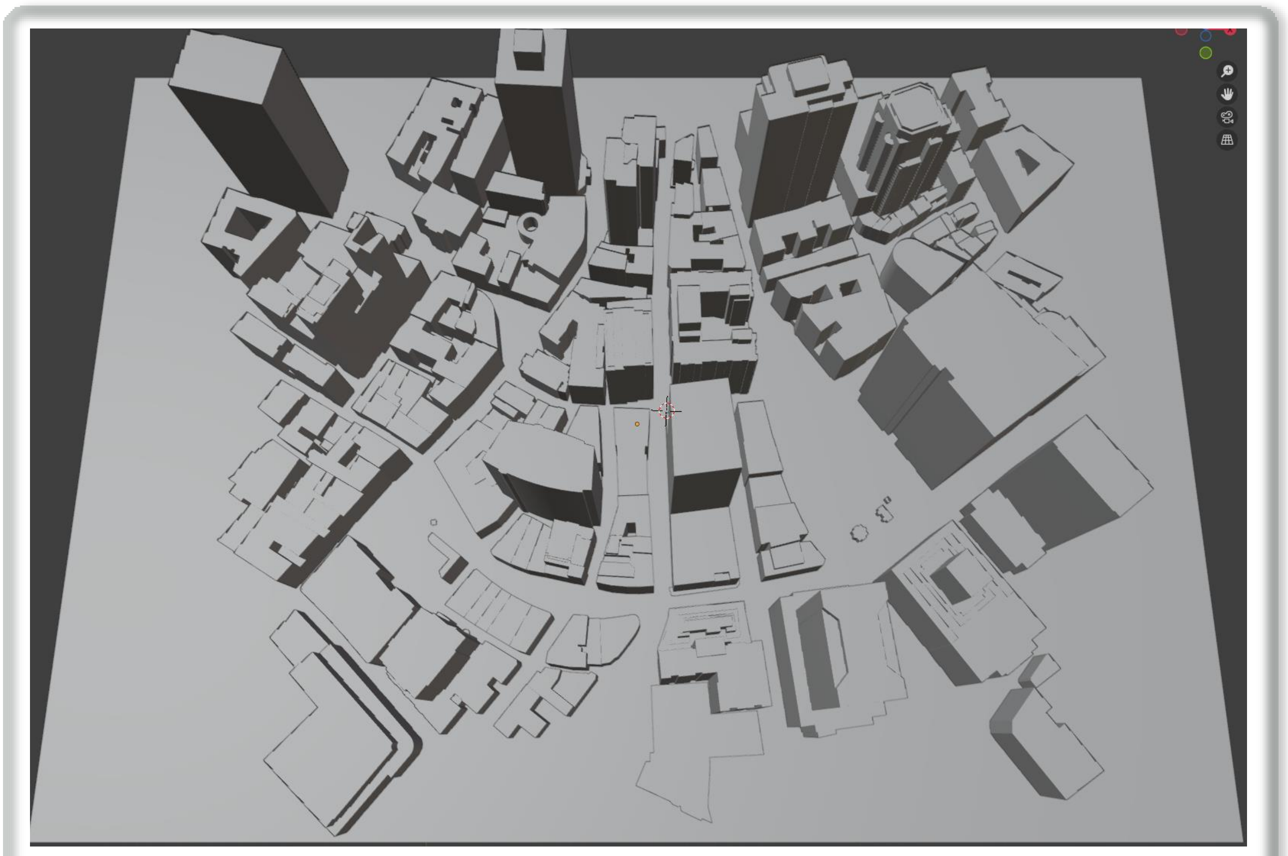


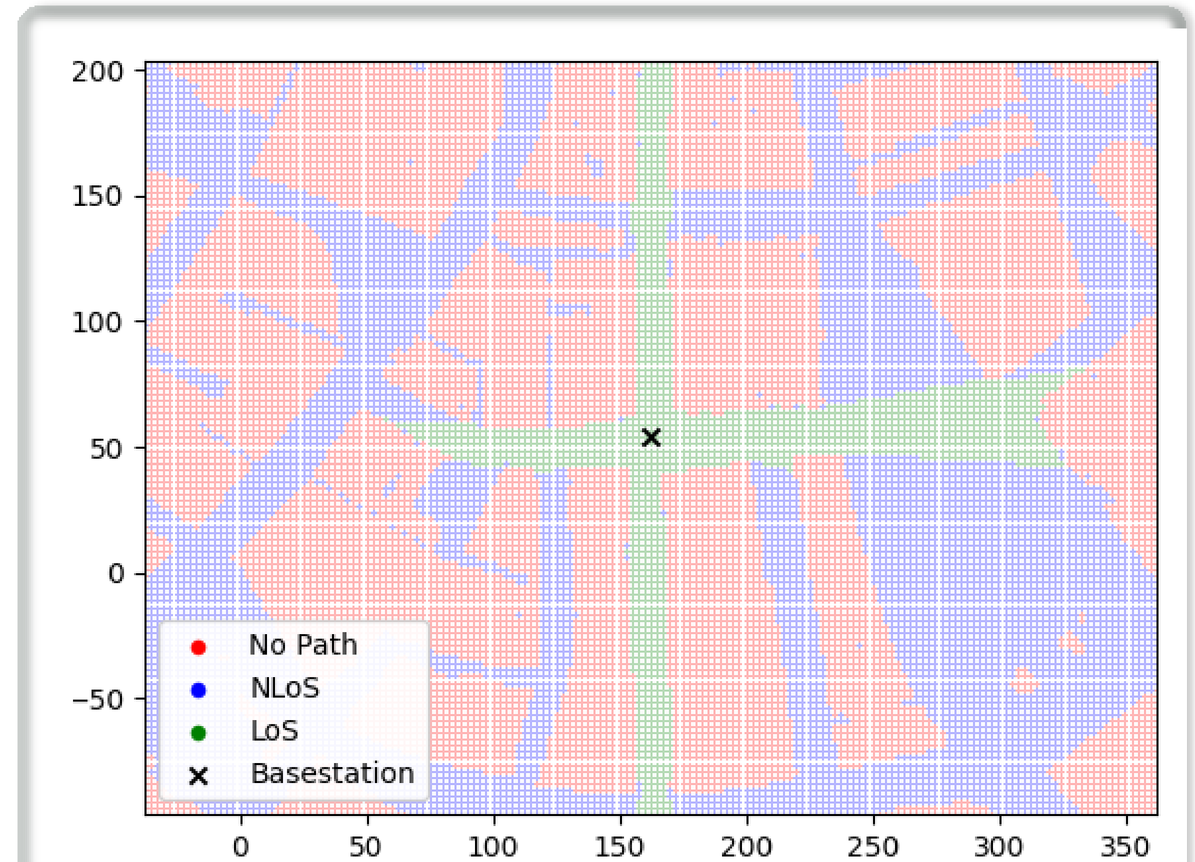
- Full building modeling
- High-fidelity ray tracing

For specific task and user position, we may adopt digital twin with diff. fidelity level

Simulation setup of codebook-based CSI feedback

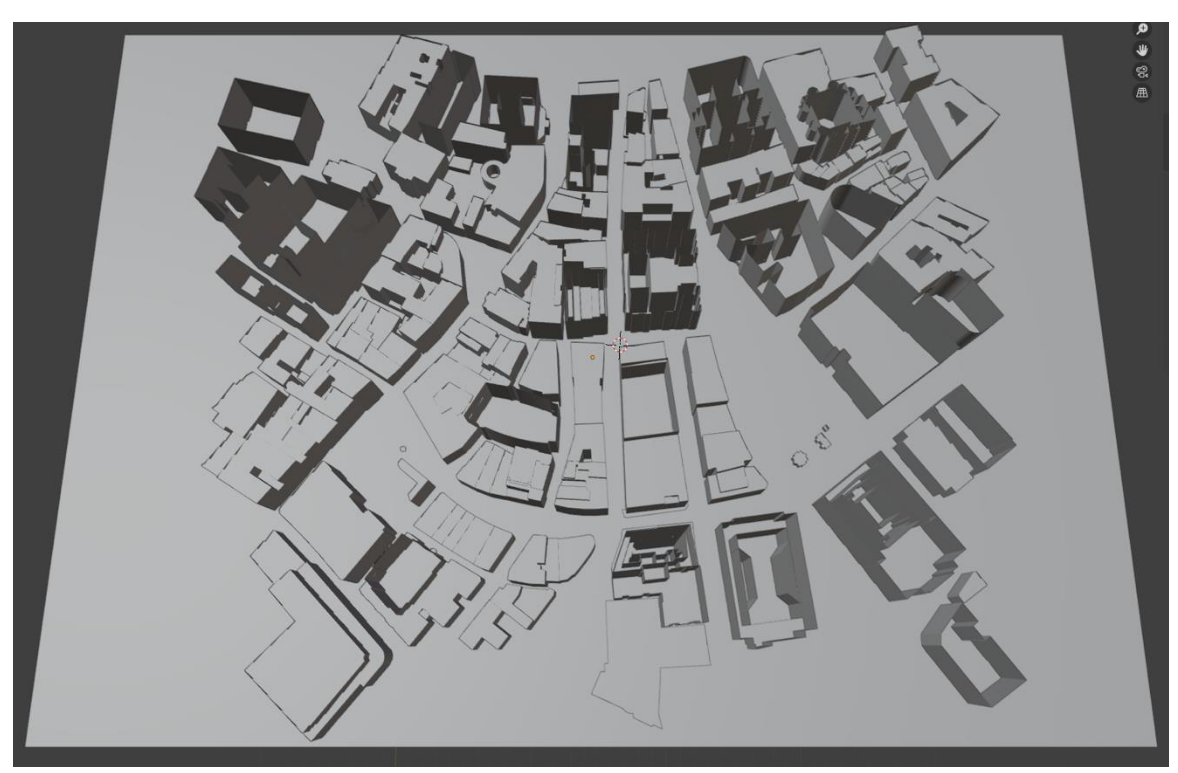
- System parameters
  - 3.5 GHz
  - 32x1 uniform linear array
  - BS height: 15 meters
- Ray-tracing setup
  - Boston scenario
  - Max depth of interaction: 4
  - Reflection enabled
  - Scattering enabled



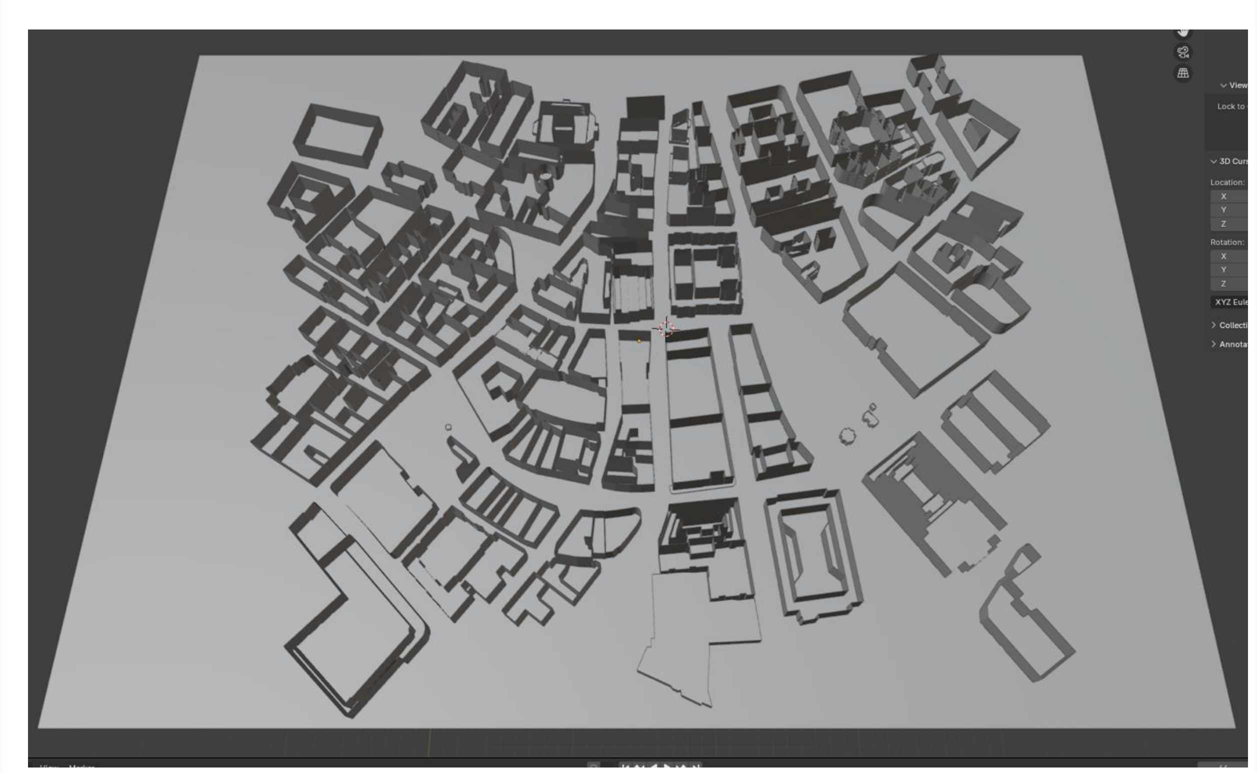


- After cutting off the building above a certain height

50m



20m



Trade-off between ray-tracing runtime and performance

Number of interactions	Ray-tracing runtime (ms)		Spectral efficiency (bps/Hz)		Coverage (%)	
	Building clipping (20 m) (All | LoS | NLoS)	**Original geometry (All | LoS | NLoS)**	**Building clipping (20 m) (All | LoS | NLoS)**	**Original geometry (All | LoS | NLoS)**	**Building clipping (20 m) (All | LoS | NLoS)**	**Original geometry (All | LoS | NLoS)**
2	13.8 | 14.0 | 12.4 (-57% | -56% | -62%)	18.6 | 17.6 | 16.5 (-42% | -45% | -46%)	8.49 | 21.33 | 6.00 (-8% | -0% | -13%)	8.66 | 21.35 | 6.20 (-6% | -0% | -10%)	79.93 | 100 | 76.03 (-17% | -0% | -20%)	93.66 | 100 | 92.43 (-4% | -0% | -4%)
3	21.5 | 18.6 | 16.9 (-33% | -42% | -44%)	30.6 | 30.8 | 23.9 (-5% | -4% | -21%)	8.71 | 21.33 | 6.26 (-6% | -0% | -9%)	8.95 | 21.35 | 6.54 (-3% | -0% | -5%)	82.98 | 100 | 79.67 (-14% | -0% | -17%)	95.90 | 100 | 95.11 (-2% | -0% | -2%)
4	25.7 | 25.6 | 20.7 (-20% | -20% | -32%)	*32.3 | 32.0 | 30.4*	8.89 | 21.33 | 6.46 (-4% | -0% | -7%)	*9.26 | 21.36 | 6.91*	84.96 | 100 | 82.06 (-12% | -0% | -15%)	*97.38 | 100 | 96.81*

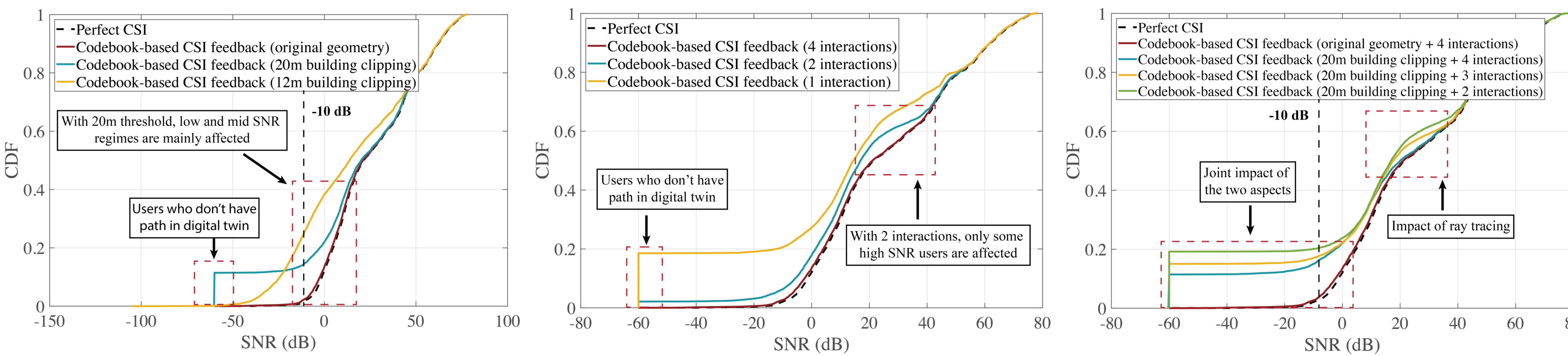
Both complexity reduction perspective can effectively reduce ray-tracing runtime

The performance of LoS users is not affected by complexity reduction methods

This trade-off motivates a multi-tier approach for NLoS users

How much time can complexity reduction save?

3D geometry model | **Ray-tracing configurations** | **Both perspectives combined**



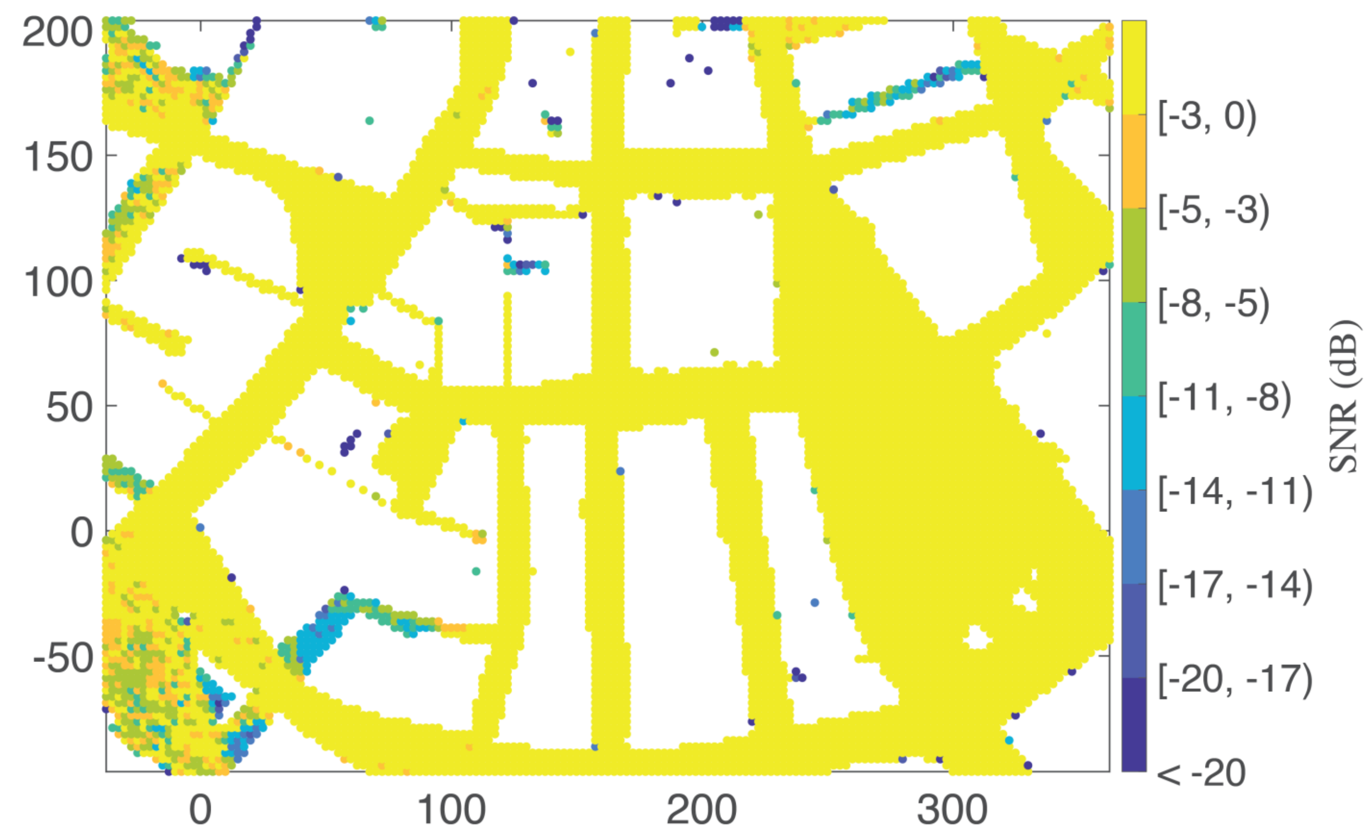
When clipping threshold is above BS height, low and mid SNR users are mainly affected

Reducing ray-tracing complexity affects some high SNR users' performance

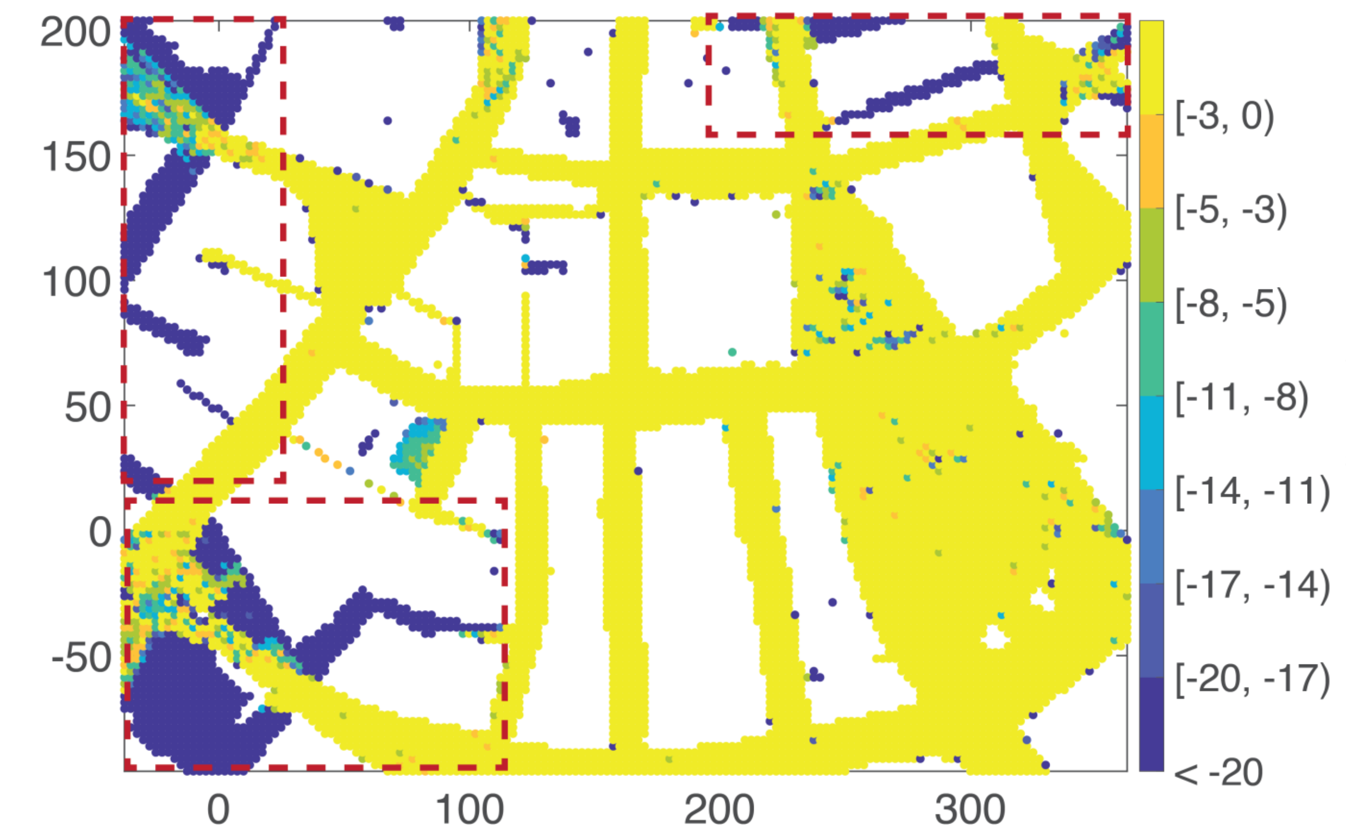
Building clipping and ray tracing affects the users in different regimes

How are the affected users distributed across the deployment?

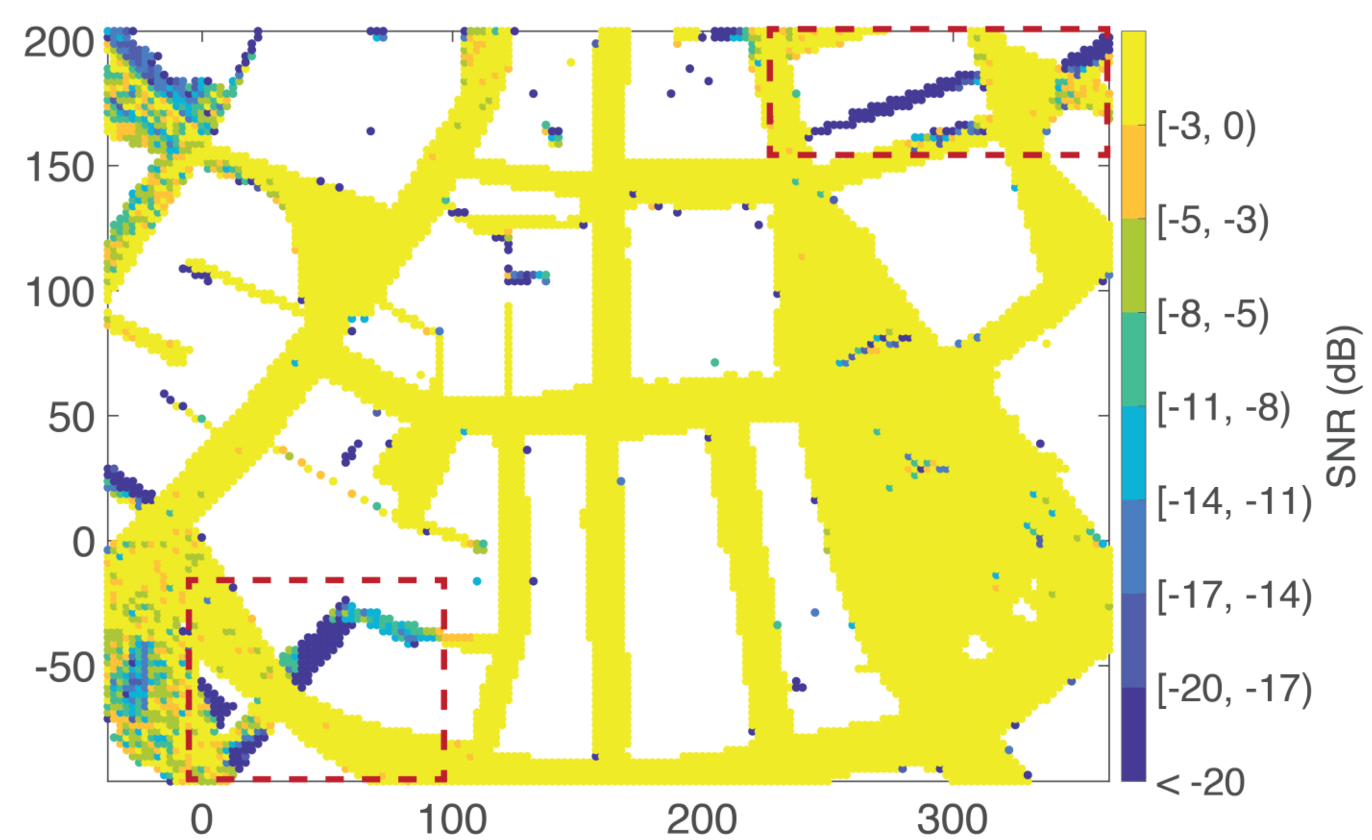
Reference scenario



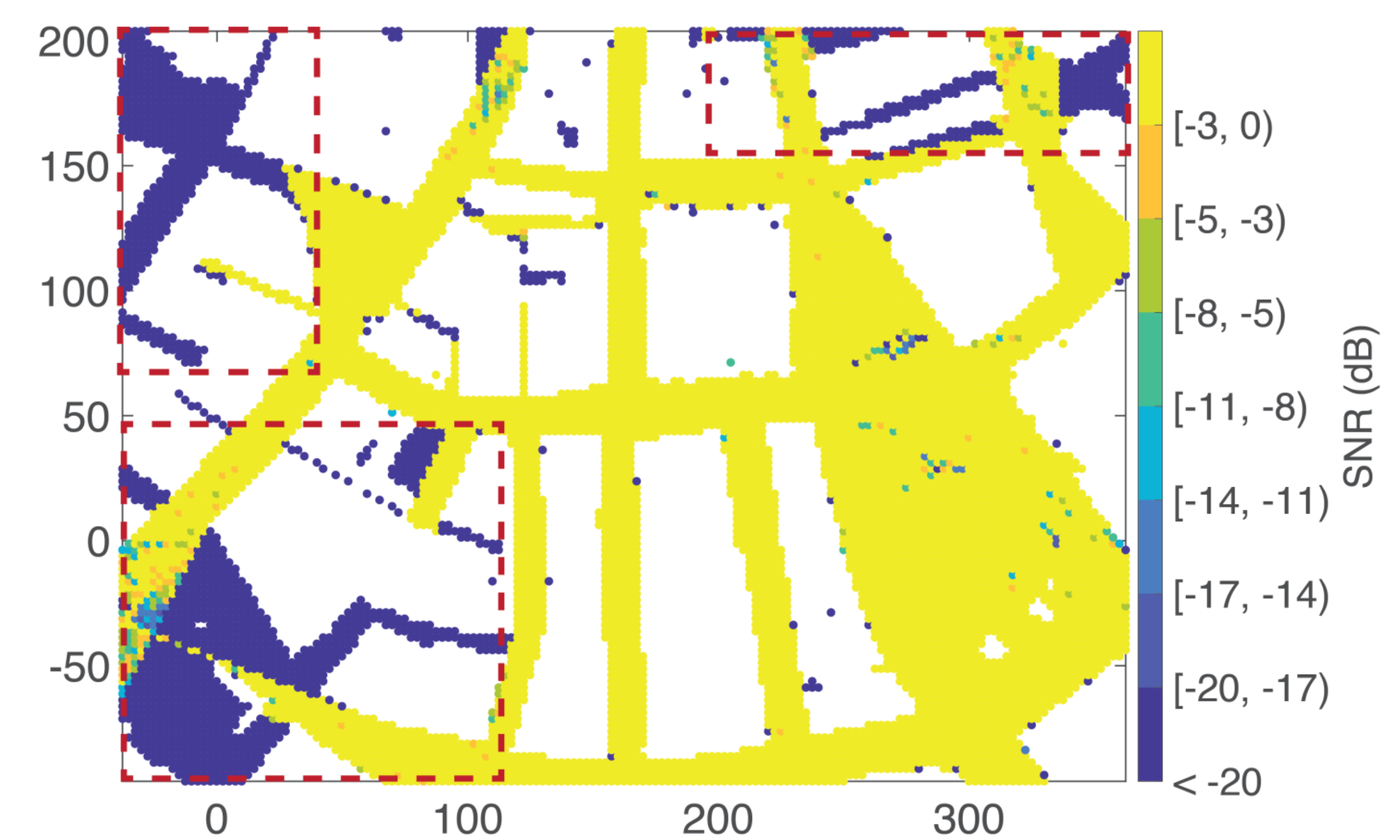
Geometry



Ray-tracing



Both perspective combined



The affected users are mainly located at the cell edge

Multi-tier digital twin aided codebook-based CSI feedback

Algorithm 1 Tier assignment procedure

```
τ ← −10 dB                                              ▷ SNR coverage threshold
for i in all in-coverage user locations do
    for j = 1 to 4 do                                   ▷ Lowest to highest tier
        if j = 4 then
            Assign location i to Tier 4.
        else if SNR_{i,j} > τ then
            Assign location i to Tier j.
            break                                       ▷ Next location
        end if
    end for
end for
```

Table 1: Multi-tiered digital twin and per tier UE assignment.

	Maximum building height	**Maximum no. of interactions**	**% LoS UEs**	**% NLoS UEs**
Tier 1	20m	2	100 %	$76.03/96.81 = 79$ %
Tier 2	Original	2	0 %	$16.4/96.81 = 16$ %
Tier 3	Original	3	0 %	$2.68/96.81 = 3$ %
Tier 4	Original	4	0 %	$1.7/96.81 = 2$ %
% runtime saving	LoS = 56 %; NLoS = $(0.79 \times 62 + 0.16 \times 46 + 0.03 \times 21) = 56.97$ %			

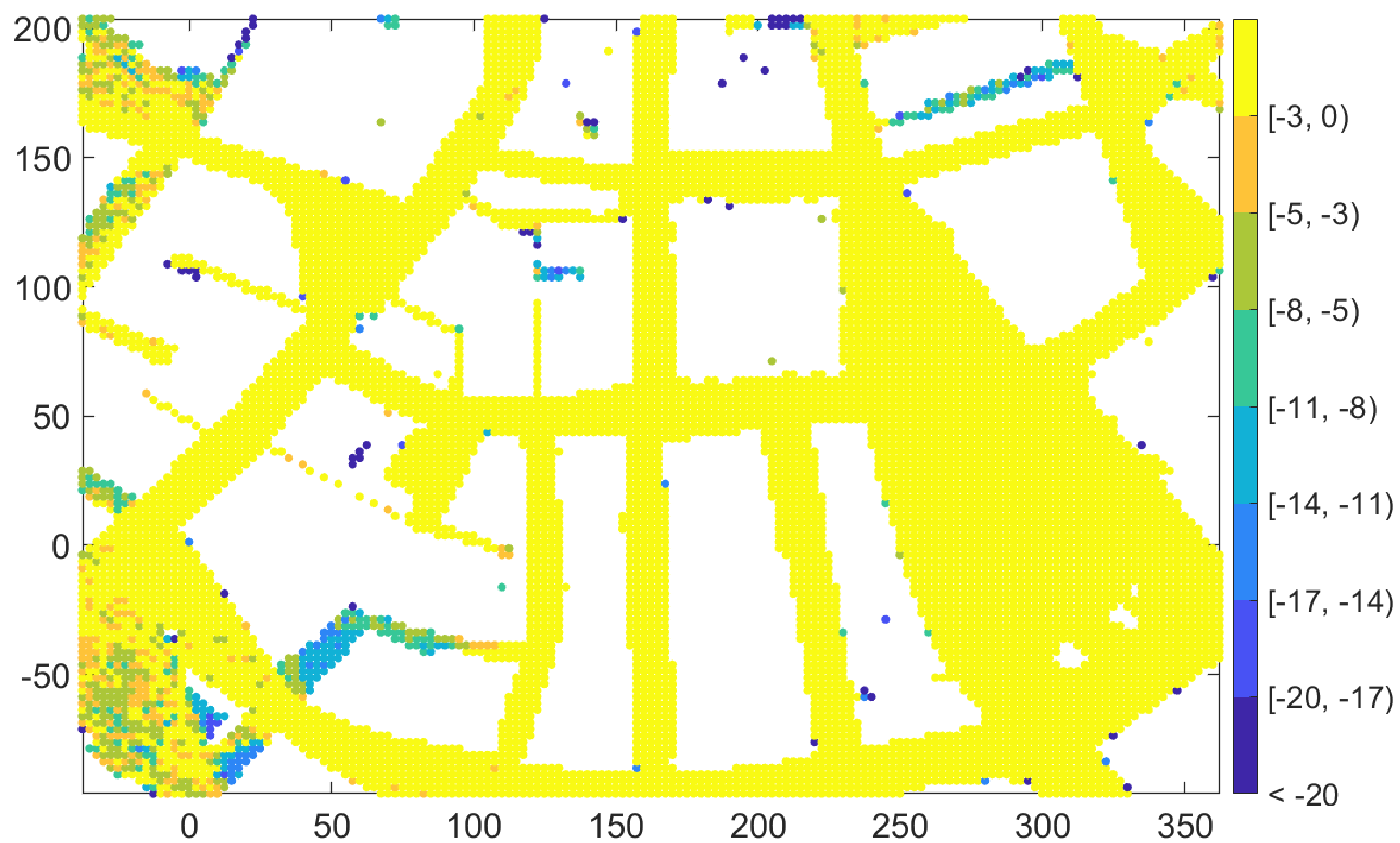
- How tiers are assigned
  - Sweep fidelity levels offline
  - Assign each grid location ot the lowest tier where prediceted SNR > -10 dB
  - Reuse assignment map at runtime

56% runtime reduction while maintaining healthy coverage and spectral efficiency

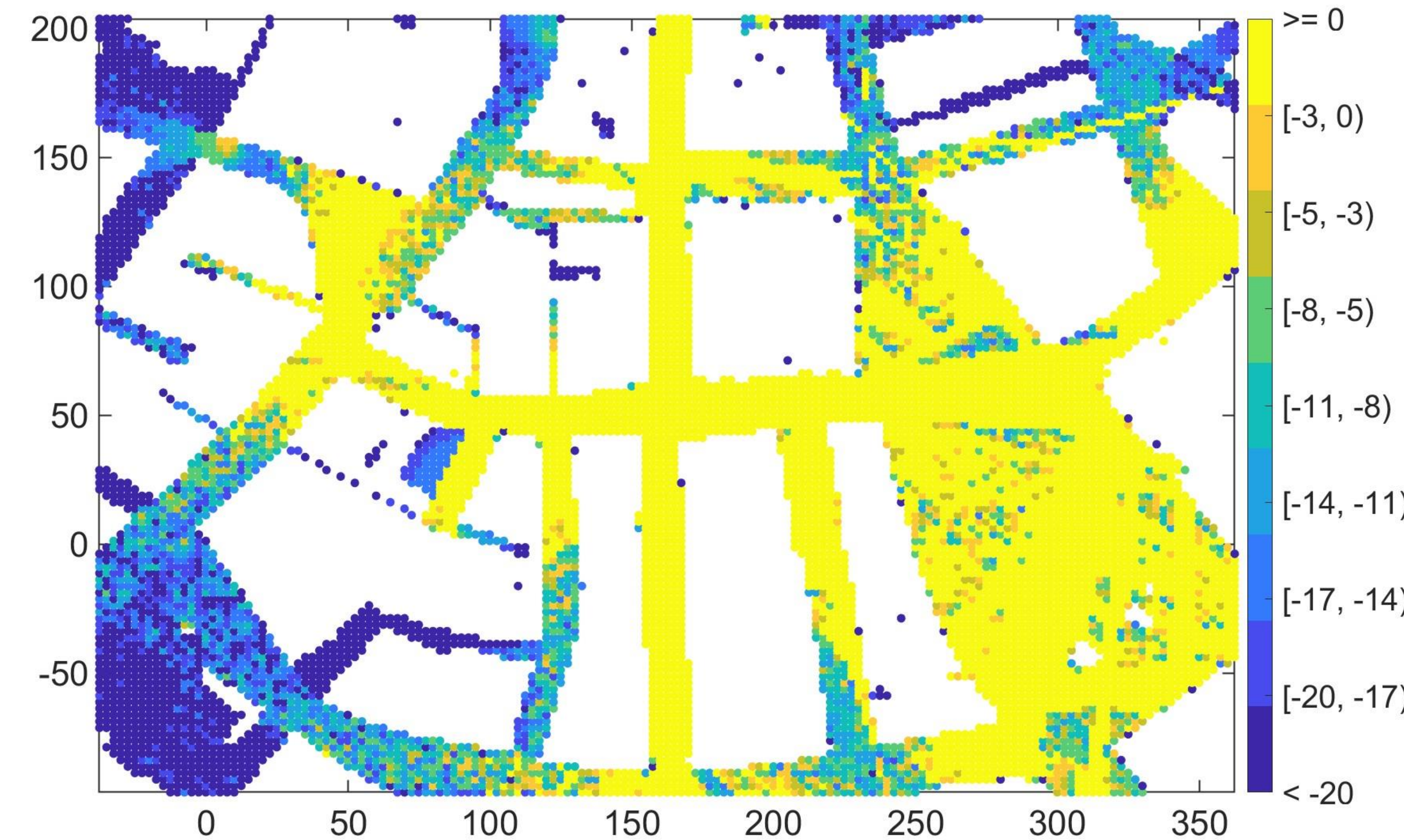
Simulation setup of mmWave beam selection

- System parameters
  - 28 GHz
  - 32x1 uniform linear array
  - BS height: 15 meters
- Ray-tracing setup
  - Boston scenario
  - Max depth of interaction: 4
  - Reflection enabled
  - Scattering enabled

Codebook-based CSI feedback (3.5 GHz)



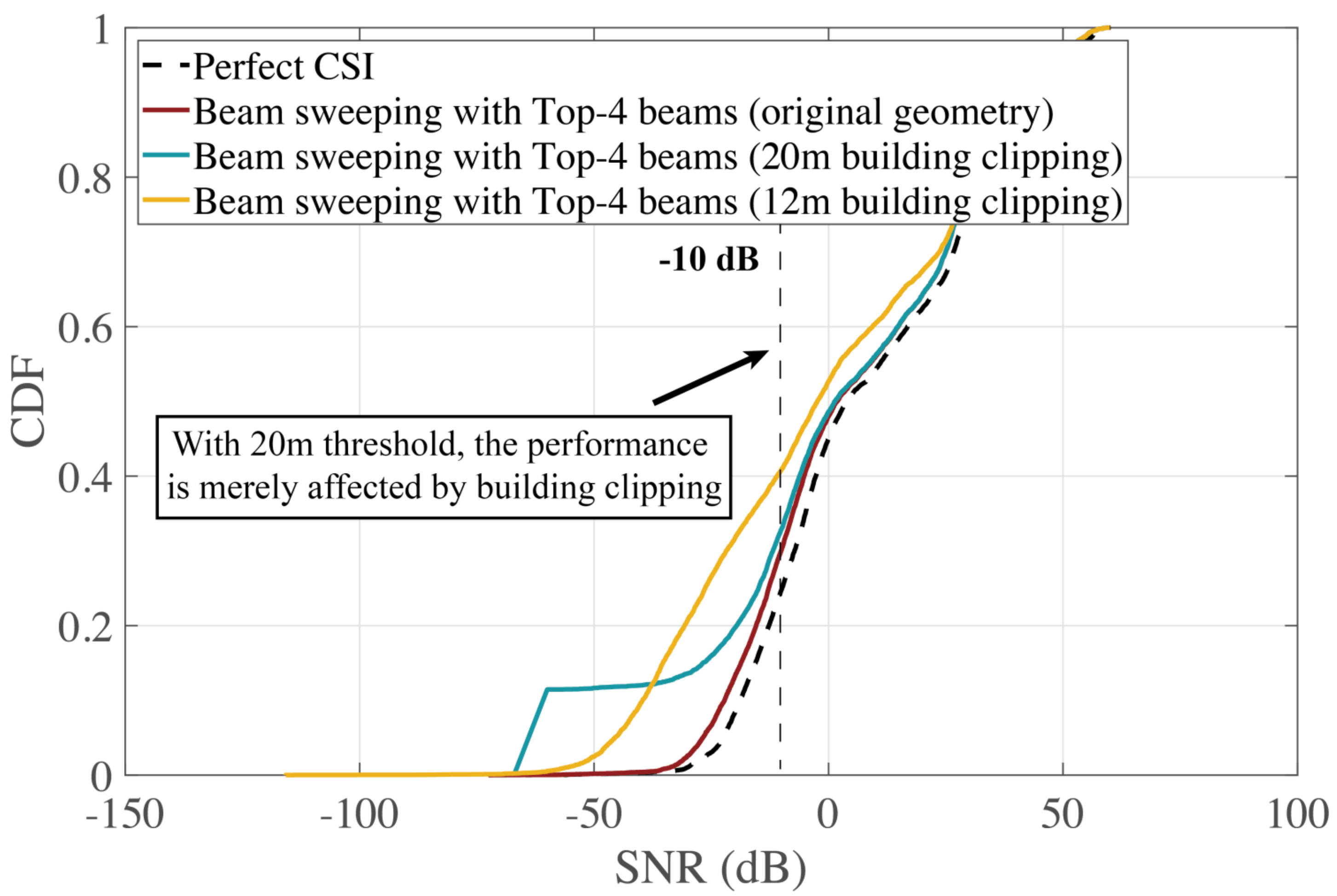
Beam selection (28 GHz)



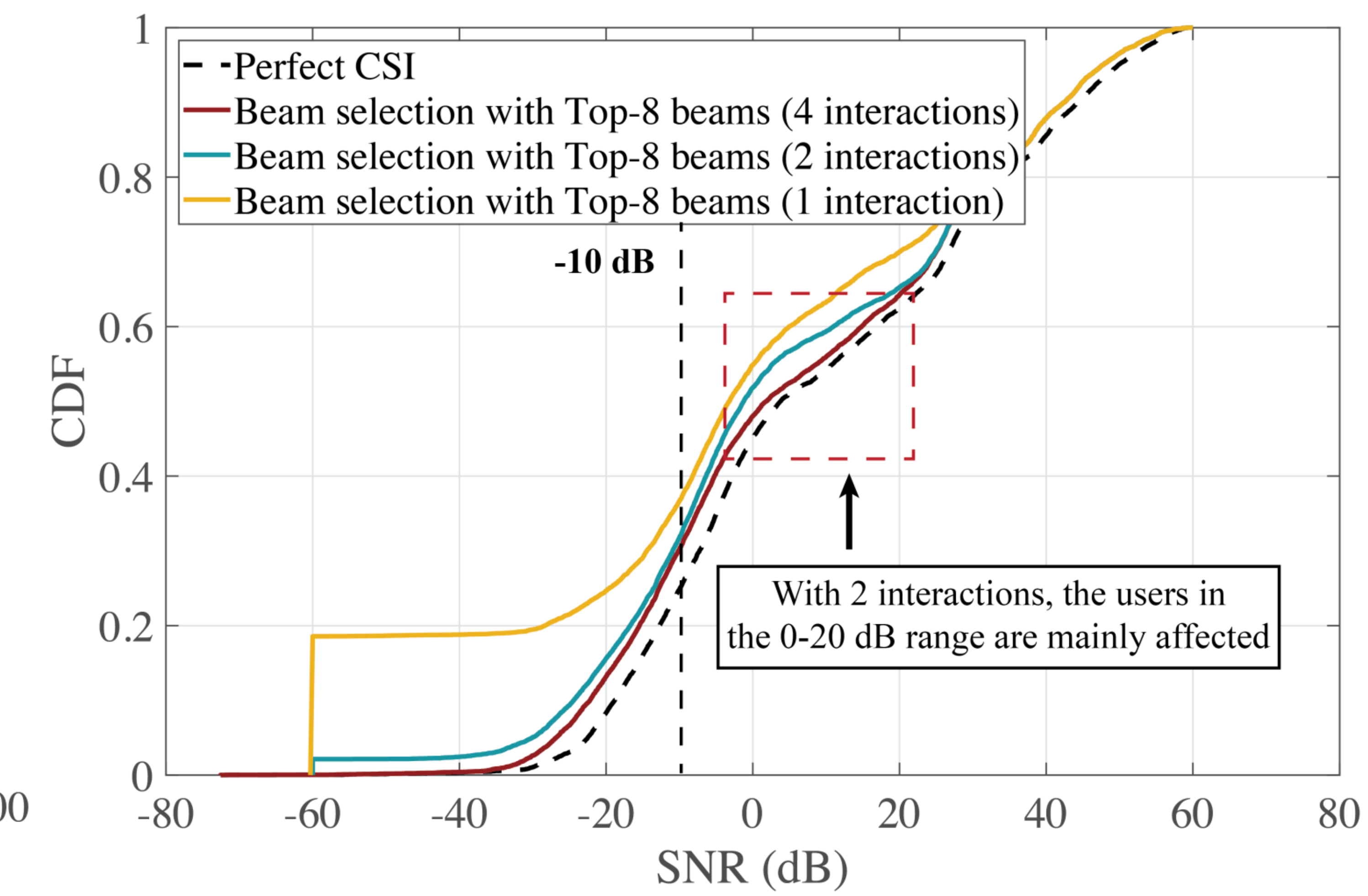
For beam selection, the coverage is significantly reduced due to the high path loss

What is the impact of complexity reduction on the performance?

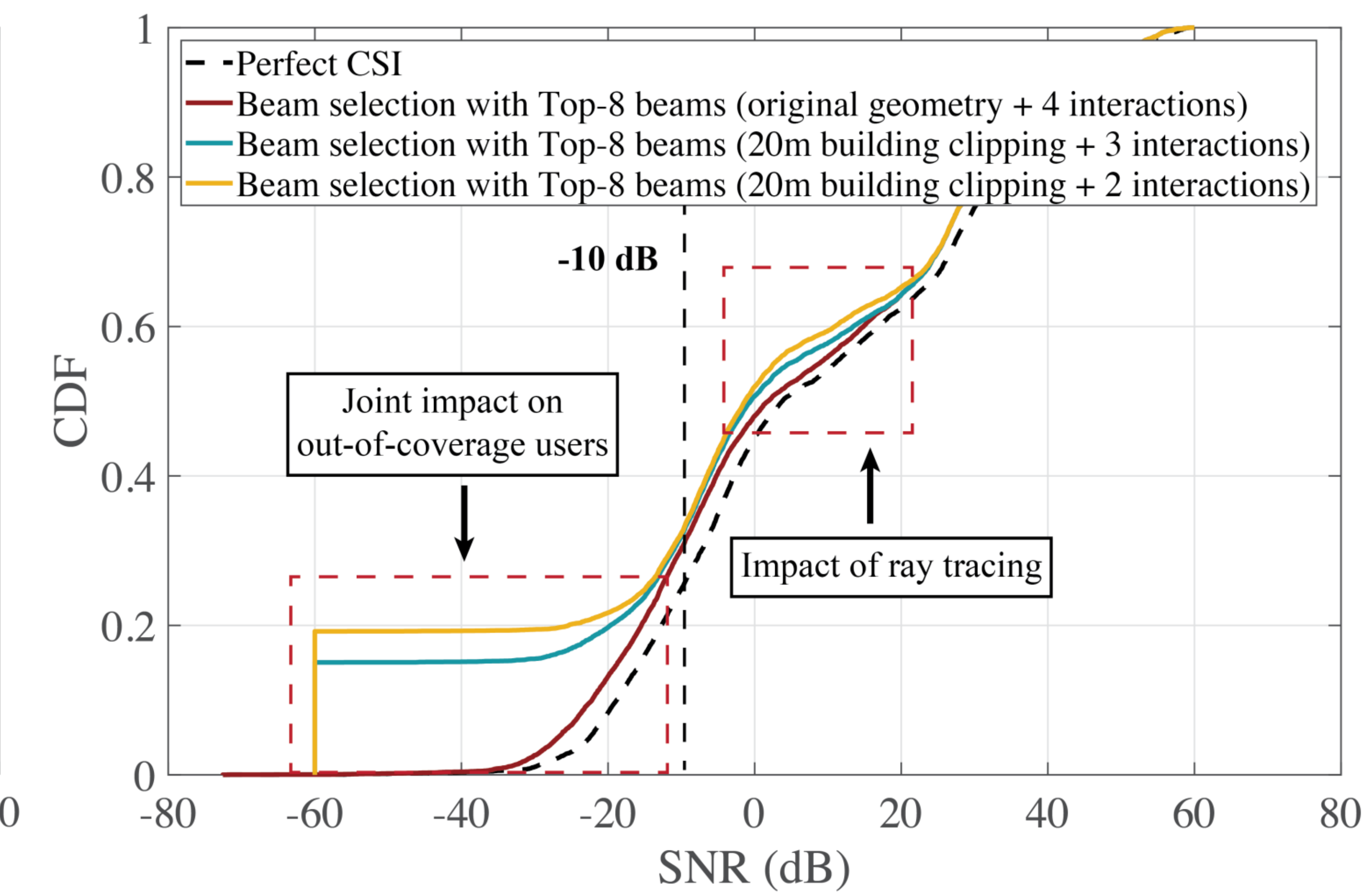
3D geometry model



Ray-tracing configurations



Both perspectives combined



Building clipping has a small impact on the performance and coverage

Ray tracing mainly affects users in the –20 dB SNR range

The performance of beam selection is mainly limited by the ray tracing

Conclusion and future work

- We propose a digital twin aided CSI feedback with multi-tier fidelity levels
  - For both codebook-based CSI feedback and beam selection, DT can help reduce overhead
  - 3D geometry – Building clipping
  - Ray tracing – Reducing the number of interactions
- Key findings
  - Both building clipping and reducing # of interactions can effectively reduce computation time
  - For sub-6 GHz, both 3D geometry and ray-tracing aspects have a noticeable impact
  - For mmWave beam selection, the ray tracing dominates the performance degradation
  - For specific task and user position, the DT fidelity level needs to be strategically decided
- Future work
  - Mobility (users/scatterers) – How often do we need to re-run ray tracing in the digital twin?
  - Multi-cell setup – Can we futher mitigate the performance loss caused by complexity reduction?

Q&A

Thank you!

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