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May, 2024 | Beijing, China

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MATLAB EXPO

Outline

- Introduction
- 5G NR Sensing-Assisted Communications: Ray-Tracing based V2I Scenario
- Frame Structures and Case Studies in NR FR2 V2I Networks

  1) Initial Access

  2) Connected Mode

  3) Beam Failure Detection and Recovery

I. Introduction

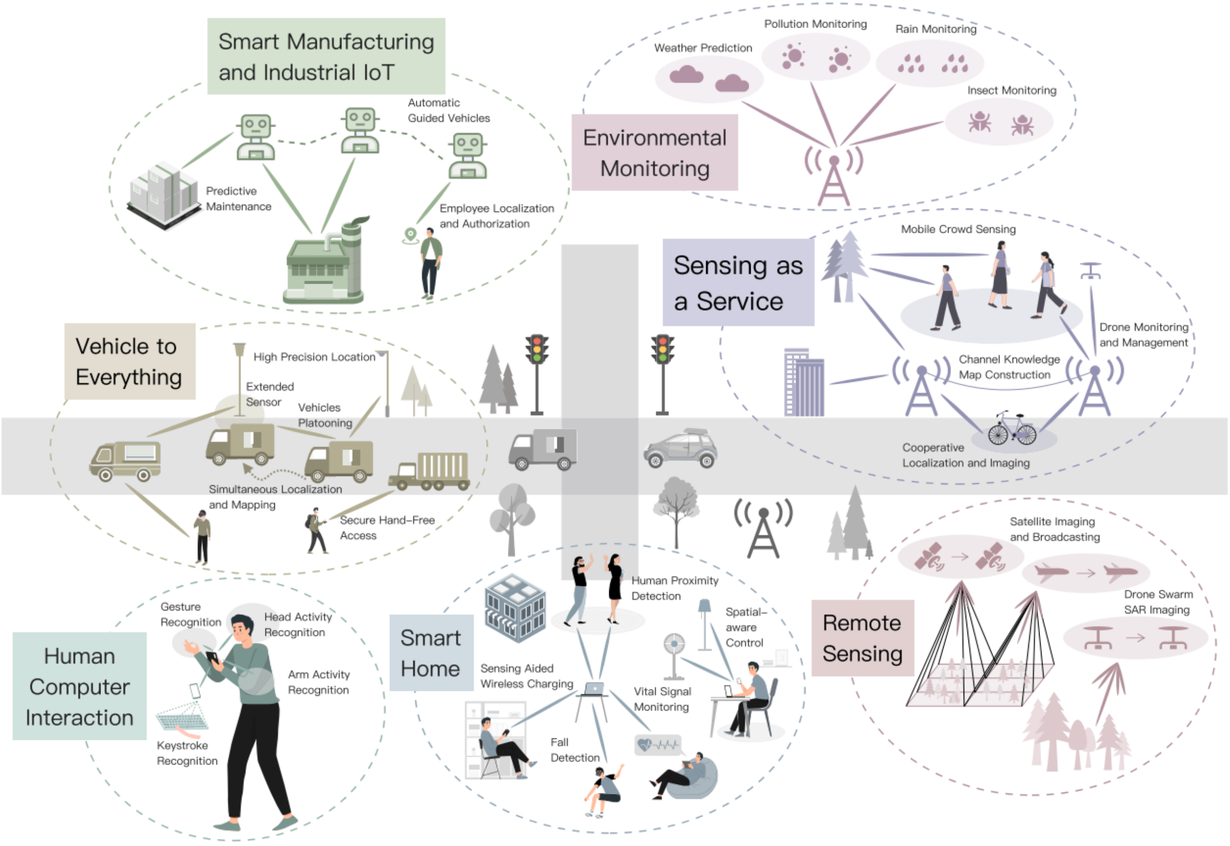
- **Integrated Sensing and Communication (ISAC) for 6G and Beyond**

Sensing & Communication (S&C) Systems:

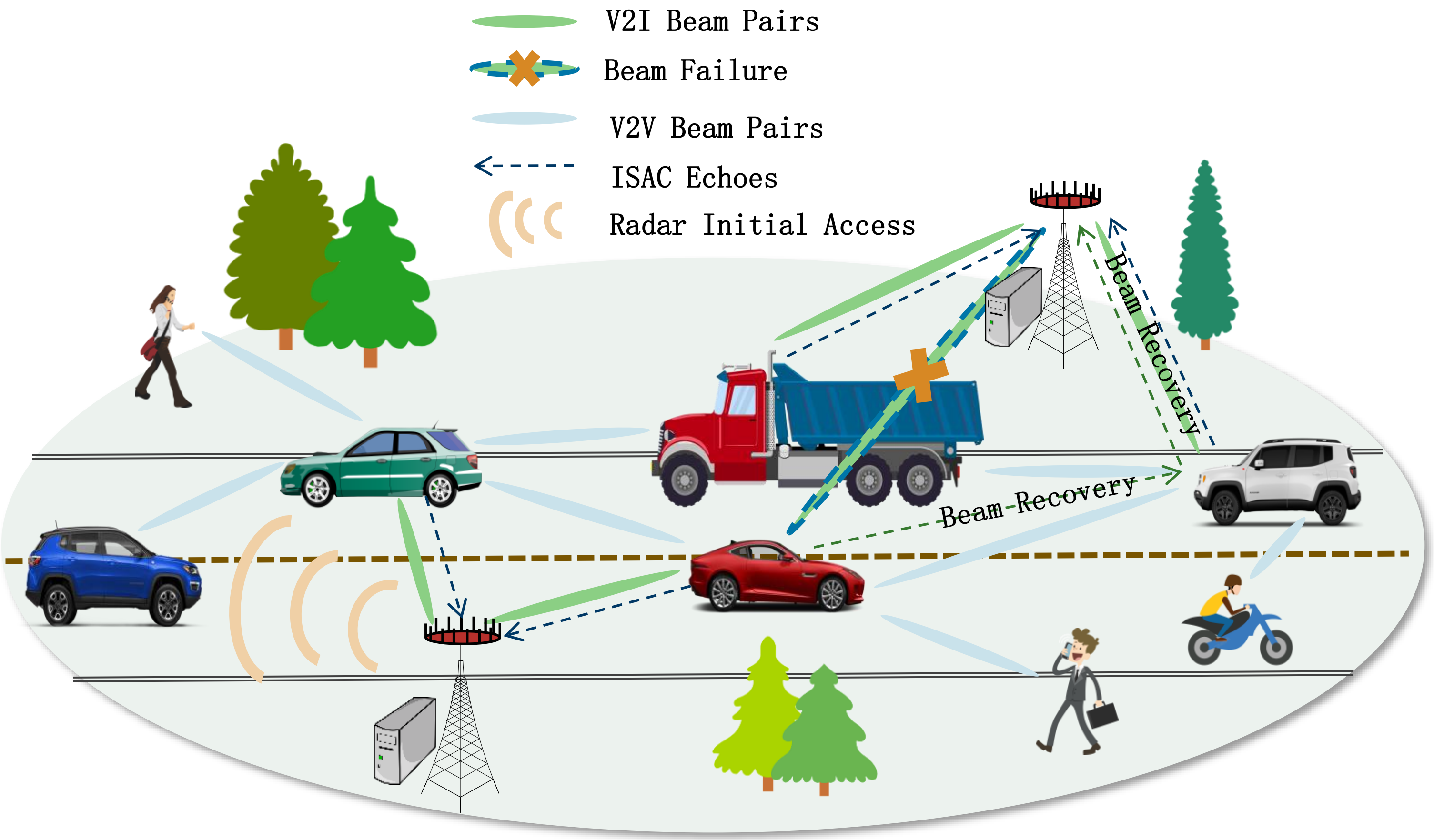
✓ *<u>Integration gain</u>*: joint exploitation of limited hardware and spectral resources

✓ *<u>Coordination gain</u>*: mutual assistance between sensing and communications (sensing centric or communication centric)

- Applications:



I. Introduction



ISAC in V2X Network

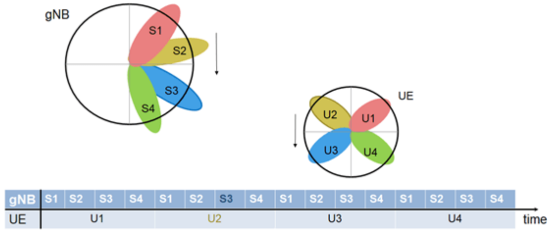
- **Conventional Communication in NR**:
  - Pilots + Reference signals
- ***ISAC in NR***:
  - Sensing with data payload signals
  - *Angles*, *range* and *velocity* of the target, locations of scatterers …

  - ***Overhead reduction***
  - ***Accurate tracking***
  - ***Efficient beam failure detection and recovery***
- ***Supported by MATLAB-Enabled Efficient End-to-End Simulation***

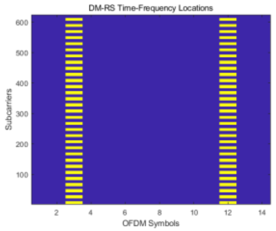
I. Introduction

- ***Major Toolbox Utilization in Simulation*** :

▪ **5G Toolbox**: Standard-compliant functions to simulate 5G NR end-to-end wireless communications links.

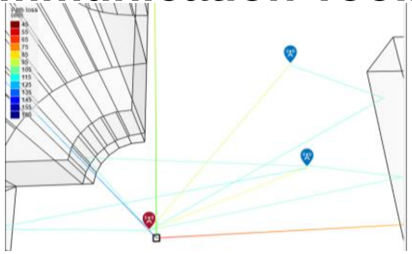


Beam Sweeping

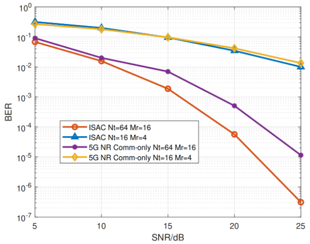


NR Frame Structure Design

▪ **Communication Toolbox**: Facilities modeling communications links from antenna to RF chain to bit processing.

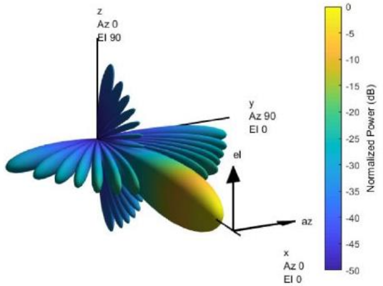


Site Viewer and Ray Tracing

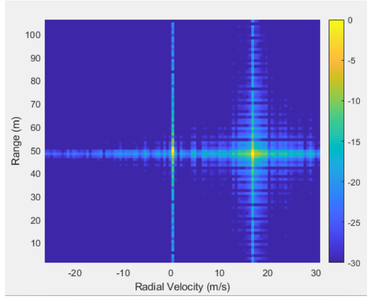


BER Calculation

▪ **Phased Array System Toolbox**: Designs phased array and beamforming in wireless communication and radars.

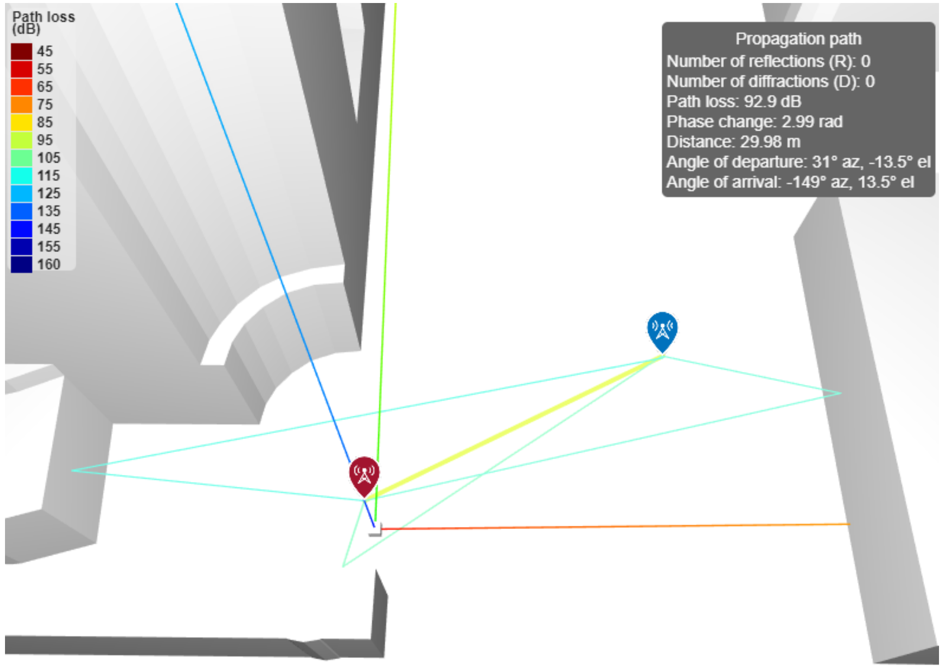


Steering and Beamforming

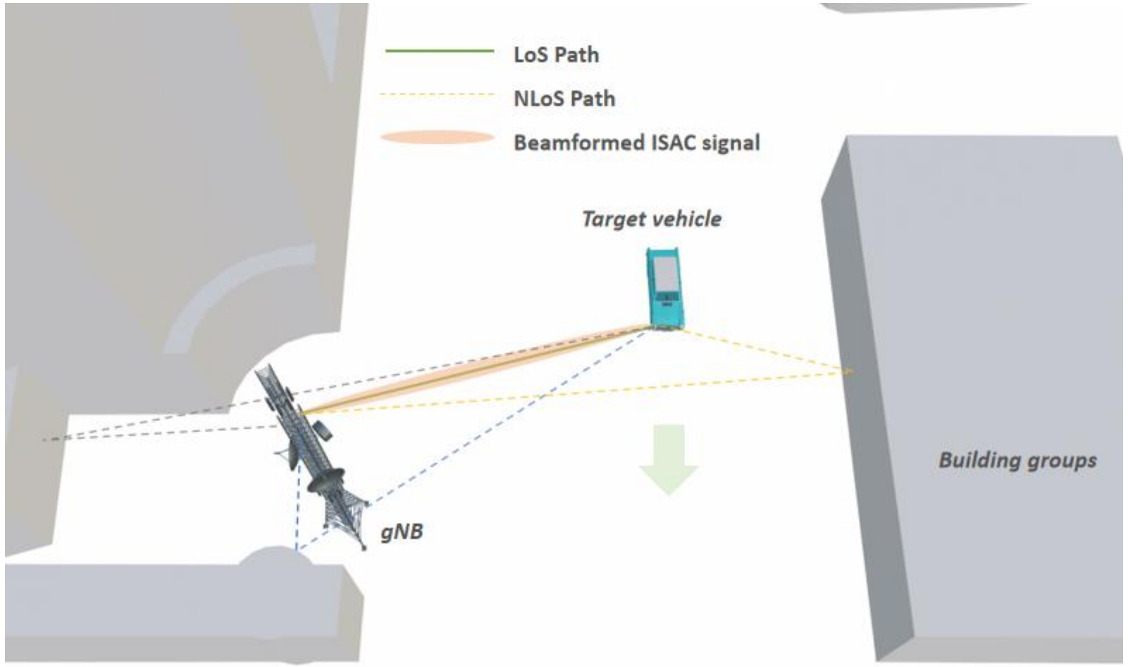


Range and Doppler Estimation in Radar

II. 5G NR Sensing Assisted Communications: Ray-Tracing based V2I Scenario



Ray tracing propagation model visualized in Siteviewer



Simulated ISAC V2I Network Scenario

Site Viewer: using Communication toolbox

- **viewer = siteviewer(SceneModel = '.stl'):** import and view the stl file using siteviewer.

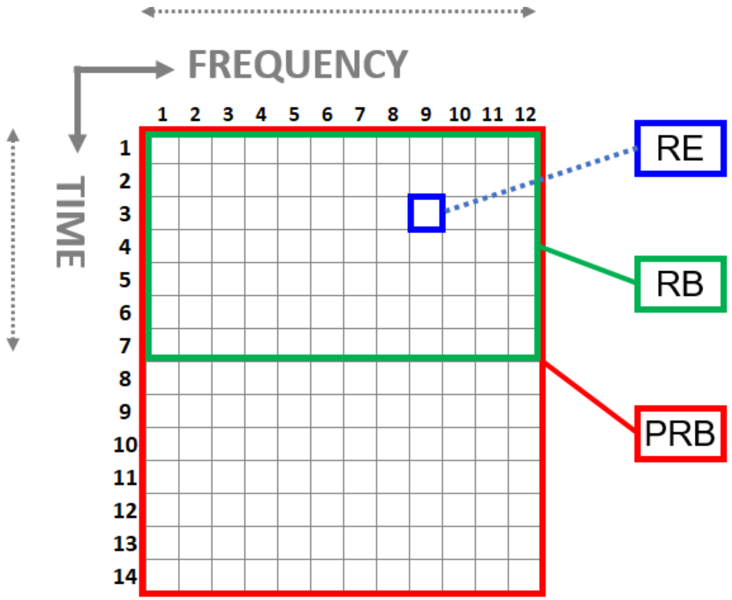
Ray trace: using Communication toolbox

- **r = raytrace(tx, rx):** displays the propagation paths from the transmitter site *tx* to the receiver site *rx* in the current Site Viewer.

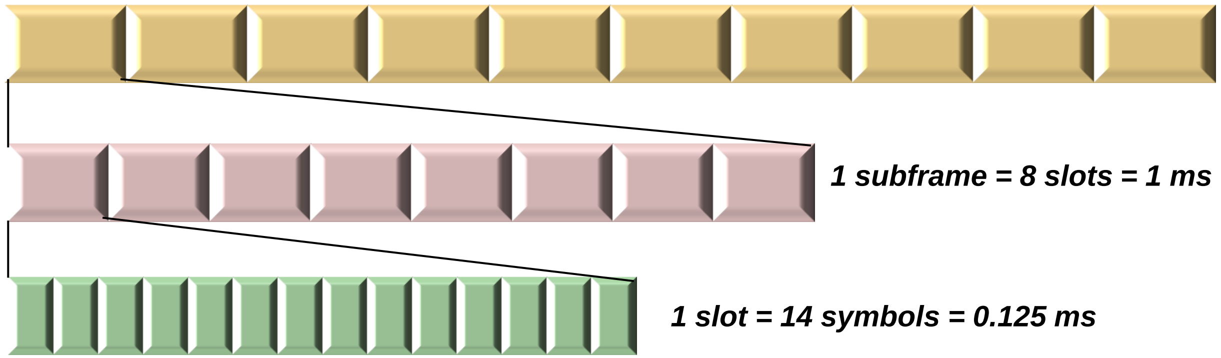
III. Frame Structures and Case Studies in NR V2I Network: OFDM General Frame Structure

- ## NR Numerology

μ	Δf=2^{μ}·15[kHz]	Cyclic Prefix	Frequency Band	Supported for Data (PDSCH, PUSCH etc)	Supported for Sync (PSS, SSS, PBCH)
0	15	Normal	FR1 (sub-6G)	Yes	Yes
1	30	Normal	FR1	Yes	Yes
2	60	Normal, Extended	FR1, FR2	Yes	No
3	120	Normal	FR2 (mmWave)	Yes	Yes
4	240	Normal	FR2	No	Yes
5	480	Normal	FR2	Yes	Yes
6	960	Normal	FR2	Yes	Yes



***μ = 3:* 1 radio frame = 10 subframes = 80 slots = 10 ms**



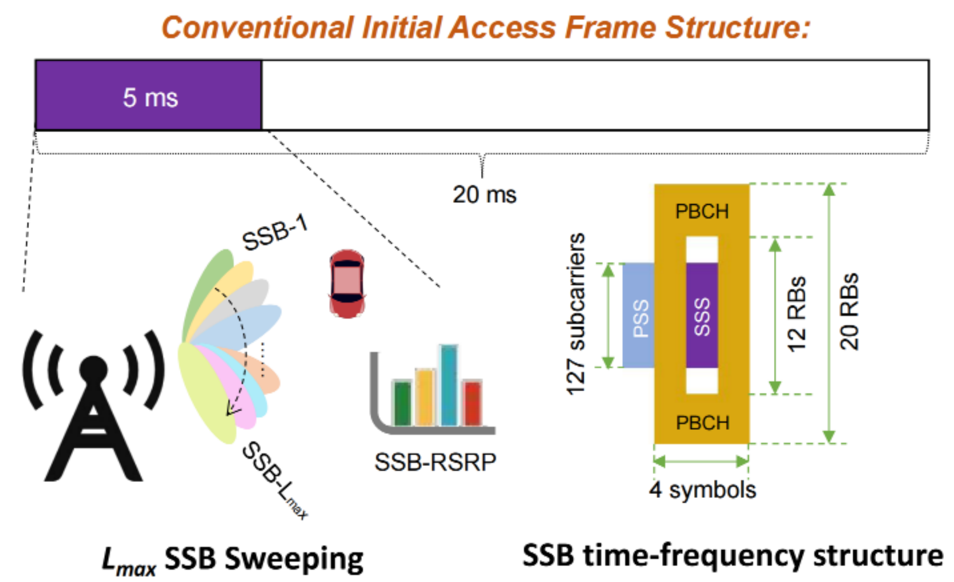
Get OFDM Information: using 5G Toolbox

- **info = nrOFDMInfo(numRB, SCS):** Input the number of resource blocks and subcarrier spacing to get OFDM Information.

3GPP, "NR; Physical channels and modulation," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.211, 2022, version 17.4.0.

III. Frame Structures and Case Studies in NR V2I Network: Initial Access (IA)

- ***IA in conventional NR***



- ***Beam sweeping:*** L_{max} SSBs (64) in first 5ms of 20ms period
- ***Beam measurement and determination:*** SS reference signal received power (SS-RSRP)

$$\text{SS-RSRP (in dBm)} = 10\log_{10}\left(\frac{1}{N}\sum_{n=1}^{N}|\mathbf{X}[n]|^2\right) + 30$$

- ***Beam reporting:*** SSB beam index feedback in RACH

Array configuration: Phased Array System Toolbox

- **arrayTx = phased.URA([8 8], 0.5*lamda):** Assign the array size and the element spacing for uniform rectangular array (URA).

SS burst waveform: 5G Toolbox

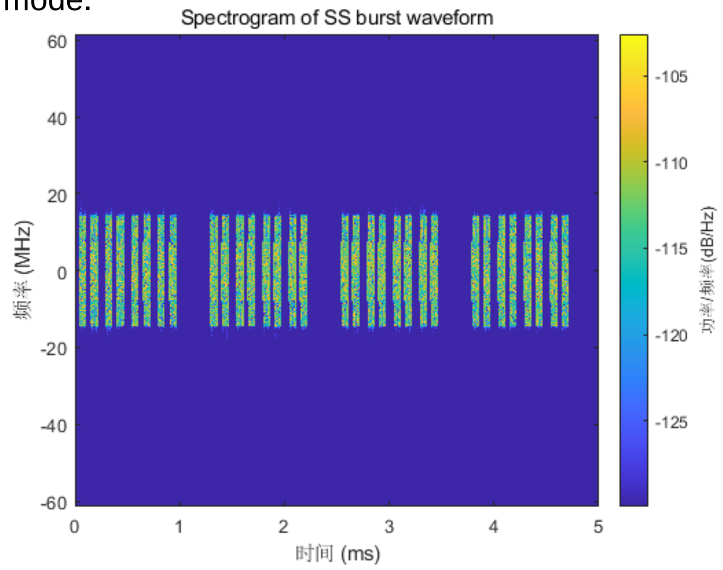
- **burstWaveform = nrWaveformGenerator( ):** Create the SS burst waveform by using nrWaveformGenerator function.

Beamforming: Phased Array System Toolbox

- **SteerVecTx = phased.SteeringVector('SensorArray', arrayTx, 'PropagationSpeed', c); wT = SteerVecTx(CenterFreq, BeamAng):** Generate weights for steering direction.

Synchronization and RSRP measurement: 5G Toolbox

- **offset = nrTimingEstimate():** Performs practical timing estimation by cross-correlating.
- **meas = nrSSBMeasurements():** Measuring the RSRP based on the specified measurement mode.



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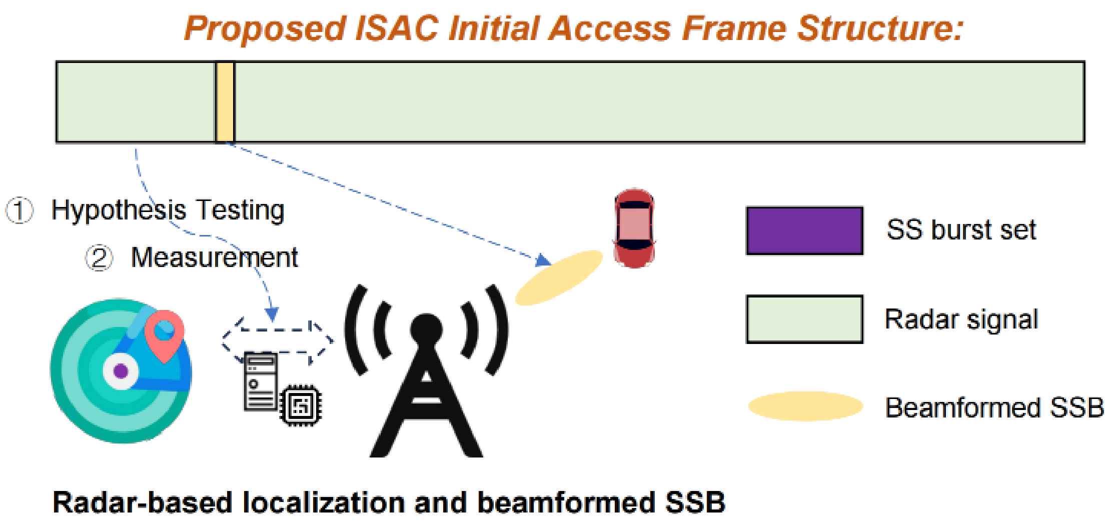
III. Frame Structures and Case Studies in NR V2I Network: Initial Access (IA)

- ## IA in ISAC NR



- ***Binary hypothesis testing:***

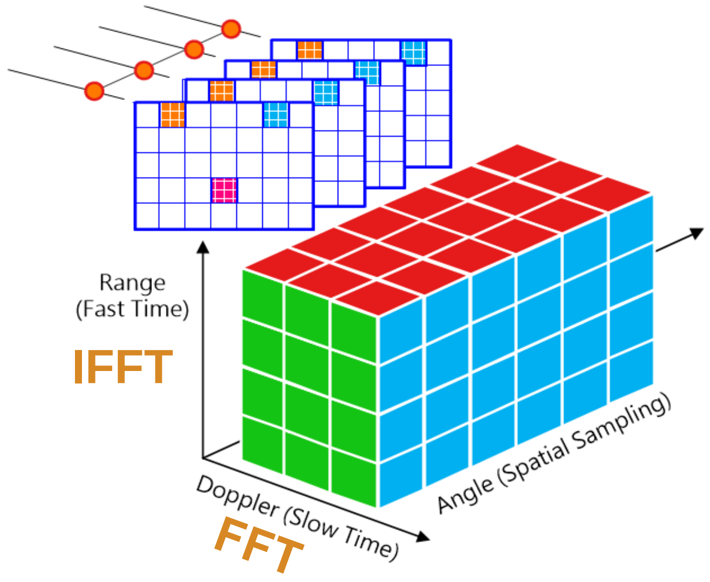
$$\begin{cases} \mathcal{H}_0 : \Re\left(\mathbf{Y}_{i,m,l}\right) \sim \mathcal{N}\left(0, \tilde{\sigma}^2/2\right) \\ \mathcal{H}_1 : \Re\left(\mathbf{Y}_{i,m,l}\right) \sim \mathcal{N}\left(\mu, \tilde{\sigma}^2/2\right) \end{cases}$$

For a certain false alarm rate P_{FA}:

$$\left|\Re\left(\mathbf{Y}_{i,m,l}\right)\right| \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \sqrt{\frac{\tilde{\sigma}^2}{2}} Q^{-1}\left(P_{\mathrm{FA}}\right)$$

- ***Beamformed SSB with only synchronization purpose***

- ***OFDM Radar Signal Channel: Phased Array System Toolbox***
- **rdchannel = phased.FreeSpace(OperatingFrequency, SampleRate, TwoWayPropagation):** Design two-way propagation free-space radar channel.
- ***OFDM Radar Signal Processing:***
- 2D-DFT Processing: FFT in slow time domain and IFFT in fast time domain

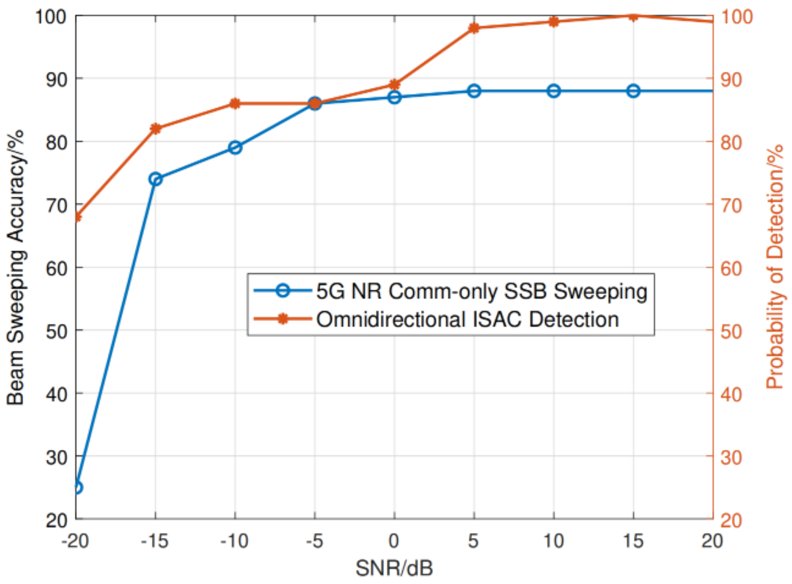


$$d = \frac{\tau c}{2}, v = \frac{\mu c}{2 f_c}$$

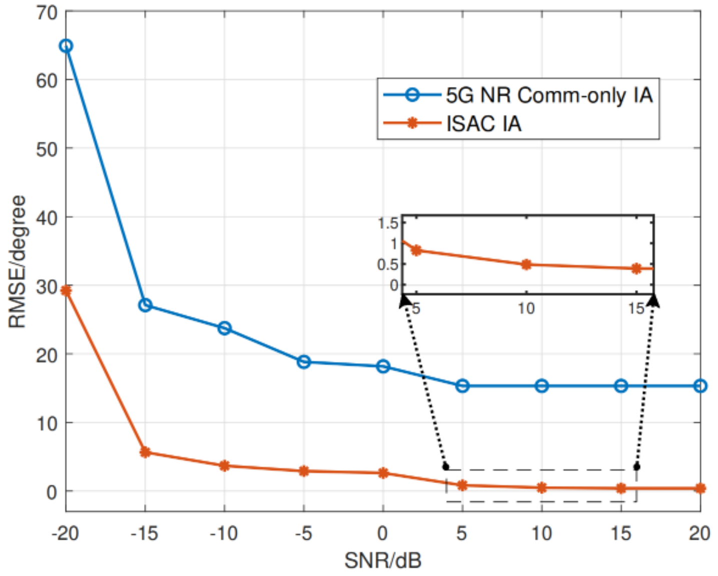
S. Ehsanfar, A. Bazzi, K. Moßner, and M. Chafii, "Hypothesis testing on FMCW and OFDM for joint communication and radar in *IEEE 802.11bd," in Proc. IEEE Int. Conf. Commun. Workshops*, 2023, pp. 464–469.

III. Frame Structures and Case Studies in NR V2I Network: Initial Access (IA)

- ***Accuracy Comparison***



- ***RMSE Comparison***



- ***Access Time Delay Comparison***

Detection Accuracy and Access Delay Comparison between Conventional IA and ISAC IA

IA Scheme	Number of Slots in Aggregation	Detection Accuracy (%)	Expected Access Delay (ms)
Comm	\	86.3	15
ISAC	10	88.8	1.25
	15	93.1	1.875
	20	95.0	2.5

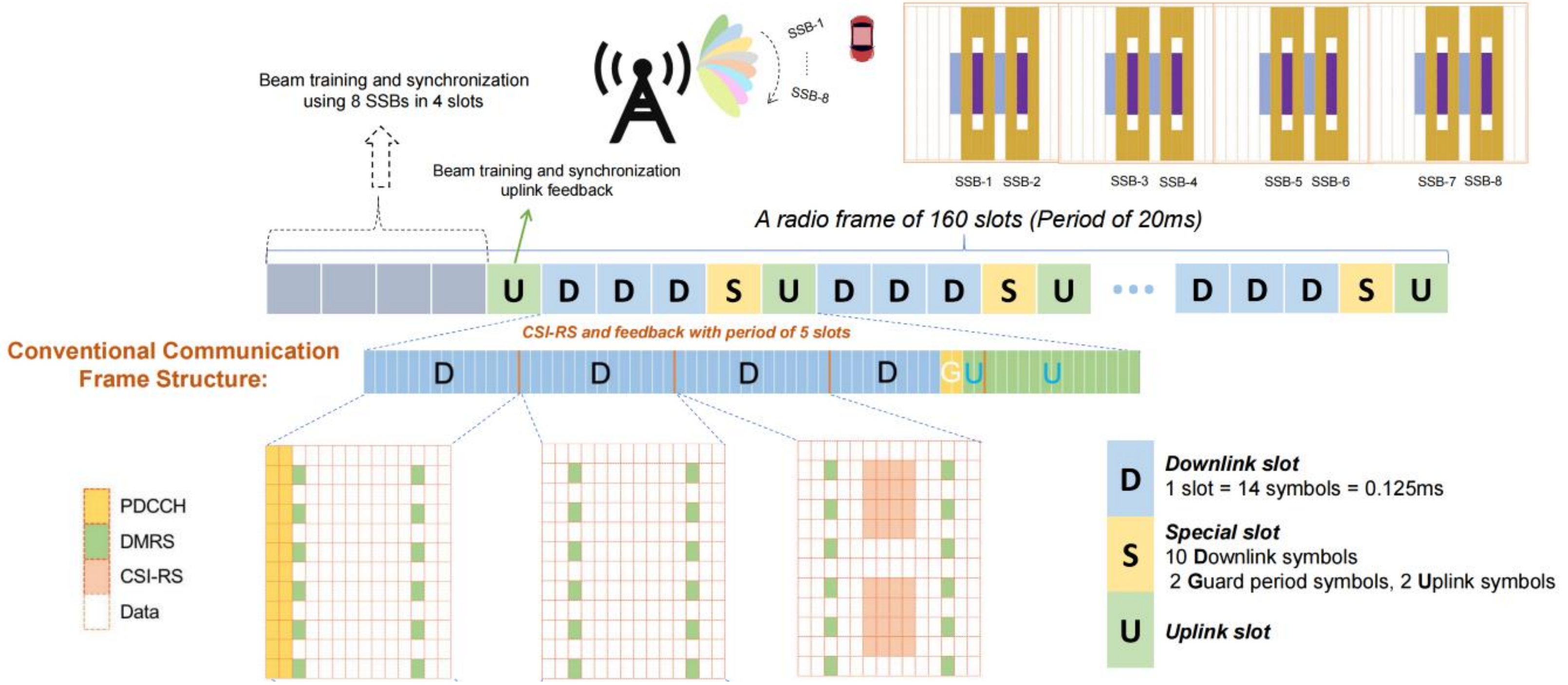
Conventional NR: RSRP-based and codebook-based;

ISAC NR: Omnidirectional-radar and beamforming SSB;

Improvement in ***higher accuracy***, ***smaller RMSE*** and ***shorter access time delay.***

III. Frame Structures and Case Studies in NR V2I Network: Connected Mode

- ## Conventional NR Frame Structure



SSB Sweeping:

Beam training and synchronization

Common Frame Structure in NR: DDDSU with period = 5 slots

D: downlink slot, S: special slot, U: uplink slot

NR Reference Signals:

- **CSI-RS**: Channel estimation, up to 32 ports are supported, feedback parameters include rank indicator (RI), precoding matrix indicator (PMI) …
- **DMRS**: Coherent demodulation, additional DMRS are supported for high mobility scenario

Frame Structure Design: using 5G Toolbox

- **pdsch = nrPDSCHConfig:** Configure the physical downlink shared channel parameters
- **nrPDSCHDMRS, nrCSIRSConfig:** Generate DMRS and CSI-RS symbols, assign antenna ports for CSI-RS

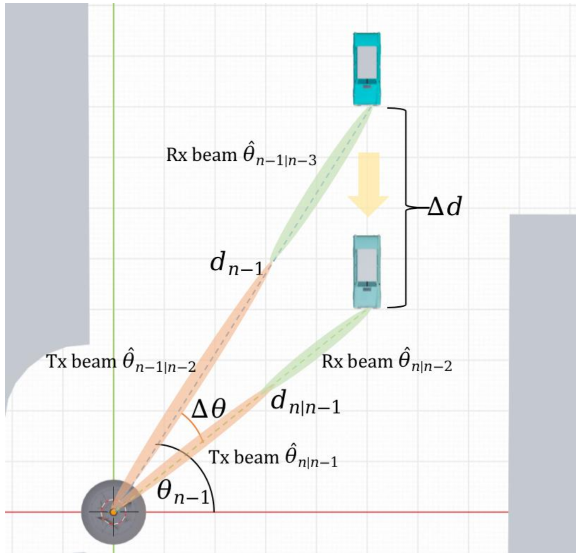
OFDM Modulation, Channel Configuration and Estimation: using 5G Toolbox

- **nrOFDMModulate, nrOFDMDemodulate:** Generate OFDM modulated waveform and demodulate
- **nrCDLChannel, nrChannelEstimate:** Configure the physical downlink channel using parameters in ray-tracing and do channel estimation using CSIRS

III. Frame Structures and Case Studies in NR V2I Network: Connected Mode

- ## ISAC tracking on straight road using Extended Kalman Filter

State Evolution Model



- **State Evolution Model:**

$$\begin{cases} \theta_n = \theta_{n-1} - d_{n-1}^{-1} v_{n-1} \Delta T \cos\theta_{n-1} + \omega_\theta \\ d_n = d_{n-1} - v_{n-1}\Delta T \sin\theta_{n-1} + \omega_d \\ v_n = v_{n-1} + \omega_v \\ \beta_n = \beta_{n-1}\left(1 - d_{n-1}^{-1} v_{n-1}\Delta T \sin\theta_{n-1}\right)^2 + \omega_\beta \end{cases}$$

- **Compact Forms:**

$$\begin{cases} \text{State Evolution Model: } \mathbf{x}_n = \mathbf{g}(\mathbf{x}_{n-1}) + \boldsymbol{\omega}_n \\ \text{Measurement Model: } \mathbf{y}_n = \mathbf{x}_n + \mathbf{z}_n \end{cases}$$

- **Linearization of State Evolution Model:**

$$\frac{\partial \mathbf{g}}{\partial \mathbf{x}} = \begin{bmatrix} 1 + \frac{v\Delta T \sin\theta}{d} & \frac{v\Delta T\cos\theta}{d^2} & -\frac{\Delta T\cos\theta}{d} & 0 \\ -v\Delta T\cos\theta & 1 & -\Delta T \sin\theta & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{2\beta v \Delta T \cos\theta}{d}\iota & \frac{2\beta v\Delta T\sin\theta}{d^2}\iota & -\frac{2\beta\Delta T\sin\theta}{d}\iota & \iota^2 \end{bmatrix} \quad \iota = \left(1 - \frac{v\Delta T\sin\theta}{d}\right)$$

- **Extended Kalman Filter (EKF):**

1) State Prediction: $\hat{\mathbf{x}}_{n|n-1} = \mathbf{g}(\hat{\mathbf{x}}_{n-1}), \hat{\mathbf{x}}_{n+1|n-1} = \mathbf{g}(\hat{\mathbf{x}}_{n|n-1})$

2) Linearization: $\mathbf{G}_{n-1} = \left.\frac{\partial \mathbf{g}}{\partial \mathbf{x}}\right|_{\mathbf{x}=\hat{\mathbf{x}}_{n-1}}, \mathbf{H}_n = \mathbf{I}_4$

3) MSE Matrix Prediction: $\mathbf{M}_{n|n-1} = \mathbf{G}_{n-1}\mathbf{M}_{n-1}\mathbf{G}_{n-1}^H + \mathbf{Q}_s$

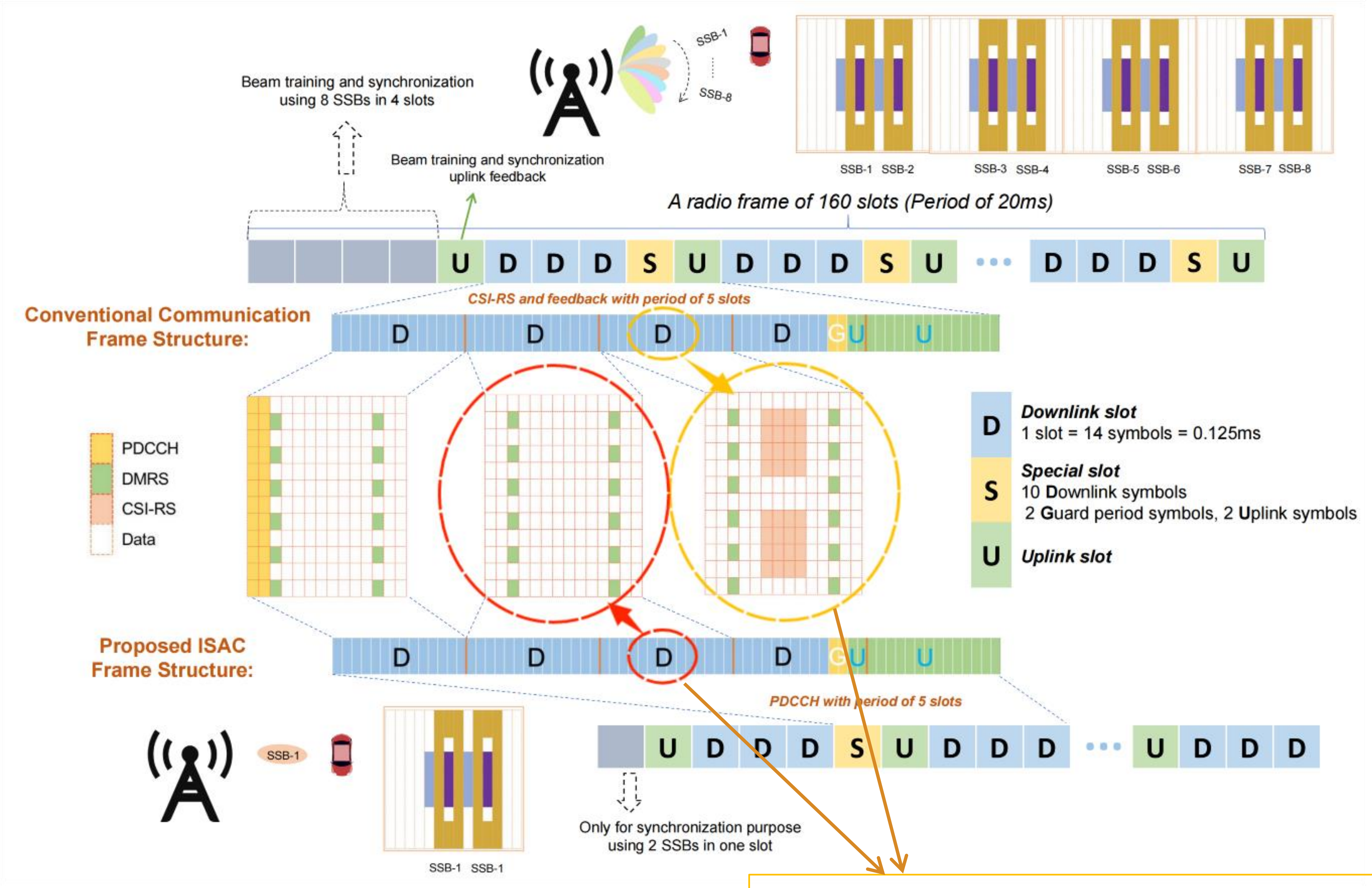
4) Kalman Gain Calculation: $\mathbf{K}_n = \mathbf{M}_{n|n-1}\mathbf{H}_n^H\left(\mathbf{Q}_m + \mathbf{H}_n\mathbf{M}_{n|n-1}\mathbf{H}_n^H\right)^{-1}$

5) State Tracking: $\hat{\mathbf{x}}_n = \hat{\mathbf{x}}_{n|n-1} + \mathbf{K}_n\left(\mathbf{y}_n - \hat{\mathbf{x}}_{n|n-1}\right)$

6) MSE Matrix Update: $\mathbf{M}_n = (\mathbf{I} - \mathbf{K}_n\mathbf{H}_n)\mathbf{M}_{n|n-1}$

III. Frame Structures and Case Studies in NR V2I Network: Connected Mode

- ## *ISAC and Conventional NR Frame Structure Comparison*



SSB Reduction:

Efficient tracking, dedicated SSB for synchronization purpose

NR Reference Signals:

- **CSI-RS**: In ***SU-MIMO V2I*** network, with the efficient tracking using EKF in ISAC scheme, CSI-RS and its feedback(PMI, RI…) are reduced, replaced with useful downlink data.
- **DMRS**: DMRS are kept for coherent demodulation

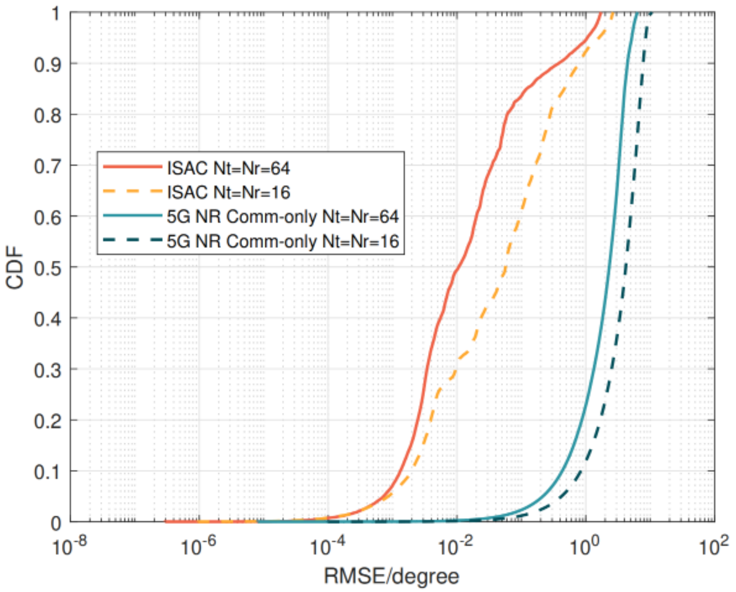
Overhead:

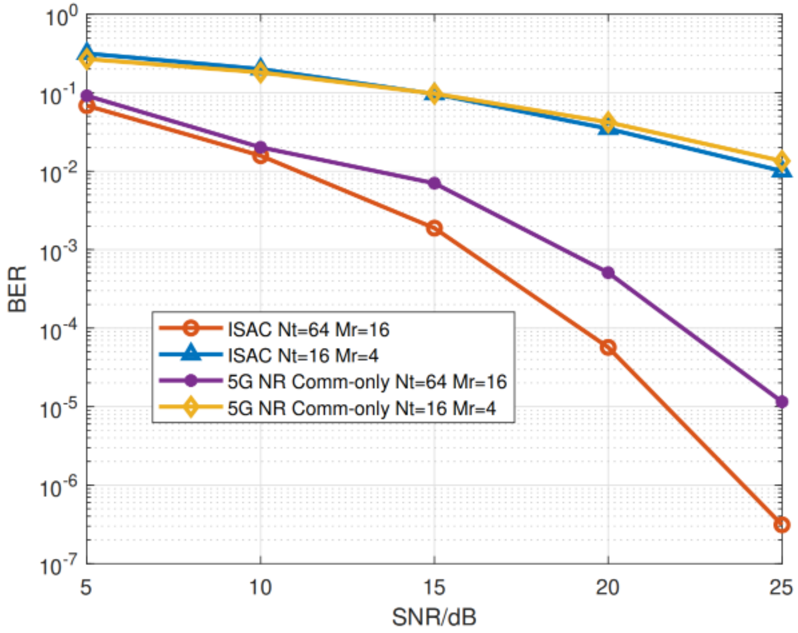
In a period of 5 time slots:
DMRS: 42 REs CSI-RS: 32 REs
Overhead could be reduced by up to ***43.24%***

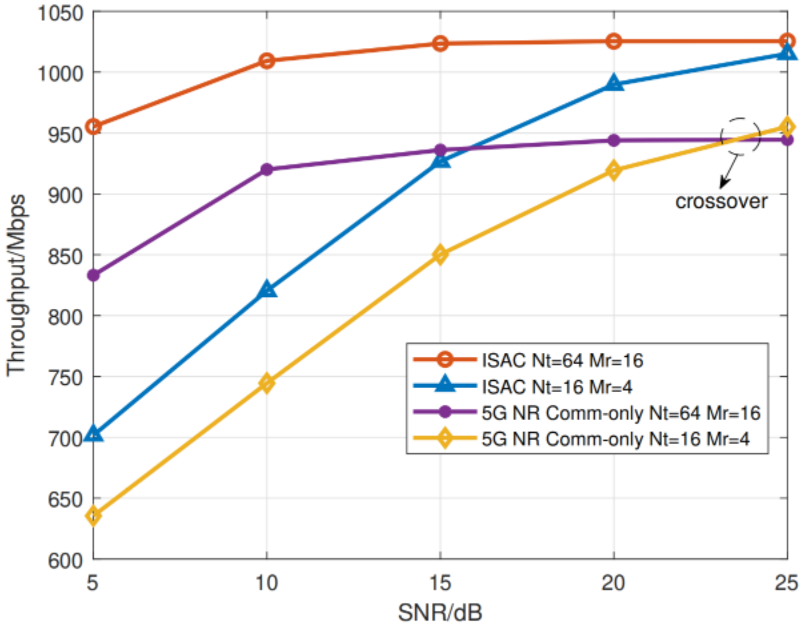
The third downlink slot in ISAC scheme compared that with conventional scheme only contains DMRS, where CSI-RS is omitted

III. Frame Structures and Case Studies in NR V2I Network: Connected Mode

- ***Tracking RMSE***
- ***Communication Performance Comparison***







BER and throughput calculation: using Communications Toolbox

- **numerrs = biterr():** Calculate the bit error rate (BER)
- **Throughtput calculation:** $\text{Throughput (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^{J} \left(N_{\text{Layers}}^{(j)} \cdot Q_{\text{M}}^{(j)} \cdot \frac{N_{\text{PRB}}^{\text{BW}(j),\mu} \cdot 12}{T_{\text{s}}^{\mu}} \cdot \left(1 - \text{BER}^{(j)} - \text{OH}^{(j)}\right) \right)$

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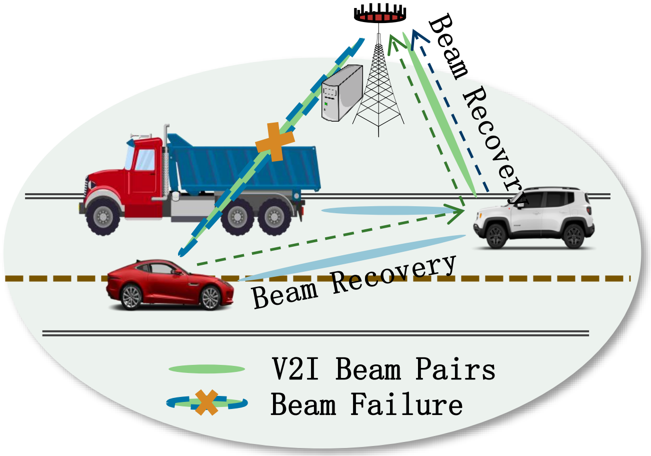
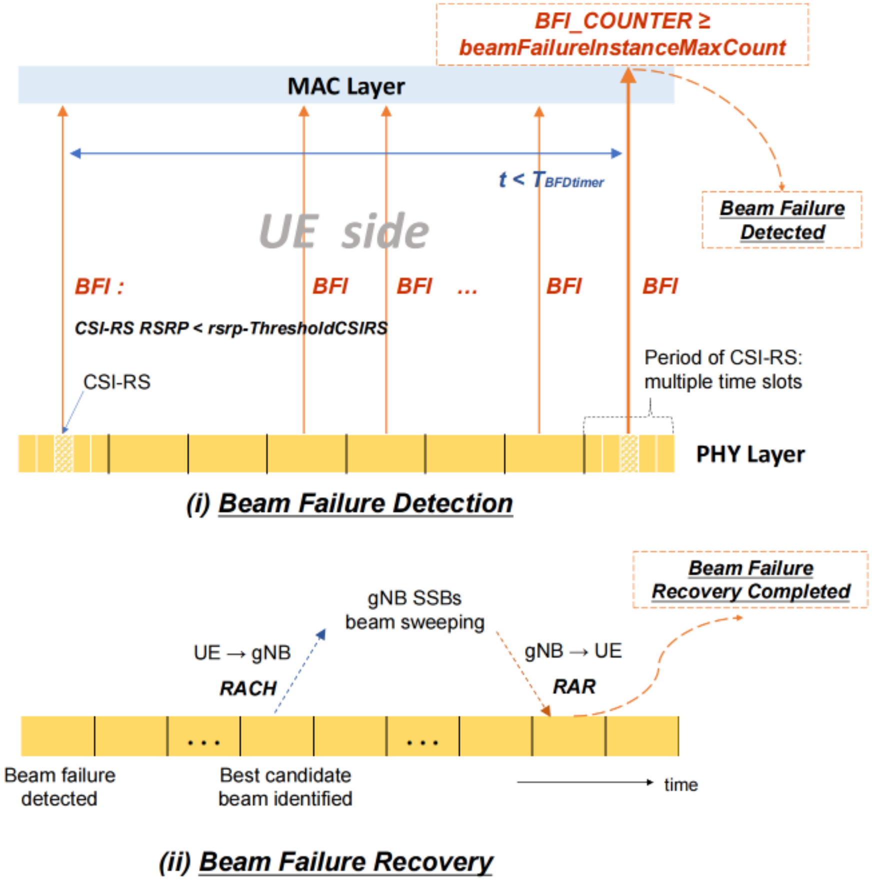
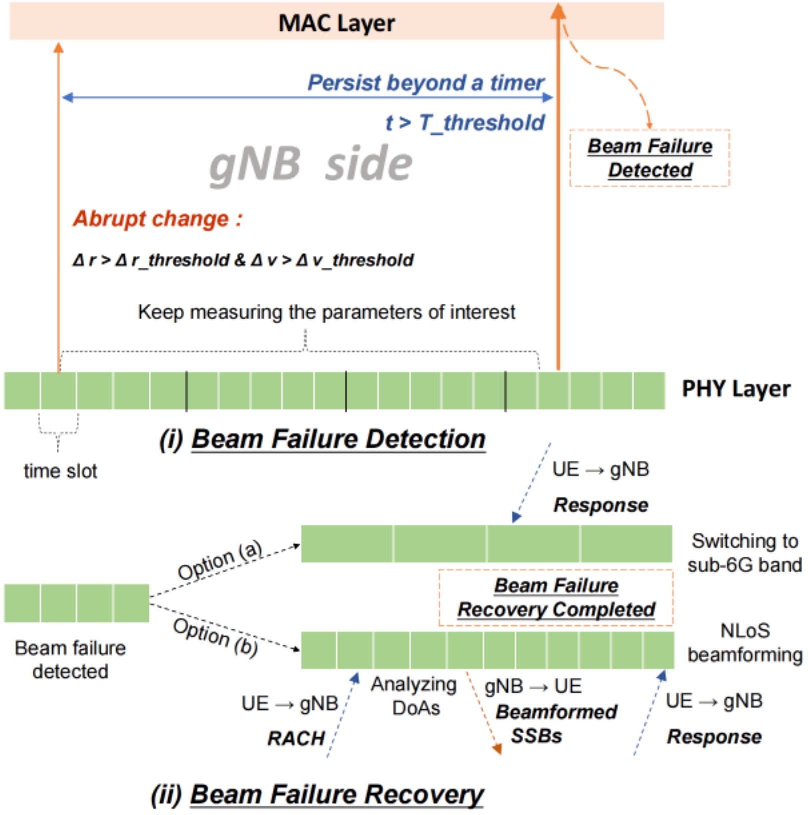
III. Frame Structures and Case Studies in NR V2I Network: Beam Failure Detection and Recovery



• BFR in conventional NR



• BFR in ISAC NR



- ***Conventional Beam failure detection:***

  Beam failure instance > threshold
- ***Conventional Beam failure recovery:***

  Candidate beam or beam sweeping
- ***ISAC Beam failure detection:***

  Abrupt change in motion parameters

  $\Delta r > r_{thre}$ & $\Delta v > v_{thre}$
- ***ISAC Beam failure recovery:***

  1) Switch to sub-6G band

  2) Beamforming through NLoS

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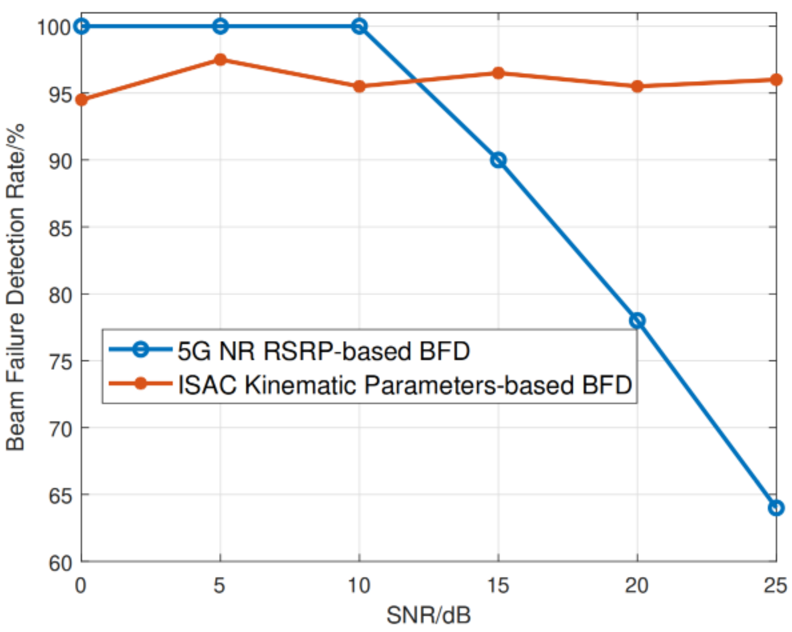
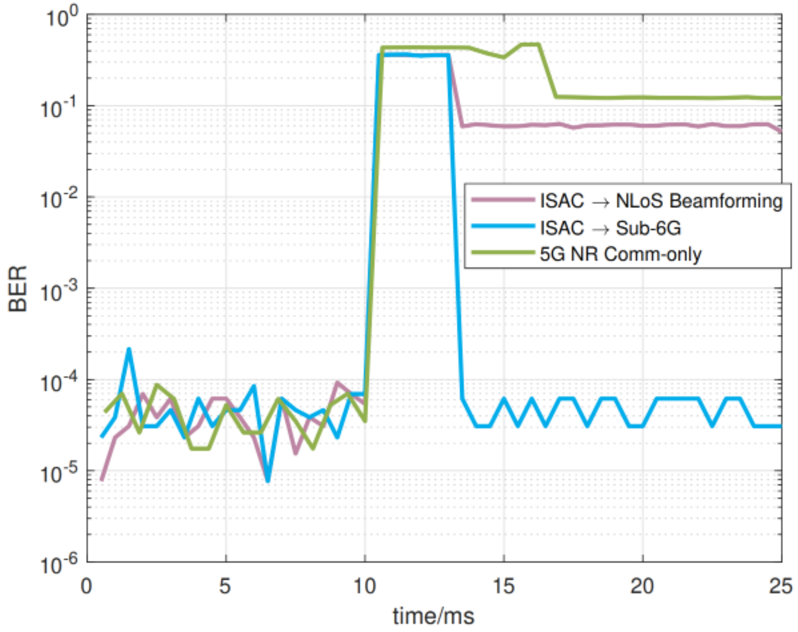
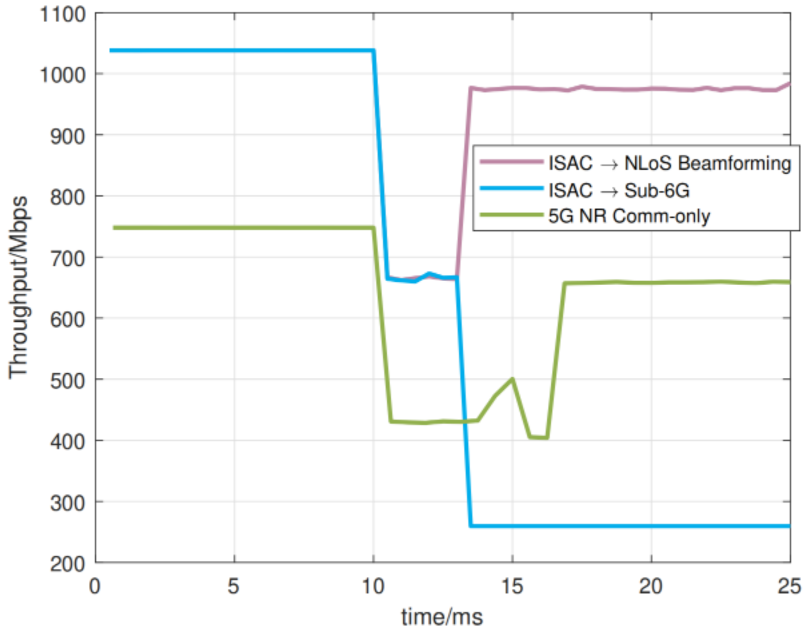
III. Frame Structures and Case Studies in NR V2I Network : Beam Failure Detection and Recovery

- ***Accuracy Comparison***
- ***Communication Performance Comparison***







Fast beam failure detection and recovery and higher accuracy

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[2] F. Liu* and C. Masouros, "A Tutorial on Joint Radar and Communication Transmission for Vehicular Networks - Part III: Predictive Beamforming without State Models", *IEEE Communications Letters*, vol. 25, no. 2, pp. 332-336, 2021. (***IEEE ComSoc Best Readings***)

[3] W. Yuan, **F. Liu***, C. Masouros, J. Yuan, D. W. K. Ng and N. G. Prelcic, "Bayesian Predictive Beamforming for Vehicular Networks: A Low-Overhead Joint Radar-Communication Approach", *IEEE Transactions on Wireless Communications*, vol. 20, no. 3, pp. 1442-1456, March 2021. (***IEEE ComSoc Best Readings***)

[4] Z. Du, **F. Liu***, W. Yuan, C. Masouros, Z. Zhang, S. Xia, and G. Caire, "Integrated Sensing and Communications for V2I Networks: Dynamic Predictive Beamforming for Extended Vehicle Targets," *IEEE Transactions on Wireless Communications*, vol. 22, no. 6, pp. 3612-3627, June 2023.

[5] X. Meng, **F. Liu***, C. Masouros, W. Yuan, Q. Zhang, and Z. Feng, "Vehicular Connectivity on Complex Trajectories: Roadway-Geometry Aware ISAC Beam-tracking," *IEEE Transactions on Wireless Communications*, vol. 22, no. 11, pp. 7408-7423, Nov. 2023.

[6] Y. Cui, Q. Zhang, Z. Feng, Q. Wen, Z. Wei, **F. Liu**, and P. Zhang, "Seeing Is Not Always Believing: ISAC-Assisted Predictive Beam Tracking in Multipath Channels," *IEEE Wireless Communications Letters*, vol. 13, no. 1, pp. 14-18, Jan. 2024.

[7] Y. Li, **F. Liu***, Z. Du, W. Yuan, Q. Shi, and C. Masouros, "Frame Structure and Protocol Design for Sensing-Assisted NR-V2X Communications," *IEEE Transactions on Mobile Computing*, early access.

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