Channel Analytics for V2X Communication

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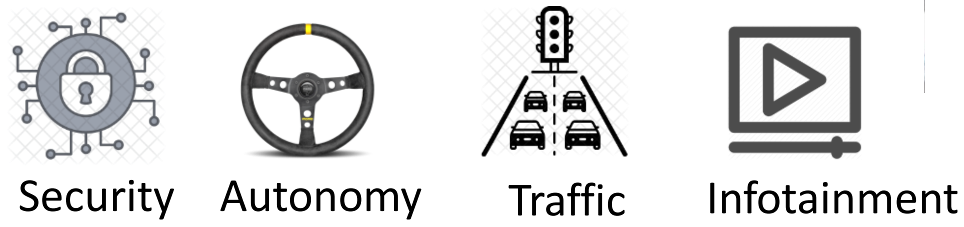
MESA

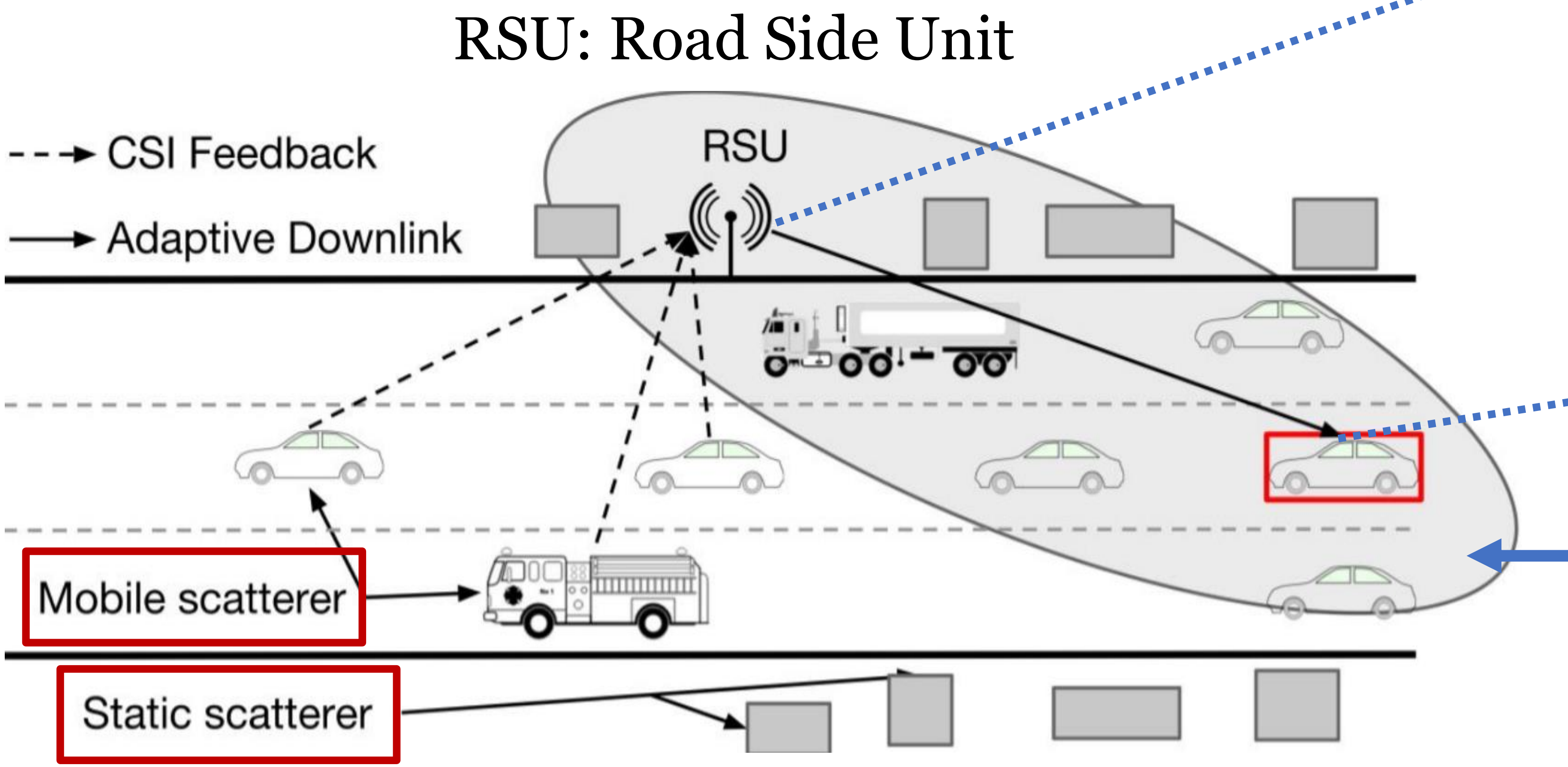
V2X Communication

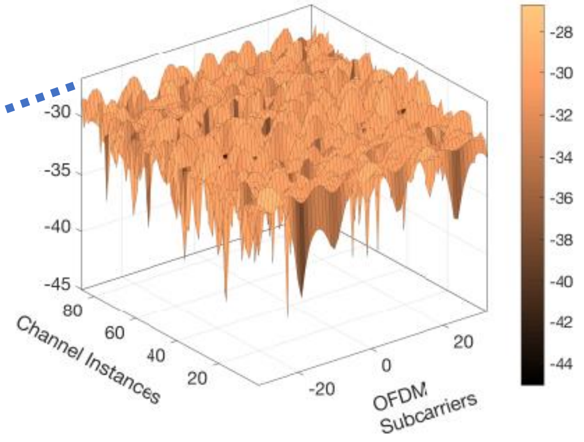
- V2I – Vehicle to Infrastructure
- V2V – Vehicle to Vehicle



Chaotic V2X Channel → Impaired Communication
Enable Reliable Communication over V2X Channels

V2X Channel Prediction





(c) Example channel profile $N_{scat}^{(i)} = 13$

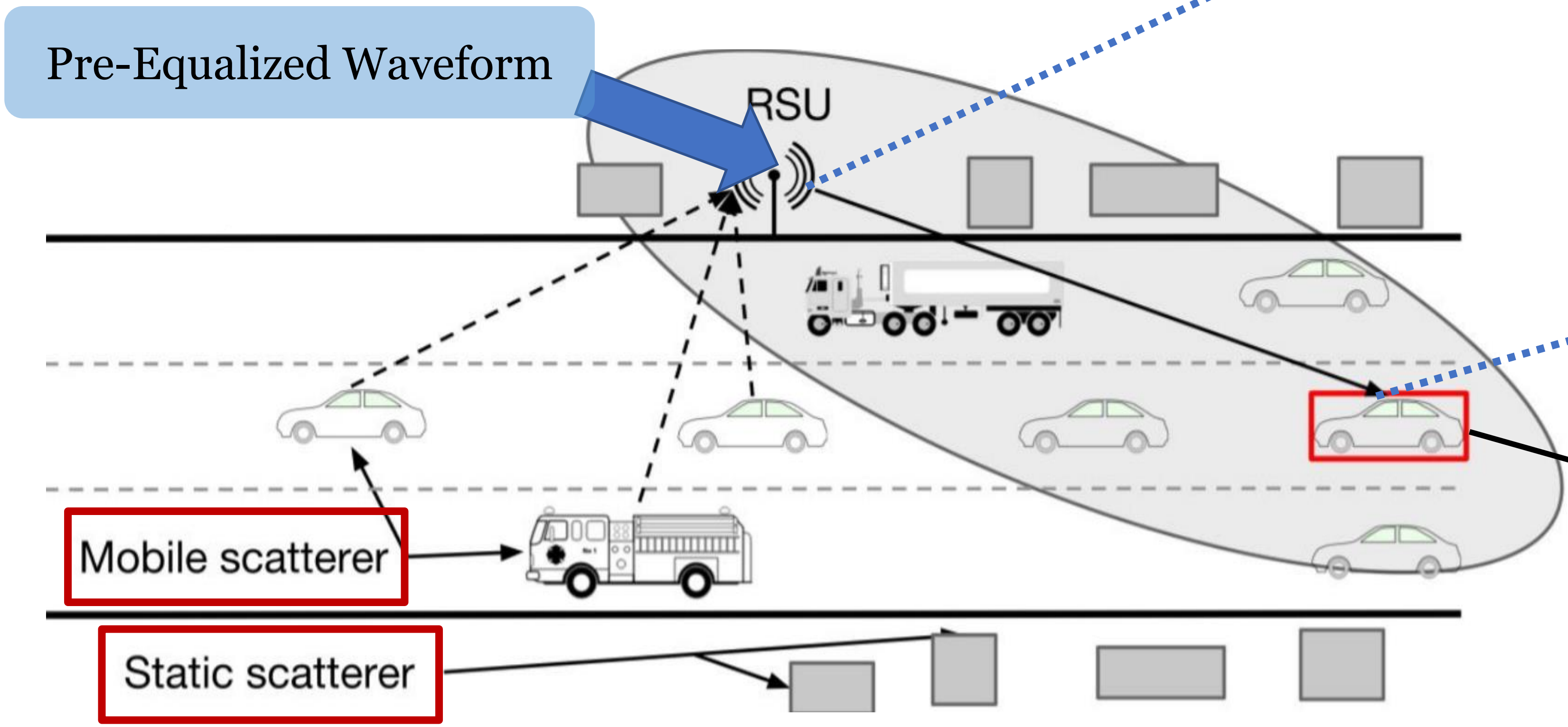
Example of a vehicular Edge network

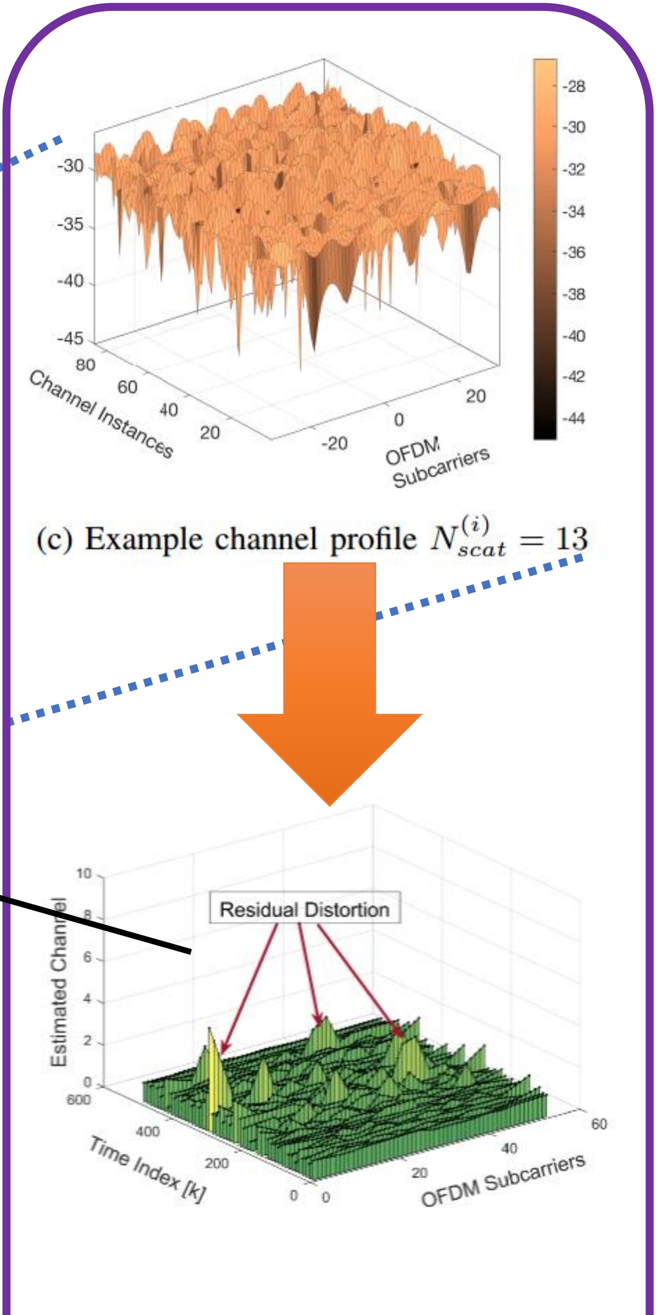
V2X Channel Prediction

- State of the Art techniques do NOT work:
    1. Time-series analysis of the channel
    2. Reactive Receiver-side Equalization

- Problem Statement
    - Prediction and Proactive Transmitter-side Pre-Equalization

Intuition

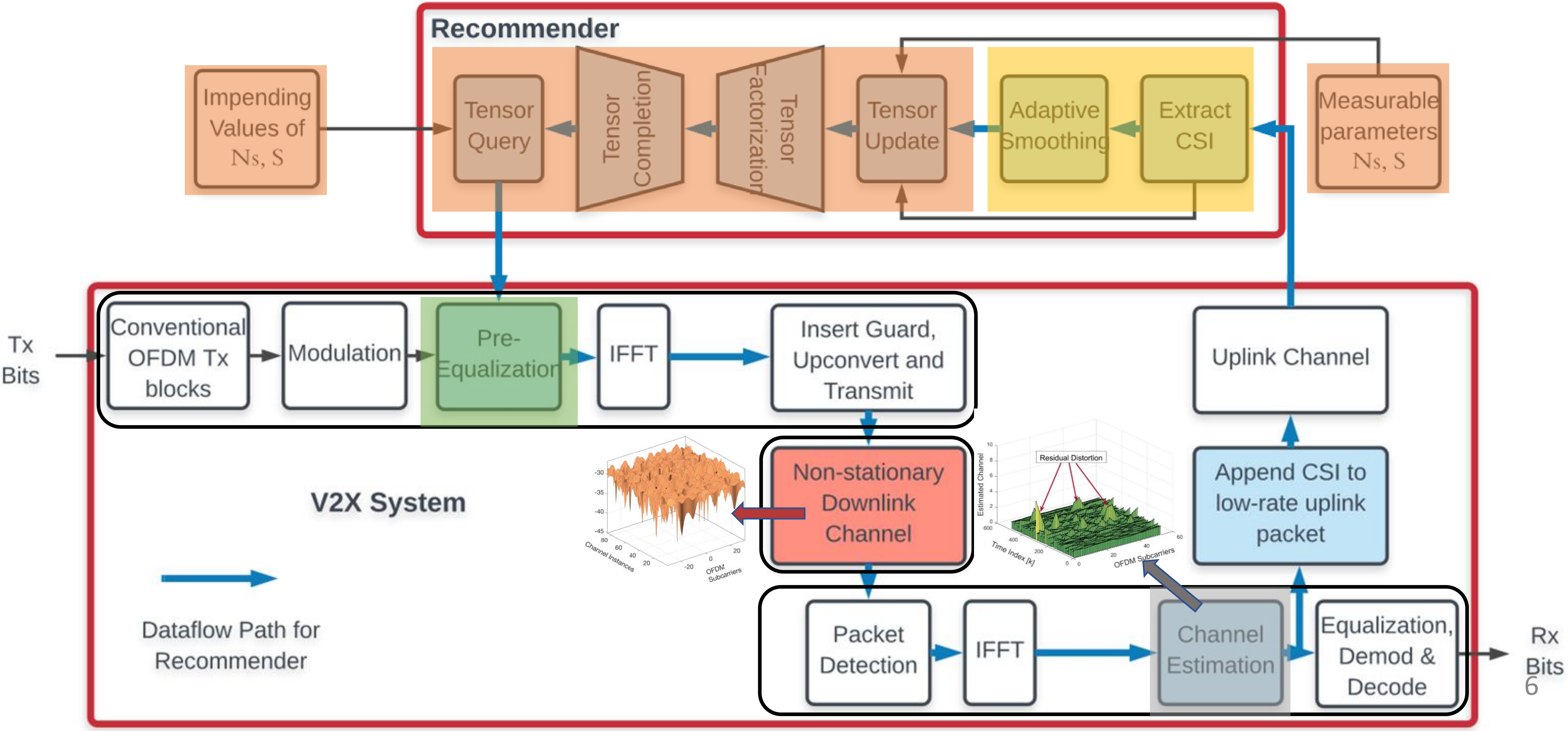




(c) Example channel profile $N_{scat}^{(i)} = 13$

(d) Equalized channel-Receiver

V2X Channel Prediction System



A typical V2X Channel Model

Model

$$h(k,n) = \sum_{\ell=1}^{N_s(k)} h(k,n,\ell) \rightarrow h(k,n,\ell) = \sum_{m=1}^{M_\ell} \alpha_m(k,n) e^{j\varphi_m(k,n)} e^{j2\pi f_{D_m}(k,n)k} \delta(\tau - \tau_m(k,n))\delta(\theta - \theta_m(k,n))\delta(\phi - \phi_m(k,n)$$ [1]

Factors

- Scatterering Environment
- Doppler frequency
- Angle of Departures & Arrivals (AoD & AoA)
- Channel gains and path delays, etc...

Latent (Uncorrelated) Factors

Measurable

- Number of Scatterers (Ns)
- Locations (S)

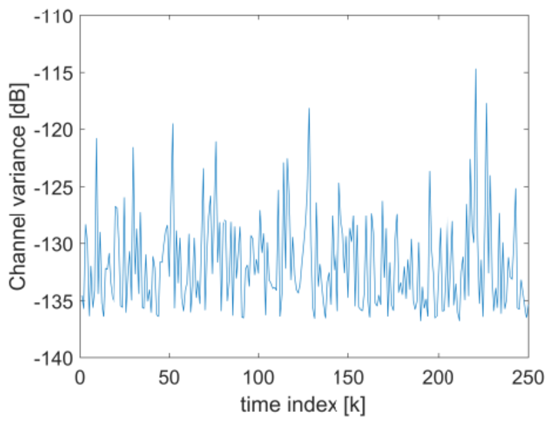
Measurable (Correlated) Factors

[1] Svensson et. al “WINNER II Channel Models”.

Non-stationarity of V2X Channel

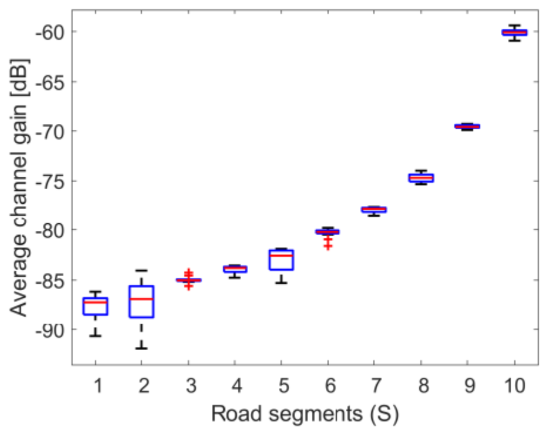
- V2X Channel is non-stationary over space, time and vehicular density.

Over time



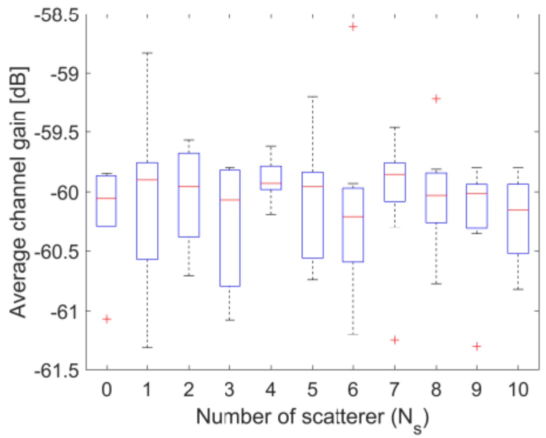
(a) Variance of channel gain varies with time (constant N_s and S)

Over Space



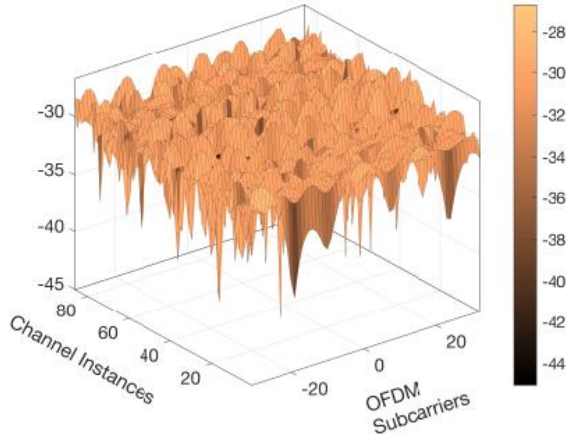
(b) Spatial Distribution of channel gain (constant N_s)

Number of scatterers



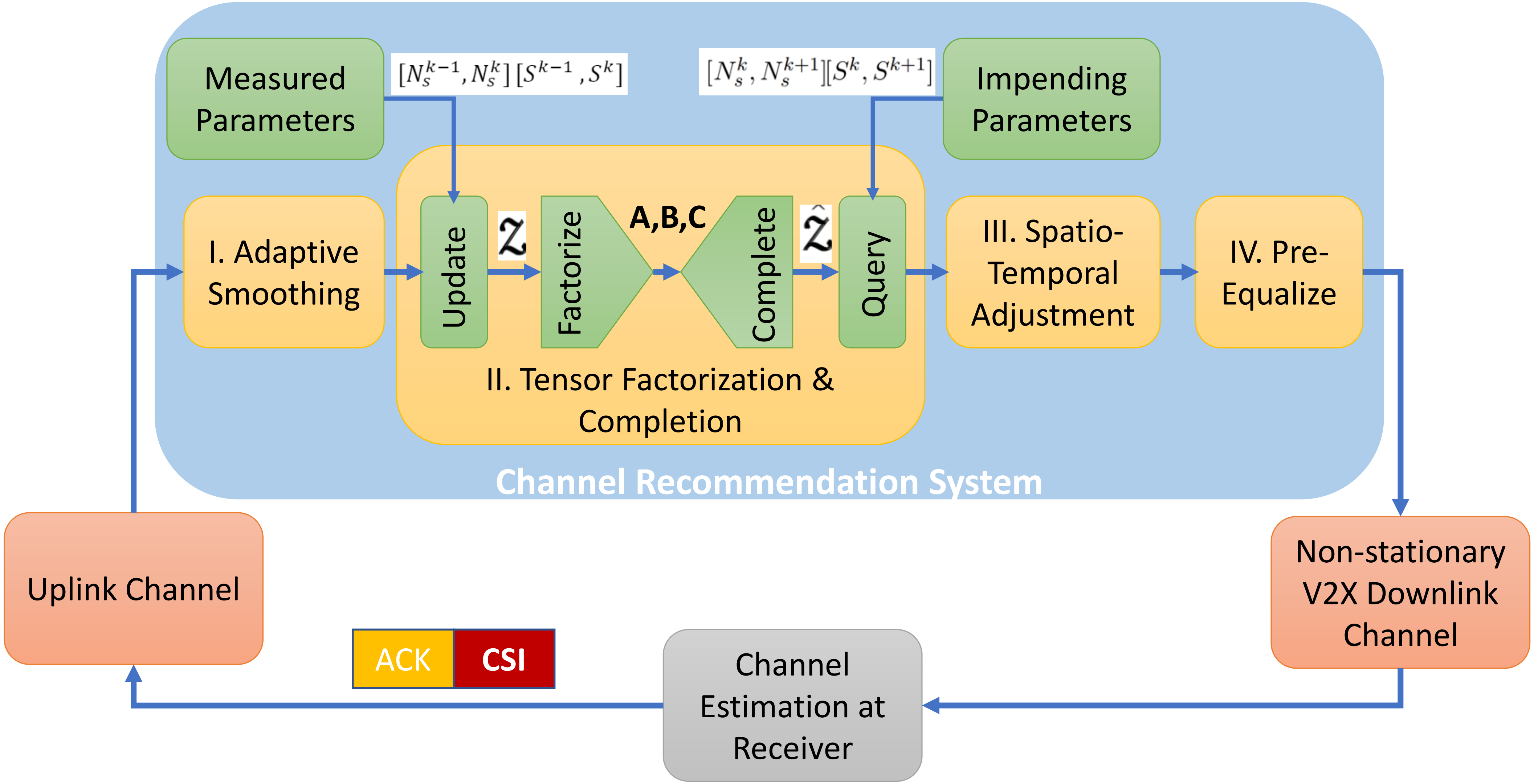
(c) Distribution of channel gain with scatterer density (constant S)

Non-stationary channel



(d) Example channel profile $N_{scat}^{(i)} = 13$

Channel Recommendation System



A. Adaptive Smoothing - Tracking

Kalman-AR Combination:

- Combination of autoregression (AR) and Kalman filter.

$$z(k) = \sum_{i=1}^{p} a_i z(k-i) + u(k)$$

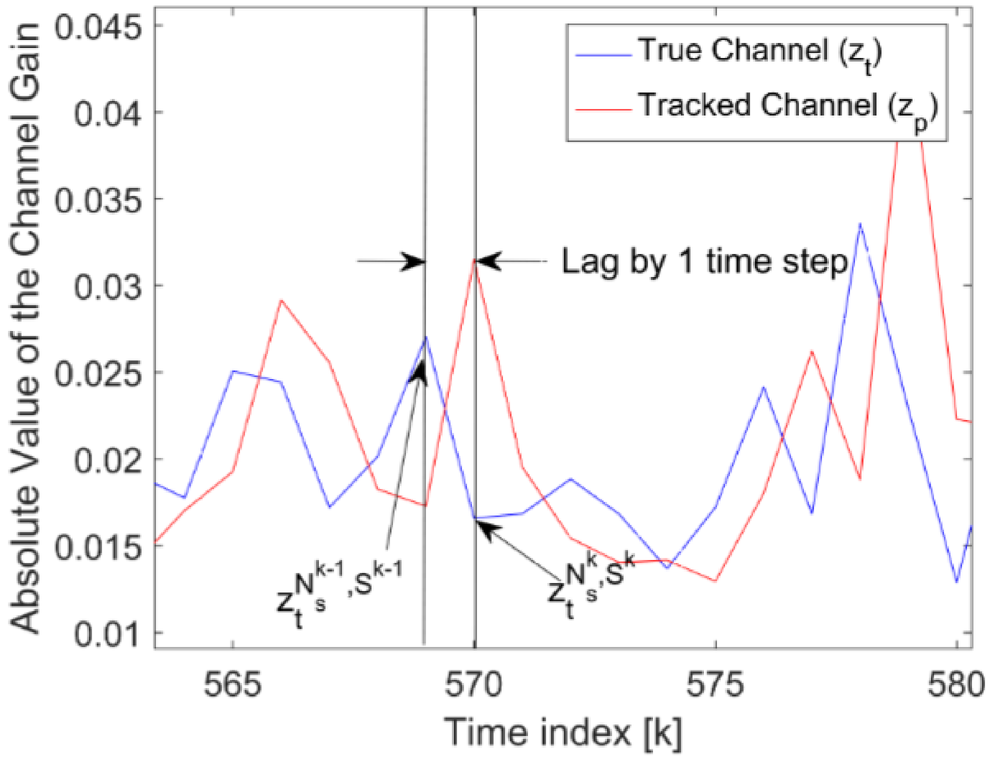
Predicted channel coefficients (z(k)) are combined by an AR model

$$\mathbf{a}(k+1) = \mathbf{a}(k) + \mathbf{u}_1(k)$$
$$\mathbf{z}(k) = \mathbf{C}(k-1)\mathbf{a}(k) + \mathbf{u}_2(k)$$

weights of the AR model are tracked and predicted by the Kalman filter

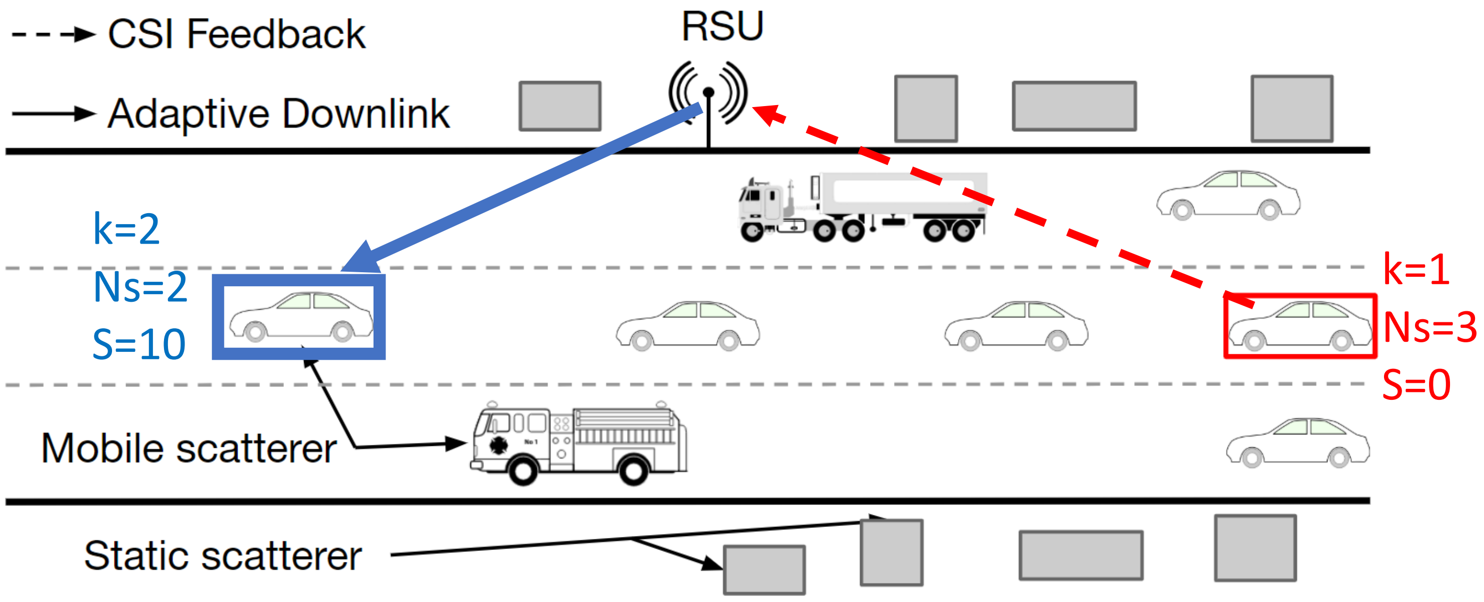
[2] Al-Ibadi and A. Dutta, "Predictive analytics for non-stationary v2i channel"

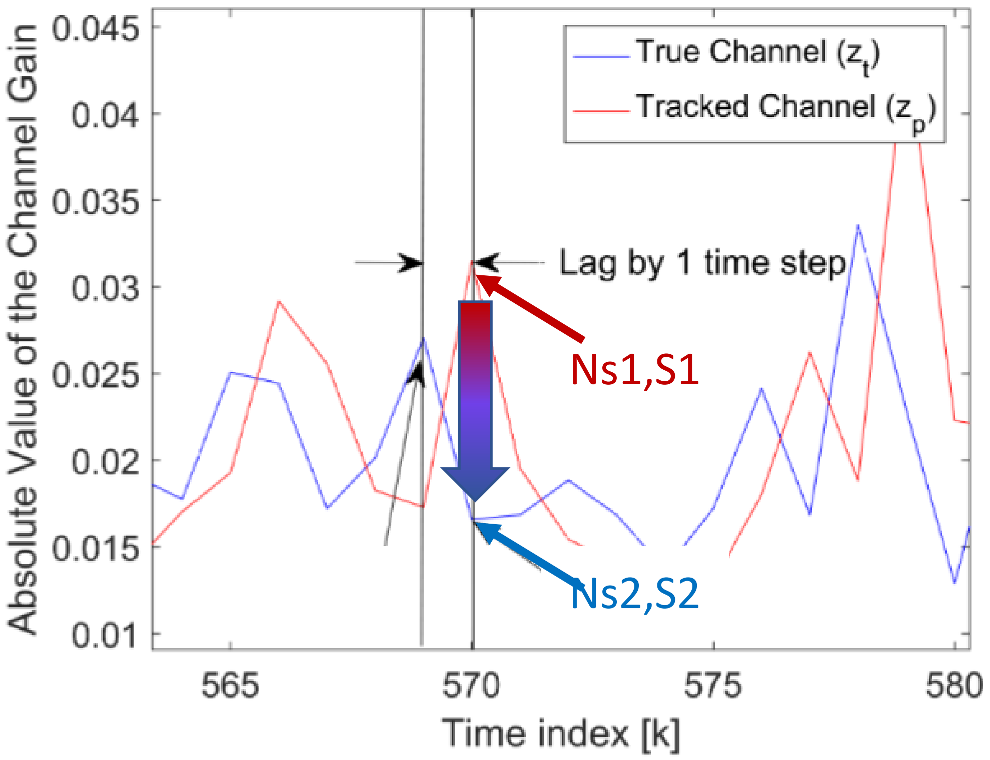
Additional Smoothing



The tracked channel lags the true channel!

Alleviating the Disparity





This can be used to track the Spatio-Temporal Evolution of V2X Channel!

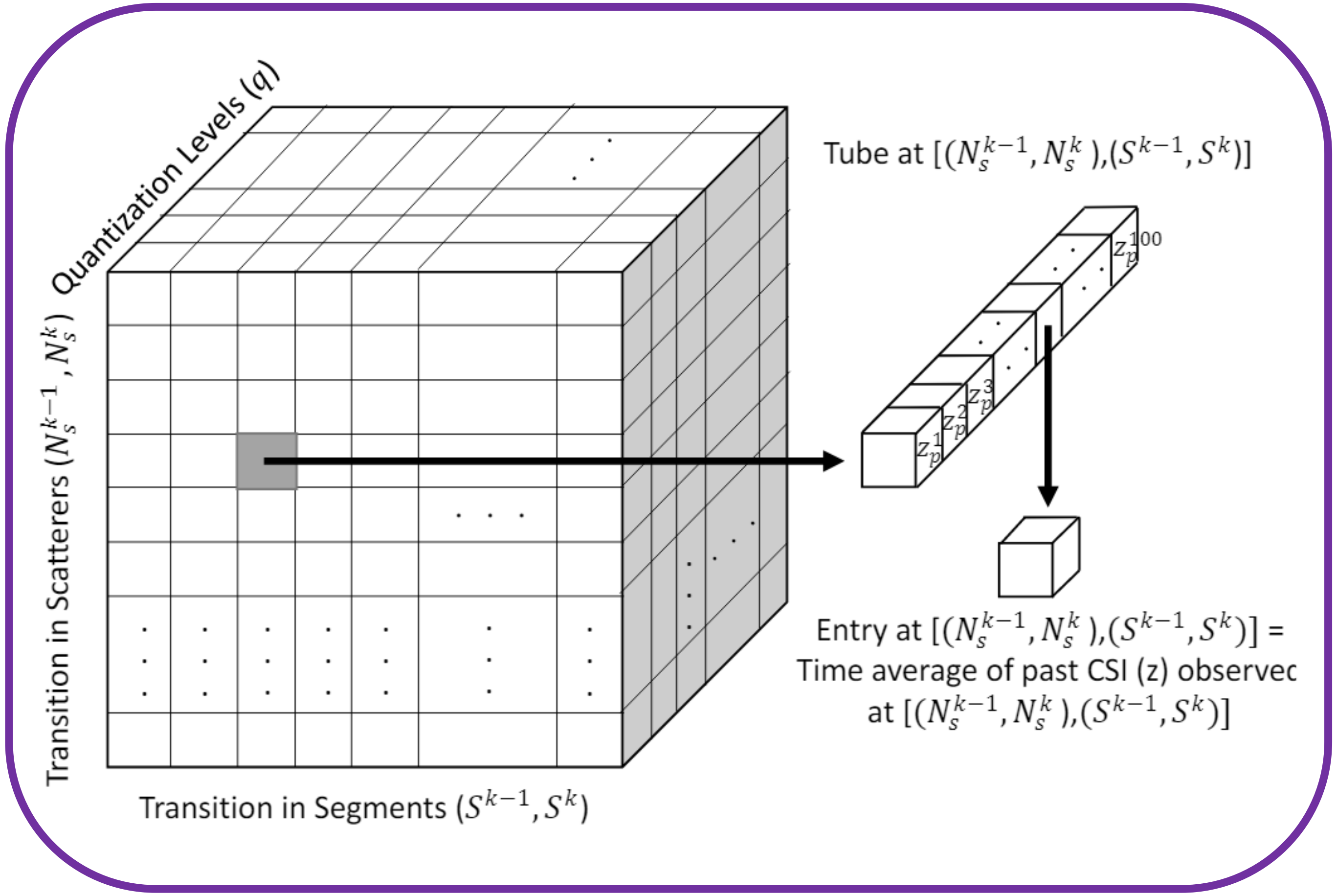
Tensor Update

Dimensions

- Transition in Number of Scatterers (Ns)
- Transition in Location (S)
- Quantization levels (q)

Entries

- Adjustments = f(CSI)



Channel Tensor $\mathfrak{Z}$

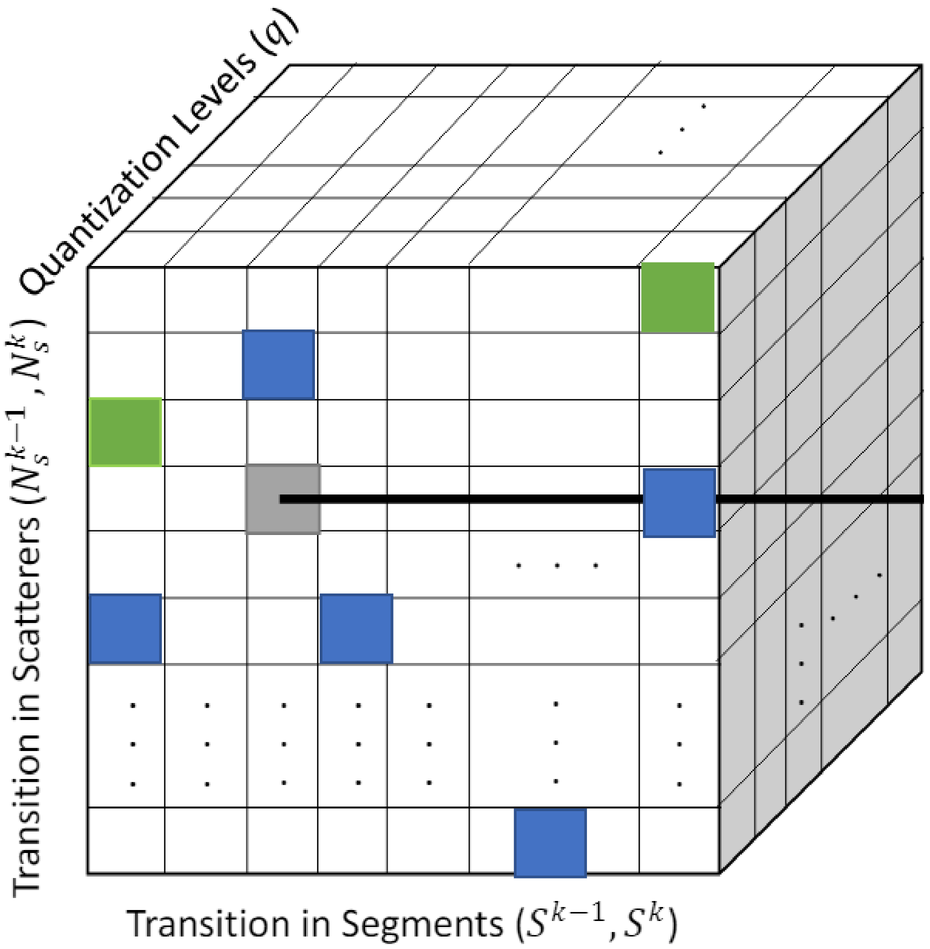
Concerns

Limitations...

- Sparsity → Missing adjustments
- Noisy data → Corrupt adjustments

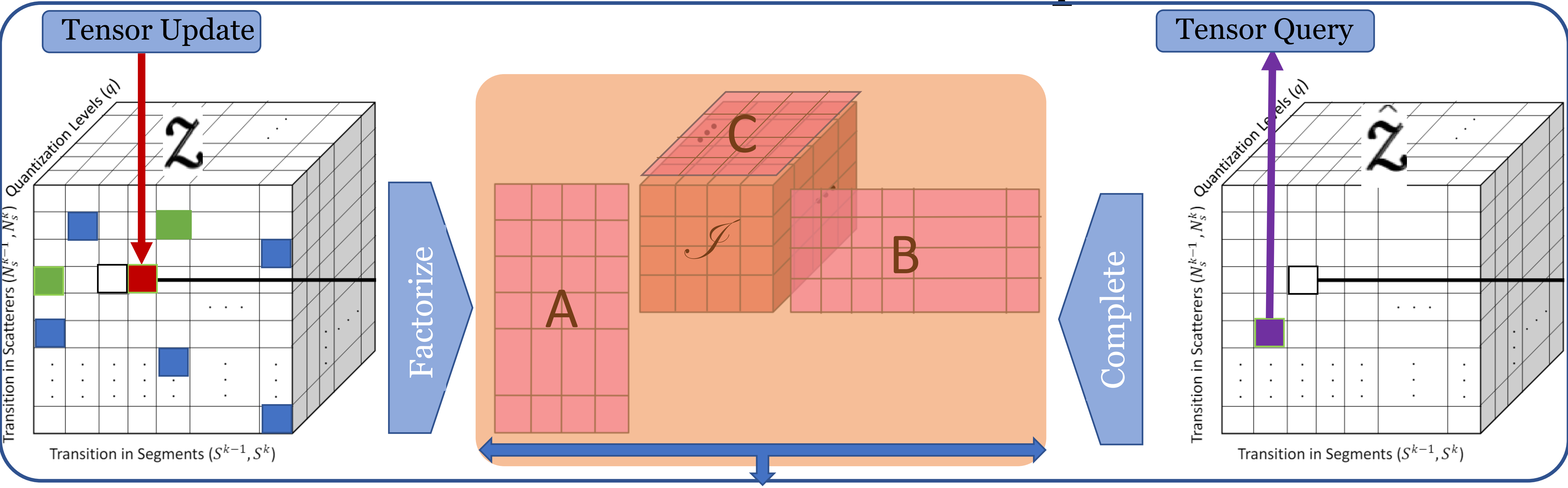
Solution

- Tensor factorization & Completion



Sparse & Noisy Channel Tensor $\mathfrak{Z}$

B. Tensor Factorization & Completion

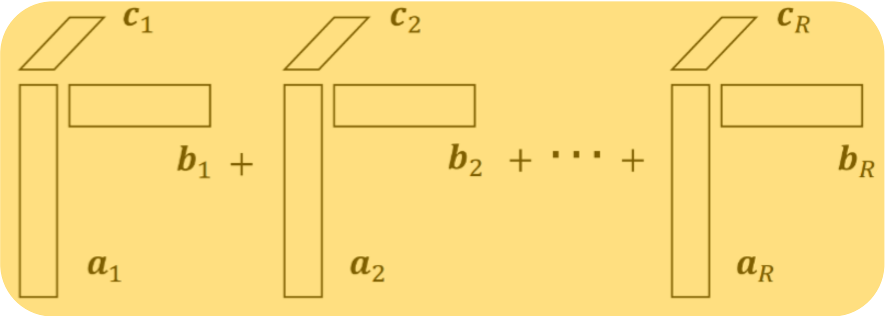


$\mathcal{Z}$ - Channel Tensor

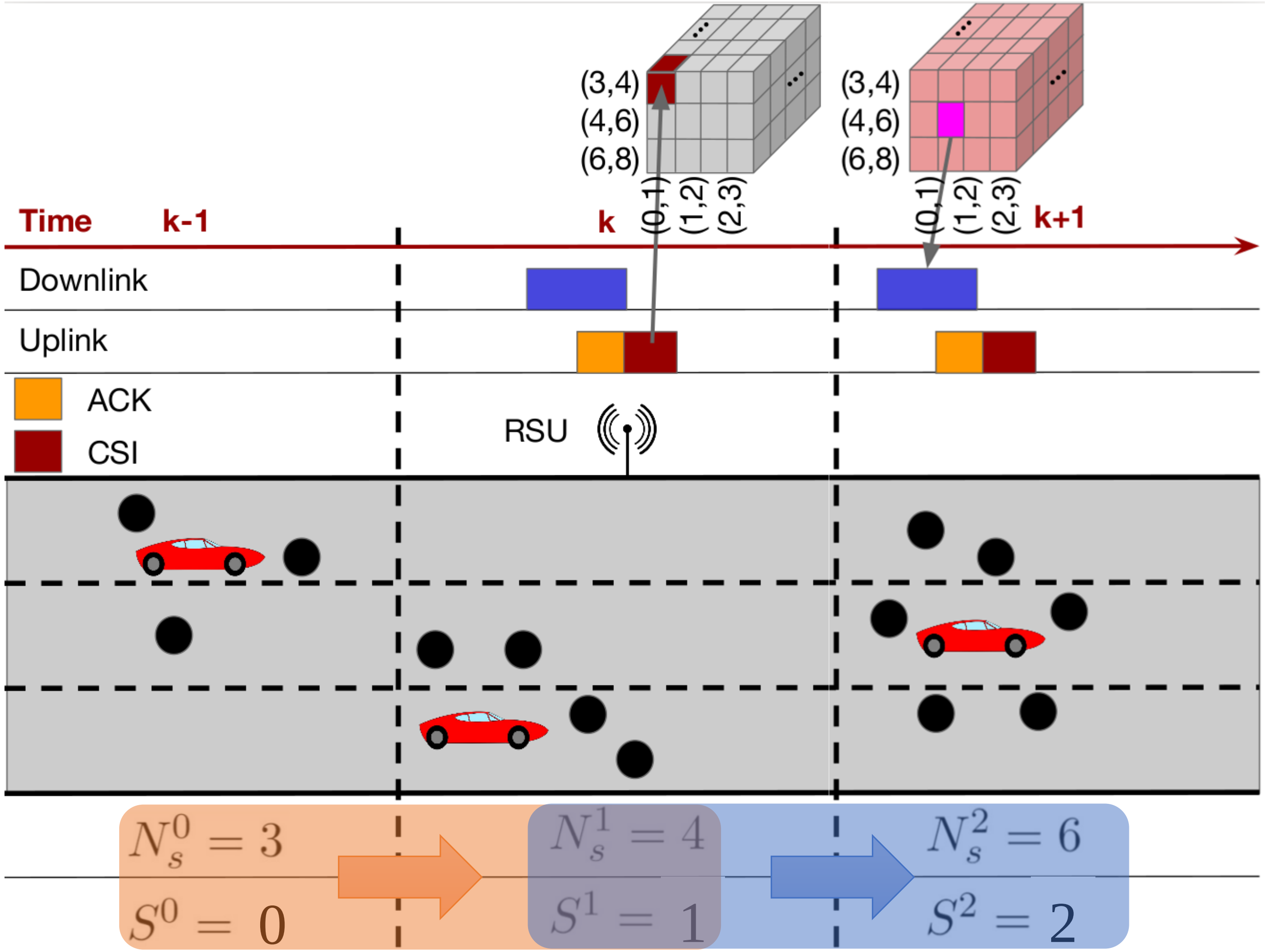
$A = [a_1, \ldots, a_R]$ - transition in scatterers (N_s^{k-1}, N_s^k)

$B = [b_1, \ldots, b_R]$ - Transition in segment (S^{k-1}, S^k)

$C = [c_1, \ldots, c_R]$ - quantized levels (q)

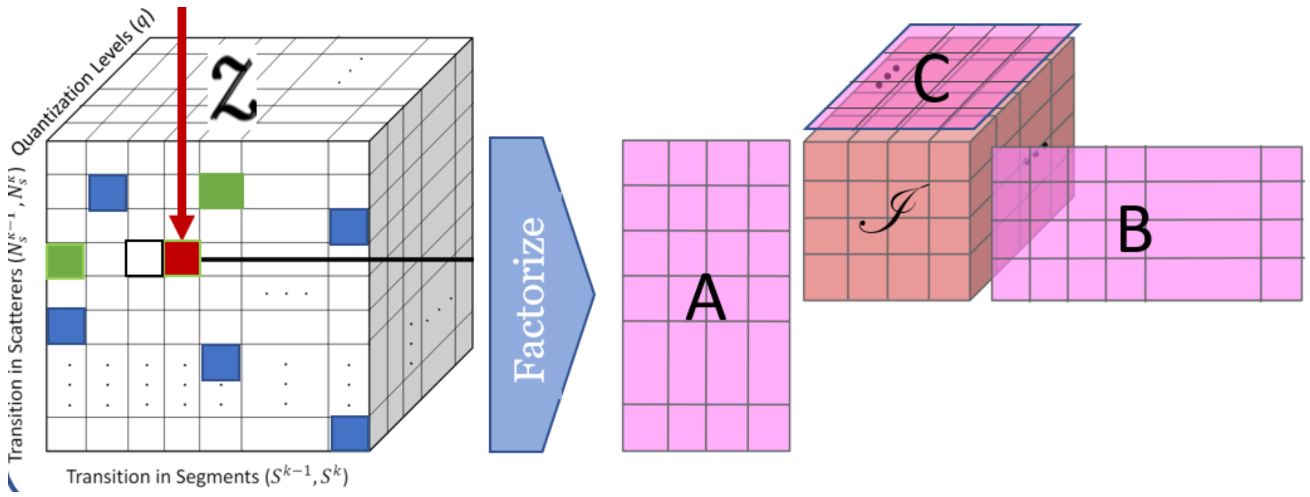


Example



(3,4)
(4,6)
(6,8)
(0,1)
(1,2)
(2,3)
Time
k-1
k
k+1
Downlink
Uplink
ACK
CSI
RSU
$N_s^0 = 3$
$S^0 = 0$
$N_s^1 = 4$
$S^1 = 1$
$N_s^2 = 6$
$S^2 = 2$

1) Tensor Factorization



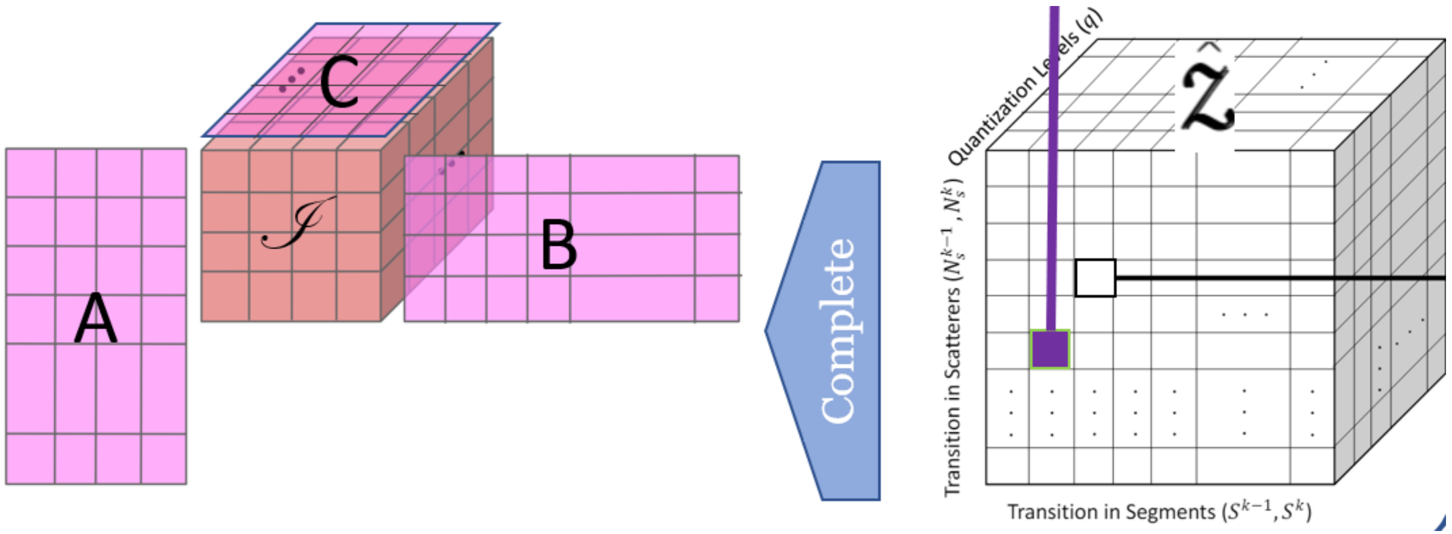
- Captures latent structure of channel tensor (CP Factorization [5])

$$f_W(\mathbf{A},\mathbf{B},\mathbf{C}) = \frac{1}{2}||\mathcal{Z} - [\![\mathbf{A},\mathbf{B},\mathbf{C}]\!]||_W^2 \quad + \frac{\lambda}{2}(||\mathbf{A}||^2 + ||\mathbf{B}||^2 + ||\mathbf{C}||^2)$$

Error Function Regularization Term

[3] T. G. Kolda and B. W. Bader, "Tensor decompositions and applications,"

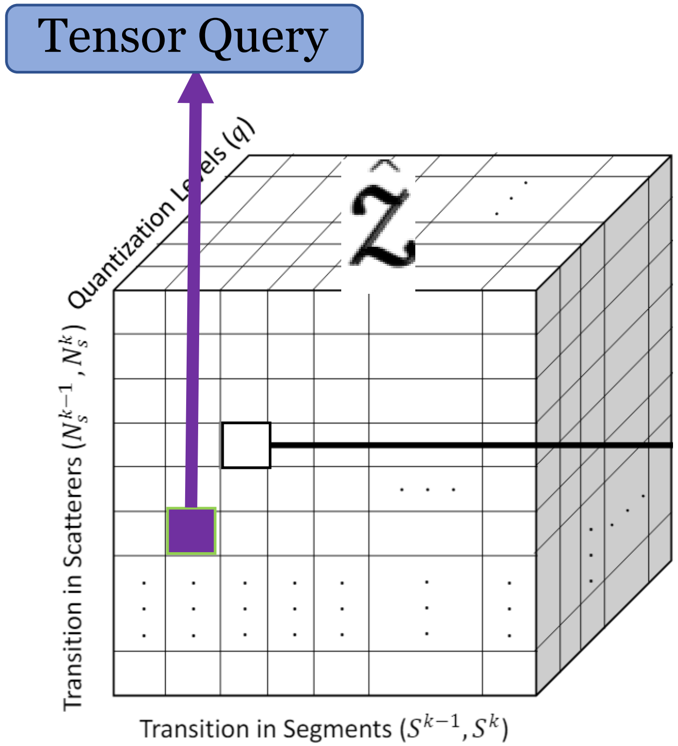
2) Tensor Completion



- Reconstructs tensor from computed factors (A , B , C)

$$\hat{\mathcal{Z}} = [\![\mathbf{A}, \mathbf{B}, \mathbf{C}]\!] = \sum_{r=1}^{R} \mathbf{a}_r \circ \mathbf{b}_r \circ \mathbf{c}_r$$

Tensor Query



- Extract Channel Adjustments,

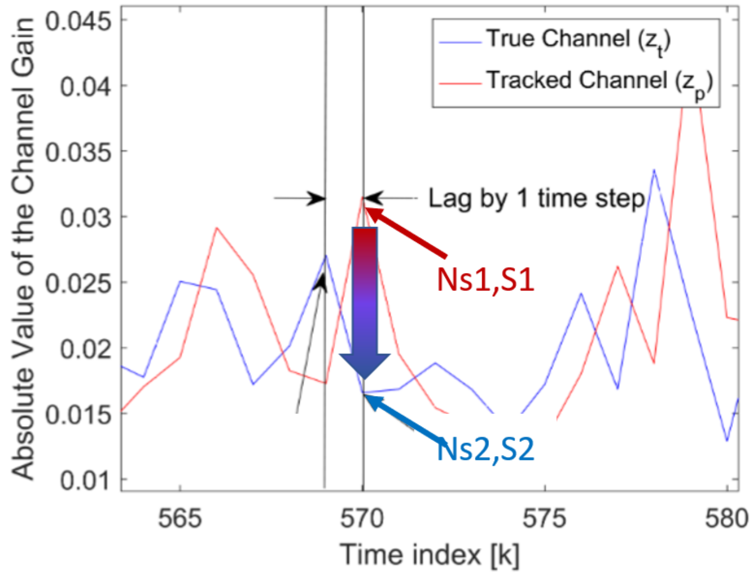
$$z_r(k,n) = \hat{\mathbf{Z}}[(N_s^{k-1}, N_s^k), (S^{k-1}, S^k), q_n]$$

C. Spatio-Temporal Adjustment

- This alleviates the lag and the disparity in Number of Scatterers and location.

$$\hat{\mathbf{z}}_p(k) = (1 - \alpha_k)\mathbf{z}_p(k) + \alpha_k \mathbf{z}_r(k))$$

Predicted Downlink Channel Profile



D. Pre-equalization at Transmitter

- The waveform of the downlink packet is pre-equalized → Net effect is a flat fading at the receiver [4].

- Inverse of the expected fading profile,

$$\tilde{\mathbf{z}}_p(k) = \mathbf{1}./\hat{\mathbf{z}}_p(k)$$

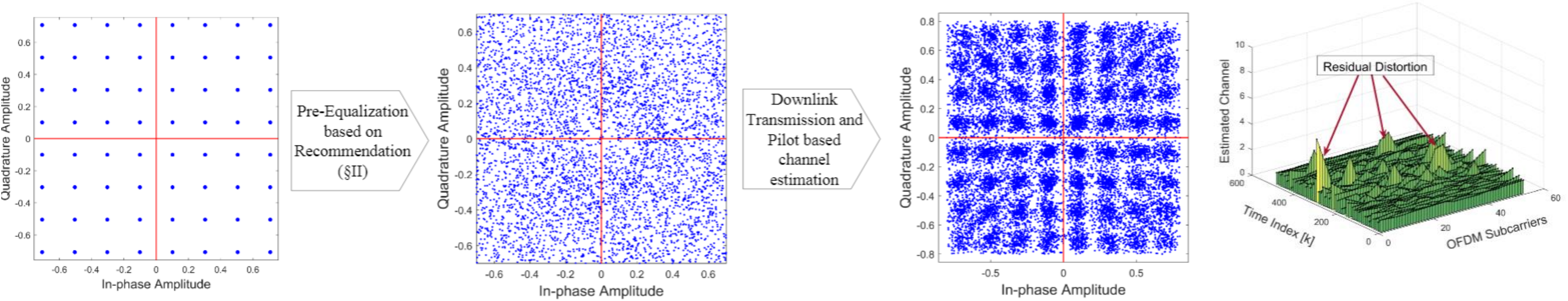
[4] Al-Ibadi and A. Dutta, "Predictive analytics for non-stationary v2i channel"

Effect of Pre-Equalization

High level system performance:

- The waveform of the downlink packet is pre-equalized

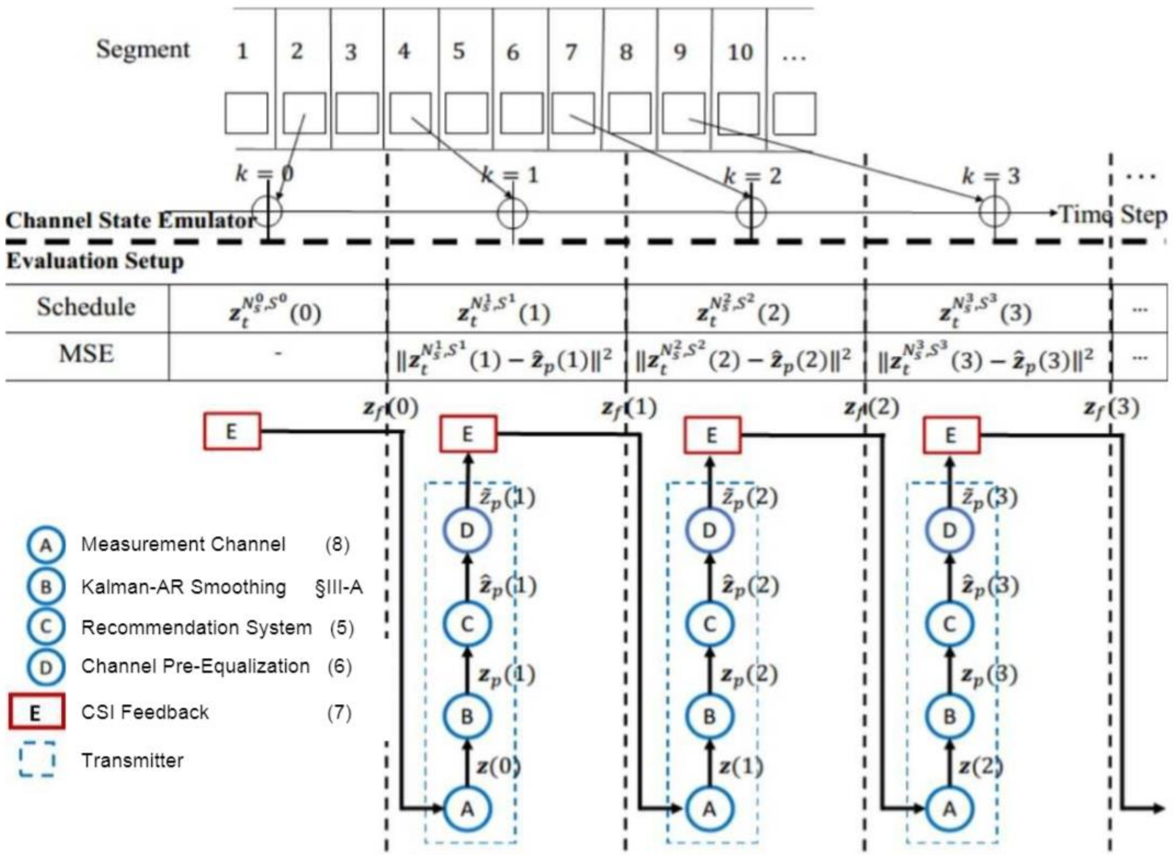
→ Result: Clean constellations and flat fading at the receiver



(a) Before compensation (b) After Pre-equalize (c) Received constellation (d) Equalized channel-Receiver

Simulation setup & testbed

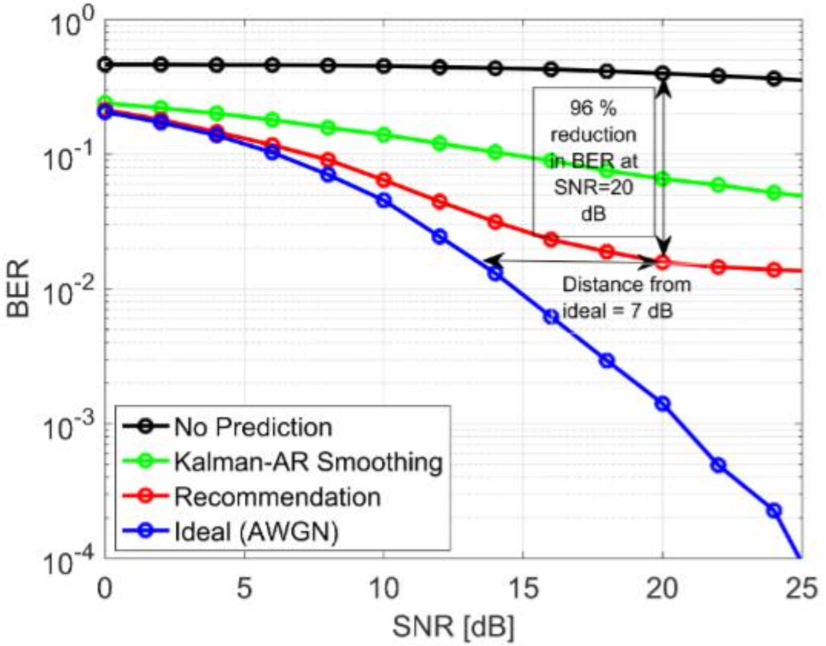
- Measurement channel life-cycle



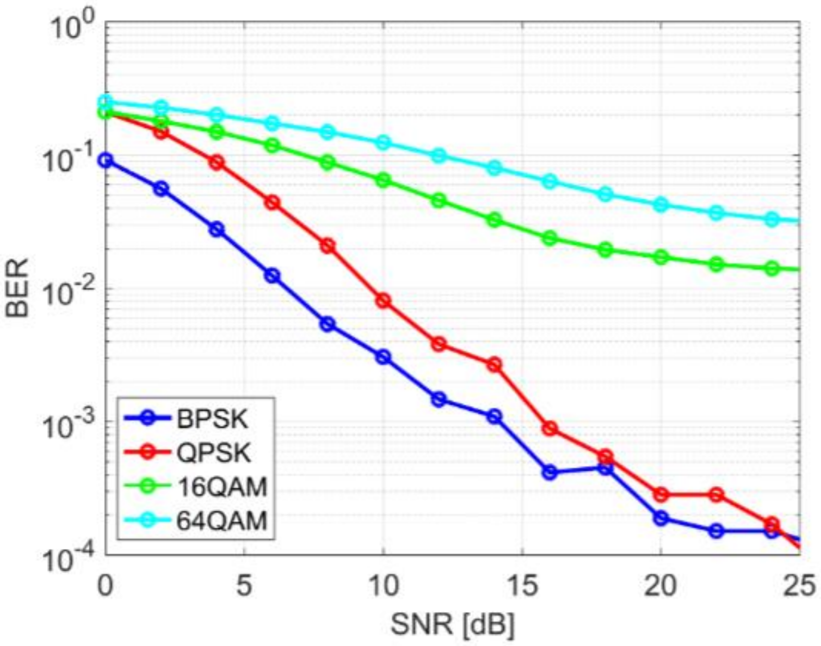
- Conventional 802.11p (OFDM packet)
- With pilot-based linear interpolation equalization
- Carrier frequency (fc) = 5.9GHz
- Vehicle Speed = 45 mph
- Segment Length = 10 m

Results: A. BER at the Receiver

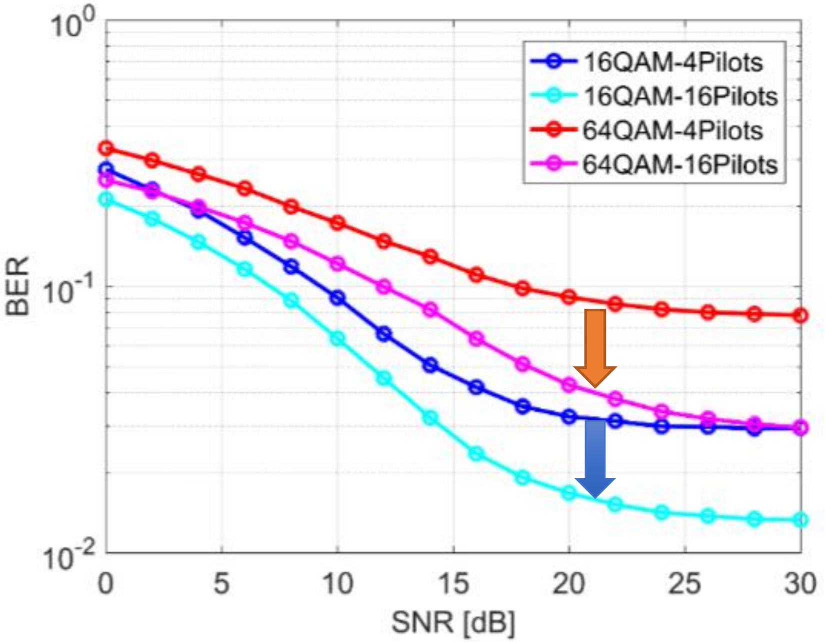
- Bit Error Rate (BER)



(a) BER for 16-QAM with 16 pilot tones.



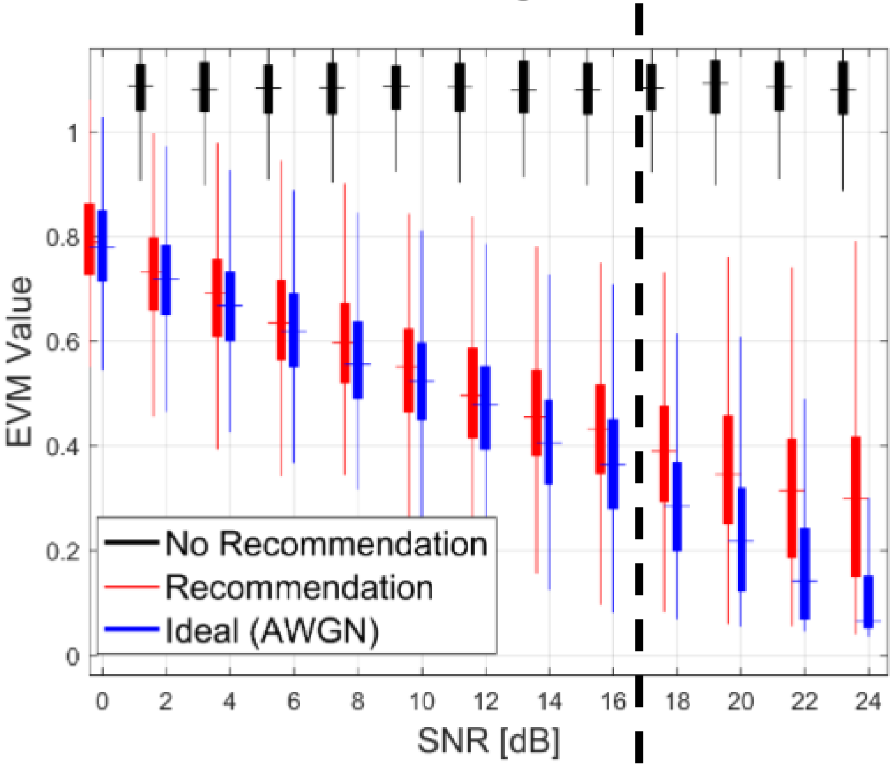
(b) BER for different modulation with 16 pilot tones.



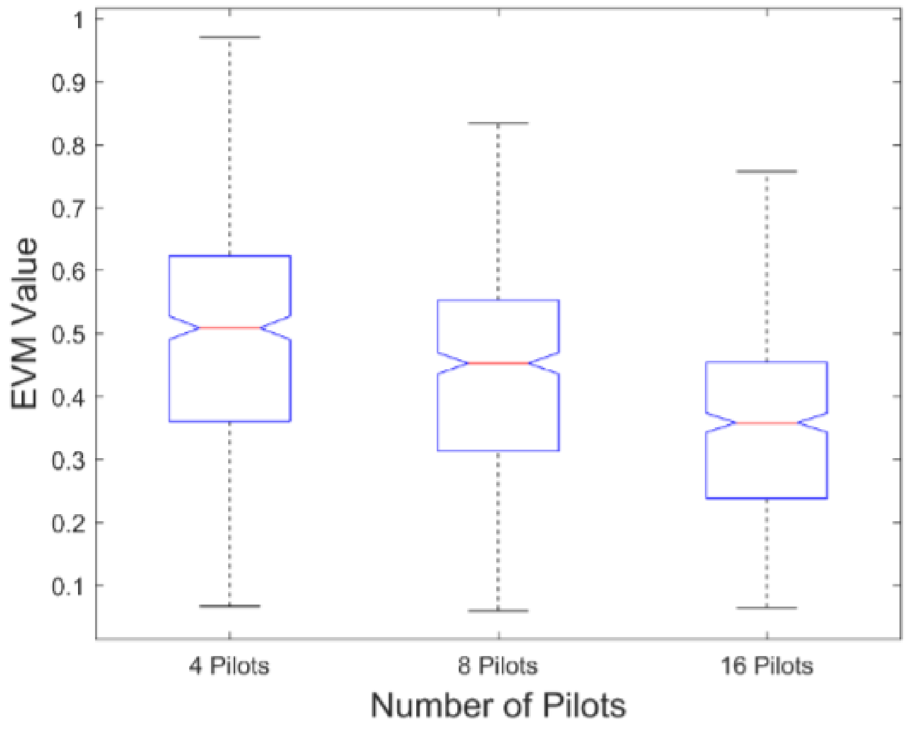
(c) BER for 16QAM and 64QAM with varying # pilot tones.

B. EVM at the Receiver

- Error Vector Magnitude (EVM)



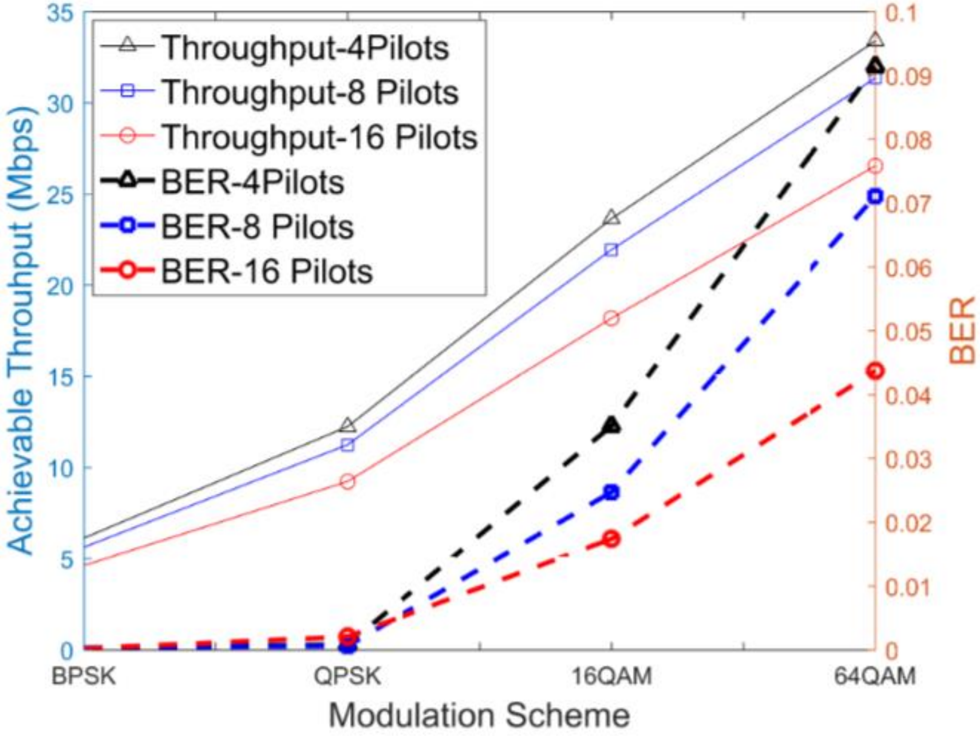
(a) EVM distribution for 16QAM with 16 pilot tones



(b) EVM plot for 16QAM with varying pilot tones at 20dB SNR.

C. Throughput-Pilot Trade-off

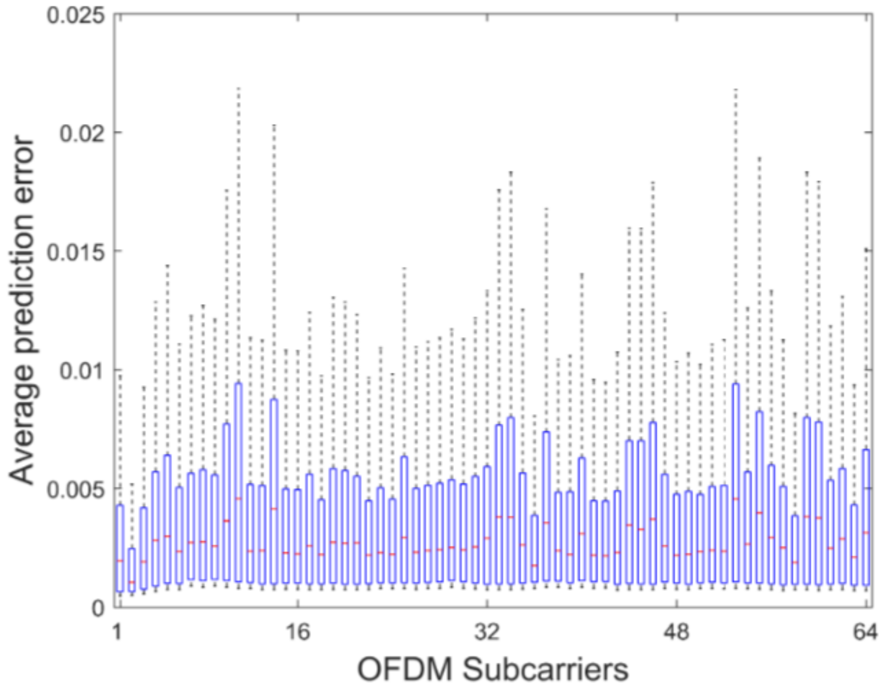
- The gain in goodput due to low BER.



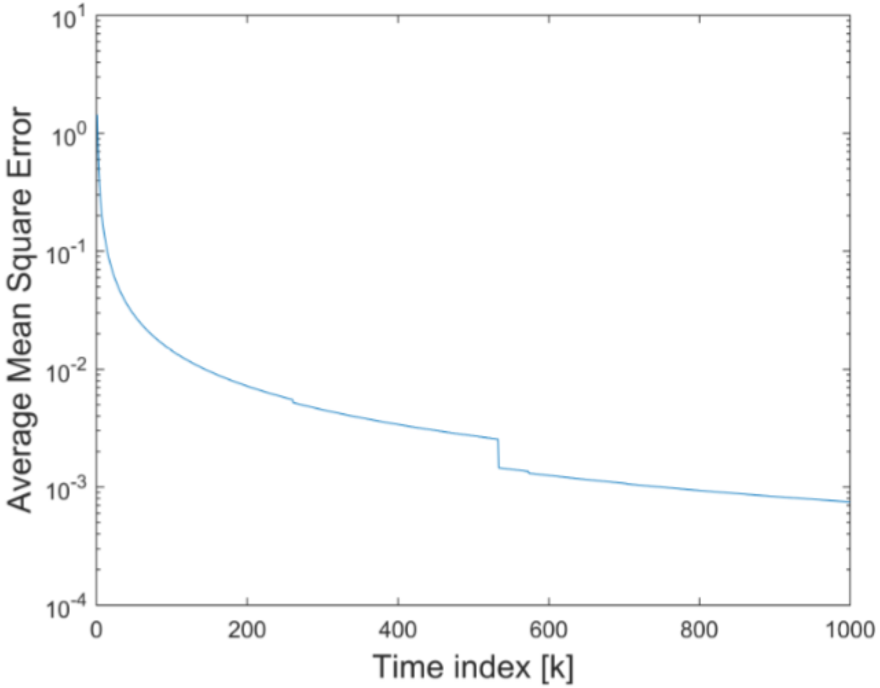
(a) Throughput and BER for different modulation for different number of pilots.

D. Accuracy of the Recommender System

- Mean Square Error (MSE) of the Recommender at Transmitter.



(a) MSE is fairly consistent for each frequency sub-carrier.



(b) MSE reduces with more CSI entries in the tensor.

Discussion

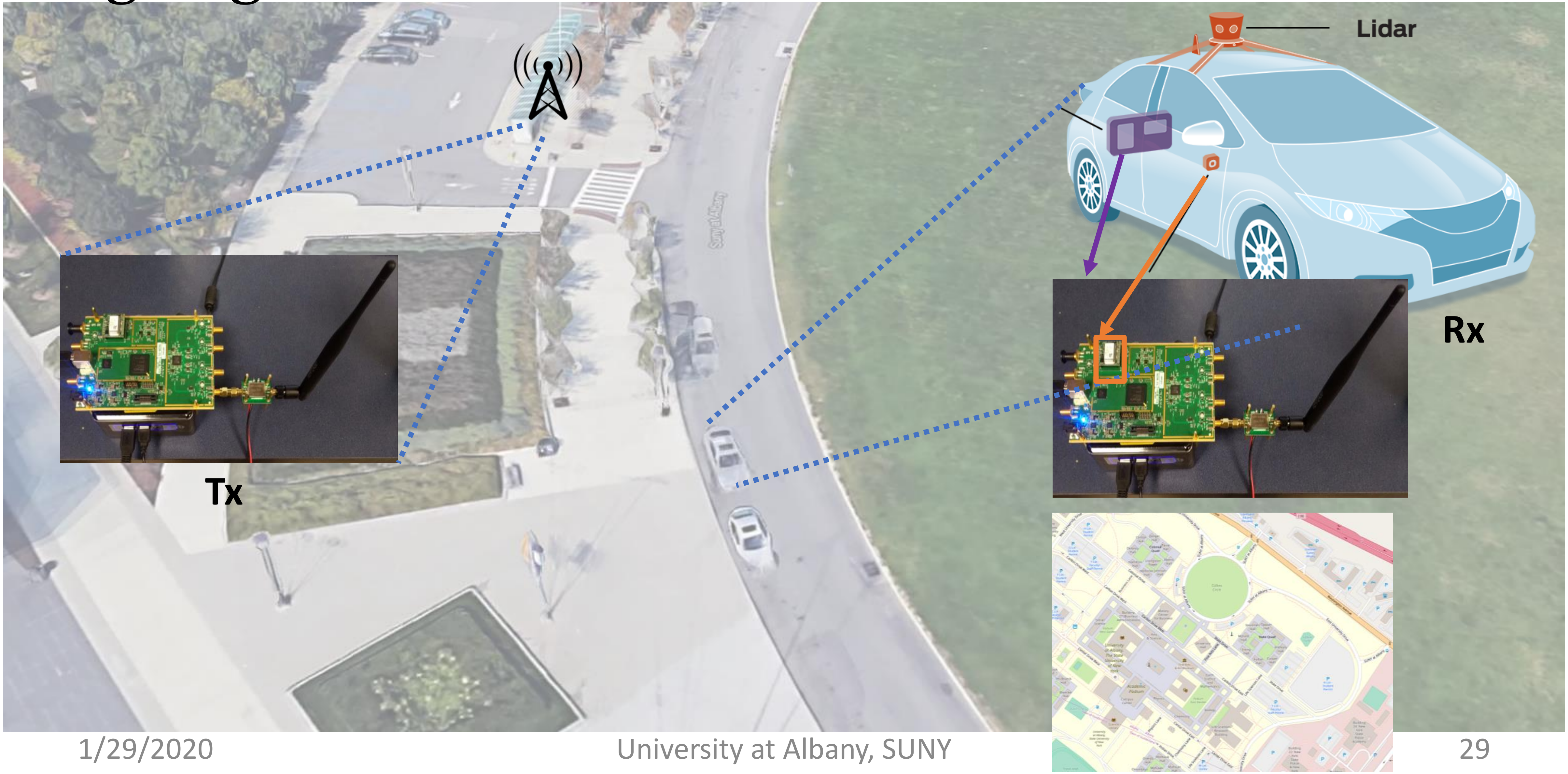
1) V2X Channels have high spatio-temporal non-stationarity.

2) Recommender at Tx is able to predict the V2X channel
→ flat fading profile → 96% lower BER

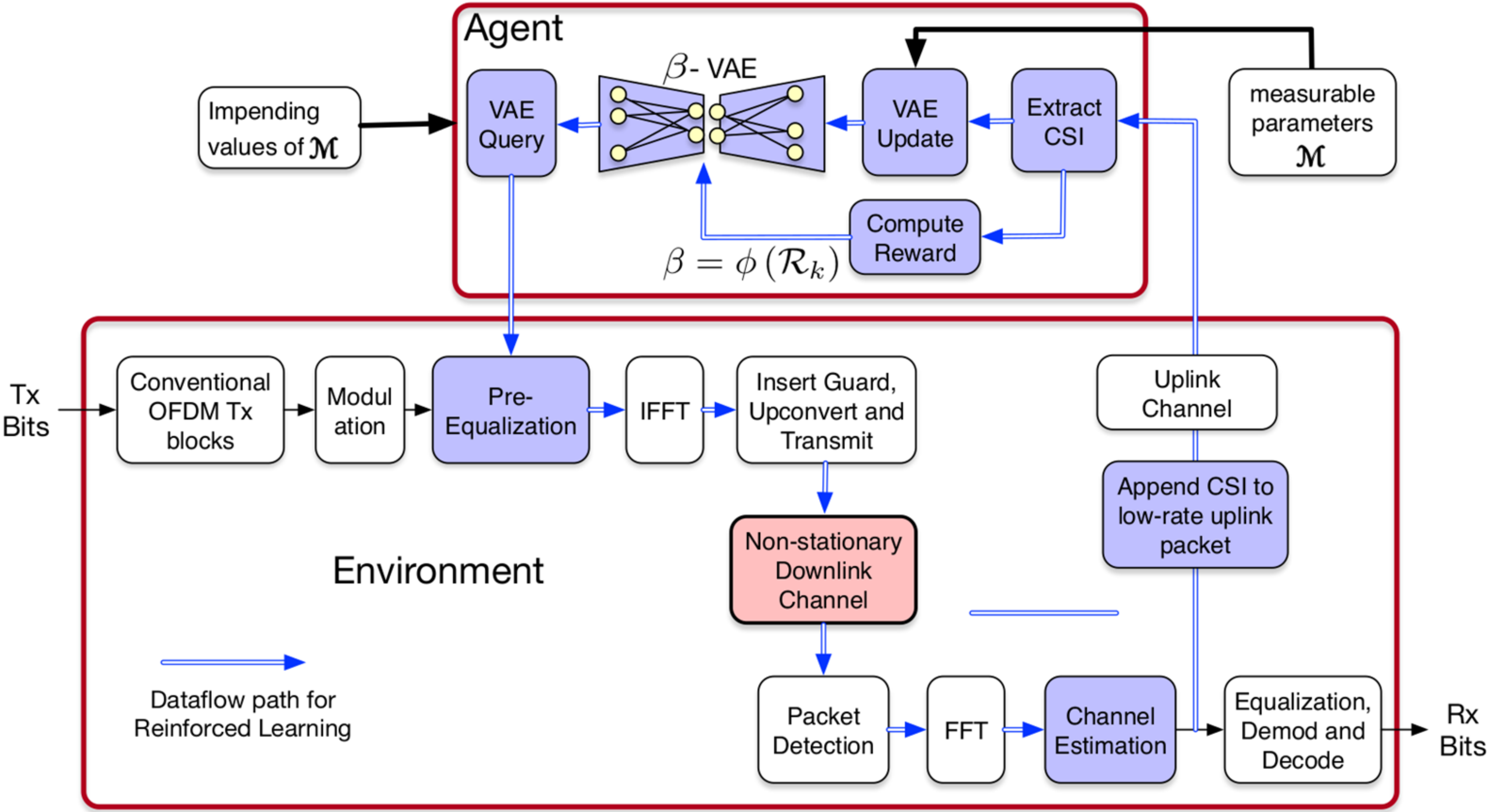
3) Higher modulation orders → V2X achieves higher Data Rates

4) Accuracy of recommender improves with time (MSE of 0.001)

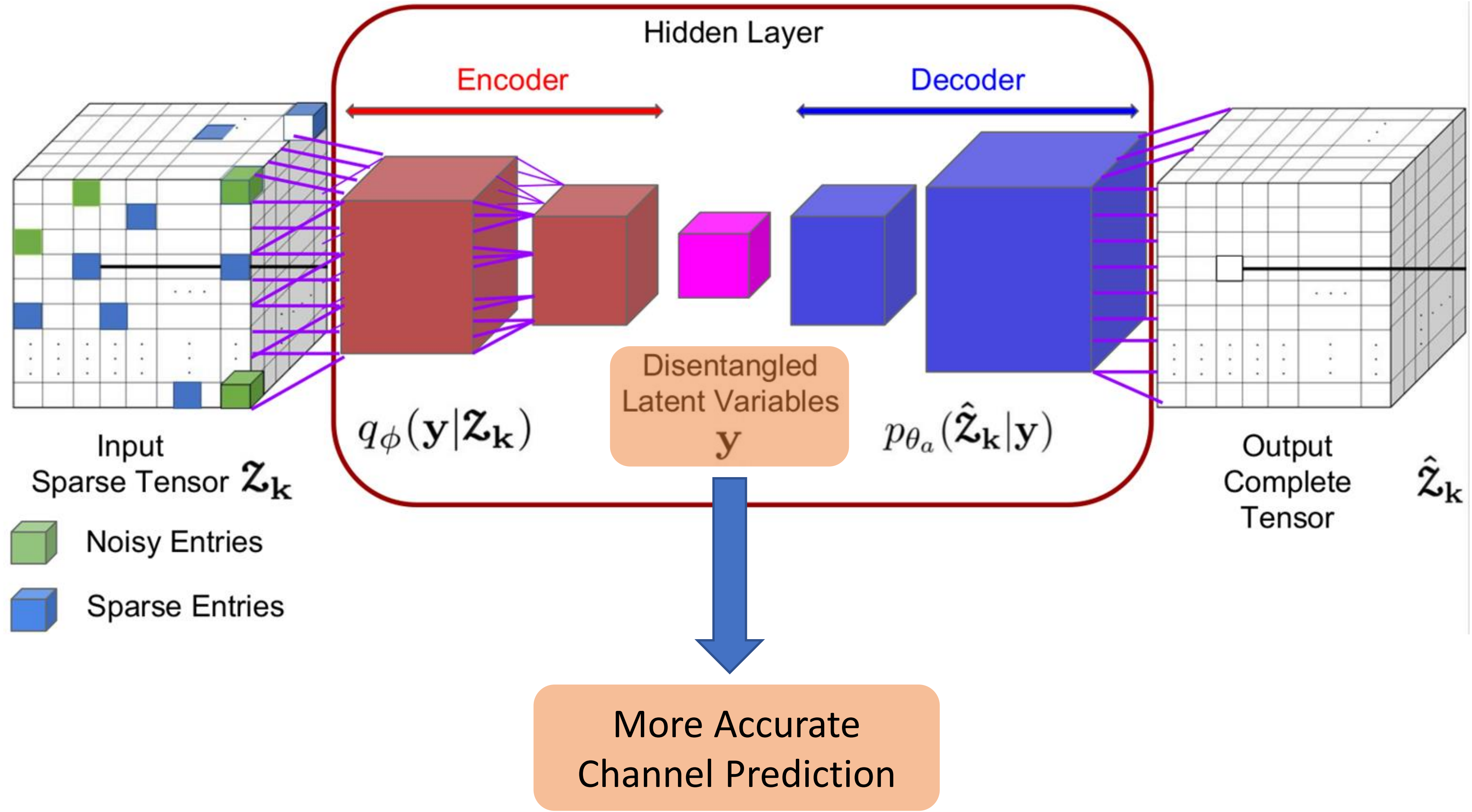
Ongoing Work: A. Outdoor V2X wireless testbed:



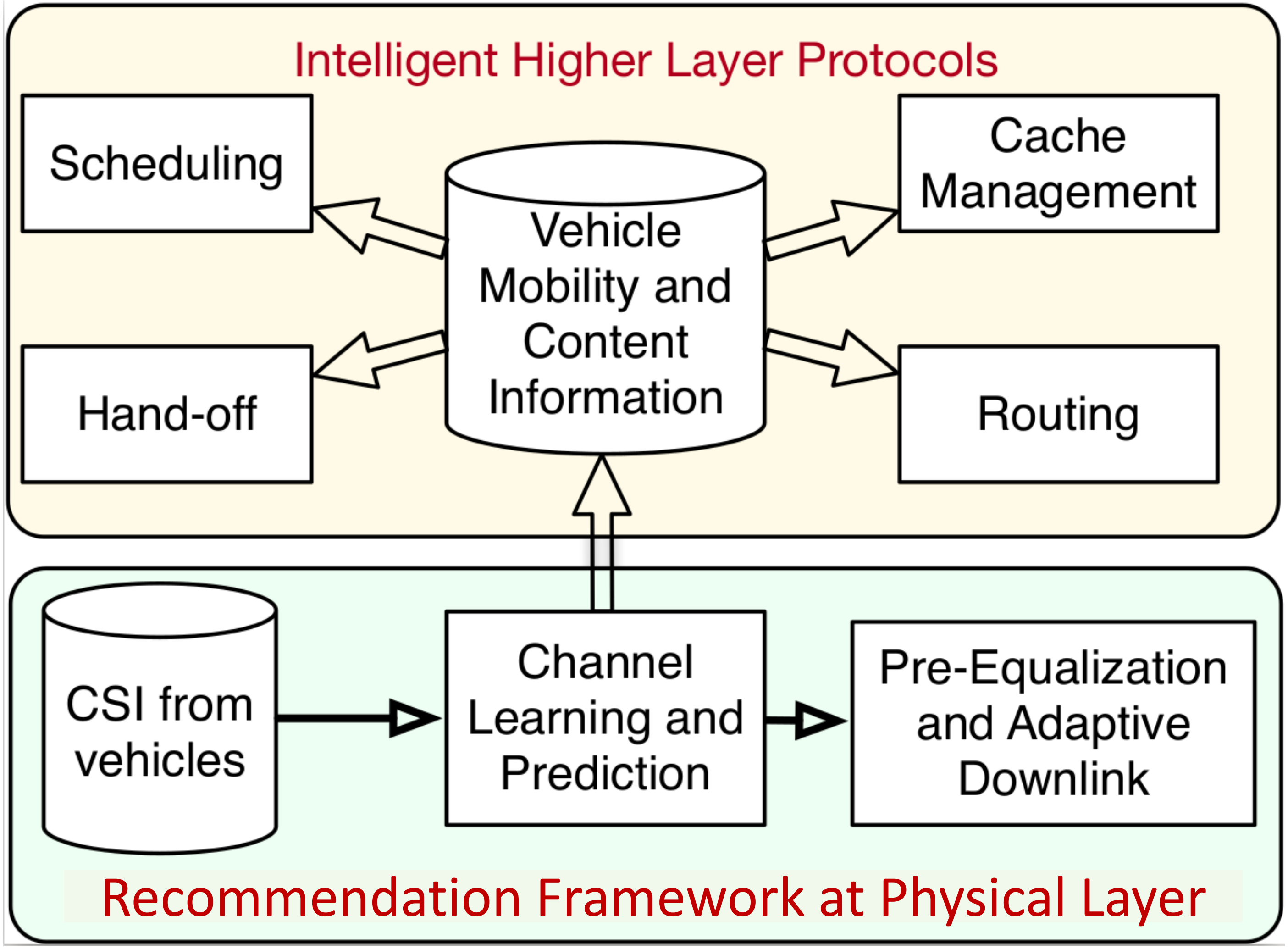
B. Deep Reinforcement Learning for V2X



Unique Advantage

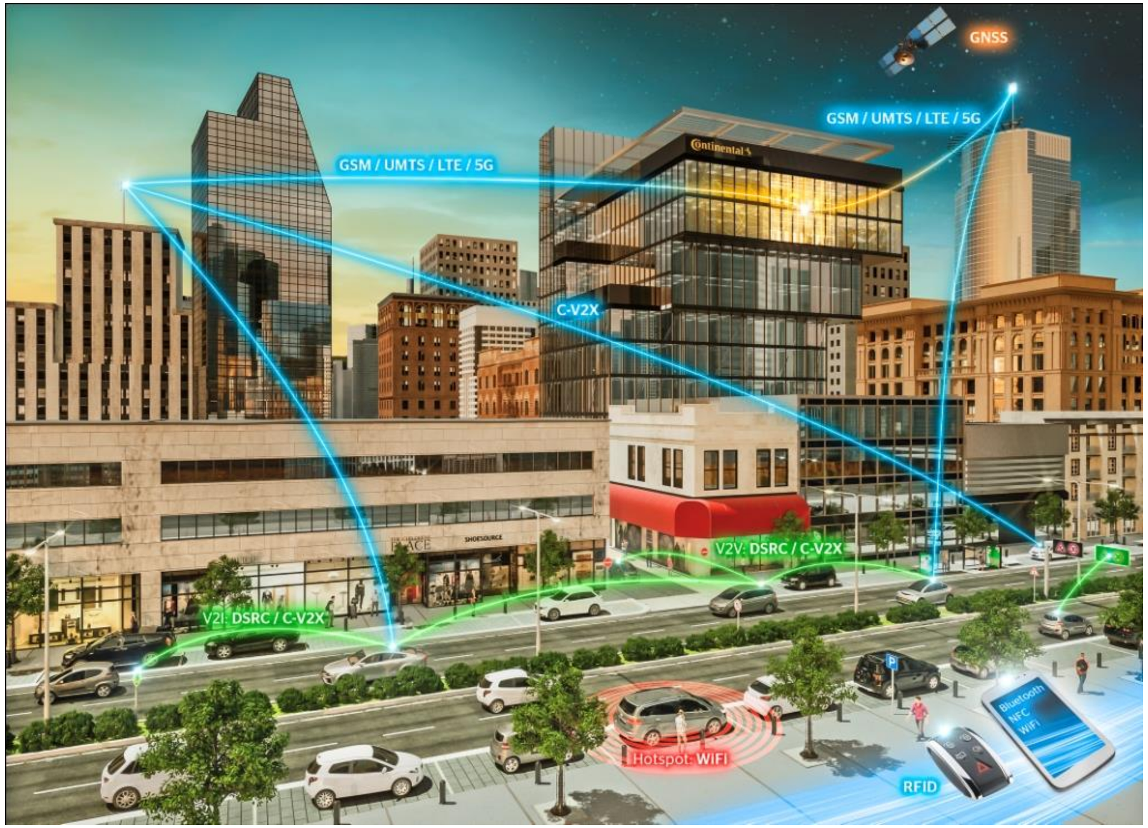


C. Intelligent Higher Layer Functions



D. Generalization to other Non-stationary Channels

- This framework can be generalized to other wireless channels,
  - 802.11-(xx),
  - C-V2X,
  - Visible Light,
  - Space communication and
  - Underwater networks



[4] Qualcomm, "C-V2X"

Courses Taken

ICSI 516 - Computer Communication Networks

ICSI 525 - Mobile Wireless Networks

ICEN 553 - Cyber-Physical Systems

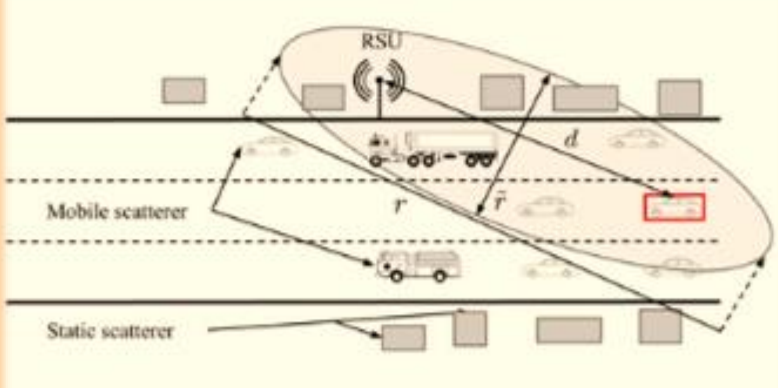
ICSI 503 - Algorithms & Data Structures

ICSI 551 - Bayesian Data Analysis

AMAT 575 - Optimization Theory

AMAT 524 - Advanced Linear Algebra

Predictive Analytics for V2X channels



Relevant Publications:

[VTC 2018] Spatio-Temporal Recommender for V2X Channels

[IEEE 5GWF] Channel Analytics for V2X Communication

[TWC*] Real-time prediction of Non-Stationary V2X channel using Tensor Decomposition

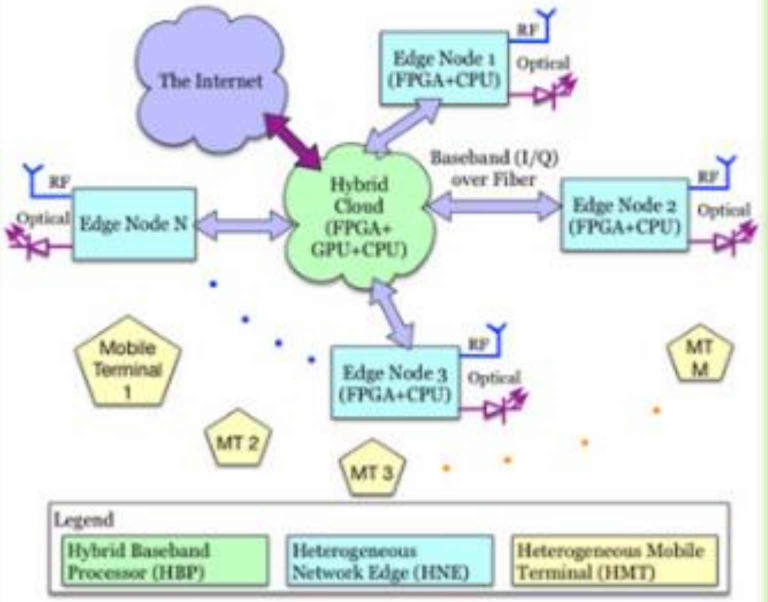
Enforcement of Spectrum Policies

Relevant Publications:

[Dyspan 2018] Multi-Agent Planning with Cardinality: Towards Autonomous Enforcement of Spectrum Policies

[TCCN] Spectrum Enforcement & Localization using Autonomous Agents with Cardinality

Cloud Radio Access Network (CRAN)



Relevant Publications:

[IEEE 5GWF] CHRONOS : A Cloud based Hybrid RF-Optical Network Over Synchronous Links

Conclusion

- My work…
  - Emerging Applications in Emerging Wireless Networks:
    Autonomous Agents, Adverse Channels, Hybrid Communications etc.
  - Emerging Techniques:
    Deep AI, Distributed Consensus Algorithms, Quantum Computing, etc.
- My Vision…
  - *Enabling Pro-active, Real-time applications via Autonomous agents (UAVs, UGVs, crowd) for emerging wireless networks*

Thank you

Questions & Feedback