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Nested Sparse Approximation: Structured Estimation of V2V Channels Using Geometry-Based Stochastic Channel Model

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Motivation: V2V channels Estimation

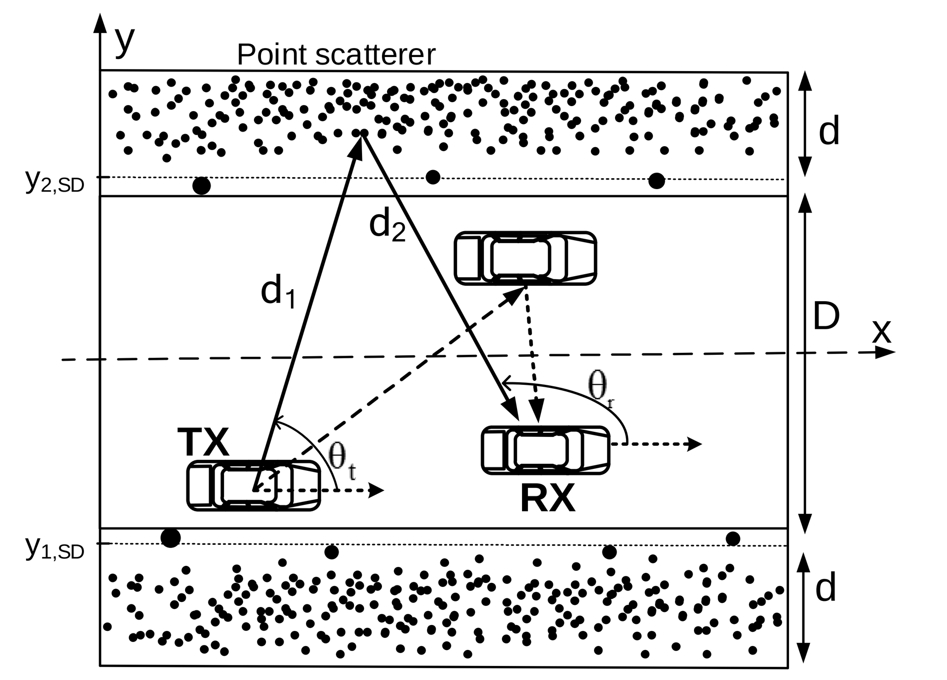
Application:
- Traffic safety
- Intelligent transportation

Differences:
- Higher speeds
- Geometry dependence

Channel Ingredients :
- *line-of-sight* (LOS)
- *Discrete Components*
  - (a) Mobile Discrete (MD) components (e.g.: other vehicles, ….)
  - (b) Static Discrete (SD) Components (e.g.: Large traffic signs, ….)
- *Diffuse Components* (all other components)

Prior Arts:
- Least-Square (Unstructured)
- Adaptive Low Rank Wiener Filtering (High Complexity)
- Compressed Sensing using basis pursuit (Mismatching, …)
- Hybrid Sparse diffuse model (Information complexity)

Geometry-Based Stochastic Model

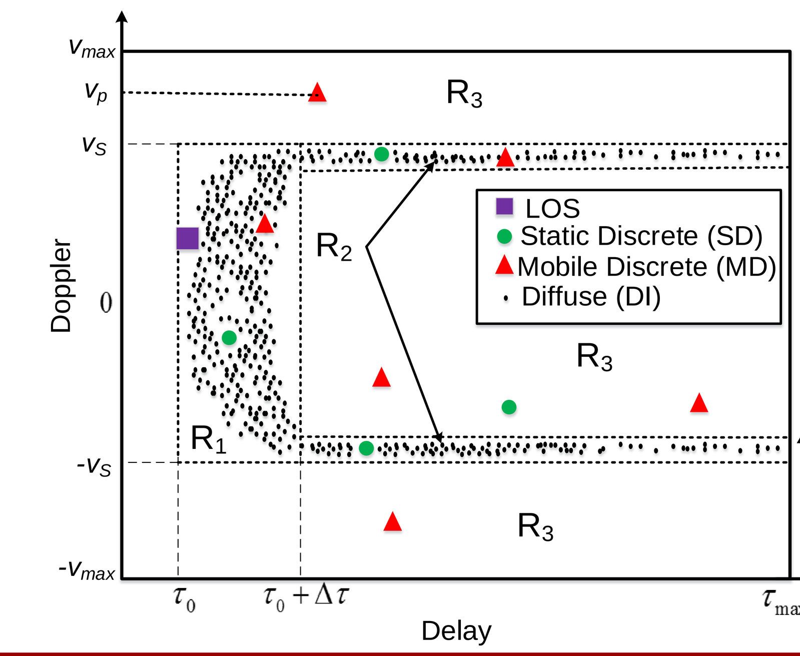


GBSM: For any ensemble of point scatters with V2V channel statistical properties, compute its contribution at the receiver

- **Delay (Specific ensemble):** $\tau = \dfrac{d_1 + d_2}{c_0},$
- **Doppler Shift (Specific ensemble):**

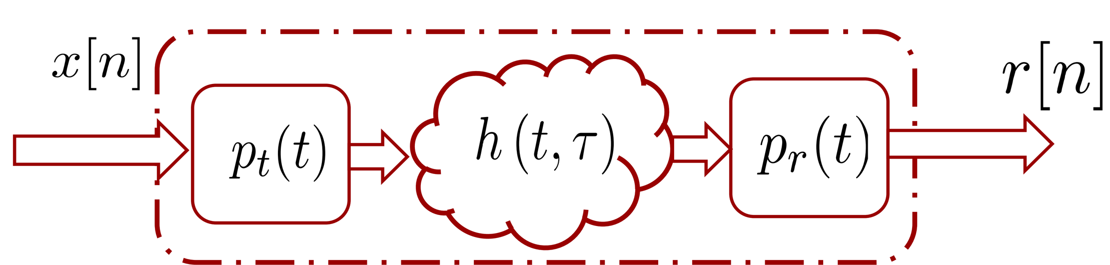
$$\nu(\theta_t, \theta_r) = \frac{1}{\lambda}\left[(v_T - v_P)\cos\theta_t + (v_R - v_P)\cos\theta_r\right]$$

Delay-Doppler Representation



- Diffuse contribution (only) in U-shape area
- Huge area with zero/small value components
- Symmetry of Diffuse scatterers contribution
- Diffuse components follow exponential profile (Delay wise)
- Sparse Region = Mobile Discrete Scatterers
- Sparse Components = All Discrete components
- Sparse Components exist in all Three Regions

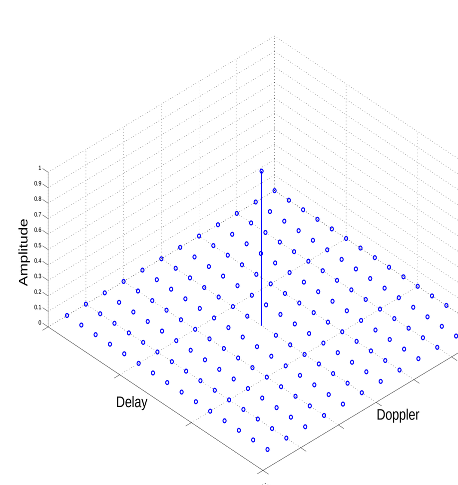
Pulse Shape/Leakage Effect



$p_t(t)$: Interpolating Filter
$p_r(t)$: Anti-aliasing Filter

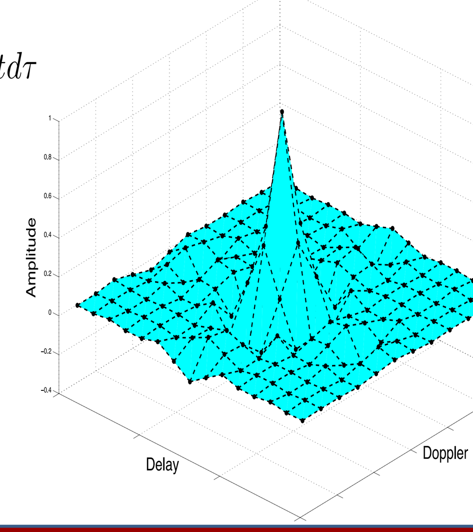
Input-Output relationship:

$$r[n] = \sum_{m=-\infty}^{+\infty} h_l[n,m]\, x[n-m] + z[n]$$



Leaked Channel:

$$h_l[n,m] = \iint_{-\infty}^{+\infty} h(t+nT_s,\tau)\, p_t(t-\tau+mT_s)\, p_r(-t)\, dt\, d\tau$$



- Finite transmit Bandwidth
- Finite pilot sequence length

Leakage Effect Template Computation

True Channel: $H_i[k,m] = a_i \delta[m-m_i]\delta[k-k_i]$

Leaked Channel: $H_{l,i}[k,m] = a_i L_\tau[m-m_i] L_\nu[k-k_i]$

Leakage Template:

$L_\tau[m-m_i]$ (Delay direction) Filters correlation function, Sampling Time

$L_\nu[k-k_i]$ (Doppler direction) Dirichlet function, Pilot sequence length

- Independent in delay and Doppler direction
- Given the system parameters, Leakage template is known

Compensation Approach $\Rightarrow$ $\mathbf{x}_l = \mathbf{G}\mathbf{x}$

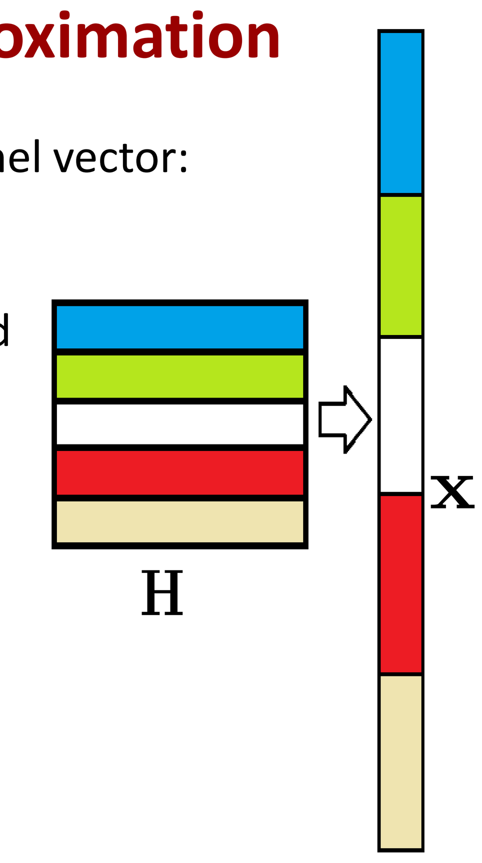
depends only on Leakage template

Nest Sparse Approximation

- Convert 2D Channel to 1D Channel vector:

$\mathbf{H} \longrightarrow \mathbf{x}$

Vector x has both ***element-wise*** and ***group-wise*** sparsity.



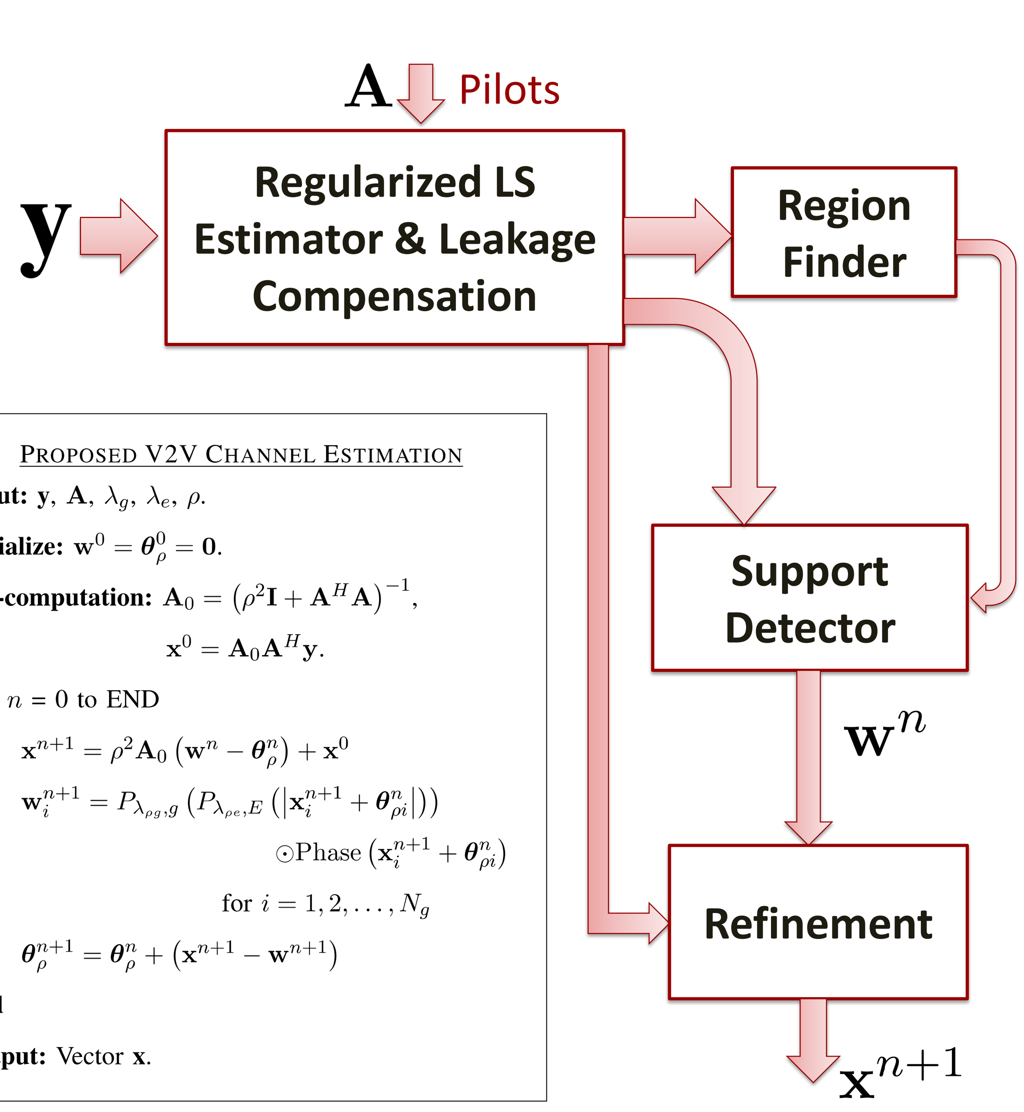
- **Proper Regularization:**

$$\phi_g(|\mathbf{x}|;\lambda_g) = \sum_{j=1}^{N_g} f_g\left(\|\mathbf{x}_j\|_2;\lambda_g\right),$$

$$\phi_e(|\mathbf{x}|;\lambda_e) = \sum_{i=1}^{N} f_e\left(|x[i]|;\lambda_e\right).$$

$$\hat{\mathbf{x}} = \underset{\mathbf{x}\in\mathbb{C}^N}{\operatorname{argmin}} \left\{\frac{1}{2}\|\mathbf{y}-\mathbf{A}\mathbf{x}\|_2^2 + \phi_g(|\mathbf{x}|;\lambda_g) + \phi_e(|\mathbf{x}|;\lambda_e)\right\}$$

Proposed Algorithm to Estimate the V2V Channel

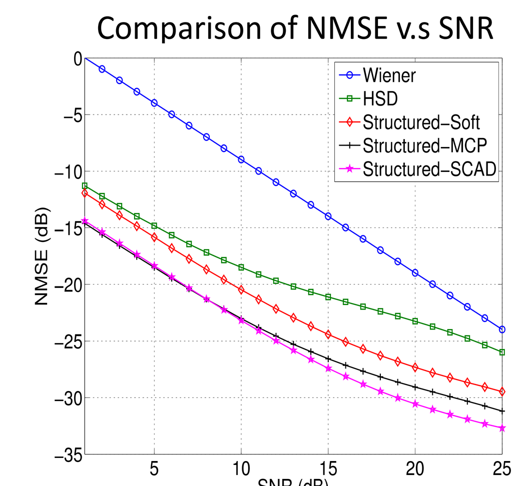


PROPOSED V2V CHANNEL ESTIMATION

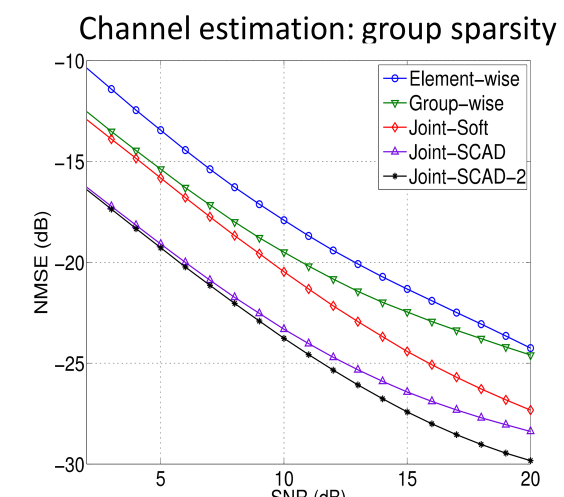
Input: $\mathbf{y}$, $\mathbf{A}$, λ_g, λ_e, ρ.
Initialize: $\mathbf{w}^0 = \boldsymbol{\theta}_\rho^0 = 0$.
Pre-computation: $\mathbf{A}_0 = (\rho^2 \mathbf{I} + \mathbf{A}^H\mathbf{A})^{-1}$,
$\mathbf{x}^0 = \mathbf{A}_0 \mathbf{A}^H \mathbf{y}$.
For $n = 0$ to END
$\mathbf{x}^{n+1} = \rho^2 \mathbf{A}_0 (\mathbf{w}^n - \boldsymbol{\theta}_\rho^n) + \mathbf{x}^0$
$\mathbf{w}_i^{n+1} = P_{\lambda_{g},\mathcal{G}}\left(P_{\lambda_{e},E}\left(|\mathbf{x}_i^{n+1} + \boldsymbol{\theta}_{\rho i}^n|\right)\right) \odot \text{Phase}\left(\mathbf{x}_i^{n+1} + \boldsymbol{\theta}_{\rho i}^n\right)$
for $i = 1, 2, \ldots, N_g$
$\boldsymbol{\theta}_\rho^{n+1} = \boldsymbol{\theta}_\rho^n + (\mathbf{x}^{n+1} - \mathbf{w}^{n+1})$
End
Output: Vector $\mathbf{x}$.

Simulation Results

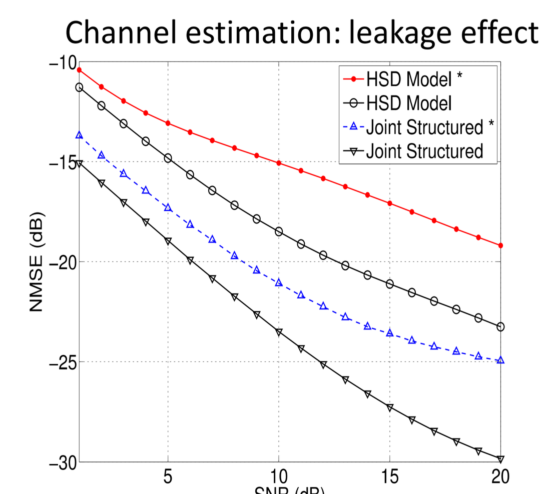
Comparison of NMSE v.s SNR



Channel estimation: group sparsity



Channel estimation: leakage effect



- Non-convex vs. convex regularizers: 3 dB at low SNR and 5 dB at high SNR values with the same computational complexity.
- In MSE = −20 dB, the performance curve related to the structured estimator shows a 6dB improvement in SNR compared to HSD estimator, and 15 dB improvement in SNR compared to the Wiener Filter.
- Significant improvement (6 dB to 10 dB) of joint-sparsity.

- Different group sizes for key regions up to 4 dB for high SNR.
- Uncompensated leakage effect reduces performance severely, more than 7 dB, particularly at higher SNR, due to the channel mismatch introduced by the channel leakage.

Conclusions

- Geometry-based stochastic model for V2V channel
- V2V channel structure in the delay Doppler (Three Key Regions)
- Leakage effect, independent in delay Doppler directions
- Low complexity, structured joint Sparse
- Nested estimation of the channel vector based on the group and element wise penalty functions

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