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:
  - Mobile Discrete (MD) components (e.g.: other vehicles, …)
  - Static Discrete (SD) Components (e.g.: large road 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

\[ \nu \left( \theta_i, \theta_j \right) = \frac{1}{N} \left( v_T - v_P \right) \cos \theta_i + \left( v_R - v_P \right) \cos \theta_j \]

Delay-Doppler Representation

- Diffuse contribution (only) in U-shape area
- Huge area with zero/small value components
- Symmetry of Diffuse scatters 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

Delay-Doppler Leakage Effect Template Computation

True Channel: \( H_{0, \text{true}}(k, n) = a_0^n - m_0(k - n) \)

Leaked Channel: \( H_{0, \text{leak}}(k, n) = a_0^n - m_0 - m_0(k - n) \)

Leakage Template:
- \( L_m(k - n) \) (Delay direction) Filters correlation function, Sampling Time
- \( L_m(k - n) \) (Doppler direction) Dirichlet function, Pilot sequence length

\[ \phi(x | \lambda) = \sum_{i=1}^{N} \phi_i(x | \lambda_i) \]

\[ \phi_i(x | \lambda) = \sum_{i=1}^{N} \phi_i(x | \lambda_i) \]

\[ \hat{x} = \text{argmin}_{x \in \mathbb{C}^N} \left\{ \frac{1}{2} || y - Ax ||^2 + \phi(x | \lambda) + \phi_A(x | \lambda) \right\} \]

Proposed Algorithm to Estimate the V2V Channel

A \( \hat{x} \) Pilots

Regularized LS Estimator & Leakage Compensation

Region Finder

Support Detector

Refinement

\[ X^{n+1} \]

Simulation Results

Comparison of MSE vs SNR

Channel estimation: group sparsity

- Non-convex, cones regulations
- 5 dB at low SNR and 5 dB at high SNR values with the same computational complexity.
- In MSE > 10 dB, the performance curve related to the finite structured estimator shows a 4 dB improvement in SNR compared to full estimator and 1.5 dB improvement in SNR compared to the full estimator.
- Significant improvement (2 dB to 10 dB) of post-processing.

- Different group sizes for key regions: up to 4 dB for high SNR.
- Unstructured 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

Acknowledgments:
This research was funded in part by one or all of these grants: ONR N00014-09-1-0700, AFOSR FA9550-08-1-0315, DOT CA-26-7084-00, NSF CCF-1117896, NSF CNS-1213128, NSF CCF-1400009, NSF CPS-1446901, Barbro Osher Pro Suecia Foundation, Ericsson’s Research Foundation FFS17FT-13-038, and Adlerbert Research Foundation.