Iterative Vehicular Channel Estimation for IEEE 802.11p

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Outline

- Part I
  - Generalized discrete prolate spheroidal (DPS) sequences for iterative time-variant frequency-selective channel estimation
  - Backward compatible IEEE 802.11p pilot pattern evolution
  - Numerical simulation results for vehicle-to-infrastructure communications
- Part II
  - Outlook: Dynamic subspace selection

Introduction (I)

- Dependable connectivity is crucial for intelligent transportation systems (ITS)
  - Reliable
  - Low-latency
  - Strict packet delay bounds
- Safety-improvements
  - Collision avoidance
  - Emergency vehicle warning
  - Wrong-way driving warning
  - Lane change assistance

FTW Forschungszentrum Telekommunikation Wien

- 65 people carrying out research and development of technologies for future communication systems
- funded in the competence center program COMET by FFG
- with partners from academia and industry

FTW's ITS industry partners

FTW's ITS scientific partners
Safety Critical Scenarios

- Road crossing
  - Emergency vehicle warning
  - Intersection collision warning
  - Pre-crash sensing

- Merging lanes
  - Wrong way driving warning
  - Co-operative merging assistance

- Traffic congestion
- In-tunnel

Introduction (II)

- Intelligent transportation systems are based on
  - Vehicle-to-infrastructure (V2I) communications
  - Vehicle-to-vehicle (V2V) communications

- IEEE 802.11p protocol intended for vehicular communications
  - Based on the WiFi standard (802.11a)
  - Orthogonal frequency division multiplexing (OFDM)
  - 5.9 GHz band

Communication Scenarios

- mobile stations (MS) are moving, base station (BS) is fixed
- time-variant multi-path propagation
- interference

- transmitter and receiver are mobile
- safety critical scenarios

Measurement Scenario
**Power Delay Profile**

- Strong line of sight (LOS)
- Weak tail following LOS
- Multiple reflecting objects
- Delays change over time, as well as Doppler shifts
- Non-stationary fading process - can be assumed wide-sense stationary for a limited time interval (stationarity time) only

**Local Scattering Function (LSF)**

- Sampled time-variant frequency response $H[m, q]$
- Local scattering function [Matz 2005]

**Time-Variant Multipath Propagation**

- Time-variant frequency response
  \[
g[m, q] = g_{Tx}[q]g_{Rx}[q] \sum_{\ell=0}^{P-1} \eta_{\ell} e^{-2\pi i \nu_{\ell}(q) \theta_{\ell}} e^{2\pi i \nu_{\ell}}\]

  with $\nu(q) = ((q + N/2 \mod N) - N/2)$

- $P$ propagation paths, with delay $\tau_{\ell}$, Doppler shift $f_{\ell}$ and complex weight $\eta_{\ell}$
- Normalized Doppler shift $\nu_{\ell} = f_{\ell} T_{S}$
- Normalized delay (in an OFDM system) $\theta_{\ell} = \tau_{\ell} B / N$
A Priori Knowledge (I)

Local scattering function

A Priori Knowledge (II)

Doppler domain

- Maximum normalized Doppler bandwidth
  \[ \nu_{\text{Dmax}} = \frac{\nu_{\text{max}} f_c}{c_0} \]
  \[ T_S = B_{\text{Dmax}} T_S \ll \frac{1}{2} \]

- symmetric interval \( \mathcal{W}_t = (-\nu_{\text{Dmax}}, \nu_{\text{Dmax}}) \)

A Priori Knowledge (III)

Delay domain

- Maximum normalized path delay
  \[ \theta_{\text{max}} = \frac{\tau_{\text{max}}}{B} < 1 \]

- asymmetric interval \( \mathcal{W}_t = (0, \theta_{\text{max}}) \)

Subspace Design (I)

- Two dimensional subspace channel model
  \[ g[m, q] \approx \sum_{i=0}^{D_1-1} \sum_{k=0}^{D_2-1} u_i[m] \cdot u_k[q] \psi_{i,k} \]
  exploiting the low-dimensional subspace of the time-variant impulse response \( D_1D_2 < MN \).

- Discrete prolate spheroidal sequences (Slepian 78, Zemen et al. 05)
  - band-limited to a symmetric interval \( (-\nu_0, \nu_0) \)
  - energy-concentrated in \( m \in \mathcal{I}_M = \{0, \ldots, M - 1\} \)
  - generalization needed for time-variant frequency-selective channels!
Subspace Design (II)

- Generalized discrete prolate spheroidal (DPS) sequences (Zemen et al. 2007)
  - band-limited to a region $\mathcal{W}$
    \[ \mathcal{W} = \bigcup_{i=1}^{D} B_i \cup B_2 \cup \ldots \cup B_J \]
  - energy-concentrated in $m \in I_M = \{0, \ldots, M-1\}$
    \[ \sum_{\ell=0}^{M-1} u_i[\ell, \mathcal{W}, \ell] \int_{\mathcal{W}} e^{i2\pi(\ell,m)\nu} d\nu = \lambda_i(\mathcal{W}, M) u_i[m, \mathcal{W}, M] \]
  - $\{u_i[m, \mathcal{W}, M]\}$ are doubly orthogonal on $I_M$ and $\mathcal{Z}$
  - Essential subspace dimension $D'(\mathcal{W}) = |\mathcal{W}| + 1$


Subspace Design (III)

- Two dimensional generalized DPS channel model (Zemen et al. 11)
  \[ g[m, q] \approx \sum_{i=0}^{D-1} \sum_{k=0}^{D-1} u_i[m, \mathcal{W}_i, M] \cdot u_k[q, \mathcal{W}_i, N] \psi_{i,k} \]

  - Time domain subspace:
    - models $g[m,q]$ for a single subcarrier $q$ and $m \in I_M$
    - parameterized by max. support of Doppler power spectral density:
      \[ \mathcal{W}_i = [-\nu_{\text{Dmax}}, \nu_{\text{Dmax}}] \]
  - Frequency domain subspace:
    - models $g[m,q]$ for a single OFDM symbol $m$ and $q \in I_N$
    - parameterized by max. support of power delay profile:
      \[ \nu_{\text{D}} = [0, \nu_{\text{Dmax}}] \]


IEEE 802.11p Pilot Pattern

OFDM Channel Estimation

- Coherent detection based on channel state information (CSI)
- CSI obtained from pilot symbols interleaved in time and frequency
- Pilot placement
  - Distance in time: $\Delta_t \leq \frac{B}{2f_{\text{Dmax}}(N + G)}$
  - Distance in frequency: $\Delta_f \leq \frac{N}{\tau_{\text{max}}B}$

IEEE 802.11p pilot pattern violates sampling theorem for non-line of sight situations when both $\tau_{\text{max}}$ and $f_{\text{Dmax}}$ are large!
We introduce a postamble in a transparent fashion:

- The LENGTH field of the header indicates the length of the data symbols as before.
- One of the reserved SERVICE bits is used to indicate the existence of the postamble.

**Iterative Channel Estimation**

- Linear minimum mean square error (MMSE) filter used for
  - time-variant channel estimation
  - data detection

**Frame Lengths Dependence**

- Simulation parameters:
  - Modulation: QPSK
  - Car speed: 100 km/h
  - Frame length: 200 bytes
  - Channel model: exp. decaying PDP plus Clarke Doppler spectrum, non line of sight (NLOS) most critical situation

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from a distribution with mean along a highway is shown in Fig. 18. A road-side Tx and a ve-

heits from vehicular measurements at

11p compliant

11p compliant + transparent postamble

Simulation parameters
- Modulation: QPSK
- Car speed: 100 km/h
- Frame length: 800 bytes
- Channel model: Clarke’s, non line of sight (NLOS) – most critical situation

Geometry Based Channel Model

Initial geometry

Diffuse Scatters

Discrete Static Non-Stationary Scatterers

Discrete Mobile Scatters

Rx

Tx

Diversity Changes Over Distance

Simulation parameters
- Modulation: QPSK
- Car speed: 100 km/h
- Frame length: 200 bytes
- Channel model: non-stationary GSCM
- Distances: 1, 50, 100, 200 m
- Perfect channel state information (CSI)

Required Number of Iterations

Simulation parameters
- $E_b/N_0$: 10 dB
- Modulation: QPSK
- Car speed: 100 km/h
- Frame length: 200, 400, and 800 bytes
- Channel model: JAKES, non line of sight (NLOS) – most critical situation
Non-Stationary Channel Model

Simulation parameters
- $E_b/N_0$: 8 dB
- Modulation: QPSK
- Car speed: 100 km/h
- Frame length: 200 bytes
- Channel model: non-stationary GSCM with strong line of sight component
- Distances: 1, 50, 100, 200 m

Summary – Part I

- IEEE 802.11p pilot pattern violates sampling theorem for NLOS situations
- Generalized DPS sequences enable tight two dimensional subspace design for time-variant channel estimation
- Iterative channel estimator reduces bit error rate by more than three magnitudes for NLOS and LOS situations
- Pilot pattern with transparent postamble reduces iterative channel estimation complexity by a factor of two to three