Time-domain channel estimation for wideband millimeter wave systems with hybrid architecture

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MIMO and massive MIMO systems at mmWave

mmWave and massive MIMO are key ingredients of 5G

- Large antenna arrays needed at Tx and Rx
- Leveraging beamforming gain to realize large data rates
- Low-overhead channel estimation techniques needed
  - Crucial for efficient precoder/combiner design in both mmWave MIMO and mmWave massive MIMO systems
- Large matrix sizes also complicate channel estimation

MIMO channel estimation at mmWave is complicated due to hardware constraints
MIMO architectures at mmWave: analog beamforming

Phase shifters apply for the entire band

Beam training used to get the best Tx and Rx beamforming directions

Limited to single stream and single user MIMO


MIMO architectures at mmWave: **hybrid precoding**

- **Baseband Precoding**: \( N_s \) x \( F_{BB} \)
- **RF Precoding**: \( L_t \) x \( F_{RF} \)
- **RF Combining**: \( N_r \) x \( W_{RF} \)
- **Baseband Combining**: \( N_s \) x \( W_{BB} \)

**Combine analog and digital precoding**

- Fully digital MIMO is not feasible at mmWave
- Rules out several digital channel estimation techniques
- \# of DACs/ADCs << \# of antennas
  - *Low resolution mixed circuit components not considered here

**Hybrid precoding can support multi-stream and multi-user MIMO at mmWave**

MmWave channel estimation with hybrid architecture

Channel estimates are an alternative to beam training, work with multi-stream.

- Large bandwidth $\rightarrow$ frequency selective channel
- Low link SNR without beamforming
- No direct access to antenna outputs
- Multistream beam training $\rightarrow$ large training overhead
Prior work

Hierarchical beam training

- Single stream support only
- Used for analog architectures
- Avoids explicit channel estimation

Sparsity-based channel estimation

- Support for multi stream
- Most prior work on narrowband channel model
- Wideband systems assumed ideal setting
- Works for any architecture

Most prior work on narrowband channel model

Works for wideband channel

Support for multi stream

Wideband systems assumed ideal setting

Works for any architecture
Contributions

Wideband mmWave channel estimation technique

Sparse problem formulation in time domain

Useful in single-carrier mmWave systems

Works for both MIMO and massive MIMO wideband mmWave systems

Include system constraints

Frame structure

Finite bandwidth of pulse shaper

Hybrid architecture
Wideband mmWave channel model

Clustered in time:

\[ L \ll N_r N_t \]

\[ H_d \in \mathbb{C}^{N_r \times N_t} \]

\[ d = 0, 1, \ldots, N_c - 1 \]

Clustered in space:

\[ H_d = \sum_{\ell=1}^{L} \alpha_\ell p_{rc}(dT_s - \tau_\ell) a_R(\phi_\ell) a_T^*(\theta_\ell) \]

Complex path gain

Path delay

Angle of arrival/departure

Obtain \{\phi_\ell, \theta_\ell, \alpha_\ell, \tau_\ell\} for channel estimation

Exploit sparsity in the angular and delay domain in the problem formulation
Key idea of the proposed channel training

- Uniform random phase from quantized angles
- Hybrid precoding for training-frame transmission
- Estimate AoA/AoD and ToA using sparse recovery
- Leverage the sparse structure in the mmWave channel & the hybrid architecture
- Fixed RF precoder/combiner for the whole frame
Channel training stages

\[ N_c - 1 \quad \text{Length} \quad N \quad \text{training data} \]

**ZP**

Training sequence

\[ m^{th} \text{ training frame} \begin{bmatrix} 0 & \cdots & 0 & s_m[1] & \cdots & s_m[N] \end{bmatrix}_{N_c - 1} \]

\[
\begin{bmatrix}
    y_m[1] \\
    y_m[2] \\
    \vdots \\
    y_m[N]
\end{bmatrix}^T = w_{RF}^{(m)\ast} \begin{bmatrix} H_0 & \cdots & H_{N_c - 1} \end{bmatrix} \begin{bmatrix}
    f_{RF}^{(m)} s_m[1] \\
    f_{RF}^{(m)} s_m[2] \\
    \vdots \\
    f_{RF}^{(m)} s_m[N]
\end{bmatrix} + e^{(m)}
\]

Zero-padding facilitates RF circuit reconfiguration across frames

(zeros used for beam switching)
Exploiting sparsity in the angular domain

\[
y_m = \left( S_m \otimes f_{RF}^{(m)T} \otimes w_{RF}^{(m)*} \right) \Phi_m + \text{vec}(H_0) + \text{vec}(H_1) + \ldots + \text{vec}(H_{N_c-1}) + e_m
\]

Training data matrix

\[
\begin{bmatrix}
    s_m[1] & 0 & \ldots & 0 \\
    s_m[2] & s_m[1] & \ldots & . \\
    \vdots & \vdots & \ddots & \vdots \\
    s_m[N] & \ldots & \ldots & s_m[N - N_c + 1]
\end{bmatrix}
\]

Sparse formulation

\[
\text{vec}(H_d) = (\tilde{A}_T \odot A_R)
\]

Angle domain dictionary

\[
N_r N_t \times G_r G_t
\]

Evaluated on the angle grid

\[
G_r G_t >> L
\]

Goal: Estimate the non-zeros elements of the sparse vector \( \mathbf{x} \)
Exploiting group sparsity due to pulse shaping

\[
y_m = \Phi_m \left( I_{N_c} \otimes \bar{A}_{tx} \otimes A_{rx} \right) \Gamma x + e_m,
\]

where

\[
\Gamma = \begin{bmatrix}
I_{G_tG_r} \otimes p_0^T \\
I_{G_tG_r} \otimes p_1^T \\
\vdots \\
I_{G_tG_r} \otimes p_{N_c-1}^T
\end{bmatrix}
\]

\( p_d(n) = p_{rc} \left( (d - n \frac{N_c}{G_c}) T_s \right) \)

\( G_c \gg N_c \)

Delay grid sizes

Pulse shaping function

Sampled version

\( p_d \) has entries

\( p_d(n) \quad n = 1, 2, \ldots, G_c \)

\( d = 0, 1, \ldots, N_c - 1 \)

Unknown \( x \) is \( G_tG_rG_c \times 1 \), \( L \)-sparse vector containing the complex channel gains
Compressive channel estimation

Stack $M$ measurements

$$y = \sqrt{\rho} \Phi \Psi x + e$$

Effective dictionary matrix

Measurement matrix

Measurement 1

$$y_1 = \sqrt{\rho} \left( S_1 \otimes f_{RF}^{(1)^T} \otimes w_{RF}^{(1)^*} \right) \left( I_{N_c} \otimes \bar{A}_{tx} \otimes A_{rx} \right) \Gamma x + e_1$$

Contains quantized grid of ToA

Random beamforming matrices

Measurement $M$

$$y_M = \sqrt{\rho} \left( S_M \otimes f_{RF}^{(M)^T} \otimes w_{RF}^{(M)^*} \right) \left( I_{N_c} \otimes \bar{A}_{tx} \otimes A_{rx} \right) \Gamma x + e_M$$

Quantized grid of AoA/AoD

Dictionary with columns $a_T^c(\tilde{\phi}_x) \otimes a_R(\tilde{\theta}_y)$

Dictionary matrix constructed using antenna array response

Angle grid & delay quantization can be made as fine as required for sparsity

Extends directly to multiple RF chains during training
Simulation results

Setup

- Tx has 32 antennas, Rx has 32 antennas
- Dictionary generated using AoD/AoA with grid size = 64
- Frequency selective channel with 4 delay taps and 2 paths
- Pulse shaping filter with 0.8 roll-off factor
- Frame length = 16
- 2 bit quantization for precoder and combiner phase shifters
- **Orthogonal Matching pursuit** followed by **least square estimation**

\[
\text{NMSE} = \frac{\sum_{d=0}^{N_c} ||H_d - \hat{H}_d||_F^2}{\sum_{d=0}^{N_c} ||H_d||_F^2}
\]

80-100 training frames are enough to ensure low channel estimation error
Employing hybrid architecture

Using multiple RF chains at Tx and Rx gives better channel estimates

Effectively increases the precoding and combining beam patterns
Reducing the training overhead

- Leverage multiple RF chains
- Increased number of measurements per training frame
- Hybrid precoding can give rates close to fully-digital MIMO

Assuming fully-digital MIMO rates w/o water-filling

Using multiple RF chains reduces training overhead
Conclusion and future work

Wideband mmWave channel estimation needs to consider hardware constraints
- Fewer number of baseband measurements
- Effective baseband channel is less sparse

Proposed time domain channel estimation using hybrid architecture
- Sparse formulation enables use of compressive sensing tools
- Multiple RF chains at the transceivers reduce the number of training step

Future work
- Compare complexity with frequency domain channel estimation techniques
- Comparison of performance between beam training and CS based approaches
References

References