Wideband Millimeter-Wave Beam Training with True-Time-Delay Array architecture

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Beam Training in mmW System

• Millimeter-wave (mmW) requires antenna array
  • Provide beamforming gain to combat high prop. loss

• Key procedure: beam training
  • Goal: find best beam steering directions
  • Challenge in mmW evolution
    • Handle larger T/Rx arrays
    • Low overhead & complexity

• Simultaneous multi-beam
  • Promising beam training acceleration
  • Typically requires multiple RF-chains
  • This work: novel arch. w/ single RF-chain

Outline

• Preliminary: true-time-delay (TTD) array
• System model
  • Frame structure and received signal model
  • Problem formulation
  ★ TTD array based simultaneous multi-beam design
    • Analysis and codebook design
    • Numerical results
  ★ TTD array based wideband beam training
    • Algorithm design
    • Numerical results
• Conclusions and future works
Phased Antenna Array (PAA)

- Implemented with phase shifters
  - Example\(^1\): freq. constant phase shifting \(\phi\)

\[
\phi_1, \phi_2, \ldots, \phi_N
\]

- Mathematical model of ideal PAA
  - Frequency-flat antenna weight vector (AWV)

\[
w_{\text{PAA}} = [e^{j\phi_1}, e^{j\phi_2}, \ldots, e^{j\phi_N}]^T
\]

\(^1\) J. Han et al., "A Ka-band 4-ch bi-directional CMOS T/R chipset for 5G beamforming system," IEEE RFIC, 2017
True-Time-Delay (TTD) Array

• Implemented with delay modules
  • Example\(^1\): freq. constant group delay \( \tau \)

\[ \text{TTD based array} \]

\( \tau_1 \quad \tau_2 \quad \cdots \quad \tau_N \)

Delay taps \([\tau_1, \cdots, \tau_N]^T\)

RF-chain

• Mathematical model of ideal TTD array
  • Frequency-dependent AWV

\[ \mathbf{w}_{\text{TTD}}(f) = [e^{j2\pi f \tau_1}, \cdots, e^{j2\pi f \tau_N}]^T, f \in [f_{\text{min}}, f_{\text{max}}] \]

Multi-Beam in TTD Array

- Novel TTD beam steering mode
  - Example: two tones arrives at Rx array from boresight

\[
\tau_n = 2.5(n - 1) \, \text{ns} \\
\tau_1, \tau_2, \ldots, \tau_N
\]

**Phase shift @** \(f_1\)

\[
\text{mod}(2\pi f_1 \tau_n, 2\pi) = 0 \\
w_{\text{TTD}}(f_1) = [0, 0, 0, \ldots]^T
\]

**Phase shift @** \(f_2\)

\[
\text{mod}(2\pi f_2 \tau_n, 2\pi) = 0.5\pi(n-1) \\
w_{\text{TTD}}(f_2) = [0, 0.5\pi, \pi, \ldots]^T
\]

\(f_1 = 28\text{GHz}\)
\(f_2 = 28.1\text{GHz}\)

TTD array as “prism”

White light
\(f_{\text{min}}\) to \(f_{\text{max}}\)

\(f_{\text{min}}\)
\(f_{\text{max}}\)
System Model and Problem Statement
System Model

- **5G-NR like system**
  - Downlink single user beam training
    - BS PAA \( N_T\)-ULA
    - UE TTD array \( N_R\)-ULA
  - Cyclic-prefix OFDM waveform
    - Bandwidth \( BW \) and \( M_{\text{tot}} \) subcarriers (SC)
    - Pilot \( S_k[m]; S_k[m] \neq 0, m \in \mathcal{M} \); power limits
      \[
      \frac{1}{M_{\text{tot}}} \sum_{m=1}^{M_{\text{tot}}} |S_k[m]|^2 = 1, k \leq K_{BT}
      \]
  - BS procedure during beam training
    - Single BS RF-chain for training
    - BS know best steering angle\(^1\)
    - Focus on one cycle of periodic beam training

1. Typically conducted in the initial access; jointly consider this procedure is left as future work.
Received Signal Model

- The received OFDM pilot symbols
  - We proved that TTD freq-dependent AWV applies in OFDM
    \[ X_k[m] = \mathbf{w}_{TTD,k}[m] \mathbf{H}[m] \mathbf{v} S_k[m] + \mathbf{w}_{TTD,k}[m] \mathbf{n}[m], m \in [1, M_{tot}] \]
    \( m \): SC index; \( k \): OFDM symbol index

- TTD hardware model
  \[ \mathbf{w}_{TTD,k}[m] = [e^{j 2\pi f_m \tau_1 + j \phi_1,k}, \ldots, e^{j 2\pi f_m \tau_{N_Rx,k} + j \phi_{N_Rx,k}}]^T, \]
  \( f_m \): frequency of \( m \)-th SC \( (f_m = f_c - (m - \frac{M_{tot}}{2}) \frac{BW}{M_{tot}}) \)
  - TTD resolution & range (SOTA: \( \tau_{\text{min}} = 5 \text{ ps} \) and \( \tau_{\text{max}} = 15 \text{ ns} \))
  \[ \tau_n \in \{0, \tau_{\text{min}}, 2\tau_{\text{min}}, \ldots, \tau_{\text{max}}\}, \forall n \]
  - Commonly has phase shifter \((\phi_{n,k})\) cascaded with \( n \)-th TTD module

---

1. So long as the cyclic-prefix is longer than the joint delay introduced by both multipaths and TTD circuits
Wideband Channel Model

- Multipath channel model

\[ H_t[i] = \sum_{l=1}^{L} p_l p_c(i T_s - \tau_l) a_R(\theta_l^{rx}) a_T^H(\theta_l^{tx}) \]
\[ H[m] = \sum_{i=1}^{m} H_t[i] e^{j \frac{2 \pi i m}{M_{tot}}} \]

- Multipath delay spread larger than 1/BW
- Single path delay spread across array aperture \( \ll \) 1/BW

\[ [a_R(\theta)]_n = e^{j \pi (n-1) \sin(\theta)}, n \leq N_R \]
\[ [a_T(\theta)]_n = e^{j \pi (n-1) \sin(\theta)}, n \leq N_T \]

Factors: 
- Sample index \( i \) (times 1/BW)
- Index \( l \) and total number of multipath
- Subcarrier index \( m \)
- UE
- BS
- Coefficients of the \( l \)-th multi-path
- AoA: \( \theta_l^{rx} \)
- AoD: \( \theta_l^{tx} \)
- Propagation delay: \( \tau_l \)
- Path gain: \( p_l \)
Problem Formulation

- **P1 TTD beam training codebook**
  - Design delay taps $\tau_n$ for simultaneous scanning
  - Focus on uniform spaced TTD $\tau_n = (n - 1)\Delta \tau$
    and uniform spaced PS $\phi_{n,k} = (n - 1)\Delta \phi_k$
  - Study impact of TTD hardware constraint
- **Metrics**
  - Angular coverage

- **P2 TTD beam training algorithm**
  - Algorithm to estimate AoA of dominant path $\hat{\theta}_{\text{rx}}$
  - **Metrics**
    - Beam mis-alignment probability
    - Post-training gain & rate
    - Overhead

<table>
<thead>
<tr>
<th>Symb.</th>
<th>Description</th>
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<tbody>
<tr>
<td>$f_c$</td>
<td>Carrier frequency</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>$N_R$</td>
<td>Number of Rx antennas</td>
</tr>
<tr>
<td>$\tau_{\text{min}}, \tau_{\text{max}}$</td>
<td>TTD resolution &amp; max range</td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>TTD delay tap in antenna $n$</td>
</tr>
<tr>
<td>$\phi_{n,k}$</td>
<td>PS in $k$-th slot and antenna $n$</td>
</tr>
<tr>
<td>$K_{\text{BT}}$</td>
<td>Training slots</td>
</tr>
<tr>
<td>$M, \mathcal{M}$</td>
<td>Size and set of subcarriers for training ($</td>
</tr>
</tbody>
</table>

**Parameters to study**

**Design parameters**
Simultaneous Multibeam Design
Freq-Dependent Beams in TTD Array

- Each beam is a pencil beam
  - Antenna weight vector of the $m$-th SC
  $$w_{\text{TTD}}[m] = [1, e^{j(2\pi f_m \Delta \tau + \Delta \phi)}, \ldots, e^{j(N_{\text{Rx}} - 1)(2\pi f_m \Delta \tau + \Delta \phi)}]^{\text{T}}$$

- Properties of beams in TTD array
  - Width of beams
  $$\text{width}_{3\text{dB}} = 105^\circ / N_R$$
  - Steering directions of $m$-th SC
  $$\alpha_m = \sin^{-1}\left(\mod\left(\frac{2f_m \Delta \tau + \Delta \phi}{\pi} + 1, 2\right) - 1\right)$$

\[\tilde{\psi} = 2\pi f \Delta \tau + \Delta \phi\]

\[\psi = \pi \sin(\alpha)\]

Note: we focus on scenario where cascaded phase shifters have unit weight, and therefore time index $k$ is omitted for clarity.
One-Shot Scan Codeword Design

• Design principle
  • Phase difference b/w adjacent antennas completely covers region of $2\pi$

$$\tilde{\psi}_{\text{M}_{\text{tot}}} - \tilde{\psi}_1 = 2\pi f_{\text{M}_{\text{tot}}} \Delta \tau - 2\pi f_1 \Delta \tau = 2\pi$$

• Full scan codeword

\[ \Delta \tau = \frac{1}{f_{\text{M}_{\text{tot}}} - f_1} = \frac{1}{\text{BW}} \]

Phase diff. b/w adjacent antenna $\tilde{\psi}$ vs. subcarriers

Phase $\tilde{\psi} = 2\pi f \Delta \tau + \Delta \phi$
Design with Max TTD Constraint

- One-shot codeword may not meet constraint of $\tau_{\text{max}}$
  - It requires to set delay tap at $N_R$-th element to be $(N_R - 1)/\text{BW}$

Satisfied constraint

$$\tau_{N_R} = \frac{(N_R - 1)}{\text{BW}} \leq \tau_{\text{max}}$$

Unsatisfied constraint

$$\tau_{N_R} = \frac{(N_R - 1)}{\text{BW}} > \tau_{\text{max}}$$

Find minimum $S \in \mathbb{Z}$ such that:

$$\frac{(N_R - 1)}{S} \Delta \tau \leq \tau_{\text{max}}$$

- $S$ times reduced scan in angular domain
- Requires additional TTD codeword to cover full angular domain
Codebook with Multi-Beam Rotation

- Phase shifters can be used for codebook rotation
  - Provides larger angular scan region in time division manner
  - Provides diversity in frequency & angle mapping

Rotation for Scan Completion

\[ \tilde{\psi} = 2\pi f \Delta \tau + \Delta \phi \]

Rotation for Redundant Mapping

\[ \tilde{\psi} = 2\pi f \Delta \tau + \Delta \phi \]

\[ \text{Freq.} \]

\[ f_1 \quad f_{M_{\text{tot}}} \]

\[ \text{BW} \]

\[ \psi \]

\[ \phi \]

\[ \Delta \phi \]

\[ \Delta \tau \]

\[ (f_m, \alpha_m) \rightarrow (f_m, \alpha_{m+1}) \]
Beam design w/o maximum delay constraint

BW = 400MHz, $N_R = 16$, TTD delay tap $\tau_n = 2.5(n-1)$ ns

Training Slot $k=1$
PS tuning $\phi_{n,1} = 0$

Training Slot $k=2$
PS tuning $\phi_{n,2} = \pi(n - 1)$

Propogation path passes spatial filter of a SC

Spatial filter of a different SC
Beam design w/ max delay constraint

\[ \text{BW} = 400\text{MHZ}, \quad \tau_{\text{max}} = 20 \text{ ns}, \quad N_R = 16, \quad \text{TTD delay tap } \tau_n = 1.25(n-1) \text{ ns} \]

**Training Slot \( k=1 \)**
- PS \( \phi_{n,1} = -0.5\pi(n - 1) \)

**Training Slot \( k=2 \)**
- PS \( \phi_{n,2} = 0.5\pi(n - 1) \)

**Training Slot \( k=3 \)**
- PS \( \phi_{n,3} = 0 \)

**Training Slot \( k=4 \)**
- PS \( \phi_{n,4} = \pi(n - 1) \)
Wideband Beam Training Algorithm
Proposed Beam Training Algorithm

• **RSSI based beam training algorithm**
  
  - The look-up-table from angle candidates to SC
    \[
    \mathcal{M}_k(\alpha_m) = \{m|\alpha_m = \sin^{-1}(\text{mod}(2f_m\Delta \tau + \Delta \phi_k/\pi + 1, 2) - 1)\}\]
  
  - UE measures received signal strength (RSSI) of pilots
    \[
    \text{RSSI}(\alpha_m) = \sum_{k=1}^{K_{\text{BT}}} \sum_{m_k \in \mathcal{M}_k(\alpha_m)} |X_k[m_k]| \]
  
  - Estimating dominant AoA using
    \[
    \hat{\theta}_{\text{rx}} = \arg \max_{\alpha_m} \text{RSSI}(\alpha_m) \]
Subcarrier Selection for Training

• Subcarrier selections
  • Uniformly selected subcarriers
    \[ M = \left\{ (i - 1) \frac{M_{\text{tot}}}{M} + 1 \mid i \leq M \right\} \]
  • Extension to resource block\(^1\)
    \[ M = \left\{ (i - 1) \frac{M_{\text{tot}}}{M} + r \mid i \leq M, r \leq 12 \right\} \]

\(^1\) Strictly speaking, Resource Block in the cellular system has predefined grid in the axis of subcarrier. Here simplification are made.
## Beam Training Simulation Setup

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$f_c$</td>
<td>Carrier frequency</td>
<td>28 GHz</td>
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<td></td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
<td>400 MHz</td>
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<td></td>
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<tr>
<td>$N_R$</td>
<td>UE Rx antenna size</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{tot}$</td>
<td>Total number of subcarrier</td>
<td>2048</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{M}$</td>
<td>Selected subcarriers for beam training</td>
<td>16 to 64 uniform spaced resource block; $</td>
<td>\mathcal{M}</td>
<td>= 192$ to 768</td>
</tr>
<tr>
<td>$\tau_{\min}$</td>
<td>TTD resolution &amp; maximum delay</td>
<td>5 ps No limit or 20 ns</td>
<td>Channel 1. S-V model (single multipath cluster, 20 rays; no angular spread; delay spread $\sigma_t$) 2. QuaDriGa channel simulator (mmMAGIC 28GHz UMi LoS)</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\max}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_n, \phi_n, k$</td>
<td>TTD and PS taps</td>
<td>See the previous section (pp17,18)</td>
<td>$\mathbf{w}$</td>
<td>Post-training Rx beamformer $\mathbf{w} = a_R(\hat{\theta}_{\text{TX}})$</td>
</tr>
</tbody>
</table>

1. Consider scenario where BS uses EIRP 40dBm (good alignment to UE in Tx side), pathloss is [105, 145] dB which covers cell edge scenario, and -75dBm in-band AWGN (400MHz noise BW). Note that this refers to baseline SNR which assumes full subcarrier loading.
Subcarriers for TTD Beam Training

- Trade off in subcarrier selection
  - Fewer resource block: improved noise performance
  - More resource block: improved resolution

SV channel w/ 20 rays; propagation delay spread $\sigma_T = 0$ns
Necessity of CB Rotation

- CB rotation is necessary only for angular scan completion
  - Repetition and diversity gain exists in medium SNR regime

\[
\text{SV channel w/ 20 rays}
\]
\[
\text{Propagation delay spread } \sigma_{\tau} = 0 \text{ ns}
\]
\[
\text{TTD } \tau_n = 2.5(n - 1) \text{ ns}
\]

\[
\text{SV channel w/ 20 rays}
\]
\[
\text{Propagation delay spread } \sigma_{\tau} = 50 \text{ ns}
\]
\[
\text{TTD } \tau_n = 2.5(n - 1) \text{ ns}
\]

\[
\text{SV channel w/ 20 rays}
\]
\[
\text{Propagation delay spread } \sigma_{\tau} = 50 \text{ ns}
\]
\[
\text{TTD } \tau_n = 1.25(n - 1) \text{ ns}
\]

High degradation due to incomplete angular scan
Comparison w/ PAA Scan

28GHz UMi LoS Environment

![Graph showing spectral efficiency vs. SNR for TTD, PAA with different values of K_BT, and complex symbol training.]

<table>
<thead>
<tr>
<th></th>
<th>PAA</th>
<th>TTD Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx beam training</td>
<td>$K_{BT} = N_R$</td>
<td>$K_{BT} = \left\lceil \frac{(N_R - 1)}{\tau_{\text{maxBW}}} \right\rceil$</td>
</tr>
<tr>
<td>symbol (overhead)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UE DSP complexity</td>
<td>Measuring subcarrier</td>
<td>$O(</td>
</tr>
<tr>
<td></td>
<td>power &amp; look-up-table</td>
<td></td>
</tr>
</tbody>
</table>

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Summary

• True-time delay (TTD) array based simultaneous multi-beam steering
  - Array requires only a single RF-chain
  - Baseline one-shot full angle scan: $\tau_n = (n - 1)/\text{BW}$
    - Design with TTD maximum delay range

• TTD array based wideband beam training
  - Proposed method is equivalent to phased array $2N_R$ time division scan
Future Research Directions

• **TTD based beam training and channel estimation**
  • TTD in BS: Tx training & initial access
  • Combine TTD array with other methods\textsuperscript{1-6}

• **Comparison w/ other multi-beam architectures**
  • TTD array
    • SOTA module\textsuperscript{7}: $\tau_{\text{min}}=5\text{ps}$; $\tau_{\text{max}}=15\text{ns}$; BW=100MHz; 47mW
    • Trading resolution for range and power efficiency
  • Multi-panel phased antenna array
  • Fully digital array

Q&A

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