1. Introduction

Challenges of future mmW system

- Beam steering: avoid degraded directionality
- Beam training: avoid excessive overhead & latency

The true-time-delay (TTD) array

- Naturally non-degraded directionality
- Cost/power effective implementation
- How to utilize TTD for fast beam training?

Joint T/Rx beam training are needed to find AoA/AoD in outdoor mmW system. (1)

3. System Model and Problem Formulation

Beam training in 5G-NR mmW

- Frame and PHY procedures
- SSBS freq. rep [MHz]
- Data

5G-NR compliant TTD beam training model

- LoS & frequency-flat T/Rx array response

\[ H = a_{n_0}(s(t))e^{jN_0} \theta(t) \]

- Control info. s(f) \in [0, B_{SSS}]; Tx signals

BpTx uses AWV in m-th temporal rep.

\[ x_m(f) = \sum_{n=1}^{N} x_n(f) \cdot \text{Rx}(f) \]

UE TTD Rx uses combiner \( w_{TTD}(f) \).

\[ y_m(f) = \sum_{m=1}^{M} w_{TTD}(f_m) \cdot x_m(f) \]

Problem formulation

1. Design TTD taps \( \mathbf{t} \) such that \( w_{TTD}(f) \) simultaneously span \( \theta = \frac{\pi}{N} \).
2. Design algorithm to decode control info. \( s(f) \) & estimate channel AoA/AoD (\( \theta, \phi \)).

4. TTD Codebook for Wideband Dispersive Steering

Design and analysis of TTD codebook

- Focus on uniform delay taps \( \{d\}_n = (n-1)\Delta \)
- Problem 1 is equivalent to \( BW \times \Delta \geq 1 \)
- Rule-of-thumb design of delay taps

\[ \{d\}_n = (n-1)\Delta = (n-1) / BW \]

- Analysis: steering angle as function of freq. (when \( f_r \gg BW \))

\[ \phi(f_R) = \sin^{-1} \left( \text{mod}(2\pi f_R / \Delta f, 1 + 1) - 1 \right) \cdot \Delta f / f_r \in [f_r - BW / 2, f_r + BW / 2] \]

5. TTD Dispersive Steering enabled Fast Beam Training

Tx and Channel

Analog Rx Array (16-ULA with TTD)

<table>
<thead>
<tr>
<th>PSD of Transmitted Pilots (SSBs)</th>
<th>PSD of Received Pilots</th>
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6. Preliminary Numerical Results

Simulation Settings

- Carrier freq.: 28 GHz
- Bandwidth: 400 MHz
- Subcarrier spacing: 120 KHz
- SSB BW/gap: 12.5MHz/25MHz
- SSB freq. rep: 16
- Rx array size: \( N_{Rk} = 16 \) ULA
- TTD taps in training: Uniform \( \Delta \tau = 2.5 \text{ns} \)
- Control info.: BPSK modulated
- Phased array training: \( N_{Rk} \) uniform spaced beam steering

7. Conclusions and Future Work

Fast beam training using TTD Rx array

- Simultaneous full range scan w/o degrading noise robustness (v.s. phased array)
- Fits into 5GNR beam training framework
- Requires no modification in Tx (BS)

Directions of future investigation

- Jointly design for Tx/Rx TTD array
- 1D linear array \( \rightarrow 2D \) planar array
- Scalability study w/ array size & BW
- Hardware specs study, e.g., delay tap resolution & accuracy

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2. Conventional phase array model

- With frequency-dependent antenna weight vector (AWV)

\[ w_{PA} = [e^{j2\pi f_1 / 2}, ..., e^{j2\pi f_N / 2}] \]

The emerging TTD array model

- With frequency-dependent antenna weight vector (AWV)

\[ w_{TTD}(f_R) = [e^{j2\pi f_1 f_R / 2}, ..., e^{j2\pi f_N f_R / 2}] \]

- Directional mode: with delay taps such that subcarriers have quasi-identical AWVs

\[ \tau_n = \psi_n / 2f_r \]

- Dispersive mode: with delay taps such that subcarriers points to unique angles


2. Such combiner is used in time invariant way i.e., \( M_1 \), \( M_2 \),...