Beam Training with Analog TTD Arrays (Individual Project)

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Abstract

The information of AoA and AoD is needed to enable directional communication. The information can be inferred through beam training. The beam training algorithm should be designed efficiently the beam training complexity increases proportionally to the array size. And future communication systems are expected to be built in with more array antennas. In this project, a TTD-based one-shot beam training is implemented at the user side based on Dr. Boljanovic's conference paper [1]. Specifically, design a frequency-dependent beam training codebook for analog TTD arrays, implement a dictionary-based angle estimation algorithm, and study the impact of hardware impairments on beam training performance. The work mainly has are two contributions, a high resolution algo that lowers AoA errors compared to phase shifters and TTD impairments study. This report will cover the system architecture, beam training algorithm and relating results. The code is attached in the zip file. The running main file "main.m" should produce plots shown in results without issues.

Keywords: TTD, Beam Training

System Model

Assumption

BW is assumed to be able to divide into coherent K sub bands. All OFDM subcarriers are assumed to have the same channel H within the k-th sub-band. Array response is assumed to be frequency flat. Gain vector G is assumed to be a complex Gaussian.

When designing, AoA and AoD are assumed to be known. Hardware impairments are assumed to be independent.

Model

The system is modeled as in Figure 1. The user equipment (UE), as a receiver, is built with an analog TTD array which performs beam training. The UE has a phase shifter, local oscillator, set of amplifiers, and TTD element. After that the DSP components recover and process the received signal to estimate AoA.

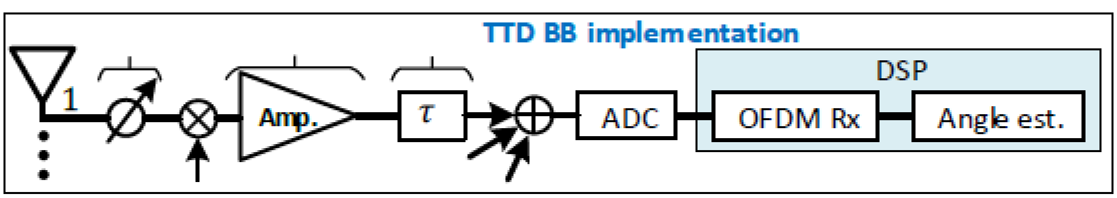

Figure 1. Chosen architecture for TTD receiver implementation and corresponding hardware impairments.

Channel describes how signal propagates from transmitter to receiver. Subcarriers in the k-th sub-band experience the same channel H. The equation is described in Equation 1. Complex gains G has a Gaussian distribution.

$$\mathbf{H}[k] = \sum_{l=1}^{L} G_l[k]\mathbf{a}_{\mathrm{R}}(\theta_l^{(\mathrm{R})})\mathbf{a}_{\mathrm{T}}^{\mathrm{H}}(\theta_l^{(\mathrm{T})}), \qquad (1)$$

Array response for receiver and transmitter are assumed to be frequency flat. In receiver side, n = 1… Nr. In transmitter side, n = 1 … Nt.

$$\begin{aligned} [\mathbf{a}_{\mathrm{R}}(\theta)]_n &= N_{\mathrm{R}}^{-1/2}\exp(-j(n-1)\pi\sin(\theta)), \\ [\mathbf{a}_{\mathrm{T}}(\theta)]_n &= N_{\mathrm{T}}^{-1/2}\exp(-j(n-1)\pi\sin(\theta)), \end{aligned} \quad (2)$$

The received signal Y at m-th sub carrier is described in equation 3.

$$Y[m] = M^{-1/2}\mathbf{w}^{\mathrm{H}}[m]\mathbf{H}[k]\mathbf{v} + \mathbf{w}^{\mathrm{H}}[m]\mathbf{n}[m], \ m \in \mathcal{M}. \ (3)$$

The vector w is a TTD frequency dependent AWV, whose n-th element is expressed as equation 4.

$$[\mathbf{w}[m]]_n = \exp\left[-j(2\pi f_m \tau_n + \phi_n)\right], \qquad (4)$$

When w is incorporated with impairments, its form is described in Equation 5.

$$[\mathbf{w}_{\mathrm{BB}}[m]]_n = \alpha_n \exp\left[-j\left(2\pi(f_m - f_{\mathrm{c}})\tilde{\tau}_n + \tilde{\phi}_n\right)\right] \tag{5}$$

The gain impairment with the form of $10\log_{10}(\alpha)$ follows a Gaussian distribution with mean 0 and standard deviation σ_A. TTD array error φ Tilda is modeled with a Gaussian with mean τ and standard deviation σ_τ.

Algorithm

Algorithm 1 TTD array based super-resolution beam training

Input: UE analog array settings in (9). Pre-computed dictionary in (14). A single received OFDM symbol $Y[m], m \in \mathcal{M}$, with subcarrier selection in (7).

Output: AoA estimate $\hat{\theta}^{(\mathrm{R})}$.

1: Compute direction powers based on (15)

2: Use (16) to find AoA estimate $\hat{\theta}^{(\mathrm{R})}$

Algorithm of this implementation is shown in Algorithm 1. The idea is to compute an angle where sub carrier m that has the most power. That angle is the estimated AoA.

D discrete Fourier transform (DFT) beams can be synthesized simultaneously by M = D selected subcarriers. The d-th selected subcarrier has the AWV with the n-th element given in Equation 6.

$$[\mathbf{f}_d]_n = \exp[-j2\pi(n-1)(d-1-D/2)/D], d \le D. \quad (6)$$

The set of indices M_d of R subcarriers mapped into direction d shown in Equation 7. By carefully design D and M, we can reach Equation 8.

$$\mathcal{M}_d = \Big\{ m \mid m = 1 + (d-1)\lfloor M_{\text{tot}}/(DR) \rfloor + (r-1)M_{\text{tot}}/R,\ r = 1, \cdots, R \Big\} \quad (7)$$

$$\mathbf{w}[m] = \mathbf{f}_d,\ m \in \mathcal{M}_d. \quad (8)$$

B represents a known dictionary obtained by generalizing the receive beamforming gains shown in Equation 9.

$$[\mathbf{B}]_{d,q} = \left|\mathbf{f}_d^{\mathrm{H}} \mathbf{a}_{\mathrm{R}}(\xi_q)\right|^2 . \tag{9}$$

Maximum likelihood pd is proposed in Equation 10. Equivalently, AoA is proposed in Equation 10. The idea is that pB will be large if you get the right AoA. Ssince B is carefully designed, so the angle we find will have the lowest propagation loss.

$$\hat{p}_d = \frac{1}{R} \sum_{m \in \mathcal{M}_d} |Y[m]|^2. \tag{10}$$

$$\hat{\theta}^{(\mathrm{R})} = \xi_{q^\star}, \ \text{where } q^\star = \underset{q}{\operatorname{argmax}} \frac{\hat{\mathbf{p}}^{\mathrm{T}} [\mathbf{B}]_{:,q}}{||[\mathbf{B}]_{:,q}||}. \tag{10}$$

Results and Discussion

Beam patterns of designed code book for analog TTD arrays is plotted using ULA array response. AoA and AoD is defined in range -pi/2 to pi/2. Steering angle θ_s is randomly chosen. Different θ_s will show different beamforming rotation. The code book is designed with Nr = 16, R = 1, D = 32.

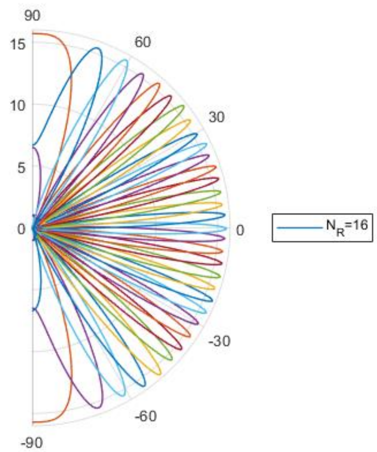

Figure 2. Beam patterns analog TTD arrays for Nr = 16, R = 1, D = 32,

RMSE of angle estimation vs. standard deviation of gain error σ_A in the range 0 dB to 4.5 dB and RMSE of angle estimation vs. standard deviation of phase error σ_τ in the range 0 to 50 degrees as shown together in Figure 3. For both algorithms, severe performance degradation occurs when gain error σ_A is greater than 2dB and phase error σ_τ is greater than 25 degrees.

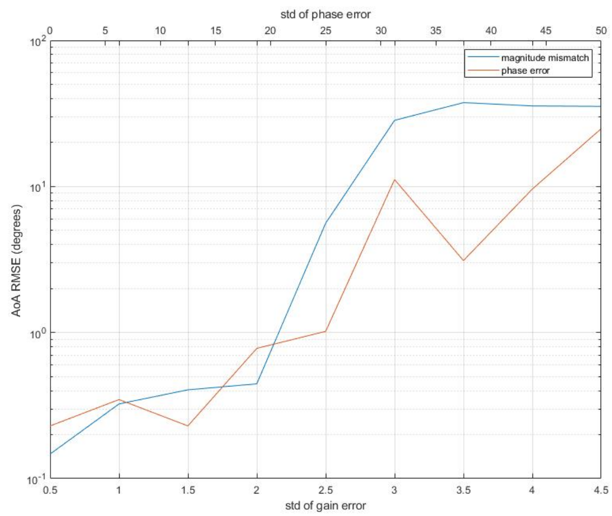

Figure 3. Impact of gain error and phase error in hardware impairments.

Conclusion:

In this implementation, I have implemented and shown that one shot beam training can be performed with TTD array. The beam training is done by exploiting frequency diversity. Hardware impairments are studied and have shown great performance if hardware errors are capped low.

Reference:

[1] Boljanovic, V., Yan, H., Ghaderi, E., Heo, D., Gupta, S., & Cabric, D. (2020, May). Design of Millimeter-Wave Single-Shot Beam Training for True-Time-Delay Array. In *2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)* (pp. 1-5). IEEE.