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Nonuniform true time delay precoding in wideband MISO systems

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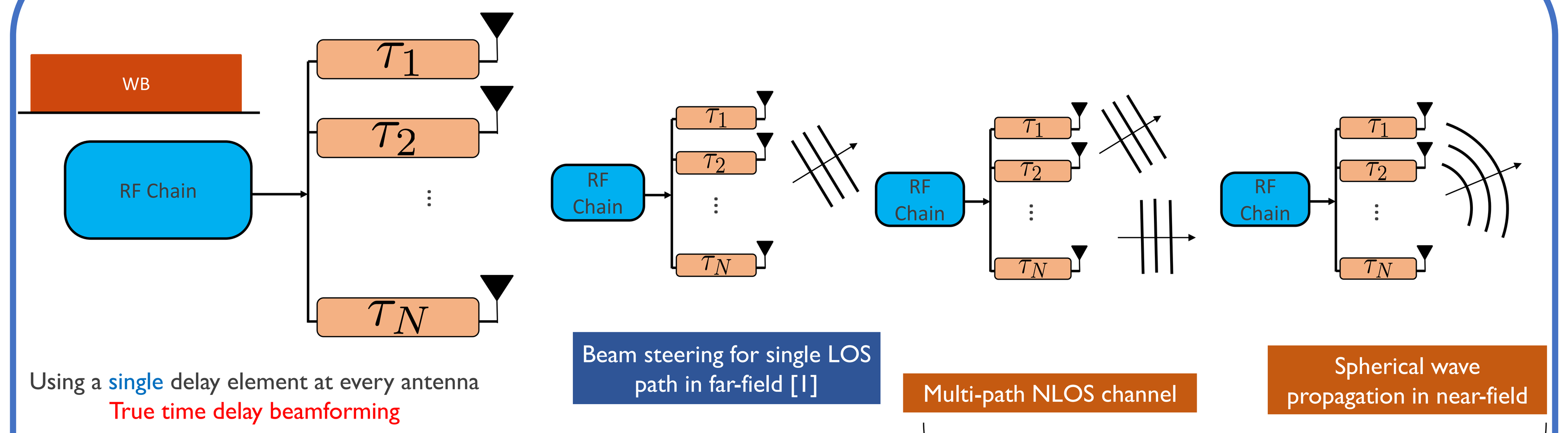
I. Introduction

Background and motivation



Delaying signal at each antenna results in correct phase shift over the entire bandwidth and mitigates the beam squint effect

Uniformly spaced delays [1]

Non-uniformly spaced delays

Objective: Develop new methods for designing delays in TTD architectures to handle complicated propagation environments

Contribution

A novel approach to optimize the delays in a TTD-based MISO system

Model the effect of TTD as an adaptive filter acting on the channel

Focus on maximizing the energy in the filtered channel response → Choose the nonuniform delays by first finding the optimal filter response that maximizes the effective channel energy and then imposing the TTD filter response constraints

Simulation results demonstrate that the proposed approach outperforms phase-shifter implementation and time-reversal TTD precoding

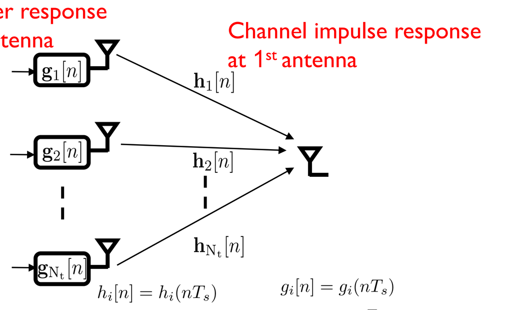
II. System model

MISO system model in the time domain

Baseband channel response:

$$h_i(t) = \sum_{\ell=1}^{L} \alpha_\ell p(t-\tau_{\ell,i}) \exp(-j2\pi f_c \tau_{\ell,i})$$

(L: Number of channel paths; p: Low Pass filter (Sinc / raised cosine); α_ℓ: Channel path gain; $\tau_{\ell,i}$: Channel path delay)



$h_i[n] = h_i(nT_s)$ $\quad g_i[n] = g_i(nT_s)$

$\mathbf{g}_i = [g_i[0], g_i[1], \dots, g_i[L_g-1]]^T$

$\mathbf{h}_i = [h_i[0], h_i[1], \dots, h_i[L_h-1]]^T$

Received signal:

$$y(t) = \sum_{i=1}^{N_t} h_i(t) * g_i(t) * x(t) + z(t)$$

(Effective channel response; i: Antenna Index)

Sampled effective channel response:

$$q[n] = \sum_{i=1}^{N_t} q_i[n] = \sum_{i=1}^{N_t}\sum_{m=0}^{L_h-1} h_i[m] g_i[n-m]$$

$\mathbf{q}_i = [q_i[0], q_i[1], \dots, q_i[L_h+L_g-2]]^T$

Expressing in matrix form $\mathbf{q}_i = \mathbf{H}_i \mathbf{g}_i$

Sampled effective channel response vector is $L_h + L_g - 1$ vector resulting from convolution of the channel response and precoder at i[th] antenna

Toeplitz matrix

$$\mathbf{H}_i = \begin{bmatrix} h_i[0] & 0 & \dots & 0 \\ h_i[1] & h_i[0] & \dots & \\ \vdots & \vdots & \dots & 0 \\ h_i[L_h-1] & h_i[L_h-2] & \dots & h_i[0] \\ 0 & h_i[L_h-1] & \dots & h_i[1] \\ \vdots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & h_i[L_h-1] \end{bmatrix}$$

Expressing sampled effective channel response in matrix form by concatenating channel matrices and precoders of all antennas

$$\mathbf{q} = \bar{\mathbf{H}}\bar{\mathbf{g}}$$

$\bar{\mathbf{H}} = [\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_{N_t}]$ $\quad \bar{\mathbf{g}} = [\mathbf{g}_1^T, \mathbf{g}_2^T, \dots, \mathbf{g}_{N_t}^T]^T$

Mutual information objective function upper bound

Total mutual information →

$$\mathrm{SE} = \sum_{k=0}^{K-1} \mathrm{SE}_k = \sum_{k=0}^{K-1} \log_2\left(1 + |s[k]|^2 \frac{\mathrm{P}}{\sigma^2}\right)$$

(K: Number of subcarriers; $\frac{\mathrm{P}}{\sigma^2}$: Signal to Noise Ratio)

Upper Bound on Average Mutual Information using Jensen's Inequality:

$$\frac{1}{K}\sum_{k=0}^{K-1} \log_2\left(1 + |s[k]|^2 \frac{\mathrm{P}}{\sigma^2}\right) \leq \log_2\left(1 + \sum_{k=0}^{K-1} \frac{|s[k]|^2}{K}\frac{\mathrm{P}}{\sigma^2}\right)$$

Equivalence of Total Energy in Time and Frequency Domain using Parseval's theorem:

$$\sum_{k=0}^{K-1} |s[k]|^2 = \|\mathbf{s}\|^2 = \|\mathbf{U}_K \mathbf{s}\|^2 = \|\mathbf{q}(1:K)\|^2 = \|\mathbf{q}(1:\tilde{L})\|^2 = \|\bar{\mathbf{H}}\bar{\mathbf{g}}\|^2 = \bar{\mathbf{g}}^* \underbrace{\bar{\mathbf{H}}^*\bar{\mathbf{H}}}_{\mathbf{R}} \bar{\mathbf{g}}$$

($\mathbf{U}_K$: Normalized K*K Inverse DFT matrix; $\tilde{L} = L_h + L_g - 1$)

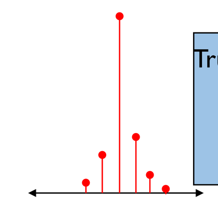
Objective function: Upper bound on mutual information

$$\log_2\left(1 + \frac{1}{K}\bar{\mathbf{g}}^*\bar{\mathbf{H}}^*\bar{\mathbf{H}}\bar{\mathbf{g}}\frac{\mathrm{P}}{\sigma^2}\right)$$

(Standard quadratic form)

III. Optimization problem and algorithm

TTD constraint and relaxed problem



True Time Delay response at i[th] antenna (Design variable T_i):

$$\mathbf{g}_i[k] = p(kT_s - \mathrm{T}_i)\exp(-j2\pi f_c \mathrm{T}_i)$$

$$\mathbf{P1}: \max_{\bar{\mathbf{g}}} \bar{\mathbf{g}}^*\mathbf{R}\bar{\mathbf{g}}, \quad \text{s.t. } \|\bar{\mathbf{g}}\|^2 = 1, \quad \mathbf{g}_i[k] = p(kT_s - \mathrm{T}_i)\exp(-j2\pi f_c \mathrm{T}_i) \text{ for delay } \mathrm{T}_i.$$

(Unit norm power constraint)

Difficult to find optimal solution directly

Solve an approximate problem

$$\mathbf{P2}: \max_{\bar{\mathbf{g}}} \bar{\mathbf{g}}^*\mathbf{R}\bar{\mathbf{g}} - \rho\|\bar{\mathbf{H}}\bar{\mathbf{g}}\|_0, \quad \text{s.t. } \|\bar{\mathbf{g}}\|^2 = 1.$$

($\|\bar{\mathbf{H}}\bar{\mathbf{g}}\|_0$: L0 Norm of effective channel; ρ: Regularizer coefficient)

$h_i(t) = \sum_{\ell=1}^{L} \alpha_\ell p(t-\tau_{\ell,i}) \exp(-j2\pi f_c \tau_{\ell,i})$ — Channel response is sparse

$\mathbf{g}_i[k] = p(kT_s - \mathrm{T}_i)\exp(-j2\pi f_c \mathrm{T}_i)$ — TTD precoder response is sparse

Convolution of channel and precoder i.e., the effective channel response is also sparse

How to solve P2 and compute delay at each antenna from precoder response?

Solving P2 and computing delay from precoder response

How to solve P2?

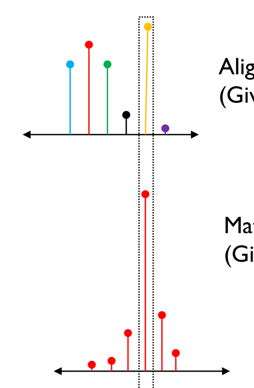
Iteratively reweighted quadratic maximization: Optimizes a sequence of approximate objective functions [2]

Approximation at k[th] iteration:

$$\max_{\bar{\mathbf{g}}} \bar{\mathbf{g}}^*\bar{\mathbf{H}}^*(\mathbf{I} - \rho\mathrm{Diag}(\mathbf{w}^{(k)}))\bar{\mathbf{H}}\bar{\mathbf{g}}, \quad \text{s.t. } \|\bar{\mathbf{g}}\|^2 = 1.$$

$$w_i^{(k)} = \begin{cases} \frac{p}{2}\epsilon^{p-2}, & |q_i^{(k)}| \leq \epsilon \\ \frac{p}{2}|q_i^{(k)}|^{p-2}, & |q_i^{(k)}| > \epsilon \end{cases}$$

How to compute delay at each antenna from precoder response?



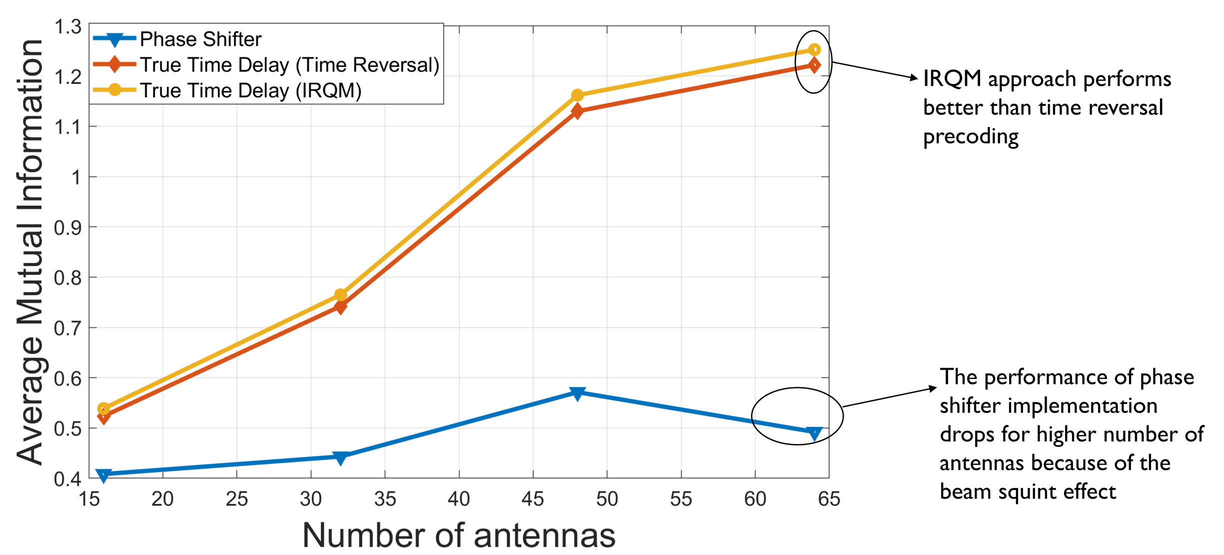
Align the dominant tap (Gives Integer delay $n^* T_s$)

Match the phase exactly (Gives fractional delay)

1. Find the index with the maximum absolute value $n^* = \mathrm{Argmax}_{n'} |\mathbf{g}_i^{(k)}[n']|$ for the precoder at the ith antenna and the kth iteration.
2. Find the principal argument corresponding to n^* as $\varphi_i^{(k)} = \angle(\mathbf{g}_i^{(k)}[n^*])$.
3. Round to the nearest integer $l^* = \mathrm{Round}(\frac{\varphi_i^{(k)} + 2\pi f_c n^* T_s}{2\pi})$.
4. Compute TTD value at each antenna as $\mathrm{T}_i^{(k)} = \frac{2\pi l^* - \varphi_i^{(k)}}{2\pi f_c}$.

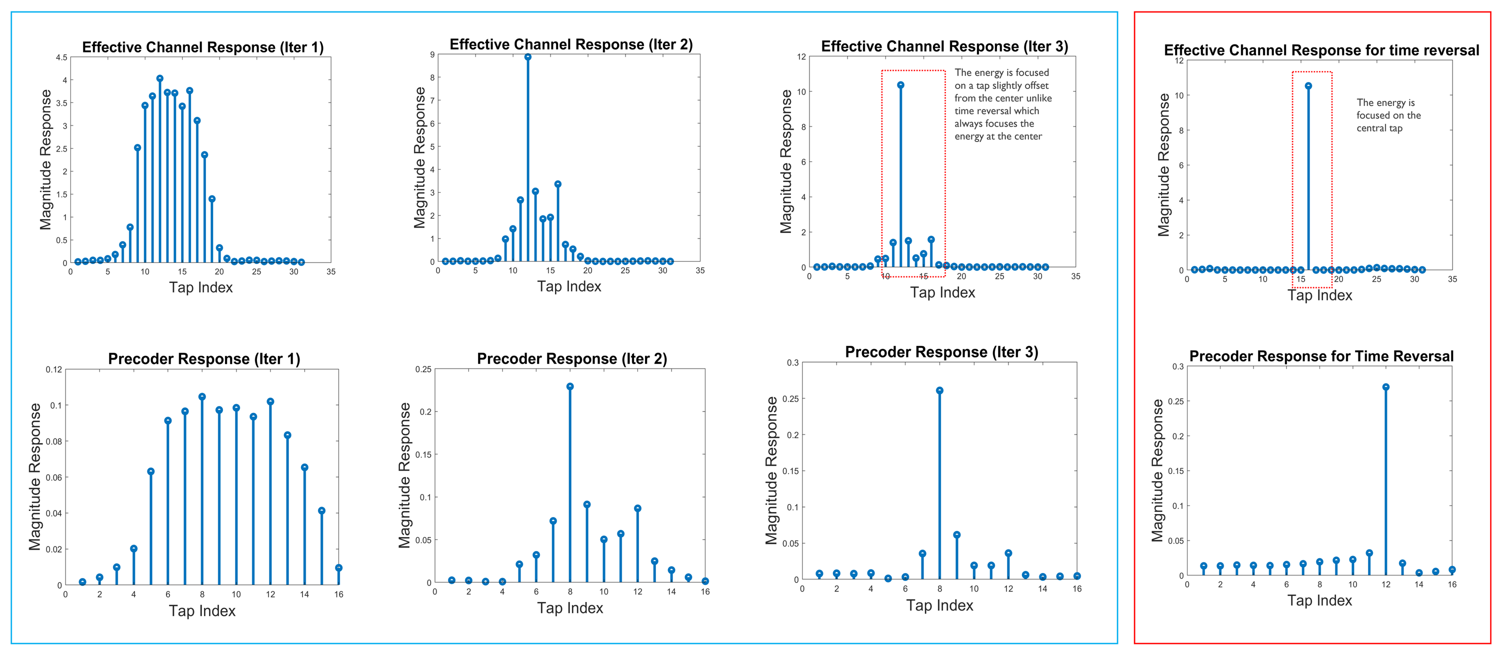
IV. Results

Mutual information vs number of antennas



Simulation parameters: Uniform Linear Array, MISO, BW= 2 GHz, Carrier frequency f_c = 4 GHz, Mean delay spread = 24 ns, $L_g = L_h$ = 50, Averaged over 150 Monte Carlo realizations

Demonstration of temporal focusing effect and comparison with time reversal



Sparsifying the effective channel (convolution of precoder and channel) also sparsifies the precoder response

Generalization of the temporal focusing property of time reversal precoding which is limited to focusing only on the single central tap

V. Conclusions and future work

Introduced the sparsity-inducing norm in the TTD optimization to exploit the idea of temporal focusing

Developed an algorithm based on minorization-maximization to obtain a sparse solution

Generalization of the temporal focusing property of the time reversal precoding

Extension to multi user MISO and spatial focusing property

Incorporate circuit aspects of MIMO, intrinsic and extrinsic noise at the receiver, mutual coupling models at the array

References

[1] F. Gao, B. Wang, C. Xing, J. An, and G. Y. Li, "Wideband Beamforming for Hybrid Massive MIMO Terahertz Communications," *IEEE J. Select. Areas Commun.*, vol. 39, no. 6, pp. 1725–1740, Jun. 2021.
[2] J. Song, P. Babu, and D. P. Palomar, "Sparse Generalized Eigenvalue Problem Via Smooth Optimization," *IEEE Trans. Signal Process.*, vol. 63, no. 7, pp. 1627–1642, Apr. 2015.

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