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# Fast Distributed Beamforming without Receiver Feedback

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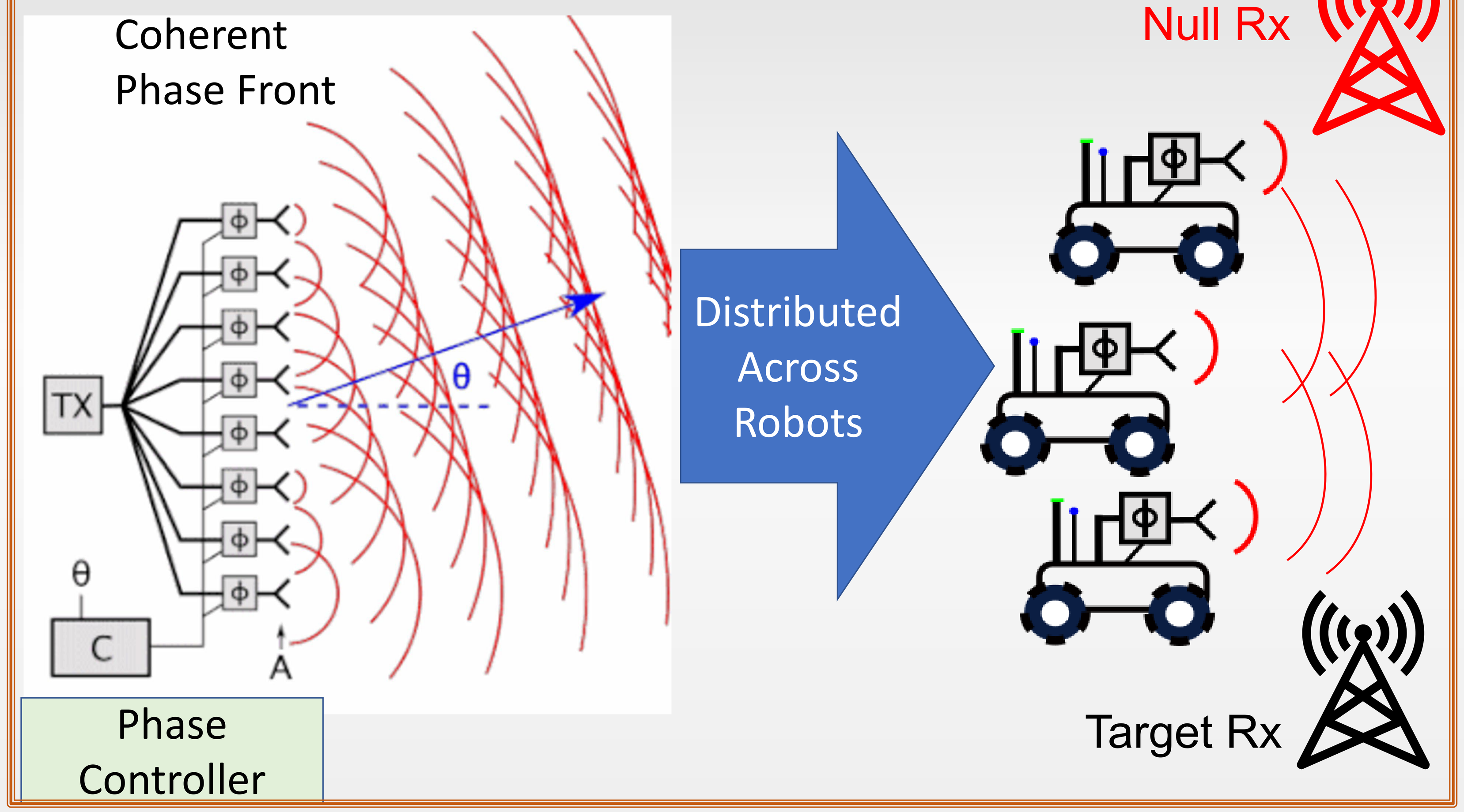
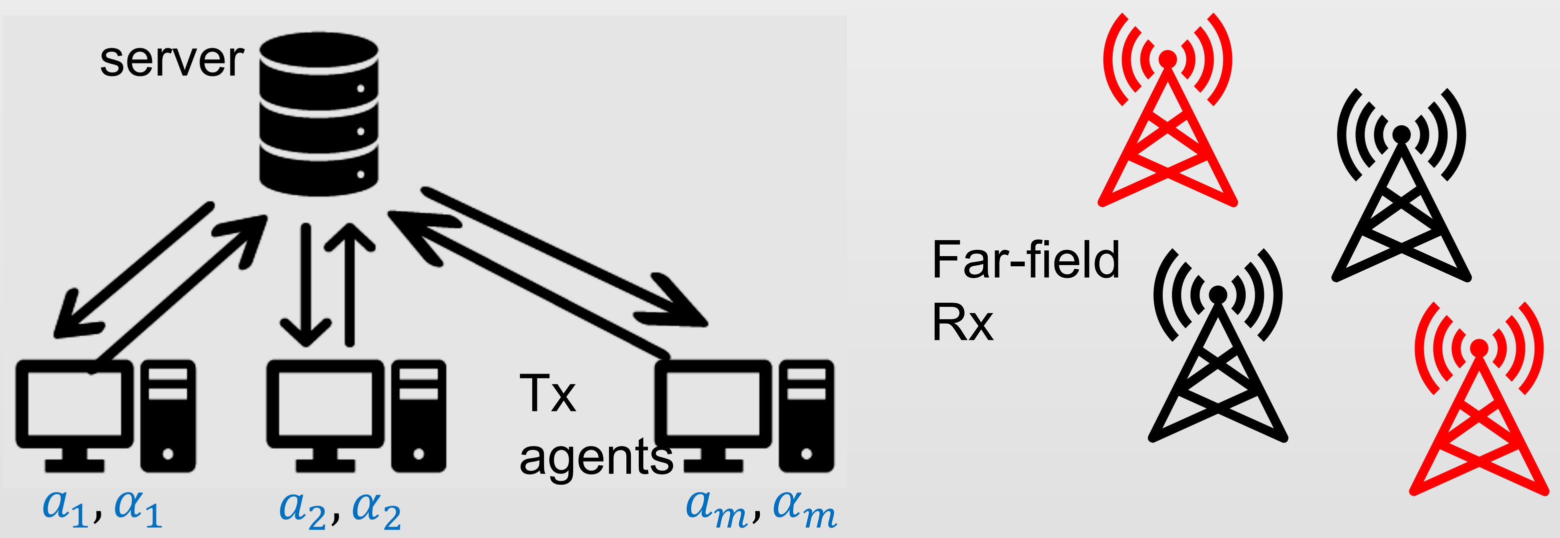
## Introduction

**Objective:** autonomous multi-robots collaboratively form an antenna array to transmit a high-power directed signal while steering nulls though precise control of interference for covert communication

**Strategy:** accelerated matching of a given far-field radiation pattern in uncertain communication environments




## Proposed Settings of Beamforming Agents




- server-agent based setting
  - agents can communicate with a common server
  - no peer-to-peer communication
- what is a server?
  - can be an auxiliary node, located close to the agents
  - can exchange information with the agents
  - can perform basic operations, e.g., addition, multiplication, etc.
  - need not know the beamforming coefficients, agents' and receivers' locations, desired beam and null values

## References


[1] Goguri et. al.. A class of scalable feedback algorithms for beam and null-forming from distributed arrays. In 2016 50th Asilomar Conference on Signals, Systems and Computers, pages 1447–1451. IEEE, 2016.

[2] George et. al.. A model-free approach to distributed transmit beamforming. In 2020 ICASSP, pages 5170–5174. IEEE, 2020.

[3] Parayil et. al.. Joint position and beamforming control via alternating nonlinear least-squares with a hierarchical gamma prior. In 2021 ACC, pages 3513–3518. IEEE, 2021.

[4] A. Muralidharan and Y. Mostofi. Energy optimal distributed beamforming using unmanned vehicles. IEEE TCNS, 5(4):1529–1540, 2017.

[5] Hanna et. al. Destination-feedback free distributed transmit beamforming using guided directionality. arXiv preprint arXiv:2108.01837, 2021.


## Comparison with Related Works

| Prior Work | Our Work |
|---|---|
| objective: maximizing gain or steering nulls at specific locations [1] | objective: beampattern matching<br>advantages: precise control over desired power at multiple locations, special case includes simultaneous beamforming and nullforming at specified locations, can include additional constraints (limited transmit power, derivative constraints when receiver locations are not precisely known) |
| utilize receiver feedbacks [2] | does not require receiver feedbacks |
| sparse beamforming, mobile agents [3] | fixed number of agents, stationary agents |
| channel model-free [2], channel prediction and path planning for minimizing power [4] | feedback-free<br>objective of beampattern matching |
| receiver feedback-free [5] | does not assume line-of-sight channels |

## Proposed Algorithm: IPG-DB

agent $m$: $(a_m(t), \alpha_m(t))$,
server: $K(t) \in \mathbb{R}^{2n \times 2n}$

before iterations, server broadcasts to each agent: $\epsilon, \beta, \delta, K(0)$

For each iteration $t \geq 0$:

at each agent $m$

$$\zeta_{im} = kx_m \cos\theta_i + ky_m \sin\theta_i + kd_{im}$$
$$u_{im}(t) = \frac{1}{d_{im}}\cos(\alpha_m(t) + \zeta_{im}),\ v_{im}(t) = \frac{1}{d_{im}}\sin(\alpha_m(t) + \zeta_{im}),$$
$$y_{im}(t) = a_m(t)(u_{im}(t) + j v_{im}(t))$$

agent $m$ to server

$$\{u_{im}(t), v_{im}(t), y_{im}(t), i = 1, \ldots, s\}, k_m(t), k_{m+n}(t)$$

at server

$$y_i(t) = \sum_{m=1}^{n} y_{im}(t)$$

server to each agent $m$

$$u_i(t) = [u_{i1}(t), \ldots, u_{in}(t)]^T, v_i(t) = [v_{i1}(t), \ldots, v_{in}(t)]^T,$$
$$Y_i(t) = [y_{i1}(t), \ldots, y_{in}(t)]^T$$
$$\{y_i(t), i = 1, \ldots, s\}, \{u_i(t), v_i(t), Y_i(t), i = 1, \ldots, s\}, K(t)$$

at each agent $m$

$$a_m(t+1) = a_m(t) - \delta k_m(t) \sum_{i=1}^{s} w_i \frac{|y_i(t)| - f_i}{|y_i(t)|}\left(\Re y_i(t) u_i(t) + \Im y_i(t) v_i(t)\right)$$
$$\alpha_m(t+1) = \alpha_m(t) - \delta k_{m+n}(t) \sum_{i=1}^{s} w_i \frac{|y_i(t)| - f_i}{|y_i(t)|}\left(-\Re y_i(t) \Im Y_i(t) + \Im y_i(t) \Re Y_i(t)\right)$$
$$k_j(t+1) = k_j(t) - \epsilon\left(H_j(t)K(t) + \beta k_j(t) - I_{2n,j}\right), \qquad j = m, m+n$$

## Problem Formulation

beamforming agents: $m = 1, \ldots, n$
receivers: $i = 1, \ldots, s$
location of agent $m$: $(x_m, y_m)$
location of receiver $i$: $(\rho_i, \theta_i)$
desired array factor amplitude at receiver $i$: $f_i$
distance between agent $m$ and receiver $i$:

$$d_{im} = \sqrt{(x_m - \rho_i \cos\theta_i)^2 + (y_m - \rho_i \sin\theta_i)^2}$$

excitation signal amplitude and phase of agent $m$: $(a_m, \alpha_m)$
synchronized carrier frequency : $f$
wavenumber: $k = \frac{2\pi f}{3 \times 10^8}\ m^{-1}$

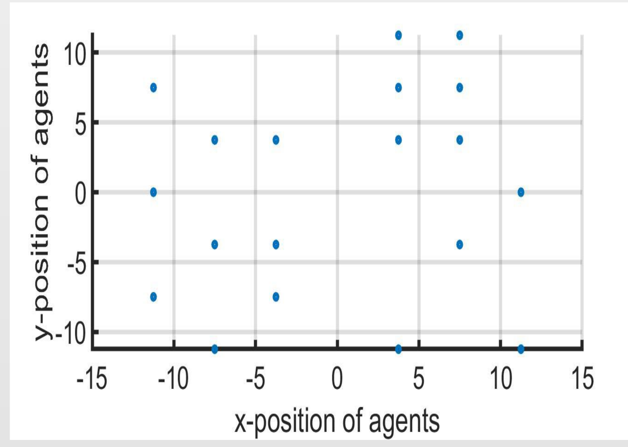
constructed array factor at receiver $i$:

$$AF_i = \sum_{m=1}^{n} \gamma_{im} \frac{a_m}{d_{im}} e^{j(\alpha_m + kx_m \cos\theta_i + ky_m \sin\theta_i + kd_{im})}$$

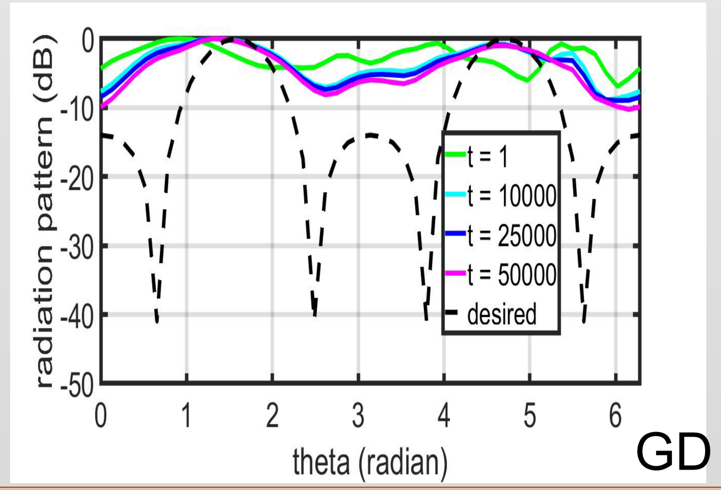
unknown multipath fading
control parameters
weightage for receiver $i$: $w_i$

$$(a_m^*, \alpha_m^*)_{m=1}^n = \underset{(a_m, \alpha_m)_{m=1}^n}{\arg\min} \sum_{i=1}^{s} w_i \| f_i - |AF_i| \|^2$$

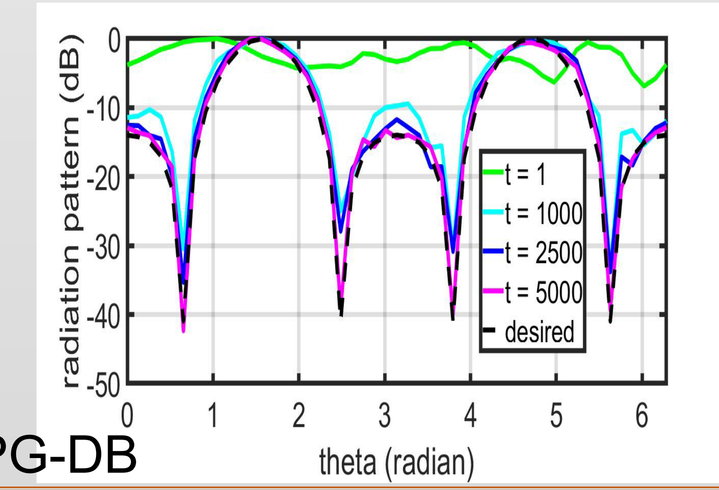
## Simulation Results: Synthetic Data




# beamforming agents: $n = 19$
# receivers: $s = 49$
location of receivers: $\rho_i = 5\lambda$, uniformly placed along $\theta_i$ in $(0, 2\pi)$
carrier frequency : $f = 40\ MHz$
unknown i.i.d. Rayleigh fading $\gamma_{im} \epsilon \mathbb{R}$ In each channel




GD




IPG-DB

## Summary

- proposed a novel algorithm: Iteratively Pre-conditioned Gradient-descent for Distributed Beamforming (IPG-DB)
- significantly faster than the gradient-descent (GD) based methods
- can be incorporated in alternate optimization framework for joint optimization of position, sparsity, and excitation: replace slower GD with faster IPG-DB
- does not rely on receiver feedbacks
- does not assume channel fading parameters: robust to noise

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