Project 1.6: Distributed Robotic Beamforming

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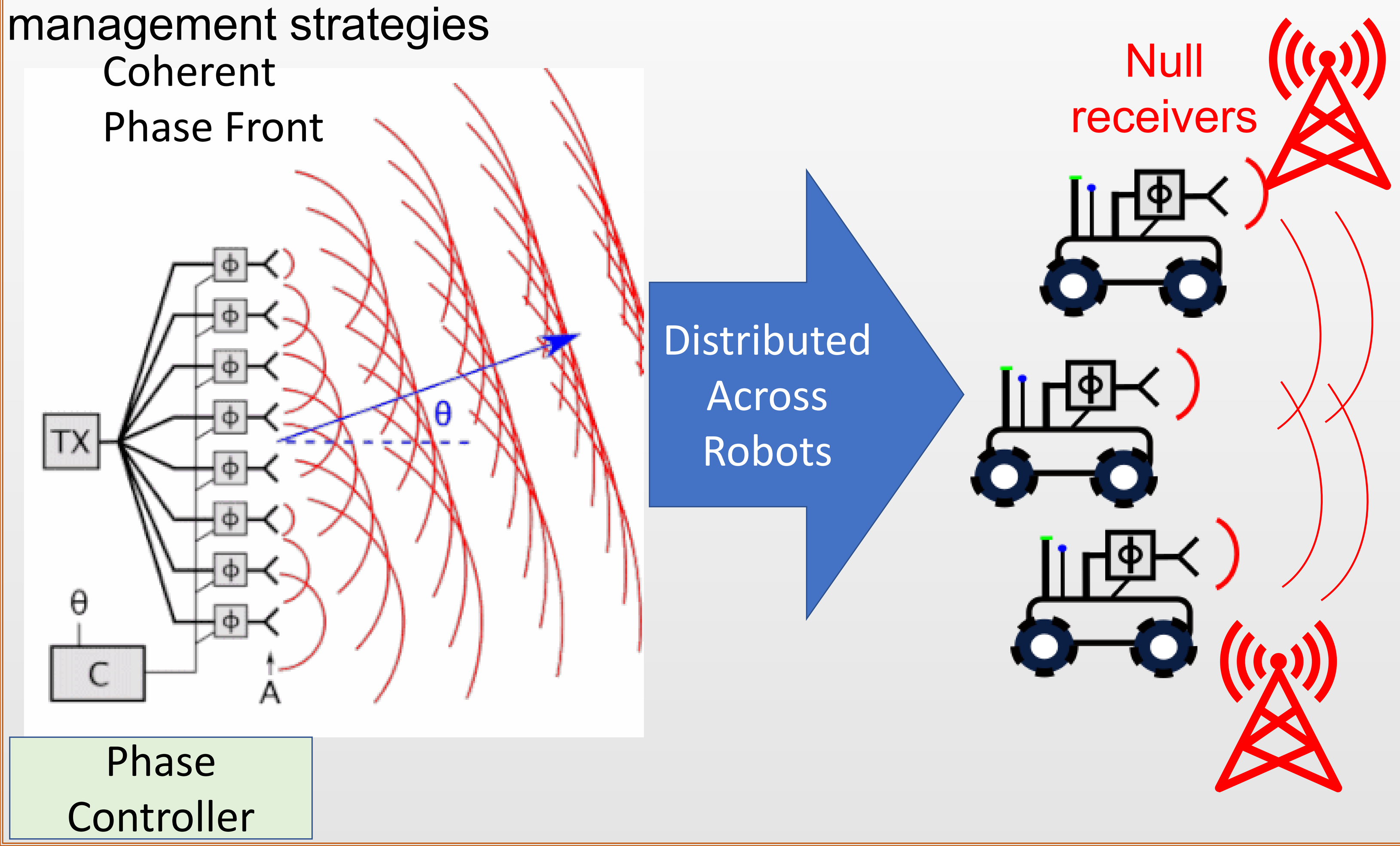
Project Summary: investigating the intersection of AI, autonomy, and networked communication, focusing on robots that self-configure to build covert, reliable communication links

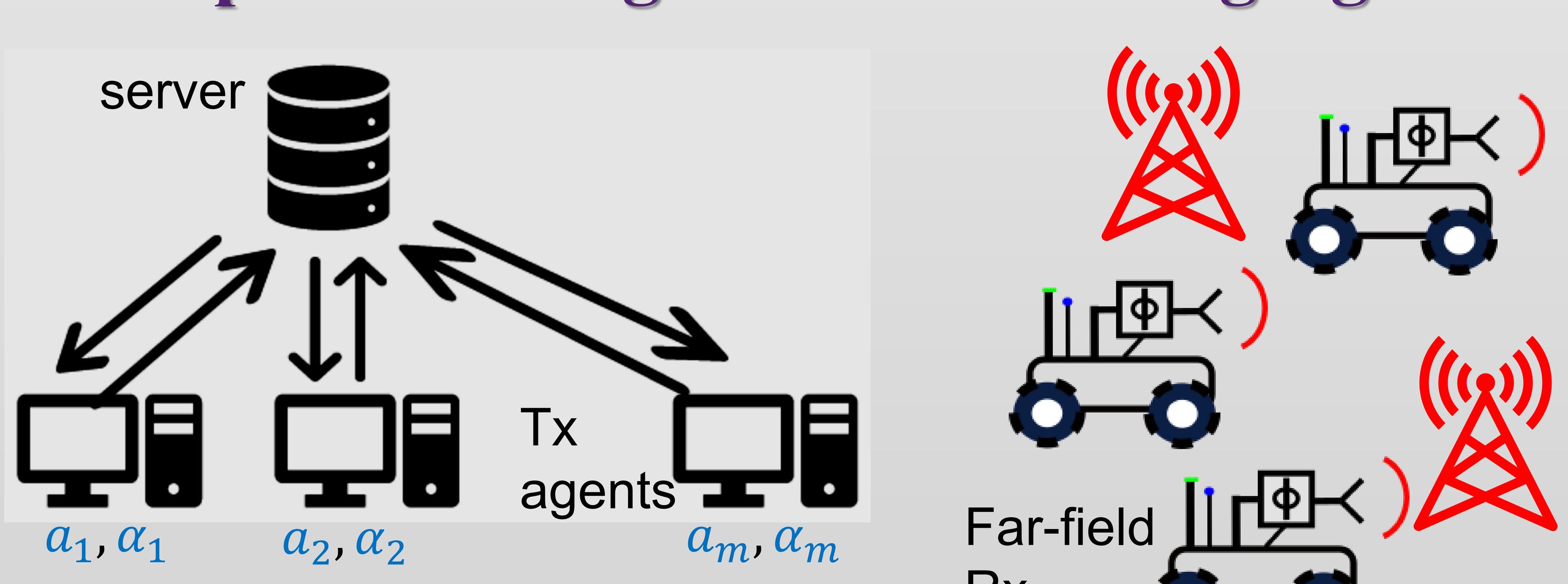
Research Goals: to investigate self-configuring algorithms and technologies for robotic systems to create a dynamic multi-robot communications system

Anticipated Outcomes: constructively characterize the minimum required number of agents for generating an arbitrary far-field radiation pattern, develop policy gradient-based accelerated RL algorithms for distributed beamforming

Army Capability: increased command post (CP) maneuverability while maintaining covert operations through sophisticated signature management strategies



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 process information (addition, multiplication, etc. basic operations)
  - need not know the beamforming coefficients, agents' and receivers' locations, desired beam and null values

Problem Formulation

beamforming agents: $m = 1, \dots, n$
receivers: $i = 1, \dots, s$
location of agent m: (x_m, y_m)
location of receiver i: (ρ_i, θ_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, α_m)
synchronized carrier frequency : f
wavenumber: $k = \frac{2\pi f}{3\times 10^8}$ Hz/m

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

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

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

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

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

agent m to server

at server

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

server to each agent m

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

at each agent m

$$a_m(t+1) = a_m(t) - \delta k_m(t) \sum_{i=1}^{s} w_i \frac{|y_i(t)| - f_i}{|y_i(t)|}\left(\Re y_i(t) u_i(t) + \Im y_i(t) v_i(t)\right)$$

$$\alpha_m(t+1) = \alpha_m(t) - \delta k_{m+n}(t) \sum_{i=1}^{s} w_i \frac{|y_i(t)| - f_i}{|y_i(t)|}\left(-\Re y_i(t) \Im Y_i(t) + \Im y_i(t) \Re Y_i(t)\right)$$

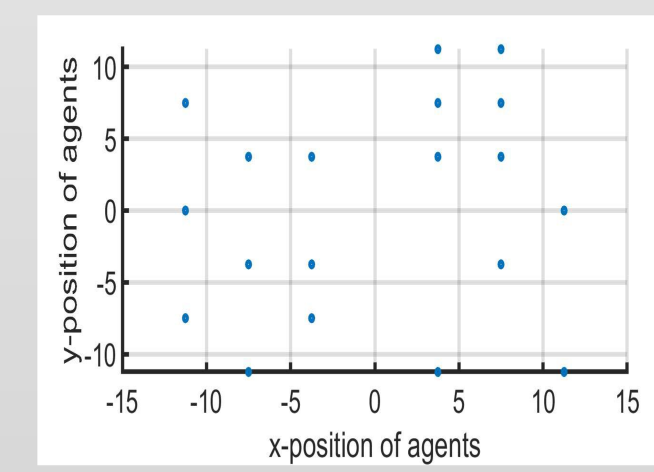
$$k_j(t+1) = k_j(t) - \epsilon\left(H_j(t)K(t) + \beta k_j(t) - I_{2n,j}\right), j = m, m+n$$

Comparison with Related Works

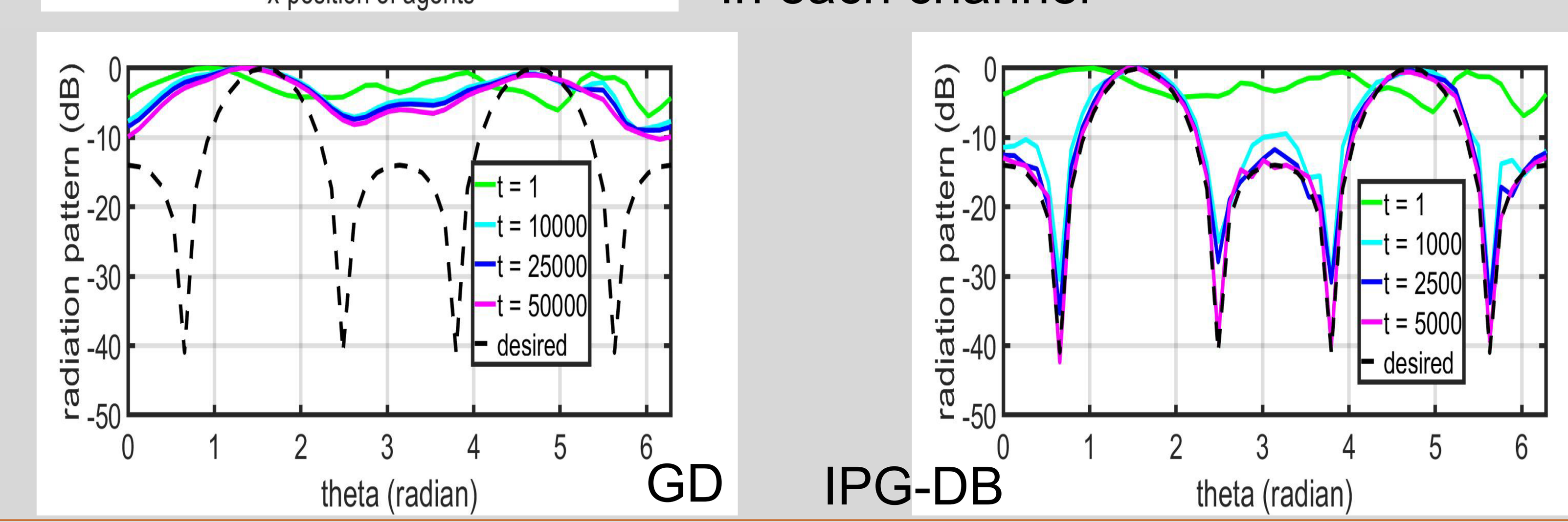
Prior Work	Our Work
objective: maximizing gain or steering nulls at specific locations	objective: beampattern matching advantages: precise control over desired power at multiple locations, inherent simultaneous beamforming and nullforming in constructive manner, can include additional constraints (limited transmit power, derivative constraints when receiver locations are not precisely known)
utilize receiver feedbacks	does not require receiver feedbacks
sparse beamforming, mobile agents	fixed number of agents, stationary agents
channel model-free, probabilistic channel prediction and path planning for minimizing power	feedback-free objective of beampattern matching
receiver feedback-free	does not assume line-of-sight channels

- 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

Simulation Results: Synthetic Data



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



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