Dynamic Spectrum Sharing via Stochastic Optimization

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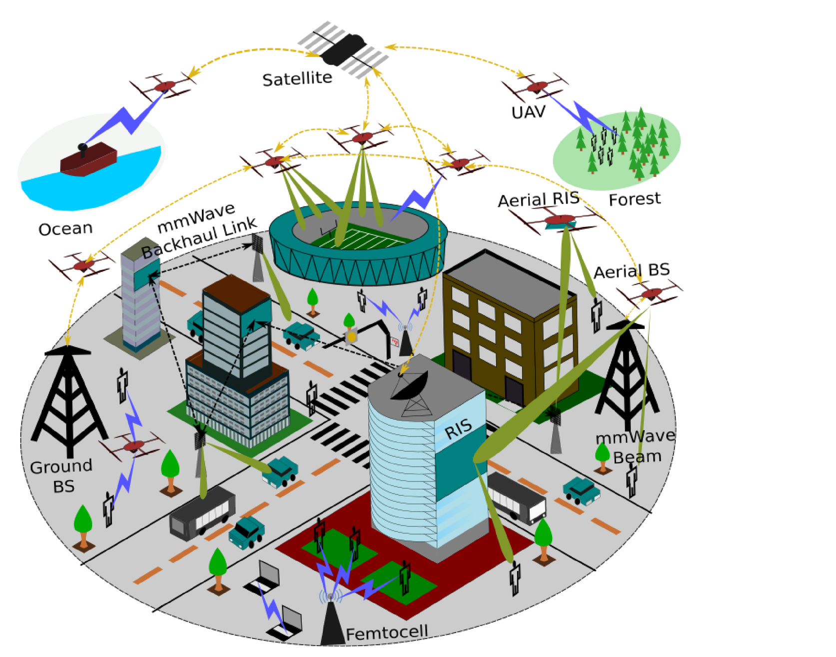
1. Overview

Challenges: General mathematical framework to integrate new technologies, e.g. UAVs and RIS, and utilize the new degrees of freedom for resilient coexistence of communication and radar over shared spectrum.

Observation: Avoiding interference between users at all times is too conservative in the wake of increasing demand for throughput and dual communication and sensing functionality.

Solutions: A new paradigm in which we move from hard deterministic constraints to stochastic schemes with desired low probability of harmful interference. Developing a stochastic optimization framework for resilient spectrum sharing in a communication network that includes new technologies like RIS and UAV. Extending the framework to include coexistence of communication and radar.



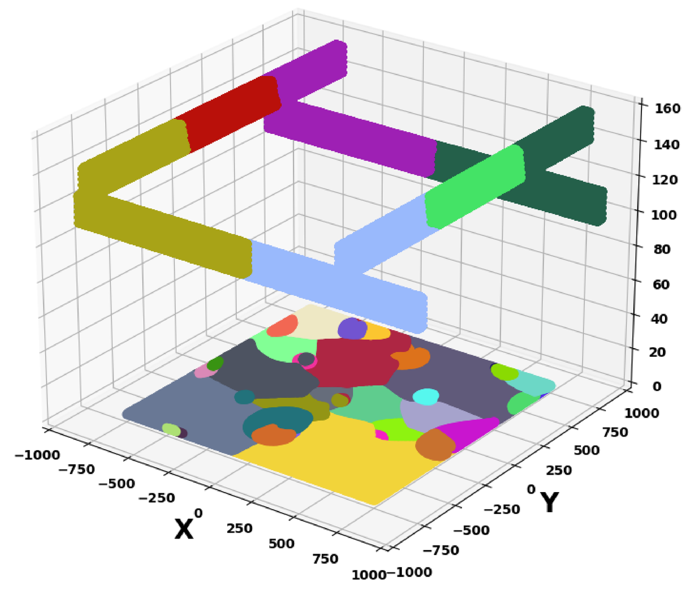
2. UAV and Ground Users in Cellular Networks

Goal: A general mathematical framework for optimizing cell deployment and antenna configuration in wireless networks

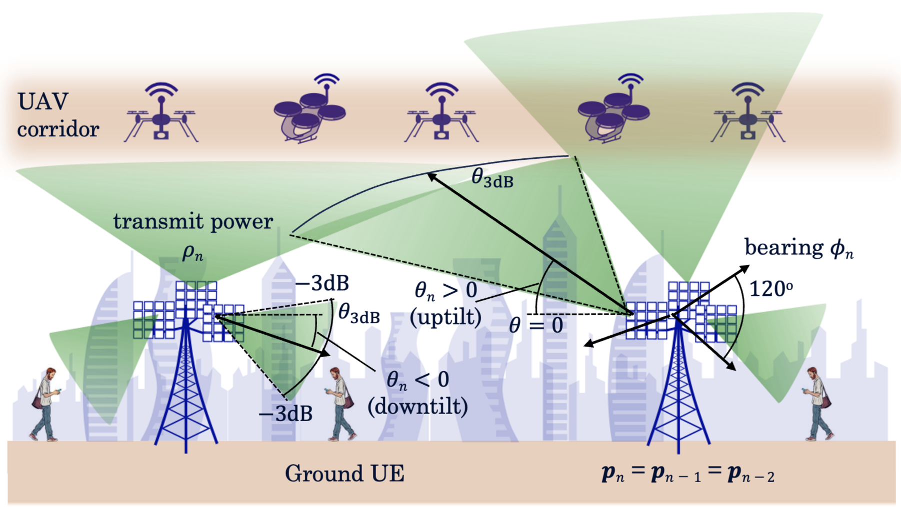
Performance Function(s): weighted sum of

Coverage $1\left(\mathrm{SINR}^{(n)}_{\mathrm{dB}}(\boldsymbol{q}) \geq T\right)$

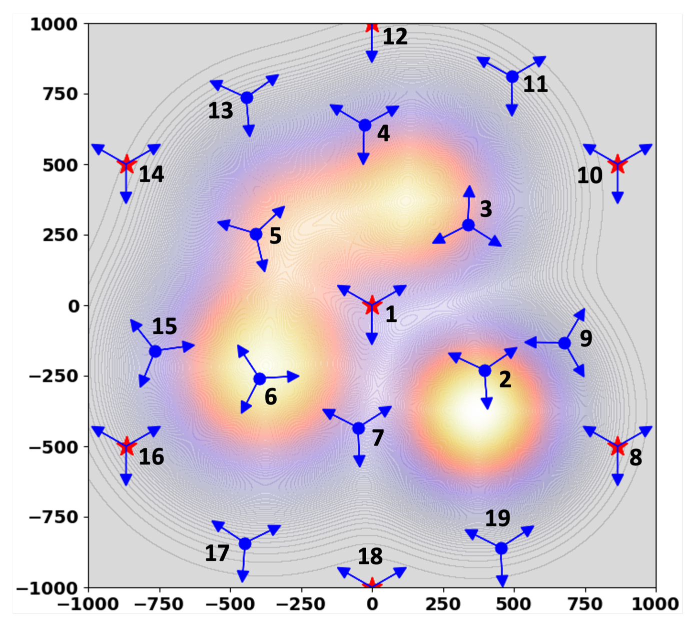
Capacity per Region $\frac{\log_2\left(1+\mathrm{SINR}^{(n)}_{\mathrm{lin}}(\boldsymbol{q})\right)}{o_n+\int_{V_n}\lambda(\tilde{\boldsymbol{q}})d\tilde{\boldsymbol{q}}}$



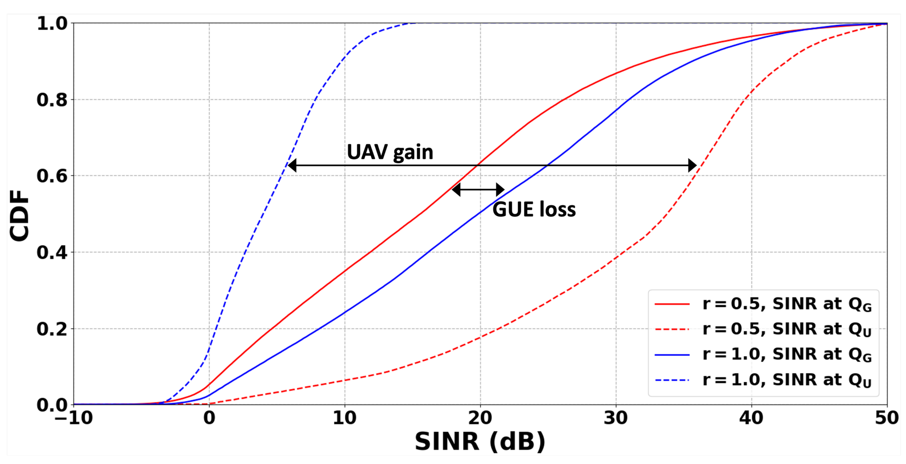
Optimal cell partitioning for GUEs and UAV corridors.



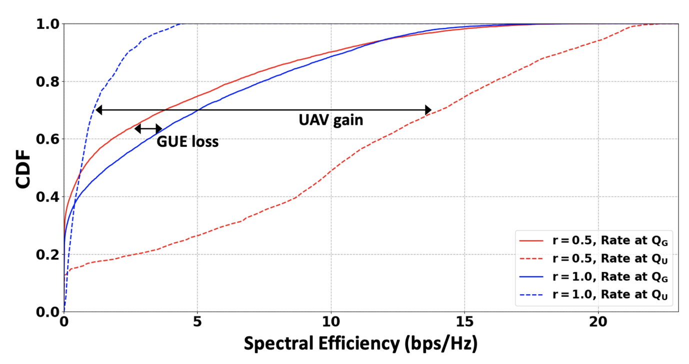
BSs serving GUEs and UAV corridors, with θ_n, $\theta_{3\mathrm{dB}}$, ϕ_n, and ρ_n denoting vertical tilt, vertical HPBW, horizontal bearing, and transmit power, respectively.



Optimal deployment and bearing of BSs overlaid on the GUE distribution.



The CDF of SINR when the cell partitioning, antenna tilts, transmission powers, and the deployment of new BSs are jointly optimized.



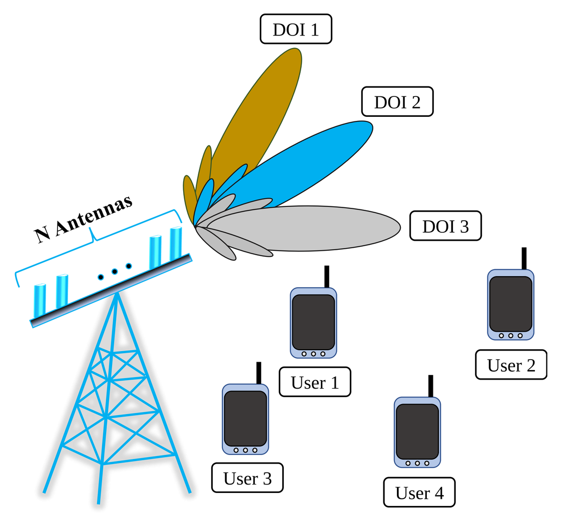
The CDF of spectral efficiency (bps/Hz) when cell partitioning, antenna tilts, transmit powers, and the deployment of new BSs are jointly optimized.

S. Karimi-Bidhendi, G. Geraci, and H. Jafarkhani, "Optimizing Cellular Networks for UAV Corridors via Quantization Theory," IEEE Trans. on Wireless Comm., Oct. 2024.

S. Karimi-Bidhendi, G. Geraci, and H. Jafarkhani, "Capacity and Coverage Optimization of Cellular Network Deployments for UAV Corridors," IEEE ICC, June 2025.

3. Dual-Function Radar-Communication Beamforming with Outage Probability Metric

System Model: Collocated MIMO DFRC system equipped with a single transmitter with N transmit antennas, M azimuth directions of interest (DOI), and K single-antenna downlink users

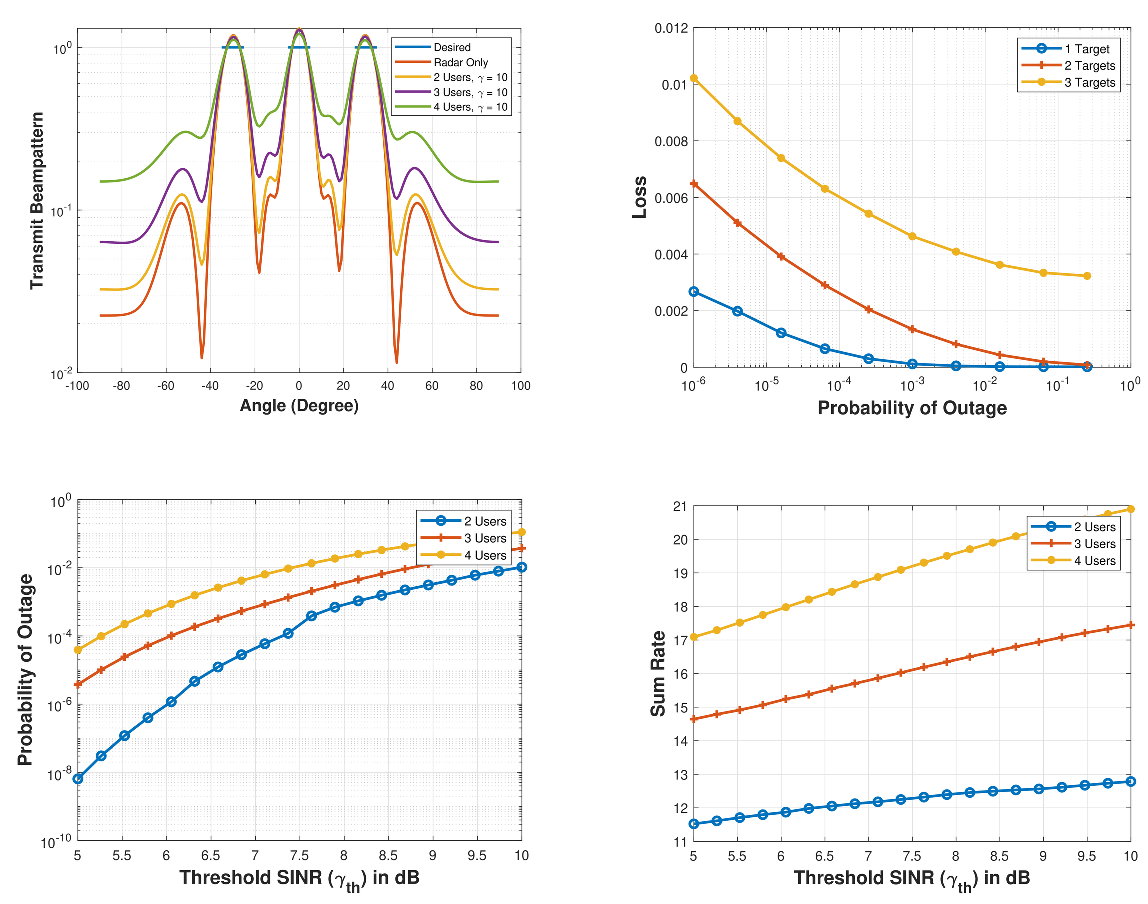


Radar-Centric Beamforming Problem: The best radar performance while ensuring that communication users receive a minimum QoS: Minimize a weighted sum of the MSE in achieving a desired beampattern and a mean-squared cross correlation of the radar returns from DOI while outage probability (comm users) $<$ threshold.

Communication-Centric Beamforming Problem: Minimize the maximum probability of outage experienced by any user while ensuring that the radar performance remains acceptable.

Goal: Develop a beamforming method for a dual-function radar-communication system despite imperfect channel state information

Solution: Both optimization problems are stochastic and untractable. We first take advantage of central limit theorem to obtain deterministic non-convex problems and then consider relaxations of these problems in the form of semidefinite programs with rank-1 constraints.



H. Maleki, C. Diaz-Vilor, A. Pezeshki, V. Tarokh, and H. Jafarkhani, "Dual-Function Radar-Communication Beamforming with Outage Probability Metric," submitted.

4. Stochastic Optimizations and Approximate Solutions

Dynamic spectrum allocation: Optimally choose a string (sequence) of spectrum allocation policies to maximize a desired spectrum usage utility function over time:

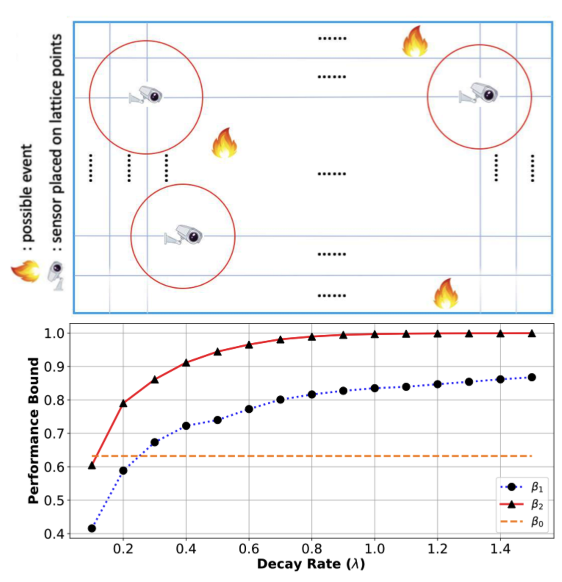
$$\text{maximize } f(S) \quad \text{subject to } S \in \mathbb{T}$$

Here f is the utility function (e.g., expected throughput or negative expected latency), $\mathbb{T}$ is the set of all permissible strings of spectrum allocation policies over time horizon of K allocation steps. An element of $\mathbb{T}$ is a sequence of policies and each *policy* is a posterior density over the action space (permissible spectrum allocations) given the current state of the network (current allocations and (probabilistic) interference constraints).

Performance bound for greedy schemes: Determining the optimal string of policies becomes computationally intractable with increasing size of state/action space and optimization horizon. Therefore, we often have to resort to approximate solutions. The most common approximation is the *greedy strategy,* in which we sequentially select the policy that maximizes the increment in the utility function at each step. We have derived a *ratio bound* for the performance of greedy scheme relative to the optional scheme. The bound guarantees that the greedy scheme achieves at least a factor of β of the optimal scheme.

$$\frac{f(G_K)}{f(O_K)} \geq \beta, \quad \beta = \frac{f(G_K)}{\sum_{k=1}^{K}\max_{s\in\mathbb{S}(G_{k-1})} f(s)}.$$

Multiagent sensor coverage: Activate a set of K (out of N sensors) on an N-point lattice to maximize the probability of detecting randomly occurring events in a mission space. Sensors are activated (given spectrum access) sequentially over K steps. A sensor activated at location $\mathbf{s}_i$ can detect any event at location $\mathbf{x}$ with probability $p(\mathbf{x}, \mathbf{s}_i) = \exp(-\lambda_i\|\mathbf{x}-\mathbf{s}_i\|)$, where $\lambda_i > 0$ is the coverage decay rate of the of the sensor at step i for $i \in \{1, \dots, K\}$.



Comparison of performance bounds: $\beta_0 = 1 - e^{-1}$ (Prior work; Requires submodularity of the utility function). Our bounds β_1 and β_2 do not require submodularity and are tighter.

B. Van Over, B. Li, E. K. P. Chong, and A. Pezeshki, "A Performance Bound for the Greedy Algorithm in a Generalized Class of String Optimization Problems," *IEEE Trans. Automat. Cont.*, accepted.

5. Outreach Activity

Mini-symposium on Data-Driven Optimization of Spectrum Sharing Networks and Beyond, held at UC-Irvine in April 2025. The program included 11 technical talks, by speakers from NSF, Duke University, UC-Irvine, Colorado State University, CalTech, UCSD, USC, and UC-Davis.

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