DRL for Power Control in Cellular Networks with Underlaying Radar Systems

Abstract

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I. System Description

A. Signal Model

We consider a cellular network with underlaying radar (CNUR) system as shown in Fig. 2. The CNUR system consists of a base station (BS) serving multiple communication users (CUs). There is a single radar that operates the same spectrum with the BS. The radar is monostatic in which its transmitter (denoted by "TX")and receiver (denoted by "RX") are co-located. The set of CUs is defined as $\mathcal{Q}$, and the cardinality of $\mathcal{Q}$ is Q. To improve the spectrum efficiency, the BS uses the rate-splitting multiple access (RSMA) technique to serve its CUs.

By using the RSMA, the BS transmits a common message of all the users and private messages to the users. In particular, the transmit signal from the BS is given by

$$x = \sqrt{p_0} s_0 + \sum_{q=1}^{Q} \sqrt{p_q} s_q, \tag{1}$$

where s_0 is the symbol of the common message of Q users and s_q is the symbol of the private message of the q-th user, p_0 is the transmit power of the common message s_0 and p_q is the transmit power of the private message s_q transmitted to user q. The received signal at CU q is

$$y_q^{\mathrm{C}} = h_q^{\mathrm{C}} \big(\sqrt{p_0} s_0 + \sum_{q=1}^{Q} \sqrt{p_q} s_q \big) + g_q^{\mathrm{RC}} \sqrt{p^{\mathrm{R}}} x^{\mathrm{R}} + n_q^{\mathrm{C}}, \tag{2}$$

where h_q^{C} is the channel between the BS and CU q, g_q^{RC} is the channel between the radar and CU q, p^{R} is the transmission power of the radar, x^{R} is the radar signal, and n_q^{C} is the channel noise with zero mean and variance σ_q^2.

The received signal at RX of the radar is

$$y^{\mathrm{R}} = h^{\mathrm{R}} \sqrt{p^{\mathrm{R}}} + h^{\mathrm{CR}} \big(\sqrt{p_0} s_0 + \sum_{q=1}^{Q} \sqrt{p_q} s_q \big) + n^{\mathrm{R}}, \tag{3}$$

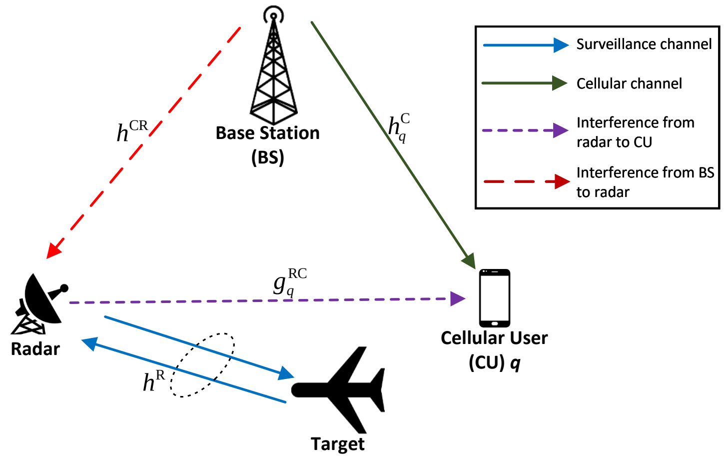

Figure 1: System model for the cellular network with underlaying radar system.

where h^{R} is the round-trip channel of the radar, i.e., the channel of the link from the TX of the radar, the target, and the RX of the radar, h^{CR} is the channel between the BS and the radar, and n^{R} is the additive channel noise with zero mean and variance σ^2.

B. Optimization Problem

We first determine the data rate achieved by each user CU. With the RSMA, the data rate achieved by the user is the sum of common data rate and private data rate. The common data rate of user CU q is

$$R_{q,0}^{\mathrm{C}} = B\log_2\left(1+\frac{(h_q^{\mathrm{C}})^2 p_0}{(h_q^{\mathrm{C}})^2\sum\limits_{q'=1}^{Q} p_{q'} + (g_q^{\mathrm{RC}})^2 p^{\mathrm{R}} + B\sigma_q^2}\right), \tag{4}$$

where B is the bandwidth. The private data rate of user CU q is

$$R_{q}^{\mathrm{C}} = B\log_2\left(1+\frac{(h_q^{\mathrm{C}})^2 p_q}{(h_q^{\mathrm{C}})^2\sum\limits_{q'=1,q'\neq q}^{Q} p_{q'} + (g_q^{\mathrm{RC}})^2 p^{\mathrm{R}} + B\sigma_q^2}\right). \tag{5}$$

Denote $a_{q,0}$ as the common data rate allocated to CU q. Then, we have the following constraint

$$\sum_{q=1}^{Q} a_{q,0} \leq \min_q \left\{R_{q,0}^{\mathrm{C}}\right\}. \tag{6}$$

The total data rate, denoted by C_q^{C}, achieved by CU q is given by

$$C_q^{\mathrm{C}} = a_{q,0} + R_q^{\mathrm{C}}. \tag{7}$$

As the radar systems reuse the spectrum owned by the cellular system that has its QoS, there is a constraint on the interference from the radar systems to the CUs, which can be expressed as follows:

$$C_q^{\mathrm{C}} \geq C^{\mathrm{TH}}, \forall q \in \mathcal{Q}, \tag{8}$$

where C^{TH} is the minimum rate requirement of CU q.

Meanwhile, the SINR at the RX of the radar is given by

$$\vartheta^{\mathrm{R}} = \frac{\left(h^{\mathrm{R}}\right)^2 p^{\mathrm{R}}}{(h^{\mathrm{CR}})^2 \left(p_0 + \sum_{q=1}^{Q} p_q\right) + B\sigma^2}. \tag{9}$$

To guarantee the radar tracking, the SINR of the radar must be larger than the threshold, i.e., $\vartheta^{\mathrm{R}} \geq \vartheta_0^{\mathrm{R}}$. The optimization problem is defined as follows:

$$\begin{aligned}
\max_{a_{q,0}, p_0, p_q, p^{\mathrm{R}}} \quad & \sum_{q=1}^{Q} C_q^{\mathrm{C}} \\
\text{s.t.} \quad & \sum_{q=1}^{Q} a_{q,0} \leq \min_q R_{q,0}^{\mathrm{C}} \\
& a_{q,0} + B \log_2 \left(1 + \frac{(h_q^{\mathrm{C}})^2 p_q}{(h_q^{\mathrm{C}})^2 \sum\limits_{q'=1, q' \neq q}^{Q} p_{q'} + (g^{\mathrm{RC}})^2 p^{\mathrm{R}} + B\sigma_q^2} \right) \geq C^{\mathrm{TH}}, \ \forall q \in \mathcal{Q}, \\
& \vartheta^{\mathrm{R}} \geq \vartheta_0^{\mathrm{R}}, \\
& p_0 + \sum_{q=1}^{Q} p_q \leq \bar{p}^{\mathrm{C}}, \\
& p^{\mathrm{R}} \leq \bar{p}^{\mathrm{R}},
\end{aligned} \tag{10}$$

where $\bar{p}^{\mathrm{C}}$ is the power budget of the BS, and $\bar{p}^{\mathrm{R}}$ is the power budget at the radar.

II. Problem Reformulation

A. Decision Epoch

B. State Space

The state space consists of all possible states. For the long-term system throughput maximization problem, a natural choice for the state is $s_n = \left[|g_q^{\mathrm{RC}}|^2, |h_q^{\mathrm{C}}|^2, |h^{\mathrm{CR}}|^2, |h^{\mathrm{R}}|^2, l_u, v_u\right]$, which includes the channel among BS, radar, cellular users, UAV, UAV's position and trajectory. Here, $l_u = \{l_{u,x}, l_{u,y}, l_{u,z}\}$ is the location tuple of UAV, and $v_u = \{v_{u,x}, v_{u,y}, v_{u,z}\}$ is the trajectory tuple of the UAV.

C. Action Space

The action space consists of all possible actions taken by the BS and the radar. For the considered throughput maximization problem, the BS power p_0, p_q, the radar power p^R, and the common data rate allocation vector $a_0 = \{a_{q,0}\}$ are chosen to be action.

D. State Transition Probability

E. Reward Function

- Long term data rate

- Choose $\sum C_q^C$

III. An Deep Reinforcement Learning Approach for CNUR

A. Parameterization for MDP

B. System Architecture

C. Policy Gradient Method

D. Deep Deterministic Policy Gradient

IV. Performance Evaluation

We consider a CNUR system as shown in Fig. 2. CUs are randomly distributed in a square of 300 m $\times$ 300 m. The target cordination is $x = 0, y = 0, z = 10000$ (m) (we can change z from 5000 m to 20000m). The location of radar is $x = 1000, y = 0, z = 0$.

The distance between any two entities is determined as follows:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{11}$$

The channel gains are defined as follows:

$$(h^{\mathrm{R}})^2 = \frac{G_t^{\mathrm{R}} G_r^{\mathrm{R}} \sigma^{\mathrm{RCS}} \lambda_c^2}{(4\pi)^3 (d^{\mathrm{R}})^4} \tag{12}$$

$$(h^{\mathrm{CR}})^2 = \frac{G_t^{\mathrm{C}} G_k^{\prime\mathrm{R}} \lambda_c^2}{(4\pi)^2 (d^{\mathrm{CR}})^2} \bar{h}^{\mathrm{CR}}, \bar{h}^{\mathrm{CR}} \sim \mathcal{N}(0,1) \tag{13}$$

$$(h_q^{\mathrm{C}})^2 = \frac{G_t^{\mathrm{C}} G_q \lambda_c^2}{(4\pi)^2 (d_q)^2} \bar{h}_q^{\mathrm{C}}, \bar{h}_q^{\mathrm{C}}, \sim \mathcal{N}(0,1) \tag{14}$$

$$(g_q^{\mathrm{RC}})^2 = \frac{G_t^{\prime\mathrm{R}} G_q \lambda_c^2}{(4\pi)^2 (d_q^{\mathrm{RQ}})^2} \bar{g}_q^{\mathrm{RC}}, \bar{g}_q^{\mathrm{RC}} \sim \mathcal{N}(0,1) \tag{15}$$

where

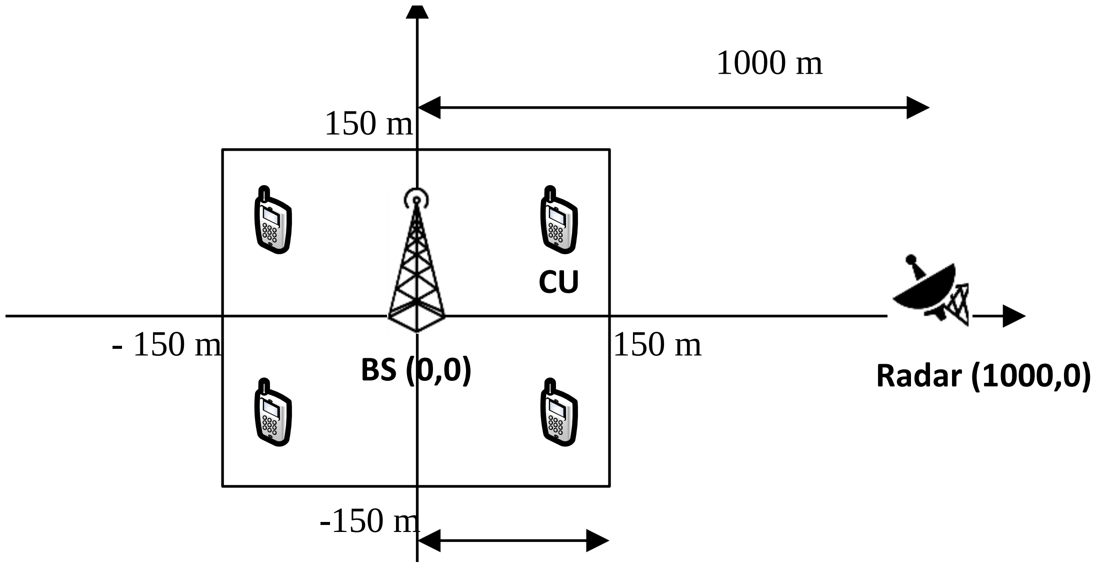

Figure 2: Locations of CNUR system.

- G_t^{R} and G_r^{R} is the gains of TX and RX of the radar, respectively,
- G_t^{C} is the transmitting antenna gain of the BS,
- G_q is the receiving antenna gain of CU q,
- σ^{RCS} is the radar cross section (RCS) of the target with respect to radar k,
- σ_q is the background noise at user q.
- f_c is the carrier frequency,
- d^{R} is the distance from radar k to its tracking target,
- d_q^{RQ} is the distance from the radar to CU q,
- d_q is the distance from BS to CU q,
- d^{CR} is the distance from BS to the radar.

REFERENCES

Table I: Simulation parameters

Parameters	*Value*
Number of CUs (Q)	3 to 6
Wave length (λ_c)	0.1 m
Communication range (d_q)	200 to 300 m
d^{CR}	1000 to 2000 m
Target range (d^{R})	5×10^3 m to 10^4 m
Maximum power of BS ($\bar{p}^{\mathrm{C}}$)	30 dBm (1 W)
Maximum power of radar ($\bar{p}^{\mathrm{R}}$)	1000 W
Transmitting antenna gain of BS (G_t^{C})	17 dBi (≈ 50)
Receiving antenna gain of CU (G_q)	0 dBi (1)
Radar antenna gain ($G_t^{\mathrm{R}}, G_r^{\mathrm{R}}$)	30 dBi (≈ 1000) [30]
$G_t^{\prime\mathrm{R}}$	-27 dBi (≈ 0.002)
$G_r^{\prime\mathrm{R}}$	-27 dBi (≈ 0.002)
σ^{RCS}	1 m^2
σ_q^2, σ^2	-150 dBm/Hz (10^{-18} W/Hz)
ϑ_0^{R}	10 dB (10)
Bandwidth B	1 MHz (10^6 Hz)
C^{TH}	10^5 bps to 4×10^5 bps