Learning Based Power Control for mmWave Massive MIMO Against Jamming

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Abstract—Millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) systems have to address smart jammers that use smart radio devices to choose the jamming policy with the goal of interrupting the ongoing transmissions. In this paper, we propose a reinforcement learning based power control strategy for the downlink mmWave massive MIMO systems. More specifically, we present a fast policy hill-climbing based power control algorithm for a base station to choose the transmit power over multiple antennas. Based on the signal-to-interference-plus-noise ratio (SINR) of the signals and the jamming strength, we evaluate the impact of the number of transmit antennas on the communication performance. Simulation results verify that the proposed schemes can increase the average SINR, sum data rate and the utility of the mmWave massive MIMO against smart jamming compared with the benchmark strategy.

Index Terms—mmWave, massive MIMO, jamming, power control, reinforcement learning.

I. INTRODUCTION

With the high improvements in the capacity and the potential bandwidth, Millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) is regard as one of the key technologies in the 5G cellular communication systems [1] [2] [3]. A switch and inverter based hybrid precoding architecture proposed in [4] can be used for the systems to reduce the hardware cost and energy consumption. Instead of using phase shifters, the analog part of the proposed architecture is realized by a small number of energy-efficient switch and inverters.

However, the mmWave massive MIMO has to address jamming attacks [5] [6], especially smart jammers that use the smart radio device such as universal software radio peripherals to choose the jamming policy such as the jamming power and channels based on the ongoing transmission status and the channel states [7]. Otherwise, jammers can interrupt the ongoing transmission of the base station (BS) to reduce the network throughput and exhaust the batteries of the mobile devices. By reducing the signal-to-interference-plus-noise ratio (SINR) of the signals, the jammers can significantly decrease the data rates of the mmWave massive MIMO transmission and even result in the denial of the service attacks.

Game theory on the power control can be used to analyze the wireless security under smart jamming with the known jamming model and channel model [8] [9]. For instance, an stackelberg equilibrium is developed in [8] for the BS to derive the optimal transmit power so as to improve the SINR of the users with a low transmission cost. However, in the dynamic interactions of the anti-jamming system, it's hard for the BS to know about the jamming model and the channel model, and the BS can't adjust the transmit power in time to improve the performance of anti-jamming [10].

The power control process in the repeated interactions between the BS and the smart jammer is a Markov decision process (MDP), thus the reinforcement learning algorithm could be used to improve the performance of anti-jamming on the basis of the communication quality without knowing the jamming model and the channel model. A transfer learning technique that is called hotbooting technique as developed in [11] is proposed for the BS to accelerate the initial learning based on the anti-jamming power control experiences.

The policy hill-climbing (PHC) algorithm [12] which keeps not only the Q-function but also the current mixed strategy is a model-free reinforcement learning technique. It chooses the action based on the mixed strategy, and updates the Q-function and mixed strategy in a time slot. More specifically, in the PHC power control strategy, the BS chooses the transmit power according to the mixed strategy with the given system state, i.e., the users' last SINR and the last jamming power to send the signals to the users. The moment when the users receive the signals, they estimate the communication quality and send the SINR to the BS.

Simulations are carried out to evaluate our algorithm, and the results show that the fast PHC based power control strategy we proposed improves the performance of anti-jamming. The average SINR, sum data rate of the users and the utility of the BS increase with time slot, and converge to a higher level compared with those of the benchmark strategy RCRA proposed in [13]. In addition, with the increase of the antennas, the average SINR, sum data rate and the utility show significantly improvement.

The rest of this paper is organized as follows. We present the system model in Section II, and propose a fast PHC-

based power control strategy for the mmWave massive MIMO system in Section III. Simulation results are provided in Section IV. In Section V, we conclude this work.
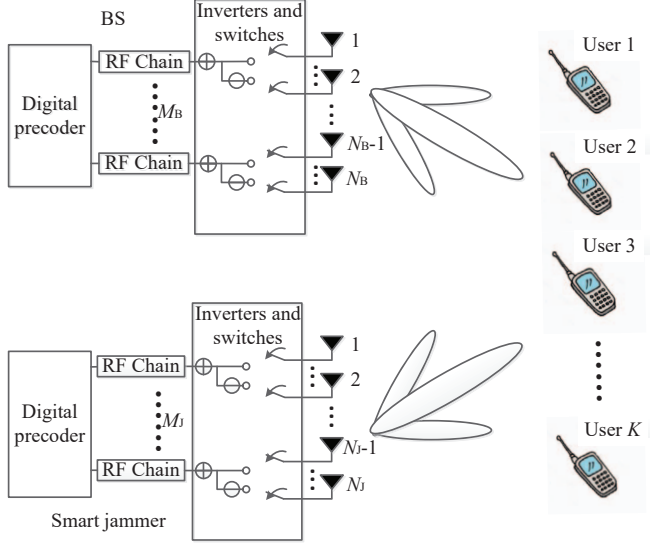
II. SYSTEM MODEL

Fig. 1. Power control in the mmWave massive MIMO system against smart jammer.

A. Network Model

As illustrated in Fig.1, we consider the mmWave massive MIMO system for K users. The BS applies a hybrid precoding architecture [4], M_B RF chains and N_B antennas to send the $K \times 1$ transmission signal vector $\mathbf{s}_B$ with transmit power, denoted by P_B, is given by $P_B = \mathbb{E}[\mathbf{s}_B^T \mathbf{s}_B]$, following the power constraint $\bar{P}_B$, i.e., $0 \leq P_B \leq \bar{P}_B$ to serve all the K single-antenna users. The moment when the K users receive the signals, they estimate the channel quality and the SINR to feed them back to the BS. The transmission cost of the BS is denoted by C_B.

In the mmWave massive MIMO system, there are L_B^k paths for the user k and the BS [14]. The complex gain, the azimuth angle and the elevation angle of departure of the path l with $1 \leq l \leq L_B^k$ for the user k and the BS are denoted by $\alpha_B^{l,k}$, $\phi_B^{l,k}$, $\theta_B^{l,k}$, respectively. We apply an geometric channel model proposed in [15] for user k to depict the characteristics of the mmWave massive MIMO channel which is quite different from that of the conventional wireless networks. Let $\mathbf{a}_B(\phi, \theta)$ denotes the array steering vector that can be calculated through [4], the $N_B \times 1$ mmWave channel vector, i.e., $\mathbf{h}_B^k$, between user k and the BS can be written as

$$\mathbf{h}_B^k = \sqrt{\frac{N_B^k}{L_B^k}} \sum_{l=1}^{L_B^k} \alpha_B^{l,k} \mathbf{a}_B(\phi_B^{l,k}, \theta_B^{l,k}). \tag{1}$$

Thus, the channel matrix between the K users and the BS can be represented by $\mathbf{H}_B = [\mathbf{h}_B^k]_{1 \leq k \leq K}^H$.

K	Number of the users
$M_{B/J}$	Number of the RF chain at the BS/smart jammer
$\mathbf{s}_{B/J}$	$K \times 1$ transmission/jamming signal vector
$N_{B/J}$	Number of antennas at the BS/smart jammer
$P_{B/J}$	Transmit power of the BS/smart jammer
$C_{B/J}$	Cost coefficient of the BS/smart jammer
$\mathbf{h}_B^k$	$N_B \times 1$ mmWave channel vector between the BS and the user k
$\mathbf{h}_J^k$	$N_J \times 1$ mmWave channel vector between the smart jammer and the user k
$\mathbf{H}_{B/J}$	mmWave channel matrix of the BS/smart jammer
$\bar{\mathbf{f}}_w^{\mathbf{R}}$	Analog beamformer of the BS on the wth sub antenna array
$\mathbf{F}_{R/D}$	Analog RF precoder/digital baseband precoder for the BS

A switch and inverter (SI) based hybrid precoding architecture [4] is considered here for the BS to reduce the hardware cost and the energy consumption of the mmWave massive MIMO system. Each RF chain of the BS is only connected to a sub antenna array with $W_B = N_B/M_B$ (assumed to be an integer) antennas instead of all N_B antennas. The $W_B \times 1$ analog beamformer of the BS on the wth sub antenna array is denoted by $\bar{\mathbf{f}}_w^{\mathbf{R}}$ with $1 \leq w \leq W_B$. Let $\mathbf{F}_R$ denotes the $N_B \times M_B$ analog RF precoder for the BS. According to the SI-based architecture, $\mathbf{F}_R$ should satisfy the hardware constraints as

$$\mathbf{F}_R = \begin{bmatrix} \bar{\mathbf{f}}_1^{\mathbf{R}} & 0 & \cdots & 0 \\ 0 & \bar{\mathbf{f}}_2^{\mathbf{R}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \bar{\mathbf{f}}_{M_B}^{\mathbf{R}} \end{bmatrix}_{N_B \times M_B} . \tag{2}$$

Since only inverters and switches are used, the N_B nonzero elements of $\mathbf{F}_R$ should satisfy the combinational constraint of $\left(-1/\sqrt{N_B}, 1/\sqrt{N_B}\right)$.

The $M_B \times K$ digital baseband precoder for the BS is denoted by $\mathbf{F}_D$ and the kth column of $\mathbf{F}_D$ is denoted by $\mathbf{f}_k^D$. An adaptive cross-entropy based hybrid precoding scheme [4] is proposed here for the BS to calculate $\mathbf{F}_D$ and $\mathbf{F}_R$. We assume the K-dimensional noise, denoted by $\mathbf{n}$, is an additive white Gaussian noise vector, i.e., $\mathbf{n} \in \mathcal{CN}(0, \mathbf{I})$.

B. Jamming Model

The smart jammer is assumed to have the same precoding architecture with the BS and it applies N_J antennas and M_J RF chains to send the jamming signals, denoted by $\mathbf{s}_J$, at the same frequency with the BS in order to block the communication between the BS and the users. More specifically, at time slot n, it chooses the jamming power, denoted by $P_J^{(n)} \geq 0$, based on the ongoing transmission status and the channel states to decrease the SINR of the

mmWave massive MIMO system. The jamming cost of the smart jammer is denoted by C_J.

The channel model between the user k and the smart jammer is assume to be a geometric channel model. Similarly, we have L_J^k paths for the users k and the smart jammer. The complex gain, the azimuth angle and the elevation angle of departure for the path i with $1 \leq i \leq L_J^k$ can be denoted by $\alpha_J^{i,k}$, $\phi_J^{i,k}$, $\theta_J^{i,k}$. Therefore, the $N_J \times 1$ mmWave channel vector between the user k and the smart jammer is given by

$$\mathbf{h}_J^k = \sqrt{\frac{N_J^k}{L_J^k}} \sum_{i=1}^{L_J^k} \alpha_J^{i,k} \mathbf{a}_J(\phi_J^{i,k}, \theta_J^{i,k}). \tag{3}$$

The channel matrix between K users and the smart jammer is denoted by $\mathbf{H}_J = [\mathbf{h}_J^k]_{1 \leq k \leq K}^H$.

Similar to the BS, the smart jammer is assume to have the SI based hybrid precoding architecture and applies an adaptive cross-entropy scheme [4] for the architecture to calculate the digital baseband precoder and the analog RF prcoder, denoted by $\mathbf{G}_D$ and $\mathbf{G}_R$. For ease of reference, the commonly used notation is summarized in TABLE 1.

III. DYNAMIC POWER CONTROL SCHEME WITH REINFORCEMENT LEARNING

In the dynamic mmWave massive MIMO anti-jamming system, on account of the fact that the smart jammer's jamming power is affected by the BS's transmit power, the power control process in the repeated interaction between the BS and the smart jammer could be formulated as an MDP. Thus, the reinforcement learning algorithm could be used to derive the optimal anti-jamming power control strategy via trial and error. In this paper, A hotbooting technique is proposed, which initializes the Q-value based on the training data obtained in advance from large scare experiments in similar scenarios to the reinforcement learning based anti-jamming power control algorithm to improve the performance of resisting smart jamming.

A. Fast Q Based Power Control Algorithm

We propose a fast Q-learning based power control algorithm that determines the transmit power $P_B^{(n)}$ in the anti-jamming scheme according to the Q-function and the current state denoted by $\mathbf{s}^{(n)}$ that is chosen as the K users' last SINR and the previous estimated jamming power.

More specifically, the BS collects the K users' previous SINR, denoted by $\hat{\mathbf{R}}^{(n-1)} = [\hat{\gamma}_k^{(n-1)}]_{1 \leq k \leq K}$ and estimate the previous jamming power, i.e., $\hat{P}_J^{(n-1)}$ according to the channel quality and the K users' SINR. The BS sets the jamming power and all the users' SINR at time slot $n-1$ as the present system state, i.e., $\mathbf{s}^{(n)} = [\hat{P}_J^{(n-1)}, \hat{\mathbf{R}}^{(n-1)}]$. Then, the BS chooses the transmit power $P_B^{(n)}$ to transmitter the signals at state $\mathbf{s}^{(n)}$ on the basis of the Q-function $Q(\mathbf{s}^{(n)}, P_B^{(n)})$. On receiving the feedback information from the users, the BS updates the new system state, i.e., $\mathbf{s}^{(n+1)} = [\hat{P}_J^{(n)}, \hat{\mathbf{R}}^{(n)}]$ and

evaluates its utility by

$$u_B^{(n)} = \sum_{k=1}^{K} \log_2\left(1 + \hat{\gamma}_k^{(n)}\right) - C_B K P_B^{(n)}. \tag{4}$$

Thus, the anti-jamming power control strategy updates the Q-function in each time by the following

$$Q(\mathbf{s}^{(n)}, P_B^{(n)}) \leftarrow (1-\alpha)Q(\mathbf{s}^{(n)}, P_B^{(n)})$$
$$+ \alpha(u_B^{(n)} + \delta V(\mathbf{s}^{(n+1)})) \tag{5}$$
$$V(\mathbf{s}^{(n)}) = \max_{P_B \in \Omega} Q(\mathbf{s}^{(n)}, P_B), \tag{6}$$

where $V(\mathbf{s}^{(n)})$ denotes the maximal Q-function on the feasible actions at state $\mathbf{s}$, $\alpha \in (0,1)$ is the learning factor of the Q-learning algorithm and $\delta \in (0,1)$ is the discount factor indicating the greedy behavior of the BS.

The ϵ-greedy policy is a decent method for the BS to make the tradeoff between exploitation and exploration during the learning process for avoiding being trapped in the local optimal power control strategy and improving the utility. According to the ϵ-greedy policy, the transmit power that maximizes the Q-function is chosen with a high probability of $1 - \epsilon$ and the other power level are chosen with a small probability, where $\epsilon \in (0,1)$ is a small positive value. Thus, the transmit power of the BS is given by

$$\mathbf{Pr}(P_B = \widetilde{P}_B) = \tag{7}$$

$$\begin{cases} 1-\epsilon & \widetilde{P}_B = \arg\max_{P_B \in \Omega} Q(\mathbf{s}^{(n)}, P_B) \\ \frac{\epsilon}{|\Omega|-1} & \widetilde{P}_B \neq \arg\max_{P_B \in \Omega} Q(\mathbf{s}^{(n)}, P_B), \end{cases} \tag{8}$$

where $|\Omega|$ is the total number of the actions. The fast Q-learning based anti-jamming power control strategy is summarized in Algorithm 1.

Algorithm 1 Fast Q-learning Based Power Control Algorithm.

1: Initialize $\alpha, \delta, \epsilon, \hat{P}_J^{(0)}, \hat{\mathbf{R}}^{(0)}$, $Q(\mathbf{s}, P_B) = Q^*(\mathbf{s}, P_B)$ and $V(\mathbf{s}) = V^*(\mathbf{s})$
2: **for** $n = 1, 2, 3, \cdots$ **do**
3:     Update the state $\mathbf{s}^{(n)} = [\hat{P}_J^{(n-1)}, \hat{\mathbf{R}}^{(n-1)}]$
4:     Choose P_B^n with ϵ-greedy policy via (7)
5:     Transmit the signals with transmit power P_B^n to serve all the K users
6:     Collect SINR $\hat{\mathbf{R}}^{(n)}$ from the K users
7:     Evaluate the jamming power $\hat{P}_J^{(n)}$ according to the channel quality and the SINR $\hat{\mathbf{R}}^{(n)}$
8:     Evaluate $u_B^{(n)}$ via (4)
9:     Update $Q(\mathbf{s}^{(n)}, P_B^{(n)})$ via (5)
10:    Update $V(\mathbf{s}^{(n)})$ via (6)
11: **end for**

B. Fast PHC Based Power Control Algorithm

The fast PHC algorithm which keeps not only the Q-function but also the current mixed strategy (strategy table π) to derive the optimal power control strategy is an extension of the fast Q-learning algorithm. On account of the fast PHC algorithm, the BS chooses the transmit power to send the signals according to the observed system state following the probability distribution table π and improve the policy by increasing the probability that it selects the most valuable action according to a learning rate $\theta \in (0, 1]$.

Similar to the fast Q-learning algorithm, the BS uses the estimated jamming power and all the users' SINR at time slot $n-1$ as the current system state, i.e., $\mathbf{s}^{(n)} = [\hat{P}_J^{(n-1)}, \hat{\mathbf{R}}^{(n-1)}]$. On basis of the system state $\mathbf{s}^{(n)}$, the BS chooses the action $P_B^{(n)}$ with probability $\pi(\mathbf{s}^{(n)}, P_B^{(n)})$. Afterwards, the BS calculates all the users' SINR and estimates the jamming power, which are used as the new system state at time slot $n+1$. Thus, the next system state is denoted by $\mathbf{s}^{(n+1)} = [\hat{P}_J^{(n)}, \hat{\mathbf{R}}^{(n)}]$ and the utility of the system is evaluated by (4).

The Q-function and the value function are updated in each time slot by (5) and (6), where the learning factor α and the discount factor δ are chosen to control the learning speed of Algorithm 2. The probability-function $\pi(\mathbf{s}^{(n)}, P_B^{(n)})$ is updated by

$$
\pi(\mathbf{s}^{(n)}, P_B^{(n)}) = \pi(\mathbf{s}^{(n)}, P_B^{(n)})
$$
$$
+ \begin{cases} \theta & \text{if } P_B^{(n)} = \arg\max_{P_B'} Q(\mathbf{s}^{(n)}, P_B') \\ \frac{-\theta}{|\Omega|-1} & \text{otherwise.} \end{cases} \quad (9)
$$

The details of the fast PHC based anti-jamming power control strategy is summarized in Algorithm 2.

**Algorithm 2** Fast PHC based Power Control Algorithm.

1: Initialize α, δ, θ, $\hat{P}_J^{(0)}, \hat{\mathbf{R}}^{(0)}$, $Q(\mathbf{s}, P_B) = Q^*(\mathbf{s}, P_B)$, $V(\mathbf{s}) = V^*(\mathbf{s})$ and $\pi(\mathbf{s}, P_B) = \pi^*(\mathbf{s}, P_B)$
2: **for** $n = 1, 2, 3, \cdots$ **do**
3:    Update the state $\mathbf{s}^{(n)} = [\hat{P}_J^{(n-1)}, \hat{\mathbf{R}}^{(n-1)}]$
4:    Choose $P_B^{(n)}$ with the probability $\pi(\mathbf{s}^{(n)}, P_B^{(n)})$
5:    Transmit the signals with transmit power $P_B^{(n)}$ to serve all the K users
6:    Collect SINR $\hat{\mathbf{R}}^{(n)}$ from the K users
7:    Evaluate the jamming power $\hat{P}_J^{(n)}$ according to the channel quality and the SINR $\hat{\mathbf{R}}^{(n)}$
8:    Evaluate $u_B^{(n)}$ via (4)
9:    Update $Q(\mathbf{s}^{(n)}, P_B^{(n)})$ via (5)
10:   Update $V(\mathbf{s}^{(n)})$ via (6)
11:   Update $\pi(\mathbf{s}^{(n)}, P_B^{(n)})$ via (9)
12: **end for**
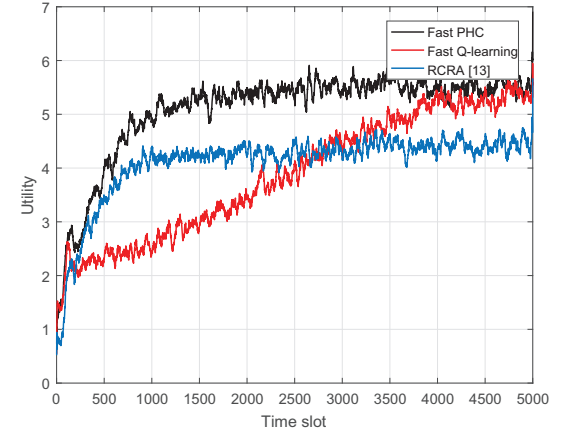

IV. SIMULATION RESULTS

Simulations have been performed to evaluate the mmWave massive MIMO system against smart jamming with a single antennas and the number of transmit antennas ranging
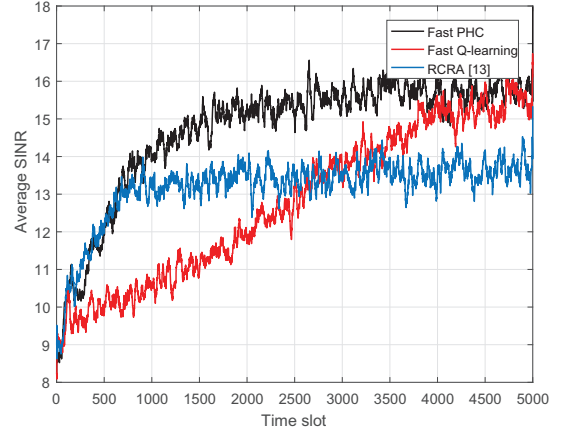
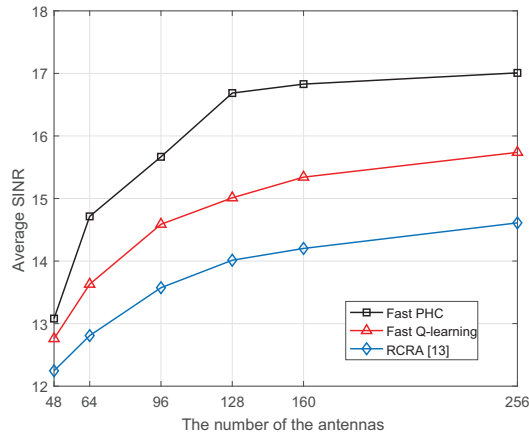(a) Average SINR of the users
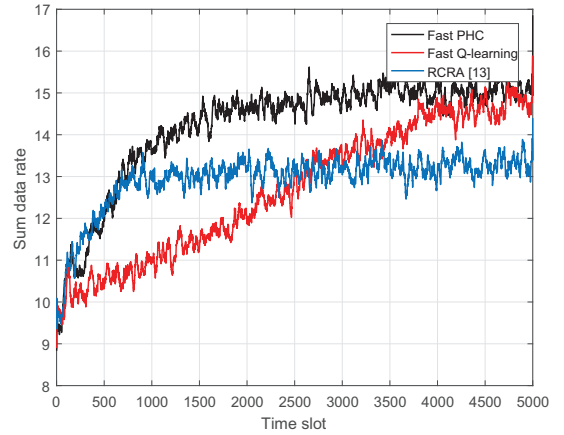
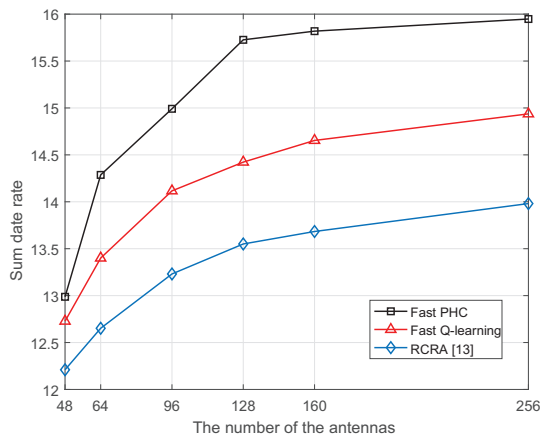(b) Sum data rate of the users

(c) Utility of the BS

Fig. 2. Performance of the reinforcement learning based power control strategies against smart jamming in the dynamic game with $P_B = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]$, $C_B = 1$, $N_B = 64$, $M_B = 16$ $K = 16$.
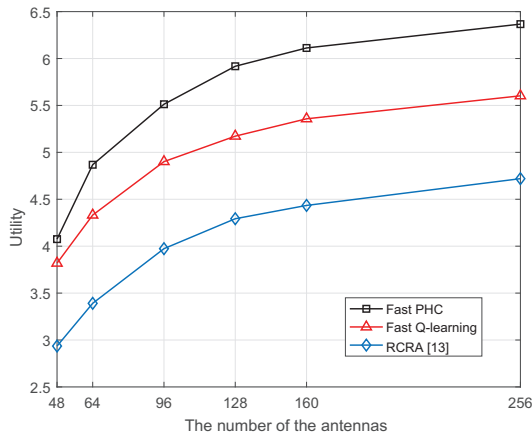
between 48 and 256. In the simulations, the BS equiped 16 RF chains and chose the transmit power from 10 levels with tansmission cost 2, to serve 16 users. The learning parameters are chosen as $\alpha = 0.5$, $\delta = 0.85$ and $\theta = 0.05$

(a) Average SINR of the users

(b) Sum data rate of the users

(c) Utility of the BS

Fig. 3. Performance of the reinforcement learning based power control strategies against smart jamming with given amount of the transmit antennas.

to achieve good performance. As a benchmark, the RCRA strategy [13] is evaluated in the same simulation setting with the reinforcement learning algorithm.

As shown in Fig.2, the fast PHC based power control

strategy which keeps the Q-function and the current mixed strategy exceeds the benchmark scheme RCRA in [13]. For instance, the fast PHC based strategy increases the average SINR by 14%, improves the sum data rate by 18% and raises the utility to 40% at time slot 1500, compared with RCRA-based power control scheme.

As shown in Fig.3, the average performance over 4000 time slots of the three strategies mentioned above increases with the number of the transmit antennas. In addition, the average performance of the fast PHC power control strategy over different antennas show significant improvement compared to that of the RCRA strategy in [13]. For instance, the average average SINR, sum data rate and utility of the fast PHC based strategy with 256 transmit antennas increase by 31%, 23% and 57%, compared to the system with 48 transmit antennas.

V. CONCLUSION

In this work, we have proposed a reinforcement learning based power control algorithm for mmWave massive MIMO system, which applies the fast PHC to achieve the optimal transmit power in the dynamic anti-jamming transmission game without being aware of the jamming model and the channel model. According to the simulation results, the fast PHC based power control strategy increase the sum SINR, sum data rate and the utility of the mmWave massive MIMO system. In addition, the performance increases with the number of transmit antennas. For instance, the fast PHC based strategy increase the average SINR by 16%, increases the sum data rate by 18% and improve the utility by 40% compared with RCRA in [13]. Compared to the system with 48 transmit antennas, the sum SINR, sum data rate and utility of the fast PHC with 256 transmit antennas incerase by 31%, 23%, 57%, separately.

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