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Intelligent secure near-field communication

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The research and development efforts for the sixth generation (6G) wireless communication are underway to fulfill the growing demands for wireless communications. 6G is expected to become the key enabler for diverse new applications and services [1]. To achieve the excellent performance, 6G will implement extremely large-scale antenna arrays (ELAAs), terahertz [2], and new types of antennas with metamaterials, leading to a paradigm shift for the electromagnetic characteristics. For instance, owing to the application of ELAAs and tremendously high frequencies, 6G networks exhibit a large near-field region on the order of hundreds of meters [3]. Moreover, with the rapid development of artificial intelligence (AI) techniques, AI has been widely applied in research in the field of communication. Therefore, new opportunities for the development of intelligent near-field communication (NFC) techniques are opened up.

As far as we know, the hybrid analog-digital beamforming (HBF) has much more effectiveness than full-digital beamforming (FB) but achieves the comparable performance [4]. Since the HBF-based secure NFC has not been fully researched, we consider an NFC system with a potential eavesdropper. The sum secrecy rate is maximized via jointly designing the HBF and position of BS, subject to the quality of service (QoS) of users. We investigate the long-term secure transmission, the whole time is evenly divided into multiple time slots. Unfortunately, the high-dimensional and coupled optimization variables make the traditional optimization algorithm intractable. Therefore, we employ a deep reinforcement learning (DRL) -based algorithm to intelligently address the high-dimensional optimization problem [5]. A twin delay deep deterministic policy gradient (TD3)-based algorithm is proposed, with the deep deterministic policy gradient (DDPG)-based algorithm serving as the benchmark. Numerical results illustrate that compared to the benchmark, the TD3-based algorithm demonstrates faster convergence speed and higher cumulative discount reward.

System model and problem formulation. Consider a secure NFC system where a base station (BS) equipped with a large-scale antenna array transmits the confidential information to K ($K \geqslant 1$) single-antenna users in front of a potential eavesdropper. To reduce the power consumption, the BS adopts the energy-effective HBF, and the number of transmit antenna and radio chain are $N_{\rm t}$ ($N_{\rm t}$ is an odd number) and $N_{\rm rf}$ ($N_{\rm rf} \ll N_{\rm t}$), respectively. The whole time is evenly divided into L time slots, so that we can study the long-term secure transmission. The channels from the BS to the kth user and to the eavesdropper in the lth time slot can be written as $\boldsymbol{h}_{k,l}$ and $\boldsymbol{h}_{e,l}$, respectively. Moreover, both the users and the eavesdropper are located in the near-field area.

The transmititted signal in the lth time slot can be formulated as

$$\boldsymbol{x}_l = \boldsymbol{F}_l \boldsymbol{W}_l \boldsymbol{s}_l, \tag{1}$$

where $\boldsymbol{F}_l \in \mathbb{C}^{N_{\rm t}\times N_{\rm rf}}$ stands for the analog beamforming matrix, $\boldsymbol{W}_l = [\boldsymbol{w}_{1,l},\ldots,\boldsymbol{w}_{K,l}] \in \mathbb{C}^{N_{\rm rf}\times K}$ refers to the full digital beamforming, and $\boldsymbol{s}_l \in \mathbb{C}^{K\times 1}$ stands for the signal vector.

The channel from the nth antenna element to the kth user can be expressed as

$$h_{k,n}(r_k,\theta_k,n) = \tilde{\beta}_k\left(\sqrt{\frac{\kappa}{\kappa+1}}h_{k,n}^{\rm LoS} + \sqrt{\frac{1}{\kappa+1}}h_{k,n}^{\rm nLoS}\right), \tag{2}$$

where $\tilde{\beta}_k$ denotes the channel gain of each link to the kth user, κ denotes the Rician factor, $h_{k,n}^{\rm LoS}$ and $h_{k,n}^{\rm nLoS}$ refer to the line-of-sight (LoS) and non LoS (nLoS) parts, respectively. $h_{k,n}^{\rm nLoS} \sim \mathcal{CN}(0,1)$, and $h_{k,n}^{\rm LoS}$ can be expressed as

$$h_{k,n}^{\rm LoS}(r_k,\theta_k,n) = {\rm e}^{-{\rm j}\frac{2\pi}{\lambda}\tilde{r}_{k,n}(r_k,\theta_k,n)}, \tag{3}$$

where $\tilde{r}_{k,n}(r_k,\theta_k,n)$ denotes the distance from the nth antenna element to user k (see Appendix A for details).

The achievable rate of the kth user in the lth time slot can be formulated as

$$R_{k,l} = \log_2\left(1+\frac{|\boldsymbol{h}_{k,l}^{\rm H}\boldsymbol{F}_l\boldsymbol{w}_{k,l}|^2}{\|\boldsymbol{h}_{k,l}^{\rm H}\boldsymbol{F}_l\boldsymbol{W}_{-k,l}\|_{\rm F}^2+\sigma^2}\right),\ \forall k,l, \tag{4}$$

where $\boldsymbol{W}_{-k,l} \triangleq [\boldsymbol{w}_{1,l},\ldots,\boldsymbol{w}_{k-1,l},\boldsymbol{w}_{k+1,l},\ldots,\boldsymbol{w}_{K,l}] \in \mathbb{C}^{N_{\rm rf}\times(K-1)}$, and σ^2 stands for the variance of additive white Gaussian noise at the user k.

Similarly, the eavesdropping rate towards the kth user in the lth time slot can be formulated as

$$R_{e,k,l} = \log_2\left(1+\frac{|\boldsymbol{h}_{e,l}^{\rm H}\boldsymbol{F}_l\boldsymbol{w}_{k,l}|^2}{\|\boldsymbol{h}_{e,l}^{\rm H}\boldsymbol{F}_l\boldsymbol{W}_{-k,l}\|_{\rm F}^2+\sigma^2}\right),\ \forall k,l. \tag{5}$$

Thus, the secrecy rate of kth user in the lth time slot can be given by

$$R_{{\rm s},k,l} = \max\left(R_{k,l}-R_{e,k,l},0\right),\ \forall k,l. \tag{6}$$

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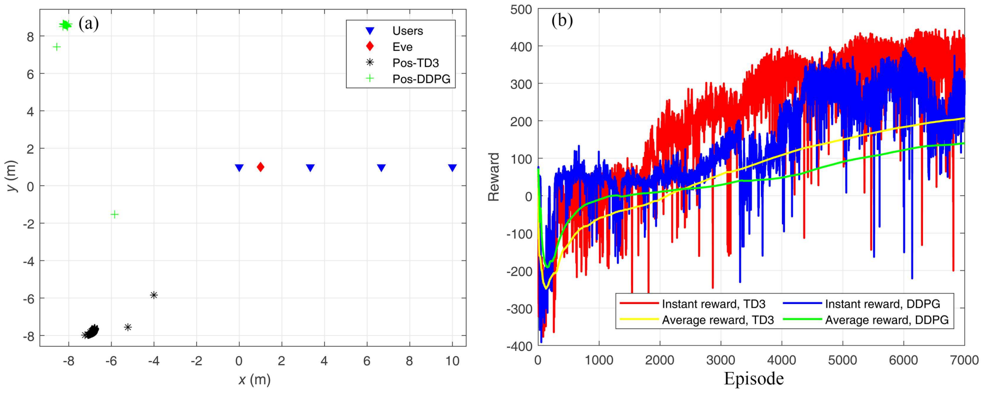

Figure 1 (Color online) (a) The optimal positions of BS obtained by DDPG and TD3; (b) the instant and average reward curves.

Accordingly, the sum secrecy rate can be maximized via jointly designing the hybrid beamforming and position of BS, yielding the problem as

$$
\begin{aligned}
\max_{\{\boldsymbol{W}_l,\boldsymbol{F}_l,\boldsymbol{p}_l\}} \quad & \sum_{l=1}^{L}\sum_{k=1}^{K} R_{\mathrm{s},k,l} && \text{(7a)}\\
\text{s.t.} \quad & |\boldsymbol{F}_l(i,j)| = 1,\ \forall i,j,l, && \text{(7b)}\\
& \|\boldsymbol{F}_l\boldsymbol{W}_l\|_{\mathrm{F}}^2 \leqslant P_{\max},\ \forall l, && \text{(7c)}\\
& R_{k,l} \geqslant \mathfrak{r}_k,\ \forall k,l, && \text{(7d)}\\
& \boldsymbol{p}_l \in \mathcal{P},\ \forall l, && \text{(7e)}
\end{aligned}
$$

where $P_{\max}$ refers to the maximal transmit power, $\mathfrak{r}_k > 0$ represents the rate threshold for the kth user, and $\mathcal{P}$ represents the set of feasible position of BS. Eq. (7b) stands for the constant modulus constraint, Eq. (7c) denotes the transmit power constraint, Eq. (7d) refers to the QoS constraint of the kth user, and Eq. (7e) is the position constraint.

TD3-based algorithm for (7). The optimization variables in (7) are high-dimensional, which could be well address by a low-complexity DRL-based algorithm [5]. According to Appendix B, a TD3-based algorithm is employed, whose neural network structure and training process can be found in Appendix B. In our system, the agent is represented by BS, and the secure NFC network serves as the environment.

Parameter settings. Assume that a BS equipped with a uniform linear array works at a frequency of 28 GHz ($\lambda \approx$ 1 cm). The antenna aperture is set to $D = 0.5$ m, resulting in a Rayleigh distance of $\frac{2D^2}{\lambda} \approx 50$ m. There are $K = 4$ users in front of an eavesdropper located in the near-field region of BS. The coordinates of the users consist of a y-coordinate of 1 m, with their x-coordinates uniformly distributed between 0 and 10 m. The location of eavesdropper is set to (1, 1) m. The details of important environmental parameters are shown in Table B1 in Appendix B.

Simulation results and conclusion. In this section, simulation results are provided to verify the performance of the TD3-based algorithm. To evaluate the performance of the proposed TD3-based algorithm, we choose the DDPG-based algorithm as a benchmark. Compared with DDPG, TD3 makes some improvements to alleviate the problem of overestimation (see Appendix B for details). Numerical results indicate that the maximum discounted cumulative reward of the baseline is 393, while that of the proposed algorithm is 444, which means that the TD3-based algorithm gets better performance. Figure 1(a) illustrates the optimal positions of the BS obtained by the DDPG algorithm and the TD3 algorithm over 7000 episodes. By adjusting the hyper-parameters, efforts are made to concentrate the optimal positions of BS. The hyper-parameters of the TD3 algorithm are listed in Table B2 in Appendix B. As shown in Figure 1(b), it can be observed that, while ensuring the concentration of the positions of BS, the TD3-based algorithm achieves a significantly higher cumulative discount reward, faster convergence speed and stable convergence curve compared to the DDPG. Therefore, the effectiveness of TD3 is verified.

In this study, we studied the long-term secure NFC transmission, and a joint HBF and position optimization problem was formulated to maximize the sum secrecy rate of users. A TD3-based algorithm was proposed to obtain the optimal HBF matrix and position of the BS. Simulation results verified the effectiveness of the proposed intelligent algorithm for this optimization problem.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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