Learning-based Robust and Secure Transmission for Reconfigurable Intelligent Surface Aided Milimeter Wave UAV Communications

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***Abstract*—The abstract goes here.**

***Index Terms*—IEEE, IEEEtran, journal, LATEX, paper, template.**

I. Introduction

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August 26, 2015

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II. System Model and Problem Formulation

A. System Model

In this letter, we consider ~~a~~ RIS-aided milimeter wave UAV secure transmission system where ~~a~~ RIS is exploited to assist the secure downlinks from the UAV to K single-antenna legitimate users in the presence of P single-antenna eavesdroppers. Specifically, ~~the UAV is equipped with a uniform linear array (ULA) with A antennas, the RIS is equipped with a uniform planar array (UPA) with $M{=}m^2$ passive reflecting elements(note that m must be an integer), denoted by $\mathcal{M}{=}\{1,2,...,M\}$. Let $\mathcal{K}{=}\{1,2,...,K\}$, $\mathcal{P}{=}\{1,2,...,P\}$ denote~~ the set of the legitimate users and the eavesdroppers, respectively. As shown in Fig.1, all entities are placed in the three dimensional (3D) Cartesian coordinate system. Let $\mathbf{w}_k{=}[x_k,y_k,0]^T$ and $\mathbf{w}_p{=}[x_p,y_p,0]^T$ denote the legitimate users' and the eavesdroppers' coordinates, respectively. The RIS is fixed at $\mathbf{w}_R{=}[x_R,y_R,z_R]^T$. ~~A~~ssume that the UAV flies at a fixed altitude in a ~~finate~~ time span which is divided into N time slots, i.e., $T{=}N\delta_t$, where δ_t is the time interval. Then the coordinate of UAV at n-th time slot ~~can be~~ denoted by $\mathbf{q}[n]{=}[x[n],y[n],H_U]^T, n\in\mathcal{N}{=}\{1,2,...,N\}$, ~~which~~ subject to the following mobility constraints:

$$\|\boldsymbol{q}[n+1]-\boldsymbol{q}[n]\|^2 \le D^2, n=1,\ldots,N-1 \tag{1a}$$

$$|x[n]|\,,|y[n]| \le B, n=1,\ldots,N-1 \tag{1b}$$

$$\boldsymbol{q}[0] \equiv [0,0,H_U], n=1,\ldots,N-1 \tag{1c}$$

Let $\boldsymbol{h}_{U,k}{\in}\mathbb{C}^{\mathrm{A}\times 1}$, $\boldsymbol{h}_{U,p}{\in}\mathbb{C}^{\mathrm{A}\times 1}$, $\boldsymbol{h}_{R,k}{\in}\mathbb{C}^{\mathrm{M}\times 1}$, $\boldsymbol{h}_{R,p}{\in}\mathbb{C}^{\mathrm{M}\times 1}$, $\boldsymbol{H}_{UR}{\in}\mathbb{C}^{\mathrm{M}\times \mathrm{A}}$ ~~denote~~ the channel gain of the UAV to k-th user, UAV to p-th eavesdropper, RIS to k-th user, RIS to p-th eavesdropper, UAV to RIS links, respectively. All the channels are modeled as milimeter wave channels [1] [2] as

$$\boldsymbol{h}_{U,i} = \sqrt{\frac{1}{L_{UK}}}\sum_{l=1}^{L_{UK}} g_{i,l}^{u}\mathbf{a}_L\left(\theta_{i,l}^{AoD}\right), \forall i\in\mathcal{K}\cup\mathcal{P}, \tag{2a}$$

$$\boldsymbol{h}_{R,i} = \sqrt{\frac{1}{L_{RK}}}\sum_{l=1}^{L_{RK}} g_{i,l}^{r}\mathbf{a}_P\left(\theta_{i,l}^{AoD},\phi_{i,l}^{AoD}\right), \forall i\in\mathcal{K}\cup\mathcal{P}, \tag{2b}$$

$$\boldsymbol{h}_{UR} = \sqrt{\frac{1}{L_{RK}}}\sum_{l=1}^{L_{RK}} g_{l}^{ur}\mathbf{a}_P\left(\theta_{l}^{AoA},\phi_{l}^{AoA}\right)\mathbf{a}_L\left(\theta_{l}^{AoD}\right)^H. \tag{2c}$$

In (2), the large-scale fading coefficients defined by $g\in\{g_{i,l}^u, g_{i,l}^r, g_l^{ur}\}$ follow a complex Gaussian distribution as $\mathcal{CN}(0,10^{\frac{PL}{10}})$, where $PL(dB) = -\mathrm{C}_0 - 10\alpha\log_{10}(\mathrm{D}) - \mathrm{PL_s}$, $C_0{=}61dB$ is the path loss at a reference distance of one meter ~~and at the frequency of 28GHz~~, D(meters) is the link distance, α denotes the path-loss exponent, and $PL_s{\sim}\mathcal{CN}(0,\sigma_s^2)$ is the shadow fading component. The steering vector of the ULA is denoted by $\mathbf{a}_L(\theta) = \left[1, e^{j\frac{2\pi}{\lambda c}d\sin(\theta)},\ldots,e^{j\frac{2\pi}{\lambda c}d(N-1)\sin(\theta)}\right]^{\mathrm{H}}$ [3], where θ stands for the azimuth angle-of-departure(AoD) $\theta_{i,l}^{AoD}$ and θ_l^{AoD}, d is the antenna inter-spacing, and λ_c is the carrier wavelength. The steering vector of the UPA is denoted by $\mathbf{a}_P(\theta,\phi) = \left[1,\ldots,e^{j\frac{2\pi}{\lambda c}d(p\sin(\theta)\sin(\phi)+q\cos(\theta)\sin(\phi))},\ldots\right]^{\mathrm{H}}$ [3],where $0\le p,q\le m{-}1$, $\theta(\phi)$ is the azimuth(elevation) AoD $\theta_{i,l}^{AoD}(\phi_{i,l}^{AoD})$ and the angle-of-arrival (AoA) $\theta_l^{AoA}(\phi_l^{AoA})$.

The cascaded channel from UAV to the i-th user or eavesdropper can be written as $\boldsymbol{H}_{C,i} = diag(\boldsymbol{h}_{R,i}^H)\boldsymbol{h}_{UR}, \forall i\in\mathcal{K}\cup\mathcal{P}$. ~~And the~~ passive beamforming matrix of the RIS [4] is defined as $\boldsymbol{\Theta} = \mathrm{diag}\left(\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ..., \beta_M e^{j\theta_M}\right)$, where $\theta_m\in[0,2\pi)$ and $\beta_m\in[0,1]$ represent the phase shift and amplitude reflection coefficient of the ~~n~~-th RIS reflection element, respectively. Let $\boldsymbol{\Psi}{=}vec(\boldsymbol{\Theta})^{\mathbf{T}}$ denote the vectorized

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passive beamforming matrix. Then, the received signal at the i-th user or eavesdropper from the UAV can be formulated as

$$y_i = (\boldsymbol{h}_{U,i}^H + \boldsymbol{\Psi}^H \boldsymbol{H}_{C,i})\mathbf{Gs} + \mathbf{n_i}, \forall \mathbf{k} \in \mathcal{K} \cup \mathcal{P}, \tag{3}$$

where s_m with $E[|s_m|^2] = 1$ and $\mathbf{G} \in \mathbb{C}^{N \times K}$ represent the transmitted symbol and the beamforming matrix at the UAV, respectively, and it is assumed that $n_i \sim \mathcal{N}(0,1), \forall i \in \mathcal{K} \cup \mathcal{P}$. Let $\boldsymbol{g}_k$ be the k-th column of the beamforming matrix $\mathbf{G}$. Then, the the achievable unsecured rate of the ~~k~~-th user is given by

$$R_k^u = \\ log_2 \left(1 + \frac{|(\boldsymbol{h}_{U,k}^H + \Psi^H \boldsymbol{H}_{C,k})\boldsymbol{g}_k|^2}{\sum_{k' \in \mathcal{K} \setminus k} |(\boldsymbol{h}_{U,k}^H + \Psi^H \boldsymbol{H}_{C,k})\boldsymbol{g}_{k'}|^2 + n_k^2}\right). \tag{4}$$

If the p-th eavesdropper aims to eavesdrop the signal of the k-th user, its achievable rate can be denoted by

$$R_{p,k}^e = \\ log_2 \left(1 + \frac{|(\boldsymbol{h}_{U,p}^H + \Psi^H \boldsymbol{H}_{C,p})\boldsymbol{g}_k|^2}{\sum_{k' \in \mathcal{K} \setminus k} |(\boldsymbol{h}_{U,p}^H + \Psi^H \boldsymbol{H}_{C,p})\boldsymbol{g}_{k'}|^2 + n_p^2}\right). \tag{5}$$

The achievable individual secrecy rate from the UAV to the k-th user [5] can be expressed by

$$R_k^{\text{sec}} = \left[R_k^{\text{u}} - \max_{\forall p} R_{p,k}^{\text{e}}\right]^+ \tag{6}$$

It is worth noting that the outdated CSI will lead to substantial performance loss in practical systems. According to [6], the outdated CSI can be expressed as statistical CSI error model. ~~Let~~ T_d ~~denote~~ the delay between the outdated CSI and the real-time CSI. The relation between the outdated channel vector $\boldsymbol{h}(t)$ and the real-time channel vector $\boldsymbol{h}(t+T_d)$ can be expressed as [7]

$$\boldsymbol{h}\left(t + T_{\text{d}}\right) = \rho \boldsymbol{h}(t) + \sqrt{1-\rho^2}\boldsymbol{e}, \tag{7}$$

where $\boldsymbol{e}$ is independent identically distributed with $\boldsymbol{h}\left(t + T_{\text{d}}\right)$ and $\boldsymbol{h}(t)$, ρ is the autocorrelation function of the channel gain $\boldsymbol{h}(t)$, given by the zeroth-order Bessel function of the first kind as

$$\rho = J_0\left(2\pi f_D T_{\text{d}}\right). \tag{8}$$

In (8), f_D is the Doppler spread which is expressed as $f_D = v f_c / c$, where v, f_c, c represent the velocity of the transceivers, the carrier frequency and the speed of light, respectively.

Then, the actual channel coefficients can be rewritten as

$$\begin{aligned} \boldsymbol{h}_{\text{U},i} &= \rho \tilde{\boldsymbol{h}}_{\text{U},i} + \Delta \boldsymbol{h}_{\text{U},i}, \forall k \in \mathcal{K} \cup \mathcal{P} \\ \boldsymbol{h}_{\text{R},i} &= \rho \tilde{\boldsymbol{h}}_{\text{R},i} + \Delta \boldsymbol{h}_{\text{R},i}, \forall k \in \mathcal{K} \cup \mathcal{P} \\ \boldsymbol{h}_{\text{UR}} &= \rho \tilde{\boldsymbol{h}}_{\text{UR}} + \Delta \boldsymbol{h}_{\text{UR}} \end{aligned} \tag{9}$$

Note that the system only ~~have~~ access to the estimated CSI $\tilde{\boldsymbol{h}} \in \{\tilde{\boldsymbol{h}}_{\text{U},i}, \tilde{\boldsymbol{h}}_{\text{R},i}, \tilde{\boldsymbol{h}}_{\text{UR}}\}$, which are outdated, to generate active and passive beamforming and UAV trajectory. And the actual CSI $\boldsymbol{h} \in \{\boldsymbol{h}_{\text{U},i}, \boldsymbol{h}_{\text{R},i}, \boldsymbol{h}_{\text{UR}}\}$ is employed to calculate achievable secrecy rate of each user which has been expressed in (4), (5), (6).

B. Problem Formulation

In this letter, ~~our objective is~~ to maximize the sum secrecy rate $\sum_{k=1}^K R_k^{\text{sec}}$ by jointly optimizing the UAV's trajectory $\mathbf{Q} \triangleq \{\mathbf{q}[\mathbf{n}], \mathbf{n} \in \mathcal{N}\}$ and the active(passive) beamforming matrix $\mathbf{G}(\boldsymbol{\Theta})$ ~~with the UAV mobility constraints, the outage probability constraints under statistical CSI error model, the total transmit power constraint and the RIS reflecting unit constraint. As such, the optimization problem is formulated as~~

$$\begin{aligned} &\max_{\mathbf{Q},\mathbf{G},\boldsymbol{\Theta}} \sum_{k \in \mathcal{K}} R_k^{\text{sec}} && (10a) \\ &s.t. \quad (1), && (10b) \\ &\Pr\left\{R_k^{\text{sec}} \geq R_k^{\text{sec,th}}\right\} \geq 1 - \rho_k, \forall k \in \mathcal{K}, && (10c) \\ &\text{Tr}\left(\mathbf{G}\mathbf{G}^{\mathbf{H}}\right) \leq P_{\max}, && (10d) \\ &\theta_m \in [0, 2\pi)\ , \beta_m = 1, \forall m \in \mathcal{M}, && (10e) \end{aligned}$$

where the rate outage constraint (10c) guarantee that the probability ~~of~~ each legitimate user can successfully decode its message at a data rate of $R_k^{\text{sec,th}}$ is no less than $1 - \rho_k$. (10b) models the UAV mobility constraint. (10d) restricts the transmission power at UAV side does not exceed the maximum value. (10e) constrains the reflection coefficients of the RIS reflecting elements. Obviously, problem (10), due to the non-convex objective function and constraints, is a non-convex problem that is rather challenging to solve. To tackle this challenging problem, the sum rate optimization problem is formulated in the context of DRL based method to obtain the feasible $\mathbf{G}$, $\boldsymbol{\Theta}$ and $\mathbf{Q}$.

III. DRL-based Solution

To solve the non-convex problem in (10), we propose a twin-DDPG deep reinforcement learning framwork, instead of using single agent to find the optimal $\mathbf{G}$, $\boldsymbol{\Theta}$ and $\mathbf{Q}$, since $\mathbf{Q}$ would be highly coupled with large scale CSI using single agent which is actually irrelevant. As shown in Fig.2, the first network takes CSI as state to obtain the optimal $\mathbf{G}$ and $\boldsymbol{\Theta}$, while the second network takes UAV position as state to obtain the movement $\mathbf{q}[\mathbf{n+1}] - \mathbf{q}[\mathbf{n}]$ of UAV at n-th time slot. Both network take the sum secrecy data rate as reward.

A. Active and Passive Beamforming

Inspired by the work of [5],

B. UAV Trajectory

IV. Simulation Results

V. Conclusion

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Appendix A
Proof of the First Zonklar Equation

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Appendix B

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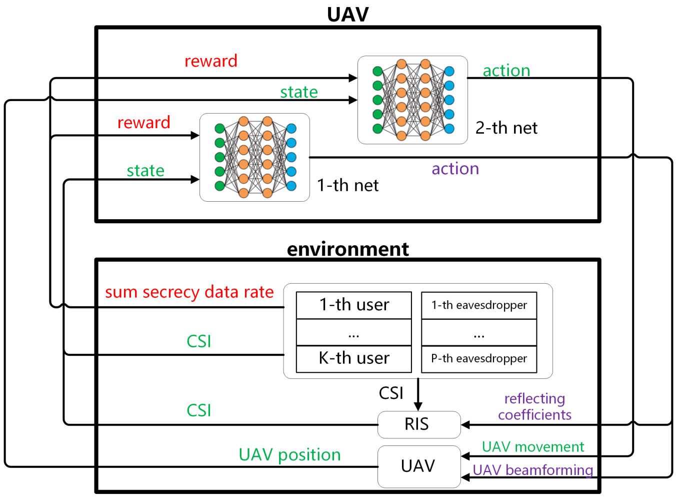

Fig. 1. structure of proposed twin-DDPG framwork.

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