IRS-aided OTFS System with Simple IRS Beamforming

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Abstract

In this paper, we investigate the performance of intelligent reflecting surface (IRS) assisted orthogonal time frequency space (OTFS) modulation with the simple IRS beamforming matching to the high power signal path under the unit modulus reflection. The simple IRS beamforming method is shown to improve the ergodic capacity significantly when compared with random phase beamforming.

Ⅰ. Introduction

OTFS has been regarded as a promising technology to combat high speed Doppler effect in 5G and beyond [1]. In addition, IRS has received significant attention due to its capability of controlling the wireless channel and increasing the coverage at very low power consumption and low complexity [2]. In this paper, we consider an IRS-aided OTFS system and verify that the simple IRS beamforming is also efficient in a more realistic IRS channel model than [2].

Ⅱ. System Model

We consider an OTFS system aided by an IRS with Q elements as illustrated in Fig. 1. An OTFS frame consists of $M\times N$ grid in the delay-Doppler (DD) domain. Let $\boldsymbol{g}_i$ ($\boldsymbol{f}_j$) denote the IRS channel response of the ith (jth) path between the IRS and BS (user) at delay l_i^g (l_j^f) and Doppler k_i^g (k_j^f), where total L_g (L_f) paths exist in the channel. Unlink [2] with independent elements in $\boldsymbol{g}_i$ ($\boldsymbol{f}_j$), we utilize the channel response with $Q=Q_v\times Q_h$ planar array as

$$\boldsymbol{g}_i=\alpha_i^g\sqrt{Q}\boldsymbol{a}(\varphi_i^g,\vartheta_i^g),\ \boldsymbol{f}_j=\alpha_j^f\sqrt{Q}\boldsymbol{a}(\varphi_j^f,\vartheta_j^f), \tag{1}$$

where $\boldsymbol{a}(\varphi,\vartheta)=[e^{j\pi\boldsymbol{q}_h\sin\varphi\cos\vartheta}]\otimes[e^{j\pi\boldsymbol{q}_v\sin\vartheta}]/\sqrt{Q}$ is the array response at azimuth angle φ and elevation angle ϑ for $\boldsymbol{q}_k=[0,1,\cdots,Q_k-1]^T$, $k\in\{v,h\}$ and α_i^x is the channel gain of each path for $x\in\{g,f\}$.

The received signal in the time domain can be expressed as

$$r[n]=\boldsymbol{\theta}^T\sum_{p\in P}\boldsymbol{h}_p e^{j2\pi k_i^h\left(n-l_p^h\right)/NM}s\left[n-l_p^h\right]_{NM}+z[n], \tag{2}$$

where $\boldsymbol{\theta}=\left[e^{j\theta_1}\ e^{j\theta_2}\ \cdots\ e^{j\theta_Q}\right]^T$ is the IRS reflection vector, $\boldsymbol{h}_p=\boldsymbol{g}_i\circ\boldsymbol{f}_j$, $l_p^h=l_i^g+l_j^f$, $k_p^h=k_i^g+k_j^f$, P is the set of resolvable multipaths, and $z[n]$ is the time domain noise. The DD domain signal of (2) with ideal pulse shaping can be expressed as

$$\boldsymbol{y}=[\boldsymbol{H}_1\boldsymbol{H}_2\cdots\boldsymbol{H}_Q]\boldsymbol{\Theta}\boldsymbol{x}+\boldsymbol{w}=\boldsymbol{H}_{eff}\boldsymbol{\Theta}\boldsymbol{x}+\boldsymbol{w}, \tag{3}$$

where $\boldsymbol{H}_q\in\mathbb{C}^{NM\times NM}$ is the cascaded channel matrix at the qth element of the IRS constituting $\boldsymbol{H}_{eff}=[\boldsymbol{H}_1\ \boldsymbol{H}_2\cdots\boldsymbol{H}_Q]$, $\boldsymbol{\Theta}=\left[e^{j\theta_1}\boldsymbol{I}_{NM}\ e^{j\theta_2}\boldsymbol{I}_{NM}\ \cdots\ e^{j\theta_Q}\boldsymbol{I}_{NM}\right]^T$, $\boldsymbol{x}\in\mathbb{C}^{NM\times 1}$ is the DD domain symbol vector subject to $E[\boldsymbol{x}\boldsymbol{x}^H]=E_s\boldsymbol{I}_{MN}$, and $\boldsymbol{w}\sim CN(\boldsymbol{0},\sigma^2\boldsymbol{I}_{MN})$ is the Gaussian noise vector in the DD domain.

Ⅲ. IRS Channel Optimization

The capacity of the IRS-aided OTFS for given IRS reflection and corresponding maximum outage probability are given as follows:

$$C(\boldsymbol{\theta})=\frac{1}{NM}\log_2\left|\boldsymbol{I}_{NM}+\frac{E_s\boldsymbol{H}_{eff}\boldsymbol{\Theta}\boldsymbol{\Theta}^H\boldsymbol{H}_{eff}^H}{\sigma^2}\right| \tag{4}$$

$$P_{out}=\Pr\{\max_{\boldsymbol{\theta}}C(\boldsymbol{\theta})<R\} \tag{5}$$

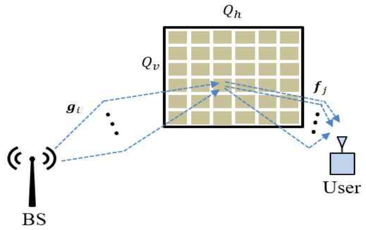

Fig. 1. IRS-aided OTFS system and channel model.

where R is the target rate. To maximize the ergodic capacity as well as to mimize the outage cpacity, we need to optimize as IRS phase vector to maximize the instantaneous channel capacity as

$$\max_{\boldsymbol{\theta}} C(\boldsymbol{\theta})\quad s.t.\quad 0\le\theta_q\le 2\pi, q=1,2,\cdots,Q \tag{6}$$

Due to the high complexity of solving (6), we apply a suboptimal approach used in [2] which obtains the IRS beamforming vector as

$$\boldsymbol{\theta}^{\star}=-\angle\boldsymbol{h}_{p^{\star}},\qquad p^{\star}=\arg\max_{i\in P}\|\boldsymbol{h}_i\|_1^2. \tag{7}$$

Ⅳ. Results and Discussion

As preliminary results, we compare the ergodic capacity of the OTFS system with $M\times N=64\times 14$, $\triangle f=15\text{KHz}$, and carrier frequency 4 GHz. The channels are $L_g=2, L_f=3$, with the Doppler taps generated from uniform distribution for each path up to maximum Doppler shift corresponding to user speed 100 km/h. Fig. 2 shows the ergodic capacity with IRS beamforming (7) (denoted by Strongest DDCR) and random phases. The results shows that the performance of the IRS-aided OTFS is improved significantly even with the suboptimal method (7) and the gain becomes larger as the IRS size increases.

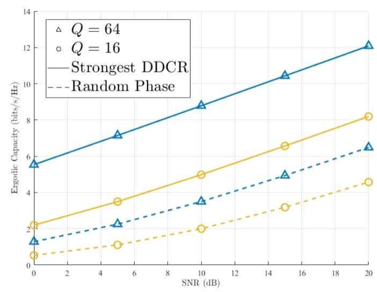

Fig. 2 Ergodic capacity versus SNR for different IRS sizes

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