IRS-Assisted Multi-user Downlink Satellite Communication Systems: Joint Optimization with Spreading Designs

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Abstract. In this paper, we investigate the issue using intelligent reflecting surface (IRS) to assist multi-user downlink satellite communication (SatCom) systems with spreading designs. Two transmission strategies for the public data and private data have been discussed, employing time division multiple access (TDMA) and code division multiple access (CDMA). The goal is to maximize the weighted sum rate (WSR) by optimizing the IRS phase shift matrix and spreading code vector (SCV). An optimization framework is designed based on the WMMSE algorithm and Taylor approximation to transform non-convex optimization problems equivalently. And we solve them using alternating iterations. The simulation results show: 1) the proposed optimization approach achieves at least a 17.66% improvement in WSR over conventional methods at the lowest received signal-to-noise ratio (SNR), 2) WSR shows an upward trend with the increase in the number of IRS reflecting elements increases, 3) WSR shows a downward trend with the increase in the length of SCV.

Keywords: Spreading code vector; Intelligent reflecting surface; Satellite communication; Weighted sum rate; Alternating optimization.

1. Introduction

In recent years, studies on the sixth generation (6G) wireless communication systems have received extensive attention due to high-speed and low-latency connectivity [1, 2]. Considering the intrinsic constraints of network capacity and coverage, it is difficult to cope with the explosive growth trend that requires high-speed and reliable global network access [3]. Under these requirements, satellite communication (SatCom) systems emerge as a critical enabler for establishing globally ubiquitous network infrastructures due to its unique advantage of seamless coverage in a wide area. In fields like radio broadcasting, the SatCom has been extensively employed [4].

However, the huge distance between spacecraft and Earth leads to significant path loss and a low signal-to-noise ratio (SNR) [5], along with signal blockage effects in some complex scenarios. They collectively constrain the SatCom performance. Intelligent reflecting surface (IRS), as a promising new technology, has been recently put forward which is able to effectively support the resolution of the issues above. IRS is a digitally-controlled meta-surface. It consists of numerous nearly passive, low-cost and low-energy consuming reflecting elements, each of which introduces specific phase shift to the signals impinging on it. By properly designing the phase shifts of each element, IRS can enhance signal reception at target destinations. This enables the artificial establishment of favorable propagation conditions without the need for any radio-frequency (RF) chains [6, 7, 8].

The complicated interference environment and scarce spectrum resource owing to massive connectivity are also critical challenges that must be addressed in the development of the SatCom. Therefore, it is of vital importance for the SatCom to develop effective strategies for multiple access (MA). There have been numerous researches on MA for the SatCom to boost performance in multi-user scenarios like [9] and [10]. Moreover, it's also significant to analyze and optimize the performance of multi-user SatCom links considering both IRS and MA, allowing for the combination of their advantages. However, the research on this topic remains quite limited, and in bandwidth-constrained environment, the data transmission rate of traditional spreading systems can no longer meet the growing demand. Inspired by [11], to address the external co-frequency interference faced by multi-user SatCom systems, spreading designs based on channel state information (CSI) can be employed to effectively reduce multiple complex interferences and to improve spectral efficiency.

In this paper, IRS is applied for multi-user downlink spreading systems for the SatCom. We consider transmission strategies of public data and private data based on designs of time division multiple access (TDMA) and code division multiple access (CDMA). Aiming at maximizing the weighted sum rate (WSR), a joint optimization algorithm of IRS phase shift matrix and CSI-based spreading code vector (SCV) is proposed. Finally, the proposed schemes are investigated via extensive simulations.

2. System Model and Problem Formulation

2.1 System Structure

A SatCom system, consisting of a primary satellite, a reflective IRS, a group of K ground users, and a base station (BS), is illustrated in Fig. 1. IRS is deployed with N reflecting components to establish reflective link. The downlink process is detailed below: The spreading signal transmitted by the satellite initially arrives at the IRS, which then reflects it to the user equipment. Considering practical application contexts, the direct links of SatComs are commonly destroyed by their long transmission distances and various blockage factors. In this case, it is reasonable to assume that the direct signal transmission link is disregarded in practical use. Additionally, interferences from BS to users are considered in the following sections.

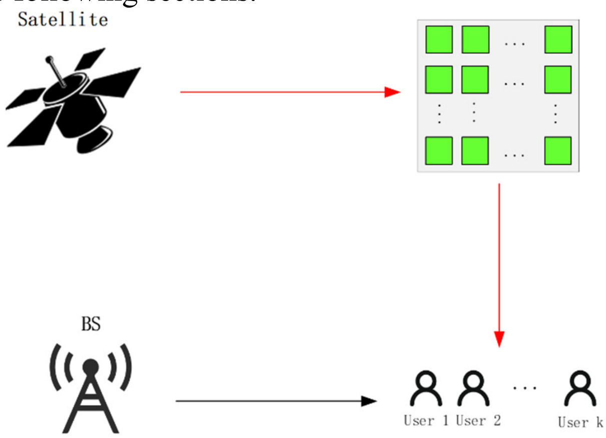

Fig. 1 System model.

Based on system solvability analysis, we build the following fundamental assumptions and channel modeling framework. First, we assume that full CSI with quasi-static characteristics is available for the satellite. Specifically, taking user-k as an example (the same for other users), the direct channel between the satellite and the IRS can be modeled as a complex matrix $\mathbf{H}_{\mathrm{sr}} \in \mathbb{C}^{N\times L}$, while the reflected channel between the IRS and user-k is illustrated by another complex matrix $\mathbf{H}_{\mathrm{ru,k}}^{H} \in \mathbb{C}^{L\times N}$, where L represents the length of the SCV. According to the physical properties of the IRS, we further assume that it meets the condition of ideal-passive reflection. To be precise, each reflecting component only brings about the controllable phase shift, without making the reflected signal weaken, which means the magnitude of reflection coefficient strictly satisfies $|\phi_{\mathrm{n}}| = 1\left(\forall n \in \{1,2,\cdots,N\}\right)$. Its phase matrix can be represented by $\mathbf{\Phi} = diag\left(e^{j\varphi_1}, e^{j\varphi_2}, \cdots, e^{j\varphi_N}\right)$ with $\phi_{\mathrm{n}} = e^{j\varphi_{\mathrm{n}}}$, where $j \triangleq \sqrt{-1}$ is used as the imaginary unit and the phase shift satisfies 4 in the continuous phase space.

Let s denote the desirable message sent by the satellite intended to be received by the specified user on the ground. Assume that the data stream being transmitted is independent and identically distributed (i.i.d.), which is a circularly symmetric complex Gaussian (CSCG) random variable with zero mean and unit variance, i.e. $s \sim \mathcal{CN}(0,1)$. At the downlink transmitting end, by applying

$\mathbf{c}=\left[c_1,c_2,\cdots,c_L\right]^T\in\mathbb{C}^{L\times1}$ as SCV of Length L to spread the initial data, the spreading signal emitted from the satellite is

$$\mathbf{x}=\mathbf{c}\mathrm{s}=\left[x_1,x_2,\cdots,x_L\right]^T. \tag{1}$$

Assume the maximum transmission power of the SatCom system is P_{t}, i.e. $E\left\{\left|x_{\mathrm{i}}\right|^2\right\}\le P_{\mathrm{t}}$, $\mathrm{i}=1,2,\cdots,L$, which is equivalent as $E\left\{\left|c_{\mathrm{i}}\right|^2\right\}\le P_{\mathrm{t}},\mathrm{i}=1,2,\cdots,L$. Here, $E\{\cdot\}$ denotes the operation of the expected value and $|\cdot|$ stands for the modulus of a complex number.

The spreading signal from the satellite experiences a multi-stage channel transmission process. The signal is first transmitted through the forward channel $\mathbf{H}_{\mathrm{sr}}$ from the satellite to the IRS, and then undergoes managed reflection by the phase matrix $\mathbf{\Phi}$ of the IRS. It ultimately reaches the target ground receiver via the reflected channel $\mathbf{H}_{\mathrm{ru,k}}^H$ from the IRS to user-k. According to this, the model of the received signal for the user-k is constructed as

$$\mathbf{y}_{\mathrm{k}}=\mathbf{H}_{\mathrm{ru,k}}^H\mathbf{\Phi}\mathbf{H}_{\mathrm{sr}}\mathbf{x}+\mathbf{n}_{\mathrm{k}}+\mathbf{v}_{\mathrm{k}}, \tag{2}$$

where the elements $n_{\mathrm{i}}\sim\mathcal{CN}\left(0,\sigma^2\right)$ in the noise vector denote additive white Gaussian noise (AWGN), characterized by a power spectral density of σ^2. In this model, the introduction of SCV results in the symbol period being expanded to L times the original period, which makes signal's bandwidth after spreading be $B=B_0/L$ as B_0 is original bandwidth. Therefore, let $B\sigma^2$ denotes the power of the noise vector $\mathbf{n}_k$. Interference component $\mathbf{v}_{\mathrm{k}}$ is modeled as co-channel interference to the ground BS.

2.2 Problem Formulation

This paper is aimed to enhance the overall performance of IRS-assisted multi-user downlink SatCom Systems, achieving flexible resource allocation through weight adjustment. Hence, given that α_{k} denotes the weight parameter for each user in the system, the objective is to optimize SCV and IRS's reflecting elements jointly to maximize the system's WSR, subject to the power constraints at the satellite transmitter and phase limitation of IRS. It should be noted that the weights for all users are positive, i.e. $\alpha_{\mathrm{k}}>0$. Consider signal transmission strategies public data and private data, with MA designs time division multiple access (TDMA) and code division multiple access (CDMA).

2.1.1 Model of Public Data

In this part, we focus on the common signal transmitted by the satellite, which carries the public message data stream composed of s_{c}. The public spreading data $\mathbf{x}_{\mathrm{c}}$, which has been processed uniformly by $\mathbf{c}_{\mathrm{c}}$, is reflected by IRS and received by all users on the ground. At the receiver, from (2), the signal received by the user-k is given as $\mathbf{y}_{\mathrm{c,k}}=\mathbf{H}_{\mathrm{ru,k}}^H\mathbf{\Phi}\mathbf{H}_{\mathrm{sr}}\mathbf{x}_{\mathrm{c}}+\mathbf{n}_{\mathrm{k}}+\mathbf{v}_{\mathrm{k}}$. With BS interference and noise all treated as noise, the public data SINR received by user-k is given as

$$\gamma_{\mathrm{c,k}}\left(\mathbf{c}_{\mathrm{c}},\mathbf{\Phi}\right)=\frac{\left|\mathbf{H}_{\mathrm{ru,k}}^H\mathbf{\Phi}\mathbf{H}_{\mathrm{sr}}\mathbf{c}_{\mathrm{c}}\right|^2}{\left|\mathbf{v}_{\mathrm{k}}\right|^2+B\sigma^2}. \tag{3}$$

According to Shannon's formula, the corresponding achievable rate of the public data at user-k can be up to

$$R_{\mathrm{c,k}}=B\log_2\left(1+\gamma_{\mathrm{c,k}}\right), \tag{4}$$

where $R_{\mathrm{c,k}}$ denotes transmission rate of user-k public data. Let $\alpha_{\mathrm{c,k}}$ denote the public weight for user-k. Accordingly, the maximization problem of WSR in this model is formulated as

$$\max_{\mathbf{c}_c,\mathbf{\Phi}} \sum_{k=1}^{K} \alpha_{c,k} R_{c,k}$$

$$s.t.\begin{cases} |\phi_n| = 1, n = 1,\cdots,N \\ E\left\{|c_{c,i}|^2\right\} \le P_t, i = 1,\cdots,L \\ R_{c,k} .. R_{c,k}^{th}, \end{cases} \tag{5}$$

where ensures that the user-k rate $R_{c,k}$ is no less than its threshold of minimum public rate set as $R_{c,k}^{th}$.

2.2.2 Model of Private Data

In order to satisfy the different communication demands of users, we consider the independent signal transmitted by the satellite, which carries the private message data stream composed of s_k. Under the scheme of TDMA, since each time slot is mutually independent [2], the satellite transmits private spreading data $\mathbf{x}_k$ via time division, which has been processed respectively by $\mathbf{c}_k$. Based on this, the multiple access interference (MAI) is effectively controlled, making it possible to divide the multi-user system into several independent single-user model for analysis. Then from (2), the signal received by the user-k is given as $\mathbf{y}_k = \mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{x}_k + \mathbf{n}_k + \mathbf{v}_k$. With BS interference and noise both treated as noise, the private data SINR received by user-k is given as

$$(\text{TDMA}): \gamma_k(\mathbf{c}_k, \mathbf{\Phi}) = \frac{\left|\mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{c}_k\right|^2}{|\mathbf{v}_k|^2 + B\sigma^2}. \tag{6}$$

So, the corresponding achievable rate of the private data at user-k can be up to

$$(\text{TDMA}): R_k = B\log_2(1+\gamma_k), \tag{7}$$

where R_k denotes transmission rate of user-k private data. In TDMA, we can treat multi-user performance as single-user performance to simplify the matter, let user-k rate R_k replace the total rate R, and formulate optimization problem as

$$(\text{TDMA}): \max_{\mathbf{c}_k,\mathbf{\Phi}} R_k$$

$$s.t.\begin{cases} |\phi_n| = 1, n = 1,\cdots,N \\ E\left\{|c_{k,i}|^2\right\} \le P_t, i = 1,\cdots,L \\ R_k .. R_k^{th}, \end{cases} \tag{8}$$

where ensures that the user-k rate R_k is no less than its threshold of minimum private rate set as R_k^{th}.

In contrast, under CDMA, multiple users accomplish concurrent transmission through shared time-domain resources. Using non-orthogonal SCV $\mathbf{c}_k$, we can get private spreading data $\mathbf{x}_k$. However, limited by the non-ideal cross-correlation characteristics of SCV, MAI inevitably occurs. Thus, (2) can be extended further owing to MAI to derive the private signal at the user as $\mathbf{y}_k = \mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{x}_k + \sum_{j=1,j\neq k}^{K} \mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{x}_j + \mathbf{n}_k + \mathbf{v}_k$. With MAI, BS interference and noise all treated as noise, the private data SINR received by user-k is given as

$$(\text{CDMA}): \gamma_k(\mathbf{c}_k, \mathbf{\Phi}) = \frac{\left|\mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{c}_k\right|^2}{\sum_{j=1,j\neq k}^{K} \left|\mathbf{H}_{ru,k}^H \mathbf{\Phi} \mathbf{H}_{sr} \mathbf{x}_j\right|^2 + |\mathbf{v}_k|^2 + B\sigma^2}. \tag{9}$$

And the corresponding achievable rate of the private data at user-k can be up to

$$\left(\text{CDMA}\right): R_{\text{k}} = B\log_2\left(1+\gamma_{\text{k}}\right). \qquad \textbf{(10)}$$

Let α_{k} denote the private weight for user-k under CDMA, and the maximization problem of WSR is given as

$$\left(\text{CDMA}\right): \max_{\mathbf{c}_{\text{k}},\boldsymbol{\Phi}} \sum_{\text{k}=1}^{K} \alpha_{\text{k}} R_{\text{k}}$$
$$s.t. \begin{cases} \left|\phi_{\text{n}}\right| = 1, \text{n} = 1,\cdots,N \\ \sum_{\text{k}=1}^{K} E\left\{\left|c_{\text{k,i}}\right|^2\right\} \le P_{\text{t}}, \text{i} = 1,\cdots,L \\ R_{\text{k}} .. R_{\text{k}}^{th}, \end{cases} \qquad \textbf{(11)}$$

where satellite's transmit power P_{t} is the sum of users' power at the same time slot, i.e. $\sum_{\text{k}=1}^{K} P_{\text{t,k}} \le P_{\text{t}}$.

3. WSR Maximization with WMMMSE Approach

In this section, we propose a solution framework based on WMMSE algorithm to solve the joint optimization problem (5), (8) and (11), which is highly non-convex and tightly coupled multivariable. By leveraging auxiliary variable and then reformulating the objective function, the NP-hard problem is equivalently transformed into a set of solvable convex optimization subproblems, and subsequently, an alternating optimization mechanism can be established to realize global convergence.

3.1 Problem Transformation

For notational convenience, the average power of the signal received by user-k in scenarios of public data, private TDMA data and CDMA data are denoted by T, and the power of both all of external interference and noise uniformly represented by I, with the detailed expression as (12). Hence, expression (4) can be derived into $R_{\text{c,k}} = B\log_2\left(\text{I}_{\text{c,k}}^{-1}\text{T}_{\text{c,k}}\right)$, and similarly, expressions (7) and (10) become $R_{\text{k}} = B\log_2\left(\text{I}_{\text{k}}^{-1}\text{T}_{\text{k}}\right)$.

$$\text{T}_{\text{c,k}} = \left|\mathbf{H}_{\text{ru,k}}^{H}\boldsymbol{\Phi}\mathbf{H}_{\text{sr}}\mathbf{c}_{\text{c}}\right|^2 + \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2, \text{I}_{\text{c,k}} = \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2$$
$$\left(\text{TDMA}\right): \text{T}_{\text{k}} = \left|\mathbf{H}_{\text{ru,k}}^{H}\boldsymbol{\Phi}\mathbf{H}_{\text{sr}}\mathbf{c}_{\text{k}}\right|^2 + \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2, \text{I}_{\text{k}} = \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2$$
$$\left(\text{CDMA}\right): \text{T}_{\text{k}} = \left|\mathbf{H}_{\text{ru,k}}^{H}\boldsymbol{\Phi}\mathbf{H}_{\text{sr}}\mathbf{c}_{\text{k}}\right|^2 + \sum_{\text{j}=1,\text{j}\ne\text{k}}^{K}\left|\mathbf{H}_{\text{ru,k}}^{H}\boldsymbol{\Phi}\mathbf{H}_{\text{sr}}\mathbf{c}_{\text{j}}\right|^2 + \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2, \qquad \textbf{(12)}$$
$$\text{I}_{\text{k}} = \sum_{\text{j}=1,\text{j}\ne\text{k}}^{K}\left|\mathbf{H}_{\text{ru,k}}^{H}\boldsymbol{\Phi}\mathbf{H}_{\text{sr}}\mathbf{c}_{\text{j}}\right|^2 + \left|\mathbf{v}_{\text{k}}\right|^2 + B\sigma^2$$

At the user-k receiving side, define $\mathbf{g}_{\text{c,k}}, \mathbf{g}_{\text{k}}$ as the equalizers of the public stream and the private stream, respectively. According to the actual CSI, the received signals at user-k are independently calculated to achieve both estimation of the original data and despread the stream, i.e. $\hat{\text{s}}_{\text{c,k}} = \mathbf{g}_{\text{c,k}}^{H}\mathbf{y}_{\text{c,k}}, \hat{\text{s}}_{\text{k}} = \mathbf{g}_{\text{k}}^{H}\mathbf{y}_{\text{k}}$. Then the mean square error (MSE) for the public and private parts of user-k is

$$\begin{aligned}\varepsilon_{\mathrm{c,k}} &= E\left\{\left|\mathrm{s_c} - \hat{\mathrm{s}}_{\mathrm{c,k}}\right|^2\right\} \\ &= 1 - 2\Re[\mathbf{g}_{\mathrm{c,k}}^H \mathbf{H}_{\mathrm{ru,k}}^H \mathbf{\Phi} \mathbf{H}_{\mathrm{sr}} \mathbf{c}_{\mathrm{c}}] + \left|\mathbf{g}_{\mathrm{c,k}}^H\right|^2 \mathrm{T}_{\mathrm{c,k}} \\ \varepsilon_{\mathrm{k}} &= E\left\{\left|\mathrm{s_k} - \hat{\mathrm{s}}_{\mathrm{k}}\right|^2\right\} \\ &= 1 - 2\Re[\mathbf{g}_{\mathrm{k}}^H \mathbf{H}_{\mathrm{ru,k}}^H \mathbf{\Phi} \mathbf{H}_{\mathrm{sr}} \mathbf{c}_{\mathrm{k}}] + \left|\mathbf{g}_{\mathrm{k}}^H\right|^2 \mathrm{T}_{\mathrm{k}}.\end{aligned} \tag{13}$$

Define $w_{\mathrm{c,k}}, w_{\mathrm{k}}$ as the auxiliary weight of the public stream and the private stream, respectively. The augmented weighted mean square error (WMSEs) are given as follows

$$\begin{aligned}\xi_{\mathrm{c,k}} &\triangleq w_{\mathrm{c,k}}\varepsilon_{\mathrm{c,k}} - \log_2 w_{\mathrm{c,k}} \\ \xi_{\mathrm{k}} &\triangleq w_{\mathrm{k}}\varepsilon_{\mathrm{k}} - \log_2 w_{\mathrm{k}}.\end{aligned} \tag{14}$$

By solving $\frac{\partial \xi_{\mathrm{c,k}}}{\partial \mathbf{g}_{\mathrm{c,k}}^H} = 0, \frac{\partial \xi_{\mathrm{k}}}{\partial \mathbf{g}_{\mathrm{k}}^H} = 0$, we gain the optimum equalizers as

$$\begin{aligned}\left(\mathbf{g}_{\mathrm{c,k}}^H\right)^* &= \left(\mathbf{H}_{\mathrm{ru,k}}^H \mathbf{\Phi} \mathbf{H}_{\mathrm{sr}} \mathbf{c}_{\mathrm{c}}\right)^H \mathrm{T}_{\mathrm{c,k}}^{-1} \\ \left(\mathbf{g}_{\mathrm{k}}^H\right)^* &= \left(\mathbf{H}_{\mathrm{ru,k}}^H \mathbf{\Phi} \mathbf{H}_{\mathrm{sr}} \mathbf{c}_{\mathrm{k}}\right)^H \mathrm{T}_{\mathrm{k}}^{-1},\end{aligned} \tag{15}$$

where characterizes a linear correlation with the despreading vector, revealing that the optimum equalizer design criterion strictly mathematically equates to the despreading process. Substituting (15) into (13), simplify and get minimum mean square error (MMSE), i.e. $\varepsilon_{\mathrm{c,k}}^{MMSE} = \mathrm{I}_{\mathrm{c,k}}^{-1}\mathrm{T}_{\mathrm{c,k}}$, $\varepsilon_{\mathrm{k}}^{MMSE} = \mathrm{I}_{\mathrm{k}}^{-1}\mathrm{T}_{\mathrm{k}}$. And then we have $\xi_{\mathrm{c,k}} = w_{\mathrm{c,k}}\varepsilon_{\mathrm{c,k}}^{MMSE} - \log_2 w_{\mathrm{c,k}}$, $\xi_{\mathrm{k}} = w_{\mathrm{k}}\varepsilon_{\mathrm{k}}^{MMSE} - \log_2 w_{\mathrm{k}}$. On this basis, solve $\frac{\partial \xi_{\mathrm{c,k}}}{\partial w_{\mathrm{c,k}}} = 0, \frac{\partial \xi_{\mathrm{k}}}{\partial w_{\mathrm{k}}} = 0$, and the optimum auxiliary weights of MMSE can be given as

$$\begin{aligned}\left(w_{\mathrm{c,k}}\right)^* &= (\varepsilon_{\mathrm{c,k}}^{MMSE})^{-1} \\ \left(w_{\mathrm{k}}\right)^* &= (\varepsilon_{\mathrm{k}}^{MMSE})^{-1}.\end{aligned} \tag{16}$$

Substituting (16) into MMSEs, the relationship between rate and WMMSE is finally derived as

$$\begin{aligned}\min_{\mathbf{g}_{\mathrm{c,k}}^H, w_{\mathrm{c,k}}} \xi_{\mathrm{c,k}} &= 1 - \log_2 (\varepsilon_{\mathrm{c,k}}^{MMSE})^{-1} = 1 - \frac{R_{\mathrm{c,k}}}{B} \\ \min_{\mathbf{g}_{\mathrm{k}}^H, w_{\mathrm{k}}} \xi_{\mathrm{k}} &= 1 - \log_2 (\varepsilon_{\mathrm{k}}^{MMSE})^{-1} = 1 - \frac{R_{\mathrm{k}}}{B}\end{aligned} \tag{17}$$

Based on the theoretical analysis above, an objective optimization function that is linearly equivalent to WSR can be found. Furthermore, for nonlinear constrain $\left|\phi_{\mathrm{n}}\right| = 1, n = 1, \cdots, N$, Taylor expansion is applied to approximate $\phi_{\mathrm{n}} = e^{j\varphi_{\mathrm{n}}}$ into $\phi_{\mathrm{n}} \approx e^{j\varphi^{[n-1]}}\left[1 + j\left(\varphi^{[n]} - \varphi^{[n-1]}\right)\right]$ so that it can be transformed into a linear constraint with respect to angles φ, where $\varphi^{[n]}$ and $\varphi^{[n-1]}$ denote the phase shift of IRS in the current and last iterations in the process of the iterative optimization. Now the equivalent optimization problems are shown as follows.

Firstly, consider the model of public data. Combined with (14), the optimization problem (8) is reformulated as

$$\min_{\mathbf{g}_{c,k}^{H}, w_{c,k}, \mathbf{\Phi}, \mathbf{c}_{c}} \sum_{k=1}^{K} \alpha_{c,k} \xi_{c,k}$$
$$s.t. \begin{cases} \varphi_{n} \in [0, 2\pi], n = 1, \cdots, N \\ E\left\{ \left| c_{c,i} \right|^{2} \right\} \leq P_{t}, i = 1, \cdots, L \\ 1 - \xi_{c,k} .. B^{-1} R_{c,k}^{th}. \end{cases} \tag{18}$$

Then consider the private of public data combined with (14). Under the scheme of TDMA, the new optimization problem transformed from (8) is shown as

$$(\mathrm{TDMA}): \min_{\mathbf{g}_{k}^{H}, w_{k}, \mathbf{\Phi}, \mathbf{c}_{k}} \xi_{k}$$
$$s.t. \begin{cases} \varphi_{n} \in [0, 2\pi], n = 1, \cdots, N \\ E\left\{ \left| c_{k,i} \right|^{2} \right\} \leq P_{t}, i = 1, \cdots, L \\ 1 - \xi_{k} .. B^{-1} R_{k}^{th}. \end{cases} \tag{19}$$

For the scheme of CDMA, the WSR maximization problem (11) is equivalently transformed into

$$(\mathrm{CDMA}): \min_{\mathbf{g}_{k}^{H}, w_{k}, \mathbf{\Phi}, \mathbf{c}_{k}} \sum_{k=1}^{K} \alpha_{k} \xi_{k}$$
$$s.t. \begin{cases} \varphi_{n} \in [0, 2\pi], n = 1, \cdots, N \\ \sum_{k=1}^{K} E\left\{ \left| c_{k,i} \right|^{2} \right\} \leq P_{t}, i = 1, \cdots, L \\ 1 - \xi_{k} .. B^{-1} R_{k}^{th}. \end{cases} \tag{20}$$

The reformulated problem consists of a decomposition into a set of convex subproblems, which are easy to tackle.

3.2 Optimal Solution of WSR

All three of the aforementioned problems can be efficiently addressed using alternating iterations algorithm. To begin with, SCV and phase matrix of IRS should be provided with appropriate initial values. In a given iteration, the SCV $\mathbf{c}$ and IRS's phase matrix $\mathbf{\Phi}$ in last iteration are firstly fixed. And using WMMSE approach, the closed-form optimal solution for the equalizer $\mathbf{g}$ and the auxiliary weight w is found sequentially through (15) and (16). Subsequently, with fixed $\mathbf{g}$ and w, $\mathbf{\Phi}$ is obtained by addressing the convex optimization problem regarding to phase shifts φ. And then, the transmission channel is reformulated. Based on updated CSI, $\mathbf{c}$ can be dynamically adapted using the CVX convex optimization toolbox, achieving joint improvement of interference suppression and spectral efficiency. At last, the WSR is calculated, and the iteration repeats until the results converge. Algorithm 1 summarizes the pseudo-code implementation, where ò denotes the preset convergence tolerance serving as the algorithmic stopping criterion.

Algorithm 1 Alternating Optimization Algorithm

Initialization $n \leftarrow 0$, $\mathbf{c}^{[n]}$, $\mathbf{\Phi}^{[n]}$, $\mathbf{WSR}^{[n]}$
repeat
    $n \leftarrow n+1$
    $\mathbf{g}^{[n]} \leftarrow \mathbf{g}^{*}\left(\mathbf{c}^{[n-1]}, \mathbf{\Phi}^{[n-1]}\right)$
    $w^{[n]} \leftarrow w^{*}\left(\mathbf{c}^{[n-1]}, \mathbf{\Phi}^{[n-1]}\right)$

6: Update $\mathbf{\Phi}^{[n]}$ using $\mathbf{c}^{[n-1]}$, $w^{[n]}$ and $\mathbf{g}^{[n]}$

7: Update $\mathbf{c}^{[n]}$ using $\mathbf{\Phi}^{[n]}$, $w^{[n]}$ and $\mathbf{g}^{[n]}$

8: Calculate $\mathbf{WSR}^{[n]}$

9: **Until** $\left|\mathbf{WSR}^{[n]} - \mathbf{WSR}^{[n-1]}\right| \le \epsilon$

4. Numerical Results

In this section, numerical results under multiple scenarios are investigated to evaluate the effectiveness of our proposed algorithm with different parameters. An IRS-assisted multi-user downlink SatCom system with spreading designs is considered, consisting of a satellite, one reflecting IRS and 3 users. Suppose that sum of users' weights is set to 1, that is, $\alpha_1 + \alpha_2 + \alpha_3 = 1$. Specifically, the users' weights is configured as $\alpha = [0.2, 0.3, 0.5]$. Let the users' rate limitation in any model be uniformly zero, i.e. $R^{th} = 0$, and the bandwidth of the original signal $B_0 = 10\text{Hz}$. Concerning algorithm parameters, we use 100 Monte Carlo simulations, set maximum number of iterations as 1000 and define the algorithm tolerance as 10^{-6}. Initialize the SCV and IRS phase with random values.

First, we compared the optimized WSR with the pre-optimization WSR as shown in Fig. 2, which has a SCV's length of 7 and 16 reflecting elements on IRS. To establish a rigorous performance benchmark for subsequent optimization comparisons, m-sequence is adopted as the unoptimized spreading code.

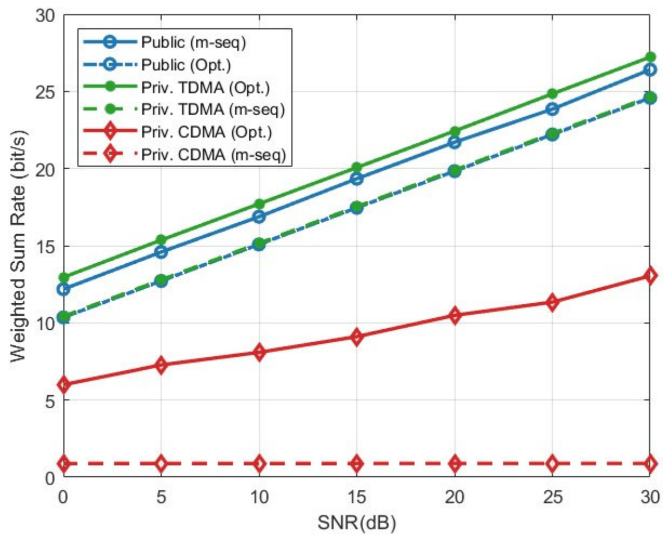

Fig. 2 WSR versus SNR with optimization or non-optimization.

Fig. 2 also shows the simulation results of WSR with different SNR. Upon comprehensive evaluation, the optimized WSR outperforms the WSR with m-sequence. And as SNR increases, WSR shows a steady trend of growth. Specifically, the WSR improvement ratio at 0dB SNR is quantified to assess the algorithm's performance under low-SNR conditions. As shown in Fig. 2, WSR corresponding to public data achieves a 17.66% WSR improvement ratio at 0 dB SNR (Δ WSR = 1.8282bit/s), from 10.3545bit/s to 12.1827bit/s . With aspect to the private TDMA data, the optimized WSR reaches 12.9022bit/s , which realizes a 24.27% performance improvement at 0dB SNR (Δ WSR= 2.5200bit/s) compared to the benchmark scheme of m-sequences (10.3822bit/s). But for the private CDMA data, the interference signals containing cross-user interference components impose significant impacts on the optimization process, leading to higher performance differences in the optimization scheme compared with the conventional transmission approach (Δ WSR = 5.1048bit/s @ SNR= 0dB). As shown in the unoptimized performance curves, the baseline system exhibits severe performance degradation with WSR values substantially regardless of the SNR.

Next, the performance of the proposed algorithm is further analyzed under different parameters with a fixed SNR of $20dB$. Fig. 3 illustrates the relationship between WSR and number of IRS reflecting elements when the length of SCV L is set to 7. It can be observed that as the number of IRS reflecting elements increases, WSR shows an upward trend. This is due to the fact that the more reflecting elements are provided, the more signal reflection paths will be built, thereby enhancing the sum rate potential of multi-user SatCom links under the given transmission conditions.

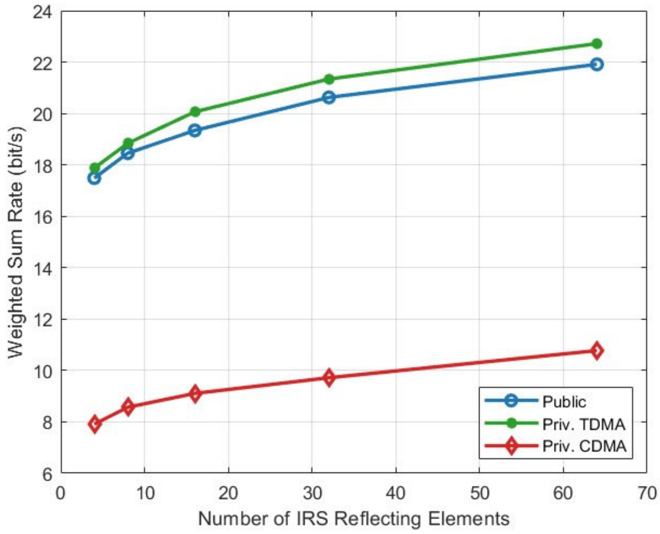

Fig. 3 WSR versus number of IRS reflecting elements.

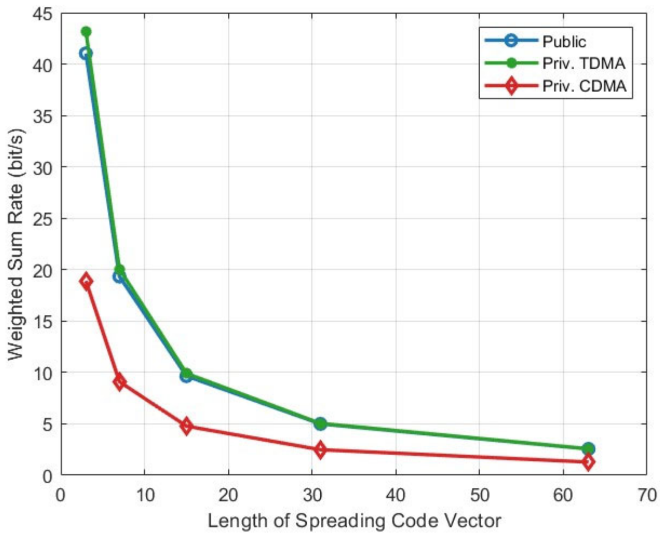

Fig. 4 WSR versus length of SCV.

Consider changing the length of SCV with a fixed 16 reflecting elements number on IRS. As depicted in Fig. 4, WSR shows a downward trend with the increase in the length of SCV. This occurs because, as the vector length of SCV increases, SatCom systems achieve enhanced anti-jamming performance at the expense of reduced transmission rates. Therefore, to strike an optimal balance between transmission rate and anti-jamming capability, selecting an appropriate vector length is critical. The analysis provided above serves as a reference for the engineering design of communication systems.

5. Conclusion

In this paper, we have developed an IRS-Assisted Downlink Multi-user SatCom System with spreading designs as well as a joint optimization approach of IRS phase shift matrix and CSI-based SCV. The optimization performance in different scenarios was investigated through simulations. Aimed to maximize the WSR of the users, we transformed the optimization problem from non-convex to convex by an approach based on WMMSE and Taylor approximation, and then solved it using alternating iterations. In addition, it's essential for further practical applications to analyze the effects of parameter changes in the number of IRS reflecting elements and length of SCV.

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