Reconfigurable Intelligent Surface-assisted Space-Time Shift Keying

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Reconfigurable Intelligent Surface-assisted Space-Time Shift Keying

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Abstract

Reconfigurable Intelligent Surface (RIS), which improves the performance of wireless communication systems by controlling the reflection/s-catttering characteristics of incident waves without increasing energy consumption, appears as a promising candidate for future wireless communication systems. In this paper, a RIS-based space-time shift keying (STSK) scheme is proposed. On the one hand, the reflection phase shifts at RIS are optimized by the channel gain maximization criterion to obtain better RIS-STSK performance; on the other hand, the theoretical average bit error probability (ABEP) of the RIS-STSK scheme is derived using a semi-analytical probabilistic approach. In addition, for improving the performance gain of the RIS-STSK scheme, an improved genetic algorithm is designed to assist the optimization of the reflection phase shifts at RIS. Simulation results show that the proposed RIS-STSK scheme performs better than the STSK scheme, and the proposed improved genetic algorithm can significantly enhance the performance gain of RIS-STSK.

Keywords: RIS, STSK, ABEP, optimization, reflection phase shift
1 Introduction

Recently, reconfigurable intelligent surface (RIS)-assisted wireless communication technology has attracted the attention of researchers and scholars [1-3]. With extremely low hardware cost and energy consumption [4], RIS is considered to be one of the key technologies promising to overcome the energy efficiency problems of the next-generation wireless communication technologies [5] [6]. An RIS is an artificial plane surface composed of a large number of reflective elements, each reflective element reflects the incident signal by applying an adjustable phase shift. In addition, since no new signal is generated at the RIS side, and with no contamination of the impinging signal with reception thermal noise [7], so there will be no performance loss at the RIS. The current research on RIS-assisted wireless communication technology is at the beginning stage, mainly by adjusting the reflected beam to improve performance gain [8-10]. For example, in the combination of RIS and modulation schemes, the specific method is to adjust the reflection phase shifts to change the transmission direction of the channel link or transmit its own information bits [11].

In terms of RIS changing the channel link transmission direction, E. Basar et al first applied RIS to the well-known index modulation (IM) [12], proposing the RIS-assisted spatial shift keying (SSK) and RIS-assisted spatial modulation (SM) schemes. These schemes were based on maximizing the received signal-to-noise ratio (SNR) to adjust the RIS reflection phase shifts, which significantly enhances the performance gains of SSK and SM schemes. Z. Yigit et al proposed a low-complexity reflection phase shift optimization algorithm based on cosine similarity, and then optimized the RIS-assisted multiple-input multiple-output (MIMO) system by maximizing the overall channel gain of the system [13]. However, there is currently no combination of RIS and space-time shift keying (STSK) schemes. As a unified MIMO architecture, STSK carries information through the index of the active dispersion matrix (DM) within the duration of each STSK block [14] [15]. Dispersion matrices (DMs) can not only realize the functions of SM and SSK modulation technologies by its different designs, but also achieve a better trade-off between diversity gain and multiplexing gain by optimizing its number and size. However, its implementation of large-scale antennas is still limited by hardware cost and energy consumption.

To this end, the RIS-based STSK scheme is proposed with the intention of realizing the low-power design of STSK technology in wireless communication systems. First, we proposed a RIS-STSK scheme with the RIS being a relay node, which is equipped with several passive reflection elements to reflect the incident signal, and we employ the cosine similarity theorem algorithm to optimize the reflected phase shifts at the RIS. Moreover, a semi-analytical expression for the average bit error probability (ABEP) of the RIS-STSK scheme is derived. Second, to achieve a good performance of the proposed RIS-STSK scheme, an improved genetic algorithm is designed to assist the optimization of the reflected phase shifts at the RIS. In the genetic algorithm,
the channel gain maximization criterion is used as the fitness value, and the randomly generated reflected phase shifts are used as the initial population to obtain the reflected phase shifts with lower bit error rate (BER) performance through an improved evolution and selection process.

The remaining of this letter is organized as follows. Section 2 presents the RIS-STSK scheme. Section 3 presents the optimization of RIS reflection phase shifts based on improved genetic algorithm. The performance analysis is presented in Section 4, and the numerical and simulation results are detailed in Section 5. Finally, conclusions are drawn in Section 6.

2 RIS-STSK scheme

2.1 System model

In this section, the RIS-STSK system model is presented. As shown in Fig. 1, in the proposed system, the transmitter and receiver have $T_x$ transmit antennas and $R_x$ receive antennas, respectively. Besides, the dispersion matrix set (DMS) $\mathbf{A}_q \in \mathbb{C}^{T_x \times T_s} (q = 1, \cdots, Q)$ is defined at the transmitter side according to the rank and determinant criterion [14] and each DM satisfies the power constraint $\text{tr} \left[ \mathbf{A}_q \cdot (\mathbf{A}_q)^H \right] = T_s$, where $T_s$ is the number of columns of the DM, indicating the duration of the STSK code word, $\text{tr} \left( \cdot \right)$ stands for trace operation, $(\cdot)^H$ stands for Hermitian transpose operations. $N$ passive reflective elements are configured at the RIS, and the phase shifts of the reflective elements are adjusted by the cosine similarity theorem algorithm based on the channel gain maximization criterion [13], $\Phi = [\beta_1 \exp (j\phi_1), \beta_2 \exp (j\phi_2), \cdots, \beta_N \exp (j\phi_N)]^T \in \mathbb{C}^{N \times 1}$ is the RIS reflection coefficient vector, where $\phi_i \in [-\pi, \pi]$ and $\beta_i \in (0, 1]$ are the phase shifts and amplitude reflection coefficients of the reflecting elements, respectively, $(\cdot)^T$ stands for transposition, and for simplicity, let $\beta_i = 1$, $i \in \{1, 2, \cdots, N\}$. Let $\mathbf{H} \in \mathbb{C}^{N \times T_x}$ and $\mathbf{F} \in \mathbb{C}^{N \times R_x}$ be the channel matrices from the transmitter to the RIS and from the RIS to the receiver, respectively, with each element having a zero mean and unit variance of independent and identically distributed (i.i.d.) complex Gaussian distribution $\mathcal{CN}(0, 1)$.

For the $j$th transmission, the number of bits carried by the STSK code word
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is $B^{(j)} = B_1^{(j)} + B_2^{(j)}$, in which $B_1^{(j)} = \log_2 Q$ bits are used to activate the DM $A_q^{(j)}$, $j \in \{1, \cdots, Q\}$, $B_2^{(j)} = \log_2 L$ bits are used to map the constellation symbols $s_l^{(j)}$, $l \in \{1, \cdots, L\}$, and $L$ is the modulation symbol order. The $j$th STSK transmit symbol can be expressed as

$$S(j) = S_{q,l}^{(j)} = s_l^{(j)}A_q^{(j)}.$$ (1)

At the received end D, the received signal can be expressed as

$$Y(j) = F^H(j)G(j)H(j)S(j) + Z(j),$$ (2)

where $G(j) = \text{diag}(\Phi(j)) \in \mathbb{C}^{N \times N}$, $Z(j) \in \mathbb{C}^{R \times T_s}$ denote the additive Gaussian noise (AWGN) matrix and each element follows the distribution $CN(0, N_0)$, where $N_0$ is the complex noise variance for each time slot. To implement single-stream maximum likelihood (ML) detection at the receiver side, the above equation can be transformed into the following linear equivalent system model by the $\text{vec} (\cdot)$ operation

$$\bar{Y}(j) = \bar{F}^H(j)\bar{G}(j)\bar{H}(j)\chi K(j) + \bar{Z}(j),$$ (3)

where

$$\bar{Y}(j) = \text{vec}(Y(j)) \in \mathbb{C}^{R T_s \times 1},$$ (4)

$$\bar{F}^H(j) = I \otimes F^H(j) \in \mathbb{C}^{R_s T_s \times NT_s},$$ (5)

$$\bar{G}(j) = I \otimes G(j) \in \mathbb{C}^{NT_s \times NT_s},$$ (6)

$$\bar{H}(j) = I \otimes H(j) \in \mathbb{C}^{NT_s T_s \times T_s},$$ (7)

$$\bar{Z}(j) = \text{vec}(Z(j)) \in \mathbb{C}^{R_s T_s \times 1},$$ (8)

$$\chi = [\text{vec}(A_1), \cdots, \text{vec}(A_Q)] \in \mathbb{C}^{T_s T_s \times Q},$$ (9)

$$K(j) = \begin{bmatrix} 0, \ldots, 0, s_l^{(j)}, 0, \ldots, 0 \\ \vdots \\ 0, \ldots, 0, 0, \ldots, 0 \end{bmatrix}_{q-1 \times Q-q}^T,$$ (10)

where $I \in \mathbb{C}^{T_s \times T_s}$ is the unit matrix and $\otimes$ stands for Kronecker product operation.

At the receiving end, single-stream ML detection is

$$\left(\hat{q}, \hat{l}\right) = \arg\min_{q,l} \left\| \bar{Y}(j) - \bar{F}^H(j)\bar{G}(j)\bar{H}(j)\chi K_{q,l} \right\|^2$$

$$= \arg\min_{q,l} \left\| \bar{Y}(j) - s_l^{(j)}(\bar{F}^H(j)\bar{G}(j)\bar{H}(j)\chi)_q \right\|^2.$$ (11)
2.2 Optimization of reflection phase shifts at RIS

In the proposed RIS-STSK scheme, the channel matrix $C \in C^{R_s \times T_s}$ from the transmitter to the receiver is

$$C = F^H G H = \sum_{i=1}^{N} f_i^H e^{j\phi_i} h_i,$$  \hspace{1cm} (12)

where $f_i^H$ and $h_i$ are the $i$th column and $i$th row of channel matrices $F^H$ and $H$, respectively. The channel gain maximization problem can be defined as

$$\max_{\phi_i} \|C\| = \max_{\phi_i} \left\| \sum_{i=1}^{N} f_i^H e^{j\phi_i} h_i \right\|. \hspace{1cm} (13)$$

The upper bound on the achievable channel gain is

$$\|C\| = \left\| \sum_{i=1}^{N} f_i^H e^{j\phi_i} h_i \right\| \leq \sum_{i=1}^{N} \|f_i^H\| \|h_i\|. \hspace{1cm} (14)$$

From the above equation, it can be seen that there exists an optimal reflection coefficient vector $\Phi$ that satisfies the channel gain maximization. Therefore, in this paper, the reflection phase shifts at RIS is optimized by the cosine similarity theorem algorithm in [13].

3 Optimization of RIS reflection phase shifts based on improved genetic algorithm

In order to improve the performance gain of the above RIS-STSK scheme, an improved genetic algorithm is designed to assist the optimization of reflection phase shifts. The flow chart of the genetic algorithm is shown in Fig. 2. The initial population $\Phi (k)$ consists of randomly generated $N_{pop}$ sets of reflection coefficient vectors, $k=1, 2, ..., N_{pop}$, each containing $N$ reflective phase shifts. And the channel gain corresponding to Eq. (14) is used as the fitness value $\Psi (k)$ of each individual, $k=1, 2, ..., N_{pop}$. The proposed selection and evolution operations are described below in detail.

3.1 Select Operation

Considering the complexity of algorithm implementation, this paper uses a tournament selection strategy. The specific operation steps are as follows.

- Determine the number of individuals per selection $N_{pop}/10$;
- Randomly select $N_{pop}/10$ reflection coefficient vectors from the population (each reflection coefficient vectors has the same probability to be selected)
to form a group, and select the reflection coefficient vector with the highest channel gain into the next generation population as $\Phi_{\text{newpop1}}^t(k)$. At the same time, the fitness value $\Psi_{\text{newpop1}}^t(k)$ of each individual in the new population is obtained, where $t$ is the number of iterations, and $\text{newpop1}$ represents the population after the selection operation;

• Repeat the previous steps until the size of the new population $\Phi_{\text{newpop1}}^t(k)$ reaches the size of the original population.

3.2 Improved evolutionary operation

In order to achieve fast convergence of the algorithm while obtaining reflection coefficient vector with lower BER performance, the following evolutionary operation is designed.

3.2.1 Crossover and Replication

A single-point crossover strategy is designed as shown in Fig. 3, where each subblock represents a reflection phase shift, and the subblocks of the same color form a reflection coefficient vector. All reflection coefficient vectors are grouped in order, two reflection coefficient vectors in each group, as paternal reflection coefficient vector $\Phi_{\text{newpop1}}^t(k)$ and maternal reflection coefficient vector $\Phi_{\text{newpop1}}^t(k+1)$ respectively. Then perform a crossover operation as...
follows with probability of $P_c$. Randomly generate a number $1 \sim N$ as the Cross position $u$, then

$$\begin{align*}
\Phi_t^{newpop_1}(k) &= \left[ \Phi_t^{newpop_1}(k)[1 : u] : \Phi_t^{newpop_1}(k+1)[u+1 : N] \right] \quad \text{if} \; (\text{rand} < P_c), \\
\Phi_t^{newpop_2}(k+1) &= \left[ \Phi_t^{newpop_1}(k+1)[1 : u] : \Phi_t^{newpop_1}(k)[u+1 : N] \right]
\end{align*}$$

(15)

and for the paternal and maternal reflection coefficient vector that does not satisfy the crossover probability $P_c$, it is replicated by the following operation:

$$\begin{align*}
\Phi_t^{newpop_2}(k) &= \Phi_t^{newpop_1}(k+1) \\
\Phi_t^{newpop_2}(k+1) &= \Phi_t^{newpop_1}(k+1)
\end{align*}$$

if $\left( \Psi_t^{newpop_1}(k) < \Psi_t^{newpop_1}(k+1) \right)$,

(16)

where $newpop_2$ represents the population after the crossover strategy, $k = 1, 3, \ldots, N_{pop} - 1$, and $\text{rand}$ is randomly generated 0-1 number.

3.2.2 Variation

The variation of the reflection phase shifts for each reflection coefficient vector with probability $P_m$ is performed as follows

$$\Phi_t^{newpop_3}(k)[i] = \begin{cases} 
\Phi_t^{newpop_2}(k)[i], & \text{if} \; (\text{rand} > P_m) \\
\exp(j\phi)_{\text{random}}, & \text{if} \; (\text{rand} < P_m)
\end{cases}$$

(18)
where $i \in \{1, 2, ..., N\}$, newpop3 represents the population after the variation operation, rand is randomly generated 0-1 number and $\exp(j\phi)_{\text{random}}$ is a random reflection phase shift.

4 Performance Analysis

In this section, the theoretical ABEP analysis is performed for the proposed RIS-STSK scheme, and according to [17], the upper bound expression for the ABEP of the proposed scheme is shown below:

$$P_e \leq \frac{1}{B^2 B^2} \sum_{\bar{S}} \sum_{\hat{S}} P\left( \bar{S} - \hat{S} \right) e \left( \bar{S} - \hat{S} \right),$$  \hspace{1cm} (19)

where $\hat{S} = s_i \bar{A}_q$, $P\left( \bar{S} - \hat{S} \right)$ is the unconditional pairwise error probability (PEP), and $e \left( \bar{S} - \hat{S} \right)$ is the number of error bits of the corresponding PEP events. To obtain the PEP expression, the system conditional PEP (CPEP) $P\left( \bar{S} - \hat{S} | C \right)$ is derived from the Q function

$$P\left( \bar{S} - \hat{S} | C \right) = Q \left( \sqrt{\frac{\Omega}{2\sigma^2}} \right),$$  \hspace{1cm} (20)

where $\sigma^2 = N_0$, and

$$\Omega = \|C \left( \bar{S} - \hat{S} \right) \|^2$$

$$= vec(C^H)^H (\Delta \otimes I_{R_x}) vec(C^H),$$  \hspace{1cm} (21)

where

$$\Delta = \left( \bar{S} - \hat{S} \right) \left( \bar{S} - \hat{S} \right)^H.$$  \hspace{1cm} (22)

Therefore, considering $Q \left( x \right) = \frac{1}{\pi} \int_0^{\pi/2} \exp \left( -x^2/2\sin^2 \theta \right) d\theta$, the CPEP corresponding to Eq. (20) can be written as

$$P\left( \bar{S} - \hat{S} | C \right) = \frac{1}{\pi} \int_0^{\pi/2} \int_{\Omega} \exp \left( -\varphi \frac{\Omega}{4\sin^2 \theta} \right) f_\Omega (\Omega) d\Omega d\theta,$$  \hspace{1cm} (23)

where $\varphi = 1/N_0$. Then, averaging (23) over the matrix $C$ through moment generating function (MGF) approach $M \left( x \right) = \int_{\Omega} e^x f_\Omega (\Omega) d\Omega$, and results in the following PEP expression

$$P\left( \bar{S} - \hat{S} \right) = \frac{1}{\pi} \int_0^{\pi/2} M_\Omega \left( \frac{-\varphi}{4\sin^2 \theta} \right) d\theta,$$  \hspace{1cm} (24)
where, the MGF of $m^H D m$, for any Hermitian $D$ matrix[18], is given by

$$M(x) = \exp \left( \frac{x \bar{m}^H D (I - x C_m D)^{-1} \bar{m}}{\det(I - x C_m D)} \right), \quad (25)$$

where $\bar{m}$ is the mean vector and $C_m$ is the covariance matrix of the vector $m$.

In the scheme proposed in this paper, $D = \Delta \otimes I_{R_x}, m = vec(C^H)$. $\bar{m} = \mu N1$ and $C_m = N I$ are the mean vector and covariance matrix corresponding to the Gaussian vector $m = vec(C^H)$, respectively, where $\mu = \frac{(1+2R_x)(1+2R_y)}{13}$, $1$ is the full 1 column vector, $I$ is the unit matrix therefore. Therefore, the PEP of the system is

$$P(S - \hat{S}) = \frac{1}{\pi} \int_0^{\pi/2} \frac{\exp(-\bar{m}^H \Delta \frac{\varphi}{4 \sin 2\theta} C_m D^{-1} \bar{m})}{\det(I + \Delta \frac{\varphi}{4 \sin 2\theta} C_m D)} d\theta. \quad (26)$$

To further simplify the calculation of (26), use the characteristic function in (20) by [19]

$$Q(x) \approx \frac{1}{12} e^{-\frac{x^2}{2}} + \frac{1}{4} e^{-\frac{2x^2}{3}}, \quad (27)$$

Then, the value of $P(S - \hat{S})$ can be approximately expressed by

$$P(S - \hat{S}) = \int_\Omega \left( \frac{1}{12} e^{-\frac{\Omega^2}{2}} + \frac{1}{4} e^{-\frac{3\Omega^2}{4}} \right) f_\Omega(\Omega) d\Omega$$

$$= \frac{1}{12} M_\Omega(-\frac{\varphi}{2}) + \frac{1}{4} M_\Omega(-\frac{\varphi}{3})$$

$$= \frac{\exp(-\bar{m}^H \frac{\varphi}{2} D (I + \frac{\varphi}{2} C_m D)^{-1} \bar{m})}{2 \det(I + \frac{\varphi}{2} C_m D)} + \frac{\exp(-\bar{m}^H \frac{3\varphi}{4} D (I + \frac{3\varphi}{4} C_m D)^{-1} \bar{m})}{4 \det(I + \frac{3\varphi}{4} C_m D)} \quad (28)$$

5 Simulation results

In this section, the BER performance of the proposed RIS-STSK scheme is demonstrated, along with simulation results for the optimization of the improved genetic algorithm-assisted reflection phase shift. Note that all results are obtained with different $R_x \times T_x$ antenna configurations and BPSK modulation ($L = 2$) with flat Rayleigh fading channel. For the simulations with the same antenna configuration, the DMS used are the same as the DMS generated based on the rank and determinant criterion with $Q = 2$. For simplicity, the RIS-STSK schemes using the cosine similarity theorem algorithm and the improved genetic algorithm are hereinafter referred to as RIS-STSK-acos and RIS-STSK-GA, respectively.

In Figs. 4(a) and 4(b), the theoretical BER performance of the proposed RIS-STSK-acos scheme is compared with the simulated performance for the antenna configurations of $2 \times 2$ and $5 \times 3$ with different numbers of reflecting elements $N$, respectively. It can be seen that the theoretical BER performance
Table 1 An Example of a Table

<table>
<thead>
<tr>
<th>$N$</th>
<th>Population size</th>
<th>Number of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>32</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>64</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>128</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

$P_c = 0.95$

$P_m = 0.05$

Fig. 4 Comparison of theoretical BER performance, simulated performance and BER performance of the proposed RIS-STSK-acos scheme with different antenna configurations of and different number of reflecting elements

is generally the same as that of the simulated performance. The BER performance of the STSK scheme is also compared, and it can be seen that with the increase in the number of reflective elements $N$ for different antenna configurations, the proposed RIS-STSK-acos scheme yields a performance gain of 3-4 dB compared to the STSK scheme due to the improvement of the channel link by the RIS.
Fig. 5 Iteration of the reflected phase shift in the improved genetic algorithm versus the fitness value (channel gain)

Fig. 5 shows the fitness values (channel gain) versus the number of iterations for $N = 16, 32, 64, 128$ in the optimization of the proposed improved genetic algorithm-assisted reflection phase shifts, where the population size $N_{\text{pop}}$, crossover probability $P_c$ and variance probability $P_m$ parameters are shown in Table 1, and the antenna configuration is $2 \times 2$. When $N = 16, 32, 64, 128$, the fitness values start to converge at 20, 30, 40 and 100 iterations, respectively. According to Figure 5, we set the number of iterations for GA-assisted reflection phase shifts optimization, as shown in Table 1.

In Fig. 6, the comparison between the channel gain based on the improved genetic algorithm, the cosine similarity theorem algorithm, and without RIS is given for different number of reflective elements $N$, where the parameters of the improved genetic algorithm are shown in Table 1. The channel gain of the proposed improved genetic algorithm apparently outperforms the channel gain of the cosine similarity theorem algorithm for different number of reflecting elements $N$ and has a significant improvement.

Finally, Fig. 7 shows the performance comparison between the RIS-STSKe and RIS-STSKe-GA schemes with different number of reflective elements. It can be seen that due to the improved genetic algorithm, a better BER performance of the RIS-STSKe-GA scheme can be achieved compared to that of the RIS-STSKe scheme with a performance gain of 12-14 dB, and with the increase in the number of reflective elements $N$, such improvement is more obvious. In addition, the trend of performance improvement of the RIS-STSKe-GA scheme is more pronounced at high signal-to-noise ratios, and the achievable performance advantage will be greater. This is due to the fact that
the improved genetic algorithm can jump out of the local optimum during rapid iterative, and thus can be optimized to obtain a better BER performance for reflection phase shift.

6 Conclusion

In this article, a RIS-assisted STSK transmission scheme is proposed to improve the achievable performance of the STSK scheme, and the theoretical BER performance of the RIS-STSK scheme is analyzed. In addition, in order to improve the achievable performance of the scheme, an improved genetic algorithm is designed to assist RIS-STSK reflection phase shift optimization. In addition, the simulation results show that the performance of the RIS-STSK scheme proposed in this paper is better than the STSK scheme without RIS, and the improved genetic algorithm proposed can enhance the performance of the RIS-STSK scheme. In subsequent research, machine learning can be used to optimize the reflection phase shift to achieve higher system performance gains.

Declarations

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• The authors declare that they have no competing interests.
• Data will be available on reasonable request.
• Matlab custom code.
• Jiayu Liu designed the system scheme and optimization algorithm, Dongxiao Chen wrote the first draft of the article, Lina Bian wrote the system model code, Xiaoting Xu wrote the algorithm code, Yueru Zhou wrote the algorithm code, and Xiaoping Jing helped review the article.

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