Hindawi
Wireless Communications and Mobile Computing
Volume 2021, Article ID 5569006, 9 pages
https://doi.org/10.1155/2021/5569006

Research Article

Reconfigurable Intelligent Surface-Based Space-Time Block Transmission on 6G

Wei Song [1] **and Bing Guan** [2]

[1]Department of Electronic Information and Communication Engineering, Applied Technology College of Soochow University, Suzhou 215325, China
[2]School of Computer Science and Engineering, Huizhou University, Huizhou 516007, China

Correspondence should be addressed to Bing Guan; binggwan@hotmail.com

Received 31 January 2021; Revised 17 March 2021; Accepted 25 November 2021; Published 16 December 2021

Academic Editor: Miaowen Wen

Reconfigurable intelligent surface (RIS) is considered to be a new technology with great potential and is being studied extensively and deeply. And the application extension of STBC in the RIS-aided scheme provides a new train of thought for the research of channel coding. In this paper, we propose we extend the scheme of using the RIS to adjust the phase and reconfigure the reflected signal and propose the design of the RIS-aided QO-STBC scheme and the RIS-aided QO-STBC scheme with interference cancellation. Particularly in the RIS-aided QO-STBC scheme with interference cancellation, the design can achieve the transmission of the full rate and full diversity using an auxiliary reflection group to eliminate the influence of interference term. Also, the advantages and disadvantages of the schemes are analyzed in the paper, and the decoding algorithms with different complexity used in the proposed schemes are described. The simulation results show that the performance of the RIS-aided QO-STBC scheme with interference cancellation is better than that of the RIS-aided QO-STBC scheme and the RIS-aided Alamouti scheme by about 5 dB and 7 dB at 10^{-3} BER because of diversity gain and coding gain.

1. Introduction

Over the last 30 years, wireless communication technologies have achieved revolutionary development. The application of multiple-input and multiple-output (MIMO) [1] systems fundamentally solved the problem of insufficient wireless channel capacity. On this basis, the research of OFDM (orthogonal frequency division multiplex) [2] promotes more rapid growth of communication.

Form 2019, the fifth-generation (5G) mobile communication are worldwide tested and applied. The performance of 5G communication with a higher rate and low latency can provide communication support for Internet-of-Things (IoT), intelligent manufacturing (IM), massive machine-type communications (MTC), etc. 5G base stations (BSs) with massive MIMO antennas supply the enhanced mobile broadband (eMBB) communication service. And massive MIMO achieves huge diversity gain, path gain, and spatial reusability [3] due to large-scale antenna arrays. The International Telecommunication (ITU) predicated that the whole mobile data flows will reach 60 zettabytes (ZB) [4] per year. As everybody knows, 5G has a superiority unmatched compared with traditional cellular communication. The European Telecommunications Standards Institute (ETSI) published the target peak rate is 10 Gb/s and 20 Gb/s in the uplink and downlink, respectively. 5G communication brings the possibility to realize the application of new technology in various fields. Meanwhile, the ITU also estimated the 5G will reach its limit in 2030, because some applications need higher transmission rate and lower time-delay and reliability, and 5G communication can not satisfy its requirements, obviously. It means that the new challenge will be coming on 6G technology. The focus of the research of 6G is being made not only to solve the insufficiency of performance of 5G but also to meet the needs of the continuous development and application of wireless communication, especially in ultrabroadband (uMUB), ultrahigh-speed-with-low-latency communications (uHSLLC), and ultrahigh data density (uHDD) [5].

Although the research of 6G wireless communication is in an early stage, the direction of revolutionary-innovative research can not be determined completely. However, it can be predicted that the research of 6G will continue many 5G technologies to make our living environment more intelligent. In the future, the main problem of 6G communication will focus on improving the intelligent service level between devices and further enhancing the intelligence level of the whole society under the condition of small samples. Internet of Intelligent Things (IoIT) and Artificial Intelligence (AI) will be widely used at all levels. At the same time, the great improvement of big data and computing power also requires more reliable and faster communication support, especially in wireless communication. The researchers have already studied the new technology of 6G in order to achieve the promised goal, which connects every smart device to the Internet. Also, the 6G will offer precisely and higher Quality of Service (QoS) such as holographic communication, augmented reality/virtual reality. It is worth mentioning that 6G will focus on Quality of Experience (QoE) to provide rich experiences. Meanwhile, the green technology solutions for energy saving and environmental protection of future mobile communication have become the key research direction of sustainable wireless communication development.

In the last two years, a new technology with great potential for significant energy consumption reductions is being studied extensively and deeply called reconfigurable intelligent surface (RIS) [6–8]. The RIS is a new concept with massive radiating and sending elements, in an ideal line-of-sight environment; the entire surface is used as a receiving antenna array. Under the condition that the surface area is large enough, the received signal after matched filtering operation can be approximated as a SINC-like intersymbol interference channel and go beyond contemporary large-scale MIMO technology. In [9], the authors proposed a dual-hop RIS-aided (RIS-DH) scheme and RIS-aided transmit (RIS-T) scheme, and neither of these two schemes can provide multiplexing gain; only diversity gain can be obtained. The channel of the RIS-T scheme looks like a transmission diversity structure, and the RIS-DH scheme is more like a keyhole MIMO channel; meanwhile, the outage probability, bit error rate, and average channel capacity are given. As a promising 6G auxiliary transmission scheme, RIS can provide higher array gain and achieve more accurate channel estimation by using lower hardware cost and energy loss compared with large-scale MIMO technology [10]. Recent results showed that nonorthogonal multiple access (NOMA) using RIS-aided [11] can make some uncontrollable factors of affected received signal quality of wireless communication become controllable, which provides an effective transmission guarantee for wireless communication. In addition, using reconfigurable passive elements, the RIS-aided scheme can allow to build a programmable wireless environment [12]. An RIS-based space shift keying (SSK) [13] scheme also can adjust the phase of the reflected signal effectively to improve energy efficiency and high transmission reliability. In [14], a new transmission protocol for wideband RIS-aided single-input multiple-output (SIMO) orthogonal frequency division multiplexing (OFDM) communication systems was proposed. And the passive beamforming of the RIS was fine-tuned to improve the achievable rate for data transmission. In conclusion, the RIS-aided transmission strategies can greatly raise the effectiveness of performance of wireless communication. Recently, from the application level, some researchers have studied the degree of the isolation of the antenna [15], the accurate characterization of probability density function (PDF) [16], the two-dimensional physical structure of RIS [17], the communication between two nodes [18], the capability of extending cellular coverage [19–25], etc., which further verifies the feasibility and applicability of RIS-aided communication. Also, the security performance of the RIS-aided wireless communication system is widely concerned [26, 27].

With the in-depth study of RIS technology, many original technologies of wireless communication have the new application scenarios and the direction of research. It is known that MIMO technology fundamentally solves the problem of channel capacity limitation of single input single output (SISO). And the space time-block codes (STBC) can provide an effective capacity gain and spatial diversity gain in MIMO systems [28, 29]. Next, the relay nodes were considered in a multiply-hop MIMO system [30–34] where several relay stations transmit jointly to the same destination node. However, the most difficult problems to solve with relay nodes are the cost and intelligent control of relay devices. In these aspects, the RIS technology opens up new ideas for researchers and makes the application of cooperative communication more feasible. In [35, 36], the authors present two different approaches to achieve classic Alamouti space-time coding wireless transmission through an RIS-aided transmitter, respectively; two proposed approaches convincingly validate the feasibility of RIS-based Alamouti space-time coding. The key difference is that two proposed schemes use different number of antennas on the source node.

Next, let us analyze the differences between the two schemes in detail. The first proposed scheme [35] uses one transmission antenna on the source node and N reflection elements on the RIS side, and RIS element was divided into two parts where each part applies phase modulation to reconfigure the singles and forward it. Thus, the RIS provides diversity gain. Compared to the first design, the second proposed scheme [36] uses two transmission antennas on the source side to realize the diversity gain. Anyway, if the time loss from source to RIS is ignored, both two plans make good use of RIS to assist the implementation of the characteristic of Alamouti code with full rate and full diversity. This application extension of STBC in the RIS-aided scheme provides a new train of thought.

As everyone knows, the Alamouti code is the only orthogonal complex coding matrix with full rate and full diversity and diversity gain is two. In this paper, we propose new extended quasiorthogonal STBC (QO-STBC) applications to improve the diversity gain of the scheme. To be specific, the new scheme applies one group of RIS to assist QO-STBC coding transmission, and another group of RIS is used to eliminate the nonorthogonal interference caused by the coding matrix simultaneously.

1.1. Prior Work. A perfect STC (space time code) should be an orthogonal coding with full rate and linear decoding complexity. The classical Alamouti [28] with these features can be expressed as

$$A_{ij} = \begin{bmatrix} x_i & x_j \\ -x_j^* & x_i^* \end{bmatrix}, \tag{1}$$

where $j = i + 1$ for any positive integer i. It is proved mathematically in [37] that complex O-STBCs with the full rate did not exist for more than two transmission antennas. Consequently, Laneman et al. presented a QO-STBC scheme [30] with the full rate. But the QO-STBC scheme reduces the diversity gain and uses the more complex algorithm with pairwise decoding. However, the QO-STBC has better performance than the orthogonal codes with a rate less than 1 at low signal-to-noise (SNR). Jafarkhani's code used Alamouti code as block element of the coding matrix for four transmission antennas denoted as

$$S_J = \begin{bmatrix} A_{12} & A_{34} \\ -A_{34}^* & A_{12}^* \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & {x_1}^* & -{x_4}^* & x_3^* \\ -x_3^* & -{x_4}^* & {x_1}^* & x_2^* \\ x_4 & -x_3 & -x_2 & x_1 \end{bmatrix}. \tag{2}$$

We can get the character matrix Q_J [38] as

$$Q_J = S_J^H S_J = \begin{bmatrix} \alpha & 0 & 0 & \beta_J \\ 0 & \alpha & -\beta_J & 0 \\ 0 & -\beta_J & \alpha & 0 \\ \beta_J & 0 & 0 & \alpha \end{bmatrix}, \tag{3}$$

where $\alpha = \sum_{i=1}^{4} |X_i|^2$ and $\beta_J = (X_1 X_4^* + X_1^* X_4) - (X_2 X_3^* + X_2^* X_3)$. From Equation (3), it is obvious that the orthogonality of Jafarkhani's code was destroyed by nonmain diagonal elements. On the condition of the full rate, the diversity gain was reduced.

1.2. Organization and Notation. The rest of this paper is organized as follows. In Section 2, we present the common scheme model and the assumption of wireless communication environment. In Section 3, we introduce the Alamouti RIS-aided scheme and extend it to the QO-STBC RIS-aided scheme and analyze advantages and disadvantages of performance of each scheme. According to the analysis results of the previous section, a new model with interference cancellation is proposed and its performance is analyzed in detail in Section 4. The simulation results are provided in Section 5. Finally, the conclusions of the research are summarized in Section 6.

In this paper, A^*, A^T, and A^H denote the complex conjugate, the transpose, and Hermitian transpose of matrix A, respectively. $\mathbb{C}$ denotes the complex-valued set. The Diag[.] denotes a diagonal matrix, and the $N \times N$ identity matrix is denoted by I_N. $\mathscr{CN} \sim (\mu, \sigma^2)$ denotes the distribution of circularly symmetric complex random vector with mean μ and variance σ^2, and $\sim$ represents "distributed as."

2. System Model

The proposed RIS-aided wireless transmission scheme has one source node S and one destination node D, as illustrated in Figure 1, and the RIS consisting of an N reflecting elements is deployed to assist transmission from the node S equipped with N_t transmitting antennas to the node D with N_r receiving antennas. In the proposed scheme, we assume and the wireless communication system is performed over a complex, additive white Gaussian noise (AWGN) coherent fading channel, in which the RIS is close to the node S, and the line of sight (LoS) channel does not exist from the node S to the node D because of some obstructions. So the node S can not communicate with the node D directly, and the signals must select the reflection channels to transmit.

At the source node S, information sequences are modulated into $L = 2L_0$ length complex symbol vector $X = \{x_1, x_2, \cdots, x_L\}$, where every two neighboring symbols become one group, and L_0 denotes the number of groups as $G_i = \{x_i, x_{i+1}\}$ for $i = 1, \cdots, L_0$. Each time interval, a complex symbol is successively transmitted from the node S to the RIS nodes, and the RIS is connected to the node S through control link, which is in charge of all controlling information from the node S. The controlling information can assist the RIS elements to reconfigure the phase of reflection signals [35].

The $S \longrightarrow$ RIS channels are assumed to be a frequency selective channel with independent propagation paths. Besides, we assume that the channel state information is quasistatic, so we can write the channel impulse response as

$$h_{S,R_i}^j(t) = \alpha_{S,R_i}^j \delta(t - \tau_{i,j}), \tag{4}$$

where α_{S,R_i}^j is the channel coefficient from the j^{th} transmission antenna of the source node S to the i^{th} element of the RIS, and $\tau_{i,j}$ denotes the corresponding path delay. The h_{S,R_i}^j denotes the channel fading from the j^{th} transmission antenna of the source node S to the i^{th} element of the RIS, and $h_{S,R_i}^j \in \mathbb{C}^{N_t \times N}$, where $i \in N$ and $j \in N_t$.

Also, the channel fading coefficient from the i^{th} element of the RIS to the k^{th} receiver antenna of the node D denotes as $h_{R_i,D}^k$, and $h_{R_i,D}^k \in \mathbb{C}^{N \times N_r}$ and $k \in N_r$. Both of h_{S,R_i}^j and $h_{R_i,D}^k$ are distributed as complex Rayleigh random distribution. So $h_{S,R_i}^j \sim \mathscr{CN}\ (\mu_1, \sigma_1^2)$ and $h_{R_i,D}^k \sim \mathscr{CN}\ (\mu_2, \sigma_2^2)$, respectively.

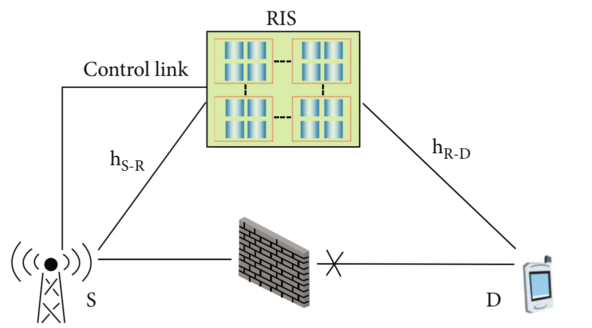

Figure 1: RIS-aided wireless transmission scheme with one source and one destination and N RIS elements.

Accordingly, the received signal at the node D is given by

$$r^k = \sqrt{E_0}\left(\sum_{i=1}^{N}\sum_{j=1}^{N_t} h^j_{S,R_i} h^k_{R_i,D}\right)x + n, \quad (5)$$

where x denotes the transmitted symbol and n is the complex AWGN $\sim \mathscr{CN}(0, N_0)$. The E_0 denotes average energy.

Without losing generality, we simply select only one transmission antenna at the node S and one receiver antenna at the node D and analyze the performance of broadcast symbols through the RIS auxiliary scheme. We get

$$r = \sqrt{E_0}\left(\sum_{i=1}^{N} h_{S,R_i} h_{R_i,D}\right)x + n = \sqrt{E_0}\mathbf{H}x + n, \quad (6)$$

where $\mathbf{H} = [h_1, h_2, \cdots, h_i]^T$ denotes the channel matrix of the $S \longrightarrow$ RIS $\longrightarrow D$. The SNR gets

$$\mathbf{SNR} = \frac{E_0 P |\mathbf{H}|^2}{N_0}. \quad (7)$$

In our proposed scheme model, the following suppositions have been given:

(i) The source node S broadcasts the symbol to each element of RIS. And each element of RIS reconfigures the symbol according to control information from the node C and reflect to the node D. And only the destination node D knows all the channel state information (CSI) h_{S,R_i} and $h_{R_i,D}$

(ii) The channel state information h_{S,R_i} and $h_{R_i,D}$ are the complex Rayleigh random variable and independent and identically distributed (i.i.d.), and all of them keep constant during one period time. And $h_{S,R_i} \sim \mathscr{CN}(\mu_1, \sigma_1^2)$ and $h_{R_i,D} \sim \mathscr{CN}(\mu_2, \sigma_2^2)$. The noise n is the complex AWGN $\sim \mathscr{CN}(0, N_0)$

(iii) All transmission antennas have been subjected to half-duplex transmission mode. At the node S, the binary signal sequences are modulated into complex MPSK symbols and the maximum likelihood (ML) decoding method is used at the node D. And the RIS is close to the node S

Suppose that the codeword belongs to the codebook X, the ML decoder should find the minimum distance following the expression to detect the symbols:

$$<x, \hat{x}> = \operatorname{argmin}_{x_i} |r - \mathbf{H}x|^2, \quad (8)$$

where $x_i \in X$. The ML method with linear complexity can achieve better performance for the proposed scheme.

3. RIS-Aided QO-STBC Model

In the previous section, we already introduce the RIS-aided Alamouti scheme [35], in which the RIS elements were divided into two parts to adjust the reflection phase. In two time slots, the RIS realizes the transmission of orthogonal coding matrix by reflecting different types of signals. The complex signal can denote as

$$x_i = \sqrt{p}e^{j\theta_i} = \sqrt{p}[\cos\theta_i + j\sin\theta_i], \quad (9)$$

where p denotes average power, and $\sqrt{j} = -1$. From the MPSK constellation map, we know the modulated signals have the same power, and the two parts can use $-(\theta_{i+1} + \pi)$ and $-\theta_i$ to adjust the phase to realize the RIS-aided Alamouti's scheme, as follows:

$$\begin{aligned} \sqrt{p}[\cos(-\theta_i) + j\sin(-\theta_i)] &= \sqrt{p}[\cos\theta_i - j\sin\theta_i] = x_i^*, \\ \sqrt{p}[\cos(-\theta_{i+1} - \pi) + j\sin(-\theta_{i+1} - \pi)] &= -x_{i+1}^*. \end{aligned} \quad (10)$$

Thus, the 2×2 OSTBC with linear complexity was achieved in MPSK modulation mode. We consider that the adjacent reflection elements will have the similar channel state information, so, the RIS with N-elements can be divided into $N/2$ groups; each group contains a pair of nonadjacent reflection elements, as shown in Figure 2. The expression is

$$\begin{aligned} r_1 &= x_1 h_1 + x_2 h_2 + n_1, \\ r_2 &= -x_2^* h_1 + x_1^* h_2 + n_2, \end{aligned} \quad (11)$$

where $h_1 = \sum_{i=1}^{N/2}(h_{S,R_{2i-1}} h_{R_{2i-1},D})$ and $h_2 = \sum_{i=1}^{N/2}(h_{S,R_{2i}} h_{R_{2i},D})$. And n_1 and n_2 are AWGN by different channels. It is thus clear that the equivalent diversity gain of the scheme comes from the reflection elements of the RIS. In the same mode [35], the proposed scheme costs more time slots because of using multiantennas at the source node S.

Although the first scheme has some limitations in modulation mode, its performance advantage can not be ignored. So we can extend this method to QO-STBC, and it is called the RIS-aided QO-STBC scheme. In the proposed RIS-aided QO-STBC model, we also divided the RIS with N-elements into $N/4$ groups. Each group has four reflection elements,

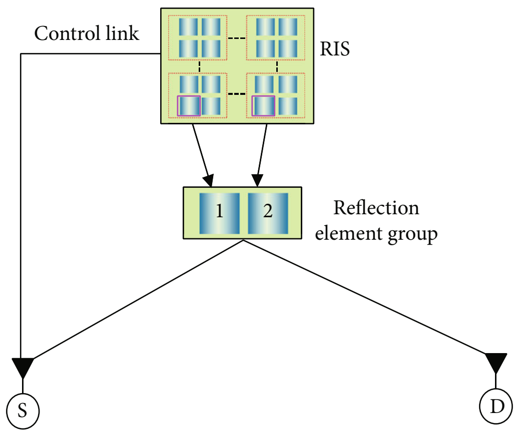

Figure 2: Alamouti RIS-aided reflection element.

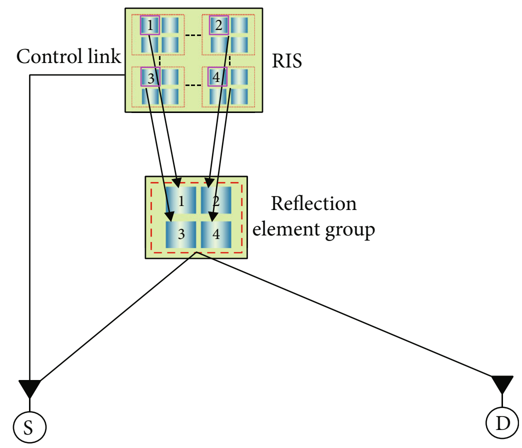

Figure 3: QO-STBC RIS-aided reflection element.

in which the four reflection elements use $-\theta_1$, $-\theta_2-\pi$, $-\theta_3$, and $-\theta_4-\pi$ to modulate the phase of reflection signals at element 1, element 2, element 3, and element 4, respectively, as shown in Figure 3. And the results of MPSK modulation of reflection elements are shown in Table 1.

Although the design of the RIS-aided QO-STBC scheme is realized in this way, it can be seen from Equations (2) and (3) that the performance of the proposed RIS-aided scheme is not very superior. The reason is that Jafarkhani's code is a quasiorthogonal code with full rate and not full rank; the nonmain diagonal elements of character matrix are the interference term and the key factor of diversity loss. In fact, Jafarkhani's code can be considered to have orthogonal performance, if the BPSK modulation is used. The rank of the code is only 2 using the others. In terms of decoding complexity, the pairwise decoding algorithm is used because Jafarkhani's code is not orthogonal. Anyway, due to the scarcity of complex orthogonal full rate coding matrix, the design of the RIS-aided QO-STBC scheme opens up a new research direction for the application of STBC technology on 6G communication.

4. RIS-Aided QO-STBC Model with Interference Cancellation

In this section, we try to design a simply RIS-aided scheme based on the RIS-aided QO-STBC model to eliminate the interference term in the character matrix Equation (3) as much as possible. Let us think about changing the transmission matrix as $\widehat{S}_J = S_J \Lambda$, where $\Lambda = \mathrm{Diag}[1, 1, -1, -1]$. The new character matrix is

$$\widehat{Q}_J = \widehat{S}_J^H \widehat{S}_J = \Lambda S_J^H S_J \Lambda = \begin{bmatrix} \alpha & 0 & 0 & -\beta_J \\ 0 & \alpha & \beta_J & 0 \\ 0 & \beta_J & \alpha & 0 \\ -\beta_J & 0 & 0 & \alpha \end{bmatrix}. \quad (12)$$

Combined the $\widehat{Q}_J$ and Q_J, we get $\widehat{Q}_J + Q_J = 2\alpha I_4$. Mathematically, this operation completely cancels out the interference term of the character matrix. Next, we design the wireless communication scheme according to this idea. At the RIS, a pair of adjacent reflection elements are selected, one of which is used for normal signal transmission, and the other is provided with interference elimination function besides ensuring transmission. In this way, two reflection groups A and B are built in RIS as illustrated in Figure 4. Meanwhile, in order to ensure the independence of the two reflection groups, the node D needs to be equipped with two adjacent receiving antennas in the assumed scheme, and one-to-one transmission is carried out through the beamforming. Because the distance of adjacent A_1 in the reflection group A and B_1 in the reflection group B and adjacent receiving antenna RE_1 and RE_2 in the node D is very closer, we assume that the corresponding transmission channels have the same CSI. During four time slots, the respective received signals can be written as

Table 1: Results of MPSK modulation of reflection elements.

Time	Element 1	Element 2	Element 3	Element 4
Slot 1	x_1	x_2	x_3	x_4
Slot 2	$-x_2^*$	x_1^*	$-x_4^*$	x_3^*
Slot 3	$-x_3^*$	$-x_4^*$	x_1^*	x_2^*
Slot 4	x_4	$-x_3$	$-x_2$	x_1

$$\begin{aligned} \mathbf{r}_{RE1} &= S_J H + \mathbf{n}_1, \\ \mathbf{r}_{RE2} &= \widehat{S}_J H + \mathbf{n}_2, \end{aligned} \quad (13)$$

where H is the CSI vector, and $H = [h_1, h_2, h_3, h_4]^T$, in which $h_i = \sum_{j=0}^{N/8-1} (h_{S,R_{A_{4j+i}}} h_{R_{A_{4j+i}},D_{RE1}})$ or $h_i = \sum_{i=0}^{N/8-1} (h_{S,R_{B_{4j+i}}} h_{R_{B_{4j+i}},D_{RE2}})$. $n_1 = [n_1, n_2, n_3, n_4]^T$ and $n_2 = [n_5, n_6, n_7, n_8]^T$. The matched reflection symbols at the reflection group A and B are reconfigured as Tables 2 and 3, respectively.

Before decoding, we first combine the received signals in (15) and (16) from the two receiving antennas; the

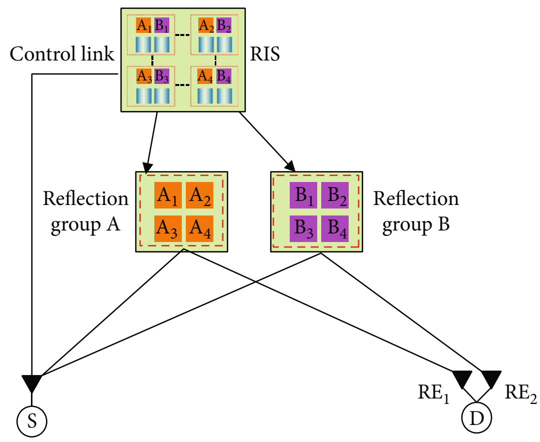

FIGURE 4: QO-STBC RIS-aided reflection element with interference cancellation.

TABLE 2: Results of MPSK modulation of reflection element group *A*.

Time	Elem-A_1	Elem-A_2	Elem-A_3	Elem-A_4
Slot 1	x_1	x_2	x_3	x_4
Slot 2	$-x_2^*$	x_1^*	$-x_4^*$	x_3^*
Slot 3	$-x_3^*$	$-x_4^*$	x_1^*	x_2^*
Slot 4	x_4	$-x_3$	$-x_2$	x_1

TABLE 3: Results of MPSK modulation of reflection element group *B*.

Time	Elem-B_1	Elem-B_2	Elem-B_3	Elem-B_4
Slot 1	x_1	x_2	$-x_3$	$-x_4$
Slot 2	$-x_2^*$	x_1^*	x_4^*	$-x_3^*$
Slot 3	$-x_3^*$	$-x_4^*$	$-x_1^*$	$-x_2^*$
Slot 4	x_4	$-x_3$	x_2	$-x_1$

equivalent transmission matrix has

$$S = \begin{bmatrix} X_1 & -X_2{}^* & -X_3{}^* & X_4 & X_1 & -X_2{}^* & -X_3{}^* & X_4 \\ X_2 & X_1{}^* & -X_4{}^* & -X_3 & X_2 & X_1{}^* & -X_4{}^* & -X_3 \\ X_3 & -X_4{}^* & X_1{}^* & -X_2 & -X_3 & X_4{}^* & -X_1{}^* & X_2 \\ X_4 & X_3{}^* & X_2{}^* & X_1 & -X_4 & -X_3{}^* & -X_2{}^* & -X_1 \end{bmatrix}^T. \tag{14}$$

Also, the equivalent transmission matrix can be written as

$$S = \begin{bmatrix} S_J \\ \widehat{S}_J \end{bmatrix}, \tag{15}$$

and the equivalent character matrix has

$$S^H S = \left[S_J^H \widehat{S}_J^H \right] \begin{bmatrix} S_J \\ \widehat{S}_J \end{bmatrix} = 2\alpha I_4. \tag{16}$$

Obviously, the equivalent transmission matrix S is a new type O-STBC transmission matrix with full rate and full diversity. The difference is that the proposed RIS-aided QO-STBC model with interference cancellation transfers the loss of time slots to an increase in the number of reflection elements by reasonable transformation. So, the use of the linear decoding algorithm [39] can greatly reduce the decoding complexity of the receiver. The decision statistics $\tilde{x}_i$ of the transmitted signal x_i can be constructed as

$$\tilde{x}_i = \sum_{t\in\eta(i)} \text{sgn}_t(i) \cdot \tilde{y}_t \cdot \tilde{h}^*_{\epsilon_t(i)}, \tag{17}$$

where $\eta(i)$ is the set of rows of the transmission matrix including x_i,

$$\begin{aligned} \tilde{y}_t(i) &= \begin{cases} y_t, & x_i \text{ belongs to the } t^{\text{th}} \text{ row of } S\,; \\ (y_t)^*, & x_i^* \text{ belongs to the } t^{\text{th}} \text{ row of } S, \end{cases} \\ \tilde{h}^*_{\epsilon_t(i)} &= \begin{cases} h^*_{\epsilon_t(i)}, & x_i \text{ belongs to the } t^{\text{th}} \text{ row of } S\,; \\ h_{\epsilon_t(i)}, & x_i^* \text{ belongs to the } t^{\text{th}} \text{ row of } S. \end{cases} \end{aligned} \tag{18}$$

To minimize each individual decision metric, we get

$$|\tilde{x}_i - x_i|^2 + \left(2\sum_{j=1}^{4} \left|h_j\right|^2 - 1 \right) |x_i|^2. \tag{19}$$

5. Simulation Results and Discussions

In this section, we present computer simulation results to evaluate the performance of the RIS-aided Alamouti scheme, the RIS-aided QO-STBC scheme, and the RIS-aided QO-STBC scheme with interference cancellation in terms of bit error ratio (BER) and analysis of the results. In the simulations, we considered the assumption of frequency-selective Rayleigh flat fading channels by employing the ML-based decoding algorithm. Considering the large number of reflection elements in RIS, the number of reflection function groups divided in different ways is consistent. Without losing generality, only one reflection function group of the RIS was selected to participate in the computer simulation.

In this paper, all of the proposed schemes are based on the reflection elements of the RIS to reconstruct the reflection signals by phase modulation. The time loss from the source S to the RIS can be ignored when calculating the transmission rate. So, the transmission rate of all proposed schemes is approximately equal to one. Figure 5 shows the simulation of the proposed schemes, in which we compared the performance of the RIS-aided Alamouti scheme, the RIS-aided QO-STBC scheme, and the RIS-aided QO-STBC

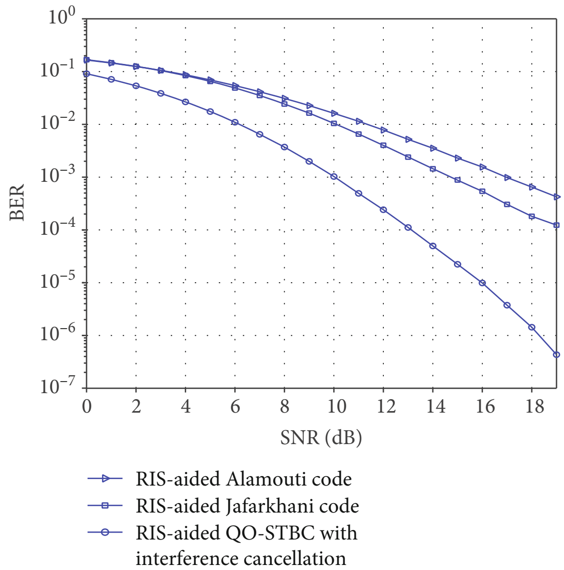

Figure 5: Performance of the proposed RIS-aided scheme with frequency-selective Rayleigh flat fading channel (transmission rate 2 bits/s/Hz).

scheme with interference cancellation for the transmission of two bits/s/Hz (QPSK).

From the simulation results, in Figure 5, we can see that the RIS-aided Alamouti scheme and the RIS-aided QO-STBC scheme achieved the same full rate characteristics as the traditional STBC transmission matrix. Due to the characteristic of nonfull rank of QO-STBC, the diversity gain can not reach the maximum order of matrix. However, compared with the RIS-aided Alamouti scheme with diversity 2, the diversity gain of the RIS-aided QO-STBC scheme is improved. The proposed RIS-aided QO-STBC scheme outperforms the RIS-aided Alamouti scheme about 2 dB at 10^{-3} BER. And the RIS-aided QO-STBC scheme with interference cancellation achieves the full rate and the full diversity and improves the coding gain due to the participation of reflection group B. The result of simulation shows that the performance of the RIS-aided QO-STBC scheme with interference cancellation is better than that of the RIS-aided QO-STBC scheme and the RIS-aided Alamouti scheme by about 5 dB and 7 dB at 1 0^{-3} BER, respectively. The analysis fits well in with simulation results.

6. Conclusions

In this paper, we extend the scheme of using the RIS to adjust the phase and reconfigure the reflected signal and propose the design of the RIS-aided QO-STBC scheme. In particular, aiming at the problem that the diversity of QO-STBC is reduced due to the nonorthogonality, a scheme called the RIS-aided QO-STBC scheme with interference cancellation using auxiliary reflection group to eliminate the influence of interference term is designed. And the advantages and disadvantages of the scheme are analyzed in detail; also, the decoding algorithms with different complexity used in the proposed schemes are described.

Through the reasonable assumption of the design of the RIS-aided QO-STBC scheme with interference cancellation, the wireless communication of full rate and full diversity is realized. The difference is that the proposed RIS-aided QO-STBC model with interference cancellation transfers the loss of time slots to an increase in the number of reflection elements by transformation.

Simulation results show that the performance of the proposed schemes has remarkable improvement due to the increase of diversity gain and coding gain. Also, the design of the RIS-aided QO-STBC scheme opens up a new research direction for the application of STBC technology on 6G communication. And the future research is to improve the received diversity gain.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. The authors declare that there are no conflicts of interest.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors would like to extend their sincere gratitude to Dr. Huaisheng Wang, for his instructive advice and useful suggestions and help on this paper. This work was supported in part by the Natural Science Foundation of Jiangsu Province, China (Grant No. BK20201201), the Professorial and Doctoral Scientific Research Foundation of Applied Technology College of Soochow University, Suzhou (Grant No. RC0006), and the Professorial and Doctoral Scientific Research Foundation of Huizhou University (Grant No. 2020JB014).

References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, 1998.

[2] S. Nanda, R. Walton, J. Ketchum, M. Wallace, and S. Howard, "A highperformance MIMO OFDM wireless LAN," *IEEE Communications Magazine*, vol. 43, no. 2, pp. 101–109, 2005.

[3] C. Han, J. M. Jornet, and I. F. Akyildiz, "Ultra-massive MIMO channel modeling for graphene-enabled terahertz-band communications," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pp. 1–5, Porto, Portugal, 2018.

[4] F. Tariq, M. R. A. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, and M. Debbah, "A speculative study on 6G," *IEEE Wireless Communications*, vol. 27, no. 4, pp. 118–125, 2020.

[5] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: key drivers, core requirements, system

architectures, and enabling technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 18–27, 2019.

[6] S. Hu, F. Rusek, and O. Edfors, "Beyond massive MIMO: the potential of data transmission with large intelligent surfaces," *IEEE Transactions on Signal Processing*, vol. 66, no. 10, pp. 2746–2758, 2018.

[7] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," 2018, http://arxiv.org/abs/1809.01423.

[8] C. Liaskos, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "Using any surface to realize a new paradigm for wireless communications," *Communications of the ACM*, vol. 61, no. 11, pp. 30–33, 2018.

[9] L. Yang, F. Meng, Q. Wu, D. B. da Costa, and M.-S. Alouini, "Accurate closed-form approximations to channel distributions of RIS-aided wireless systems," *IEEE Wireless Communications Letters*, vol. 9, no. 11, pp. 1985–1989, 2020.

[10] H. Liu, X. Yuan, and Y.-J. A. Zhang, "Matrix-calibration-based cascaded channel estimation for reconfigurable intelligent surface assisted multiuser MIMO," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2621–2636, 2020.

[11] A. Hemanth, K. Umamaheswari, A. C. Pogaku, D.-T. Do, and B. M. Lee, "Outage performance analysis of reconfigurable intelligent surfaces-aided NOMA under presence of hardware impairment," *IEEE Access*, vol. 8, pp. 212156–212165, 2020.

[12] H. Guo, Y. Liang, J. Chen, and E. G. Larsson, "Weighted sum-rate maximization for reconfigurable intelligent surface aided wireless networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 3064–3076, 2020.

[13] A. E. Canbilen, E. Basar, and S. S. Ikki, "Reconfigurable intelligent surface-assisted space shift keying," *IEEE Wireless Communications Letters*, vol. 9, no. 9, pp. 1495–1499, 2020.

[14] S. Lin, B. Zheng, G. C. Alexandropoulos, M. Wen, F. Chen, and S. Mumtaz, "Adaptive transmission for reconfigurable intelligent surface-assisted OFDM wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2653–2665, 2020.

[15] T. Manafi, M. A. al-Tarifi, and D. S. Filipovic, "Isolation improvement techniques for wideband millimeter-wave repeaters," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 2, pp. 355–358, 2018.

[16] L. Kong, Y. Ai, S. Chatzinotas, and B. Ottersten, "Effective rate evaluation of RIS-assisted communications using the sums of cascaded α-μ random variates," *IEEE Access*, vol. 9, pp. 5832–5844, 2021.

[17] L. Dai, B. Wang, M. Wang et al., "Reconfigurable intelligent surface-based wireless communications: antenna design, prototyping, and experimental results," *IEEE Access*, vol. 8, pp. 45913–45923, 2020.

[18] S. Atapattu, R. Fan, P. Dharmawansa, G. Wang, J. Evans, and T. A. Tsiftsis, "Reconfigurable intelligent surface assisted two-way communications: performance analysis and optimization," *IEEE Transactions on Communications*, vol. 68, no. 10, pp. 6552–6567, 2020.

[19] I. C. B. Garcia, A. Sibille, and M. Kamoun, "Reconfigurable intelligent surfaces: bridging the gap between scattering and reflection," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2538–2547, 2020.

[20] B. Li, Z. Zhang, Z. Hu, and Y. Chen, "Joint array diagnosis and channel estimation for RIS-aided mmWave MIMO system," *IEEE Access*, vol. 8, pp. 193992–194006, 2020.

[21] W. Yan, X. Yuan, Z.-Q. He, and X. Kuai, "Passive beamforming and information transfer design for reconfigurable intelligent surfaces aided multiuser MIMO systems," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1793–1808, 2020.

[22] L. Yang, Y. Yang, M. O. Hasna, and M.-S. Alouini, "Coverage, probability of SNR gain, and DOR analysis of RIS-aided communication systems," *IEEE Wireless Communications Letters*, vol. 9, no. 8, pp. 1268–1272, 2020.

[23] E. Basar, "Reconfigurable intelligent surface-based index modulation: a new beyond MIMO paradigm for 6G," *IEEE Transactions on Communications*, vol. 68, no. 5, pp. 3187–3196, 2020.

[24] M. Nemati, J. Park, and J. Choi, "RIS-assisted coverage enhancement in millimeter-wave cellular networks," *IEEE Access*, vol. 8, pp. 188171–188185, 2020.

[25] S. Zeng, H. Zhang, B. Di, Z. Han, and L. Song, "Reconfigurable intelligent surface (RIS) assisted wireless coverage extension: RIS orientation and location optimization," *IEEE Communications Letters*, vol. 25, no. 1, pp. 269–273, 2021.

[26] L. Yang, J. Yang, W. Xie, M. O. Hasna, T. Tsiftsis, and M. D. Renzo, "Secrecy performance analysis of RIS-aided wireless communication systems," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 10, pp. 12296–12300, 2020.

[27] A. Almohamad, A. M. Tahir, A. al-Kababji et al., "Smart and secure wireless communications via reflecting intelligent surfaces: a short survey," *Communications Society*, vol. 1, pp. 1442–1456, 2020.

[28] A. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[29] H. Jafarkhani, *Space-Time Coding: Theory and Practice*, Cambridge University Press, Cambridge, 2005.

[30] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[31] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2415–2425, 2003.

[32] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity part I: system description," *IEEE Transactions on communications*, vol. 51, no. 11, pp. 1927–1938, 2003.

[33] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity part II: implementation aspects and performance analysis," *IEEE Transactions on communications*, vol. 51, no. 11, pp. 1939–1948, 2003.

[34] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," *IEEE Wireless Communications*, vol. 5, no. 12, pp. 3524–3536, 2006.

[35] A. Khaleel and E. Basar, "Reconfigurable intelligent surface-empowered MIMO systems," *IEEE Systems Journal*, vol. 15, no. 3, pp. 4358–4366, 2021.

[36] W. Tang, J. Y. Dai, M. Z. Chen et al., "Realization of reconfigurable intelligent surface-based Alamouti space-time transmission," in *2020 International Conference on Wireless*

Communications and Signal Processing (WCSP), pp. 904–909, Nanjing, 2020.

[37] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[38] Jia Hou, Moon Ho Lee, and Ju Yong Park, "Matrices analysis of quasi-orthogonal space-time block codes," *IEEE Communications Letters*, vol. 7, no. 8, pp. 385–387, 2003.

[39] J. G. Proakis, *Digital Communication*, McGraw-Hill, New York, NY, USA, 5th ed. edition, 2008.