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LETTER

Adaptive Space Shift Keying for RIS-Aided Communication

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SUMMARY In this paper, we propose a novel communication scheme that combines reconfigurable intelligent surface with transmitted adaptive space shift keying (RIS-TASSK), where the number of active antennas is not fixed. In each time slot, the desired candidate antenna or antenna combination will be selected from all available antenna combinations for conveying information bits. Besides, an antenna selection method based on channel gains is proposed for RIS-TASSK to improve the bit error rate (BER) performance and decrease the complexity, respectively. By comparing with the RIS-aided transmitted space shift keying and RIS-aided transmitted generalized space shift keying schemes, the simulation and theoretical results show that the proposed scheme has better BER performance and appropriate complexity.

key words: *Reconfigurable intelligent surface, adaptive space shift keying, antenna selection*

1. Introduction

In recent years, multiple input multiple output (MIMO) technology has become one of the key technologies in wireless communication with the properties of better spectral efficiency and energy efficiency. However, while providing high efficiency, MIMO leads to serious inter-antenna interference due to the multiple antennas, which results in complex demodulation. In order to solve this problem, spatial modulation (SM) as one of the index modulation techniques was developed in [1]. SM systems use the antenna index to convey additional information bits and transmit traditional phase shift keying (PSK) or quadrature amplitude modulation (QAM) symbols by the selected antenna. On the basis of SM technique, a simplified scheme named space shift keying (SSK) was proposed in [2]. Since SSK does not use antenna to transmit the modulated symbols, the decoding process at the receiver is simpler than that of SM, but this simplification is achieved at the expense of losing spectral efficiency. In order to improve the spectral efficiency, generalized space shift keying (GSSK) was proposed in [3]. Unlike SSK, GSSK allows multiple antennas to be activated at the same time and uses antenna combination to transmit information. By exploiting the freedom of MIMO system, an extended space shift keying (ESSK) was proposed in [4], which allows different number of antennas to be activated and improves the performance of bit error ratio (BER) and spectral efficiency. In [5], ESSK was extended to the enhanced spatial modulation (ESM) scheme.

With the development of new materials, reconfigurable intelligent surface (RIS) as an attractive technology for future communication, adjusting the phase of incident wave to improve the received signal quality brings new opportunities for future communication, and it also has great potential in index modulation field [6]. SSK and GSSK schemes applied with RIS were proposed in [7] and [8], respectively, which bring better BER performance and spectral efficiency. To further improve spectral efficiency and maintain considerable BER performance, the other RIS-SSK scheme has been proposed in [9]. The spectral efficiency of existing schemes usually depends on the number of antennas, but increasing antennas may not be practical in some cases, so it is necessary to seek a new transmission mode. Motivated by increasing spectral efficiency without adding antennas, we propose an adaptive transmit SSK scheme with RIS named RIS-TASSK in this paper to provide better BER performance without increasing antennas.

In the proposed scheme, the system channel is assumed to be frequency flat with Rayleigh fading gains, and the RIS controller is assumed to know the channel state information (CSI) from the transmitter to the RIS and from the RIS to the receiver [6] - [9]. In each time slot, the number of activated antennas is not fixed, and single antenna or antenna combination can be used according to the designed mapping table which makes the transmission more flexible. This novel design allows RIS-TASSK scheme to achieve higher spectral efficiencies under the same number of transmit antennas by comparing with RIS assisted transmitted space shift keying (RIS-TSSK) [10] and RIS assisted transmitted generalized space shift keying (RIS-TGSSK) benchmark schemes. Besides the comparisons, the theoretical BER of RIS-TASSK scheme is also provided and analyzed. In addition, an optimized antenna selection method is proposed to achieve the optimal BER performance for RIS-TASSK, which is named as RIS-TASSK with effective antenna selection (RIS-EAS-TASSK). By considering all antenna combinations and sort-

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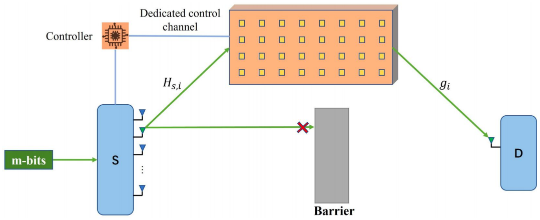

Fig. 1 RIS-assisted TASSK system model.

Table 1 Mapping For Selected Antenna Combinations With $N_t = 4$

m	Antenna combination
000	(1)
001	(3)
010	(1,2)
011	(1,3)
100	(1,4)
101	(1,2,3)
110	(1,2,4)
111	(1,3,4)

ing the channel gains, the antenna combinations with larger channel gains are selected as the candidate combinations for transmission. In this procedure, the transmitter needs to konw the CSI between transmitter and RIS, which can be achieved by using the methods in [11] - [12].

2. System Model

Fig. 1 shows the RIS-TASSK scheme where the transmitter is equipped with N_t antennas and the receiver is equipped with single antenna. In each time slot, the transmitter allows N_a antennas to be activated with N_a = 1, 2, ..., N_t. The direct channel between the transmitter and the receiver is blocked by a barrier, and the RIS equipped with N reflection elements can effectively reflect the signal to the receiver by adjusting the phase of the incident wave [6] - [10].

2.1 Transmitter

In this scheme, adaptive space shift keying works at the transmitter, which maps the incoming bits into the indices of antenna combinations. The full set of antenna combinations is denoted as Λ and $\Lambda(j)$ is a subset of antenna combinations selected from Λ, where j = 1, 2, ..., J represents the index of subset and J is given by:

$$\mathrm{J} = \sum_{N_a=1}^{N_t} \binom{N_t}{N_a} = 2^{N_t} - 1. \tag{1}$$

The data rate of RIS-TASSK system is determined by the antenna combinations which is shown as:

$$m = \lfloor \log_2(\mathrm{J}) \rfloor. \tag{2}$$

The wireless fading channel between the k-th transmit antenna and the i-th reflection element is defined by $H_{k,i}$, while the channel between the i-th reflection element and the receive antenna is denoted by g_i, where $k = 1, ..., N_t$ and $i = 1, ..., N$. Additionally, $H_{k,i}$ and g_i are assumed to be independent and identically distributed complex Gaussian random variables with $\mathcal{CN}(0,1)$, which can be expressed as $H_{k,i} = \alpha_{k,i}e^{-j\theta_{k,i}}$ and $g_i = \beta_i e^{-j\psi_i}$, where $\alpha_{k,i}$ and β_i represent the Rayleigh factors, $\theta_{k,i}$ and ψ_i represent the channel phases of these two channels. To better understand all antenna combinations, the fused channel formed by the corresponding channel of antenna combinations is regarded as the transmit channel, and the channel corresponding to the j-th antenna combination can be expressed as:

$$\hat{H}_{j,i} = \sqrt{\frac{E}{N_a}} \sum_{k\in\Lambda(j)} H_{k,i} \tag{3}$$

where E is the total conveyed signal energy. By constructing (3), the number of available channels is expanded from N_t to J, which can improve the spectral efficiency. Since the number of available antenna combinations is greater than the required, i,e., S = 2^m combinations, therefore, S candidate combinations are selected from J, and the corresponding channel is denoted as $\hat{H}_{s,i} = \hat{\alpha}_{s,i}e^{-j\theta_{s,i}}$, with $\hat{\alpha}_{s,i}$ and $e^{-j\theta_{s,i}}$ being the Rayleigh factor and the channel phase of s-th selected transmit combination, respectively, where s = 1, ..., S. A mapping sample for RIS-TASSK scheme with $N_t = 4$ is given in Table 1. Since the selected candidate combination is obtained, the received signal y at the receiver can be obtained as:

$$y = \sqrt{E}\left(\sum_{i=1}^{N} \hat{\alpha}_{s,i}\beta_i e^{j(\phi_i - \theta_{s,i} - \psi_i)}\right) + n, \tag{4}$$

where n is the additive white Gaussian noise term, which has zero-mean and variance N_0, and ϕ_i is the adjusted optimal phase for the i-th reflection element of the RIS to the receiver.

2.2 Receiver

Assuming that the CSI is perfectly known at the receiver and in order to provide the best detection for RIS-TASSK scheme, maximum likelihood (ML) detector is used to detect the bits conveyed by the index of selected antenna combination, which works as follow:

$$q = \arg\min_{s} \left\{|y - \tilde{y}|^2\right\}, \tag{5}$$

where q represents estimated antenna combination, y represents the received signal of selected antenna combination, and $\tilde{y}$ is defined as:

$$\tilde{y} = \sqrt{E}\left(\sum_{i=1}^{N} \hat{\alpha}_{q,i}\beta_i e^{j(\phi_i - \theta_{q,i} - \psi_i)}\right), \tag{6}$$

which represents that the received signal is estimated and conveyed by the q-th antenna combination, and $\theta_{q,i}$ represents the adjusted phases of the signal transmitted from the q-th estimated antenna combination to the i-th reflecting element.

3. Performance Analysis

Assuming the transmitter selects antenna combination s to convey an unmodulated signal to receiver by the RIS, however, it is detected erroneously as q. The pairwise error probability (PEP) of the RIS-TASSK can be obtained based on the detection of ML in (5), which can be expressed as:

$$\begin{aligned}
&\Pr\{s \to q \mid \hat{H}\} \\
&= \Pr\left\{\left|y-\sqrt{E}\hat{H}_s\right|^2 > \left|y-\sqrt{E}\hat{H}_q\right|^2\right\} \\
&= \Pr(\left\{\left|y-\sqrt{E}\hat{H}_s\right|^2 - \left|y-\sqrt{E}\hat{H}_q\right|^2\right\} > 0) \\
&= \Pr\left\{-E\left|\hat{H}_s-\hat{H}_q\right|^2-2\Re\left\{\sqrt{E}\left(\hat{H}_s-\hat{H}_q\right)n^*\right\}>0\right\},
\end{aligned} \tag{7}$$

where $\hat{H}_s = \sum_{i=1}^{N}\hat{\alpha}_{s,i}\beta_i$, $\hat{H}_q = \sum_{i=1}^{N}\hat{\alpha}_{q,i}\beta_i$, and n^* is the complex conjugate value of n. To facilitate subsequent calculations, we define

$$F = -E\left|\hat{H}_s - \hat{H}_q\right|^2 - 2\Re\left\{\sqrt{E}\left(\hat{H}_s - \hat{H}_q\right)n^*\right\}, \tag{8}$$

where F is a Gaussian random variable with mean $\mu_F = -E\left|\hat{H}_s - \hat{H}_q\right|^2$, variance $\sigma_F^2 = 2EN_0\left|\hat{H}_s - \hat{H}_q\right|^2$, and and $\Re\{\cdot\}$ is the real part of a complex number. Considering the PEP can also be calculated using the Q-function from $P\{F > 0\} = Q(-\mu_F/\sigma_F)$, it can be written as follow:

$$\Pr(s \to q \mid \hat{H}) = Q\left(\frac{E\left|\hat{H}_s - \hat{H}_q\right|^2}{\sqrt{2EN_0\left|\hat{H}_s - \hat{H}_q\right|^2}}\right). \tag{9}$$

Moving a step further by denoting $D = \hat{H}_s - \hat{H}_q$, we have:

$$D = \sum_{i=1}^{N}\beta_i(\hat{\alpha}_{s,i} - \hat{\alpha}_{q,i}). \tag{10}$$

At this point, D follows the Gaussian distribution with a zero mean value and a variance value of σ_D^2. Considering the RIS has sufficiently large number of reflecting elements, i.e., $N \gg 1$, according to the central limit theorem (CLT), σ_D^2 is calculated as $N(2 - \pi/2)$. Then, we define $\nu = |D|^2$, which follows a central chi-square distribution with one degree of freedom, and the average PEP (APEP) can be derived as:

$$\begin{aligned}
\overline{P}_e &= \int_0^\infty Q\left(\sqrt{\frac{E\nu}{2N_0}}\right)f_\nu(\nu)d\nu \\
&= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} M_\nu\left(-\frac{E}{4N_0\sin^2\eta}\right)d\eta,
\end{aligned} \tag{11}$$

where $M_\nu(\cdot)$ is the moment generating function (MGF) of ν. In order to obtain the upper bound of APEP, by defining $t = -\frac{E}{4N_0\sin^2\eta}$ and $M_\nu(t) = \left(\frac{1}{\sqrt{1-2\sigma_D^2 t}}\right)$, the APEP of RIS-TASSK scheme can be expressed as:

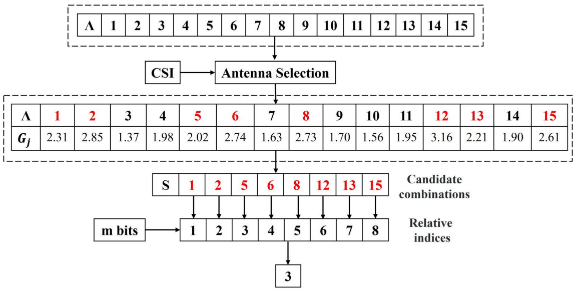

Fig. 2 Antenna selection for RIS-TASSK with $N_t = 4$.

$$\overline{P}_e = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left(\frac{1}{\sqrt{1+\left(\frac{4-\pi}{2}\right)\frac{NE}{2N_0\sin^2\eta}}}\right)d\eta. \tag{12}$$

Eventually, the average bit error rate (ABER) of RIS-TASSK scheme is calculated in the form of a union bound [6] as follows:

$$\overline{P}_b \le \frac{1}{\log_2 \mathrm{S}}\sum_q \overline{P}_e \times d(s \to q) = \frac{\mathrm{S}}{2}\overline{P}_e. \tag{13}$$

where $d(s \to q)$ denotes the Hamming distance between the binary representations of s and q, while $\sum_q d(s \to q) = (\mathrm{S}/2)\log_2(\mathrm{S})$ represents the number of bits in error for all s.

4. Antenna selection and complexity analysis with RIS-TASSK

In this section, an antenna selection method with RIS-TASSK scheme is proposed. Furthermore, the complexity of antenna selection and RIS-TASSK scheme are analyzed.

4.1 Antenna Selection Method

Since the available antenna combinations are more than the required antenna combinations and the selected antenna combinations must be a power of 2, we need to select the appropriate antenna combinations. In order to obtain better BER performance, we can flexibly select the antenna combinations with larger channel gains in antenna selection. Therefore, the instantaneous CSI corresponding to the transmit antenna can be used to activate the antenna with larger channel gain[†]. The channel gains of all possible antenna combinations are sorted as:

$$\left\|\hat{H}_{1,i}\right\|^2 > \left\|\hat{H}_{2,i}\right\|^2 > \left\|\hat{H}_{3,i}\right\|^2 > \cdots > \left\|\hat{H}_{\mathrm{J},i}\right\|^2. \tag{14}$$

In order to understand the process of antenna selection more clearly, Fig. 2. gives the antenna selection method that determines the transmission bits based on the transmit

[†]Here, the mapping between incoming bits and the candidate channel is assumed to be known at the transmitter [11]-[12], and the index corresponding to the candidate channel is in one-to-one correspondence with incoming bits.

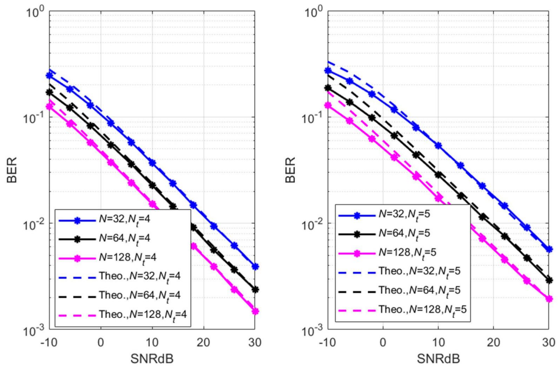

Fig. 3 The BER performance of RIS-TASSK system with increasing N in 3 bits/s/Hz and 4 bits/s/Hz.

antenna N_t. There is an example for $N_t = 4$ presented in Fig. 2, which shows that all possible antenna combinations are indicated by using indices, and then the channel gains corresponding to these antenna combinations are obtained according to the CSI of these channels. The channel gains corresponding to all antenna combinations are then sorted, and the eight largest ones (Nos. 1, 2, 5, 6, 8, 12, 13 and 15) are selected and the corresponding antenna combinations are chosen as the candidates to convey the incoming information. After the candidate antenna combinations are determined, the input three bits are mapped to these eight candidate antenna combinations. When the incoming bit sequence is 010, the third candidate antenna combination is selected to convey this information. In this way, the BER performance of the system can be improved by selecting the antenna combination with larger channel gain, because the performance of the communication system is affected by the quality of the channel.

4.2 Complexity Analysis

The complexity is calculated by the number of complex multiplications and complex additions. The average complexity of antenna selection is calculated as:

$$C_{\mathrm{Antenna-selection}} = \sum_{N_a=1}^{N_t} \binom{N_t}{N_a} [(NN_a + 2)] . \qquad (15)$$

The average complexity of RIS-TASSK is calculated as:

$$C_{\mathrm{RIS-TASSK}} = \left(\left(3 + \left(\frac{N_t+1}{2}\right)\right) N + 2\right) 2^m . \qquad (16)$$

where $\left(\frac{N_t+1}{2}\right)$ is the expected value of N_a.

The results of the complexity analysis are summarized in Table 2, which also includes RIS-TSSK and RIS-TGSSK schemes. It is clear that RIS-TSSK scheme has lowest complexity, while RIS-TGSSK and RIS-TASSK schemes have almost the same complexity. It is worth noting that in order to achieve the same spectral efficiency, the required transmit antennas of these three schemes are inconsistent, and the proposed scheme uses the least antennas.

Table 2 Detection Complexity Analysis Summary

Scheme	Complexity
RIS-TSSK	$(4N+2)N_{t(TSSK)}$
RIS-TGSSK	$\left(\left(3+\left(\frac{N_{t(TGSSK)}}{2}+1\right)\right)N+2\right)2^m$
RIS-TASSK	$\left(\left(3+\left(\frac{N_t+1}{2}\right)\right)N+2\right)2^m$

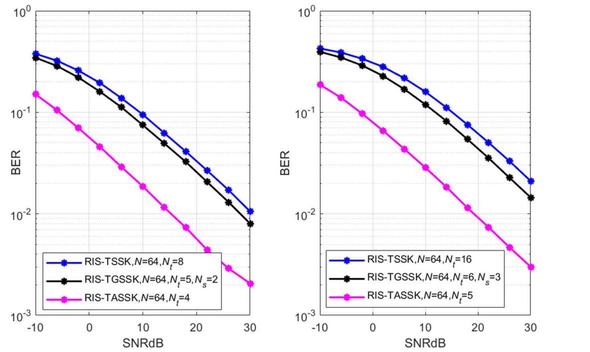

Fig. 4 Comparison of BER performance among RIS-TASSK, RIS-TSSK, and RIS-TGSSK for 3 and 4 bits/s/Hz with $N = 64$.

5. Simulation Results

In this section, the BER performance of the proposed RIS-TASSK scheme as well as its optimization scheme with antenna selection is investigated by Monte Carlo simulations. In the simulations, we compare RIS-TASSK scheme with RIS-TSSK scheme and RIS-TGSSK scheme to demonstrate the better BER performance.[†]

Firstly, the simulation and theoretical results of RIS-TASSK scheme with different number of reflection elements is shown in Fig. 3. As we can see from the figure, when $N_t = 4$ and $N_t = 5$, the system performance gets better with the increase of SNR. Here, the SNR is defined as E/N_0. In these two cases, it can be observed that doubling the number of reflection elements ensures 4 dB and 5 dB gain in the SNR at BER of 10^{-2}. Obviously, the more reflection elements that RIS is equipped with the greater system performance can be achieved. Moreover, the theoretical results are close to the simulation results, especially at high SNR.

In Fig. 4, the BER performance of RIS-TASSK scheme is respectively compared with RIS-TSSK scheme in [10] and RIS-TGSSK benchmark scheme. When N_t in RIS-TASSK scheme are 4 and 5, and the spectral efficiency are 3 bits/s/Hz and 4 bits/s/Hz, respectively. As we can see from the figure, RIS-TASSK has better BER performance than the other two schemes, and this improvement is more significant at high SNR. To achieve the same spectral efficiency, the RIS-TSSK scheme needs to increase the $N_{t(TSSK)}$ to 8 and 16, and the RIS-TGSSK scheme also needs to increase the $N_{t(TGSSK)}$ to 5 and 6. In this comparison, the RIS-TASSK scheme also

[†]RIS-TSSK reference scheme is proposed in [10], which can carry out phase cancellation at the receiver according to CSI.

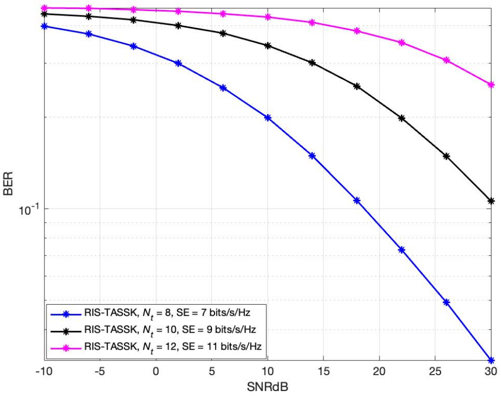

Fig. 5 The BER performance of RIS-TASSK scheme for various number of transmit antennas under $N = 64$.

has better BER performance with fewer antennas.

We then extend our analysis to the case of various number of transmit antennas for RIS-TASSK scheme, which is shown in Fig. 5. The results reveal that the BER performance for RIS-TASSK scheme deteriorates with the increase of the number of transmit antennas, and the spectral efficiency increases with the number of transmit antennas. Contrarily to other schemes, RIS-TASSK scheme does not require to adhere to the constraint of having the antenna number as a power of two to enhance spectral efficiency. Consequently, RIS-TASSK scheme can attain superior spectral efficiency without being limited by the antenna number, thereby presenting more feasible transmission.

6. Conclusion

In this paper, a RIS-TASSK scheme has been proposed for improving BER performance in wireless communication. In addition, two antenna selection methods based on CSI have been designed for RIS-TASSK scheme to achieve the performance of ideal BER and lower complexity, respectively. Simulation results have shown that RIS-TASSK has better performance than RIS-TSSK and RIS-TGSSK systems, which indicates that RIS-TASSK can be a good candidate for the future wireless communications.

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