LETTER

Intelligent Reconfigurable Surface-Aided Space-Time Line Code for 6G IoT Systems: A Low-Complexity Approach

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SUMMARY Intelligent reconfigurable surfaces (IRS) have attracted much attention from both industry and academia due to their performance improving capability and low complexity for 6G wireless communication systems. In this letter, we introduce an IRS-assisted space–time line code (STLC) technique. The STLC was introduced as a promising technique to acquire the optimal diversity gain in 1×2 single-input multiple-output (SIMO) channel without channel state information at receiver (CSIR). Using the cosine similarity theorem, we propose a novel phase-steering technique for the proposed IRS-assisted STLC technique. We also mathematically characterize the proposed IRS-assisted STLC technique in terms of outage probability and bit-error rate (BER). Based on computer simulations, it is shown that the results of analysis shows well match with the computer simulation results for various communication scenarios.

key words: *6G wireless communiations, space-time line code (STLC), intelligent reconfigurable surface (IRS), outage probability, bit-error rate (BER)*

1. Introduction

For the next-generation wireless communication systems (B5G or 6G), intelligent reconfigurable surface (IRS)-based techniques have attracted much attention due to their simple architecture and performance improving capability [1]–[3]. The IRS is basically composed of meta-material (passive) reflecting elements with electrically phase-steering capability. Based on this capability, the IRS can be applied to mmWave communication systems for providing an additional transmission link when a line-of-sight (LoS) link between terminals are not guaranteed. The IRS has been investigated for many wireless communication scenarios including multi-cell systems, non-orthogonal multiple access (NOMA) systems, etc [3].

Besides, various techniques to integrate the IRS into the legacy multiple-input multiple-output (MIMO) technique have been introduced [4]–[6]. The authors of [4] introduced, the multiple-input single-output (MISO)-based single-cell network with a IRS was investigated, where a jointly optimized beamformer for both the base station and the IRS in the sense of signal-to-interference-plus-noise ratio (SINR) was proposed. In [5], two IRS-aided MIMO systems were presented to increase spectral efficiency, where the classical Alamouti's scheme and vertical bell labs layered space-time (V-BLAST) were re-designed for the IRS-aided communication scenario and the corresponding end-to-end performance was shown to be significantly enhanced. In [6], a simple IRS-aided MIMO system was proposed based on cosine similarity relationship between vectors, where the phase steering is adjusted by considering both the maximum-likelihood (ML)-based classical MIMO and the spatial multiplexing (SM) technique.

On the other hand, a space-time line-code [7] was originally introduced as a simple full-diversity achieving scheme for 1×2 single-input multiple-output (SIMO) systems. With its simplicity and effectiveness, the STLC has been actively applied to many wireless communication scenarios such as orthogonal frequency division multiplexing (OFDM)-based transceiver systems [8], regenerative two-way relay systems [9] uplink NOMA random access systems [10], secure multiple access systems [11], $M \times 4$ MIMO systems [12] and IRS-assisted system [13], etc. In [5], [13], [14], IRS-asissted space-time block code (STBC) systems were also proposed. In [5], [14], the source node sends information symbols and the IRS encodes the received symbols into STBC symbols through partitioned groups of IRS. Hence, this technique cannot be directly integrated to STLC-based systems. Even though [13] is based on the STLC system, the proposed algorithm requires relatively high computational complexity, which may not be suitable for internet of things (IoT) devices. In addition, [13] did not mathematically analyze performance such as BER and outage probability.

In this letter, we consider an STLC system with IRS assist which is composed by one transmit antenna at the source node (S), two receive antennas at the destination node (D), and multiple passive refection elements at the IRS between S and D. In addition, we assume that there exist no direct link between S and D. Full channel state information (CSI) assumption at the S is used, and the IRS receives only the phase-steering information from S. Even though the proposed scheme yields somewhat degraded performance compared with [14], it has a similar performance with [5]. However, at the destination node, the proposed scheme requires a lower computational complexity than [5], [14] and the proposed scheme has a slightly higher complexity at the source node compared with [5], [14]. In particular, we propose a novel practical low-complexity IRS-assisted STLC system where we exploit the cosine similarity-based phase steering at the IRS. As one of the main contributions, the outage and bit-error rate (BER) performances are mathe-

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matically analyzed. The analytical results are validated for various number of IRS elements through Monte-Carlo computer simulations.

The rest of this letter is organized as followings: in Sect. 2 the system model and overall procedure of the proposed IRS-assisted STLC system are described. In Sect. 3, we present the mathematical analysis of the proposed IRS-assisted STLC system in terms of outage probability and BER. In Sect. 4, the analytical results and computer simulation results are compared to each other. Finally, conclusions are drawn in Sect. 5.

2. System Model and Proposed IRS-Assisted STLC

We propose an IRS-assisted system consisting of a single source node S with a single antenna, a single destination node D with two antennas, and a single IRS with N passive reflecting elements between the transmitter and the receiver as illustrated in Fig. 1. The proposed system employs the STLC scheme at the transmitter. The terms $\mathbf{h} \in \mathbb{C}^{N\times 1}$ and $\mathbf{G} \in \mathbb{C}^{2\times N}$ denote the wireless channel vector from the transmitter to the IRS and the wireless channel matrix from the IRS to the receiver, respectively, whose elements are assumed to follow independent and identically distributed (i.i.d.) complex Gaussian distribution $\mathcal{CN}(0, 1)$. Moreover, $\mathbf{\Phi} \in \mathbb{C}^{N\times N}$ denotes the phase-steering coefficient matrix at the IRS, which is defined by $\mathbf{\Phi} = \mathrm{diag}\{e^{j\phi_1}, e^{j\phi_2}, e^{j\phi_3}, \ldots, e^{j\phi_N}\}$. Based on these notations, the effective channel vector from the transmitter to the receiver $\mathbf{e} \in \mathbb{C}^{2\times 1}$ becomes $\mathbf{e} = \mathbf{G\Phi h} = \sum_{i=1}^{N} \mathbf{g}_i e^{j\phi_i} h_i$, where $\mathbf{g}_i$ indicates the ith column vector of $\mathbf{G}$ and h_i indicates the ith element of $\mathbf{h}$. We assume that the perfect CSI is available at the transmitter as assumed in many STLC studies [7], [10]–[12].

Let x_1 and x_2 denote information symbol with average power of σ_x^2, i.e., $\mathbb{E}[|x_k|^2] = \sigma_x^2$, $k = 1, 2$. The two information symbols are encoded into two STLC symbols s_1 and s_2 as follows:

$$\begin{bmatrix} s_1^* \\ s_2 \end{bmatrix} = \begin{bmatrix} e_1 & e_2 \\ e_2^* & -e_1^* \end{bmatrix} \begin{bmatrix} x_1^* \\ x_2 \end{bmatrix}, \tag{1}$$

where e_1 and e_2 denote the first and the second element of $\mathbf{e}$, respectively. To normalize the power at the transmitter as σ_x^2, the normalization factor η is calculated as $1/\sqrt{\|\mathbf{e}\|^2}$. After receiving two consecutive symbols, the signal at the receiver is given by

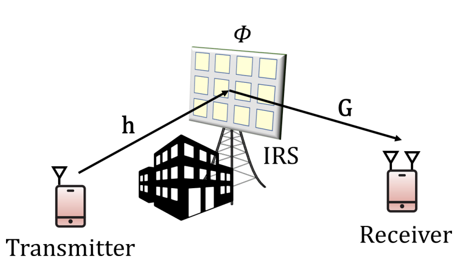

Fig. 1 System model of the proposed IRS-assisted STLC system.

$$\begin{bmatrix} r_{1,1} & r_{1,2} \\ r_{2,1} & r_{2,2} \end{bmatrix} = \eta \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \begin{bmatrix} s_1 & s_2 \end{bmatrix} + \begin{bmatrix} n_{1,1} & n_{1,2} \\ n_{2,1} & n_{2,2} \end{bmatrix}, \tag{2}$$

where $r_{i,j}$ and $n_{i,j}$ denotes the received signal and the additive Gaussian noise at the ith receive antenna in the jth symbol time, respectively. In particular, $n_{i,j}$ follows complex-Gaussian distribution with mean zero and variance σ_n^2, i.e., $n_{i,j} \sim \mathcal{CN}(0, \sigma_n^2), \forall i, j$.

The information symbols x_1 and x_2 can be decoded by linear combination of the received four signals as follows:

$$\hat{x}_1 = r_{2,2}^* + r_{1,1} = \frac{1}{\eta} x_1 + n_{1,1} + n_{2,2}^*, \tag{3}$$

$$\hat{x}_2 = r_{2,1}^* - r_{1,2} = \frac{1}{\eta} x_2 + n_{2,1}^* - n_{1,2}. \tag{4}$$

Since η can be estimated by blind SNR estimation, the receiver can obtain the information symbols without the CSI. Using the received signals, the instantaneous SNR of information symbols after combining is derived as follows:

$$\gamma = \frac{\sigma_x^2}{2\eta^2\sigma_n^2} = \frac{\|\mathbf{e}\|^2\sigma_x^2}{2\sigma_n^2} = \|\mathbf{e}\|^2\bar{\gamma}, \tag{5}$$

where $\bar{\gamma} = \sigma_x^2/2\sigma_n^2$.

As noted before, the proposed IRS-assisted STLC system assumes two antennas at the receiver. Thus, the conventional phase-steering scheme that determines $e^{j\phi_i}, \forall i \in \{1, 2, \ldots, N\}$ to compensate the phase-distortion of the wireless channel of both source-IRS link and IRS-destination link cannot be used for our case. We adopt the cosine similarity theorem [6] to adjust the phase of each element of the IRS in the proposed IRS-assisted STLC system. Then, the phase of each element of the IRS is determined as the phase difference between channel vector $\mathbf{g}_i$ and its component-wise absolute vector $\tilde{\mathbf{g}} \triangleq \left[|g_{i,1}|, |g_{i,2}|, |g_{i,3}|, \ldots, |g_{i,N}|\right]$. To be specific, the phase-steering coefficient of the ith element of the IRS is given by

$$\phi_i = -\left(\angle(h_i) + \arccos\left(\frac{<\mathbf{g}_i, \tilde{\mathbf{g}}_i>_{\mathrm{Re}}}{\|\mathbf{g}_i\|\|\tilde{\mathbf{g}}_i\|}\right)\right), \tag{6}$$

where $\angle(h_i)$ is the phase of h_i. It is notable that the complexity of phase-steering coefficient calculation for proposed system is $O(18N)$ which is much lower than the computational complexity of $O(N^3)$ in [13] for sufficiently large N. Generally we consider that $N >> 4$ in IRS-assisted systems.

3. Performance Analysis

In this section, we mathematically characterize the outage probability and BER of the proposed IRS-assisted STLC system. Since the phase steering formula in (6) can not be expressed in a linear operation, the distribution of $\mathbf{e}$ is hard to be directly obtained with a closed form unfortunately. Hence, in this letter, we follow a semi-analytical approach as in [6]. The authors of [6] analyzed the distribution of each element of the effective channel vector $\mathbf{e}$ and showed that each element of $\mathbf{e}$ can be modeled with a complex normal distribution with $\mathcal{CN}(\alpha N, N)$, where α is expressed in terms of the number of antennas at S and D, N_T and N_R:

$$\alpha = \frac{1.8}{(1+2N_T)(1+2N_R)}. \tag{7}$$

In our case, $N_T = 1$ and $N_R = 2$.

Based on the pre-described statistical model of the channel elements, the distribution of signal-to-noise ratio (SNR) at the receiver γ is a non-central chi-square distribution with degrees-of-freedom of 4 whose probability density function (PDF) is as follows:

$$f_\gamma(\gamma) = \frac{1}{2\delta^2}\left(\frac{\gamma}{\lambda}\right)^{1/2} \exp\left(-\frac{\gamma+\lambda}{2\delta^2}\right) I_1\left(\frac{\sqrt{\lambda\gamma}}{\delta^2}\right), \tag{8}$$

where $\lambda = 2N^2\alpha^2\bar{\gamma}$, $\delta^2 = \bar{\gamma}N$, and $I_1(\cdot)$ means the modified Bessel function of the 1st class. Based on this PDF, the cumulative distribution function (CDF) can be derived as

$$F_\gamma(\gamma) = 1 - Q_2\left(\sqrt{\frac{\lambda}{\delta^2}}, \sqrt{\frac{\gamma}{\delta^2}}\right), \tag{9}$$

where $Q_m(i,j)$ denotes the Marcum Q-function. Then, the outage probability of the proposed IRS-assisted STLC system is obtained by plugging the outage threshold γ_{th} into (9). With a well-known union bound, the BER of the proposed IRS-assisted STLC system is given by

$$P_e \approx \frac{m_1 m_2}{2\sqrt{2\pi}} \int_0^\infty \frac{1}{\sqrt{x}} \exp\left(-\frac{m_2^2 x}{2}\right) F_\gamma(x)\, dx, \tag{10}$$

where $m_1 = 1$ and $m_2 = \sqrt{2}$ for binary phase shift Keying (BPSK) and $m_1 = 4/\log_2 M$ and $m_2 = \sqrt{3/(M-1)}$ for M-ary quadrature amplitude modulation (M-QAM), respectively [15]. Using (9) and (10), the BER is approximated as

$$\begin{aligned} P_e \quad &\approx \tfrac{m_1 m_2}{2\sqrt{2\pi}} \int_0^\infty \tfrac{1}{\sqrt{x}} \exp\left(-\tfrac{m_2^2 x}{2}\right) dx \\ &- \tfrac{m_1 m_2}{2\sqrt{2\pi}} \int_0^\infty \tfrac{1}{\sqrt{x}} \exp\left(-\tfrac{m_2^2 x}{2}\right) Q_2\left(\sqrt{\tfrac{\lambda}{\delta^2}}, \sqrt{\tfrac{\gamma}{\delta^2}}\right) dx. \end{aligned} \tag{11}$$

According to [16, Eq. (8)], the following closed-form expression involving integration of Marcum-Q function is valid:

$$\begin{aligned} &\mathcal{G}(k,m,a,b,p) \\ &\triangleq \int_0^\infty x^{k-1} Q_m(a, b\sqrt{x}) e^{-px} dx \\ &= \frac{\Gamma(k)}{p^k} - \frac{\Gamma(k) b^{2m}}{p^k (b^2+2p)^m} e^{-\frac{a^2}{2}} \\ &+ \sum_{j=0}^{k-1} \frac{(m)_n (2p)^j}{j!(b^2+2p)^j}\, {}_1F_1\left(k; k+j; \frac{a^2 b^2}{2a^2+4p}\right), \end{aligned} \tag{12}$$

where $(x)_n$, $\Gamma(\cdot)$ and ${}_1F_1$ denote the Pochhammer symbol, gamma variable, and the Kummer hypergeometric function, respectively. Using (12), the average BER can be obtained with algebraic manipulations as

$$P_e \approx m_1 \frac{(1/\delta^2)^2}{(1/\delta^2 + m_2^2)^2} \exp\left(-\frac{\lambda}{2\delta^2}\right) {}_1F_1\left(2; 2; \frac{\lambda}{2\delta^2 + 4\delta^4}\right). \tag{13}$$

4. Simulation Results

In this section, we validate performances of the proposed IRS-assisted STLC system via Monte Carlo simulations, and compare them with analytical results. The simulations are conducted by Intel i7-8700 CPU with 32 GB RAM and Matlab software is utilized. We define $SNR = \sigma_x^2/\sigma_n^2$ with signal power $\sigma_x^2 = 1$, and assume the zero doppler frequency in the simulations. In addition, no channel correlation and no loss in IRS are assumed as many related studies in the literature. In Fig. 2, the computation time of the proposed technique and the the unit-modulus constraint relaxation (UCR) scheme [13] are compared with 10^6 independent channel generations. The computational complexity of the proposed technique is much lower than UCR-based scheme and the difference between them becomes larger as the number of IRS elements increases.

Figure 3 shows the outage probability according to the number of IRS reflection elements, $N = 5, 10, 20, 30$. Obviously, the IRS improves the end-to-end performance more than 10 dB compared with the no-IRS ($N = 0$) case for sufficiently large number of IRS elements. In particular, "No IRS" means the typical SIMO-based STLC system. For the simulation of "No IRS" scheme, the effective channel vector is set to $\mathbf{e} = \mathbf{g}_1$, where $\mathbf{g}_1$ denotes a 2×1 channel vector, i.e. only a single column vector of $\mathbf{G}$ is used for the simulation. In addition, the additional performance gain is attained by the phase-steering scheme and the performance enhancement by the phase steering becomes larger as N increases.

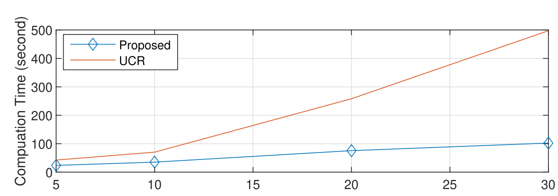

Fig. 2 Complexity comparison between proposed scheme and UCR.

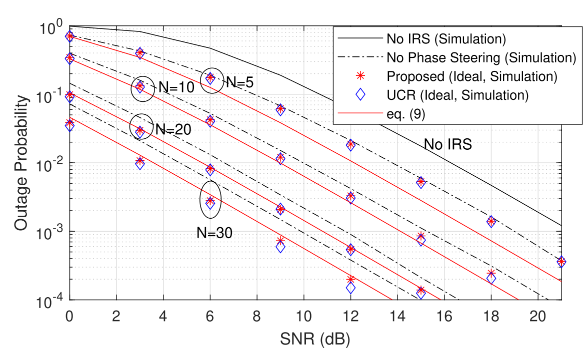

Fig. 3 Outage Probability of the proposed IRS-assisted STLC.

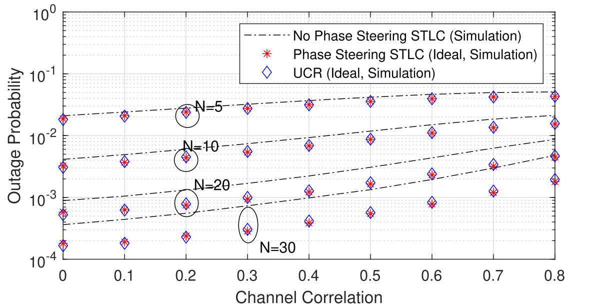

Fig. 4 Outage probability of the IRS-assisted STLC system for varying channel correlation of receiver antennas.

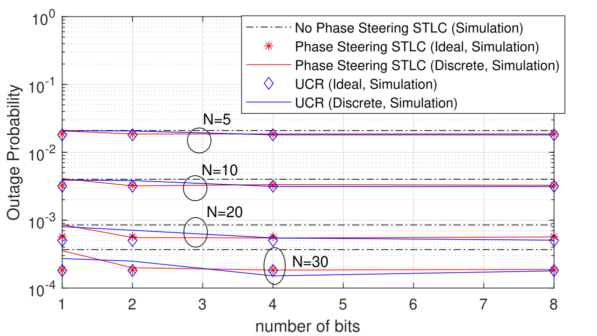

Fig. 5 Outage probability of the IRS-assisted STLC system for varying number of quantization bits.

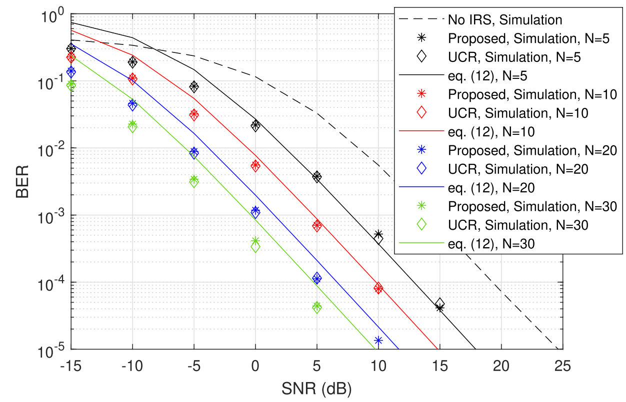

Fig. 6 BER of the IRS-assisted STLC system with BPSK for varying number of elements of IRS.

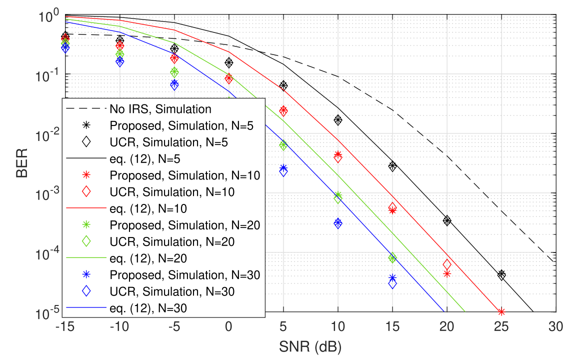

Fig. 7 BER of the IRS-assisted STLC system with 16QAM for varying number of elements of IRS.

Because of the fundamental limitation of MIMO-based IRS systems which cannot fully compensate the phase of each channel element and find the optimal phase-steering technique, the performance gap between the proposed scheme and the scheme without phase steering is not so great contrary to expectations. It is worth noting that the mathematical analysis matches well with the simulation results regardless of N and SNR values. Moreover, it can be observed that the outage performance of proposed STLC is very close to the outage of UCR-based STLC in [13] which have much computational complexity than ours. It is worth noting that the UCR-based scheme cannot obtain the sufficient performance gain even with significant computational complexity due to eigen-value decomposition (EVD). The phase-steering value of the UCR scheme can be calculated by using the eigenvector corresponding to the maximum eigenvalue of composite channel matrix. However, this channel matrix is expressed by the linear operation of limited contribution components. Hence, most results of the EVD do not have sufficient information, and thus the UCR-based algorithm does not have much additional performance gain compared with the proposed technique.

Figure 4 shows the outage probability of the proposed technique for varying channel correlation values between two receiver antennas for a given SNR of 12 dB and the number of IRS reflection elements. As expected, the outage performance becomes degraded as the degree of correlation increases. The effect of the channel correlation on the performance are similar in the proposed and UCR-based schemes. The effect of the quantization error at the IRS on the performance of the proposed technique is shown in Somewhat interestingly, the quantization error at the IRS does not significantly degrade the system performance as shown in Fig. 5.

In Figs. 6 and 7, the BER performance of the proposed system is shown under various number of IRS reflection elements, i.e., $N = 0, 5, 10, 20, 30$. The analytical results match well with the simulation results regardless of N even though somewhat difference between simulation results and analysis results exist. Most theoretical analyses have inevitable imperfections. For example, when BER is equal to 10^{-4}, the difference is measured as follows: i) BPSK, $N = 30$ case: approximately 2 dB gap between simulation and analysis ii) 16QAM, $N = 30$ case: approximately 2.3 dB gap between simulation and analysis.

5. Conclusion

In this letter, we presented a IRS-assisted STLC system, and mathematically analyzed its outage probability and BER performance. In order to further performance improvement of the IRS-aided STLC system, we adapted the cosine similarity theorem-based phase-steering scheme at the IRS. It was shown that the analysis results match well with Monte Carlo simulation results for various system parameters such as the IRS reflection elements number and SNR. We observed that the end-to-end error performance becomes significantly improved as the number of IRS reflection elements increases.

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