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Cooperative space-time line code for relay-assisted internet of things

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Abstract

We propose a novel *cooperative* space–time line code (C-STLC) scheme to improve performance of a relay-assisted internet of things (R-IoT). The proposed C-STLC operates with fully distributed manner, where each relay IoT device (RID) attempts to decode the received signal from a source IoT device at the first hop and the RIDs, that succeeded decoding, send the STLC encoded signal based on their local channel state information (CSI) to a single access point (AP) at the second hop. Then, the AP decodes the received signals without CSI. As a main result, we mathematically analyze the outage probability (OP) of the proposed C-STLC scheme. It is shown that the proposed C-STLC significantly outperforms conventional cooperative relaying techniques in terms of the OP.

Keywords: Internet of things (IoT); Space–time line code (STLC); Cooperative relaying techniques; Outage probability; Cooperative diversity; Channel station information (CSI)

1. Introduction

Internet of things (IoT) applications are expected to be main services in beyond fifth generation (B5G) networks [1]. In general, battery-powered IoT devices (IDs) are required to operate with low power consumption, and thus, have limited coverage. Therefore, a relay-assisted IoT (R-IoT) is being actively investigated to improve energy efficiency [2]. In the R-IoT, separately deployed multiple IDs may play a role of relay, i.e., relay ID (RID), to help the packet delivery from a source ID (SID) to an access point (AP) [3].

In [4], a best single relay selection (BSR) is to select a relay that has the best channel condition. With its simple methodology of BSR scheme, many relay selection schemes have been investigated for various environments with different relay selection criteria according to considered environments such as buffer aided relays [5], energy harvesting relays [6], and MIMO relays with space time coding [7]. However, in the above techniques, source or destination node is required to select the best relay for given performance metric and to notify it to all relay nodes. Then, the overhead becomes significantly increased as the number of relays increases.

Meanwhile, another cooperative relaying technique called cooperative phase steering (C-PS) was proposed to not only reduce signaling overhead but also improve performance [8]. In the C-PS technique, each relay adjusts phase of its transmit signal with a distributed manner so that the phase of the received signals at a destination node are aligned, assuming local channel state information (CSI) at relays. However, the C-PS technique cannot be applied to multi-antenna destination node.

Therefore, in this paper, we propose a novel cooperative space–time line code (C-STLC) technique for R-IoT. Note that CSIs of multiple RIDs are not required at the another device, so that all RIDs can operates with fully distributed manner, thanks to the fundamental characteristics of STLC [9,10], which leads low-complexity implementation and operation of the system. The proposed C-STLC is mathematically analyzed in terms of outage probability (OP). In simulation results, we show that the proposed C-STLC technique is matched well with Monte-Carlo simulation results and outperforms the conventional techniques, BSR scheme and C-PS technique.

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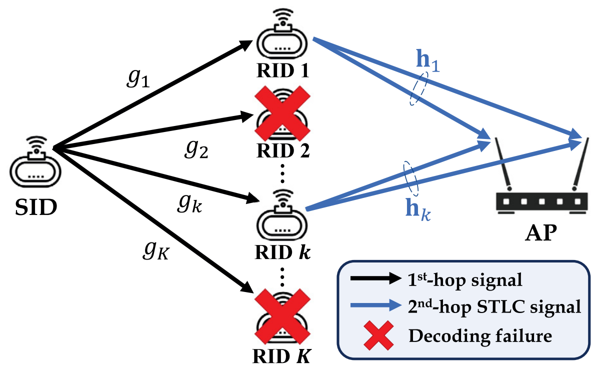

Fig. 1. System model of the proposed C-STLC for R-IoT.

2. Cooperative STLC

In this section, we describe first-hop and second-hop operation of the proposed C-STLC.

When an ID has symbols to send to the AP, it becomes an SID in our system model. Then, the SID tries to send its symbols directly to AP or send its symbols with the help from other RIDs. In the proposed technique, a well-known request-to-send (RTS) and clear-to-send (CTS) protocol is utilized for the SID to get channel access opportunity and to obtain the CSI as in practical ad-hoc networks.

First, the SID broadcasts an RTS packet to get the channel access opportunity, and then the AP and other nearby IDs obtain the CSI from the SID to themselves by receiving the RTS packet. If a channel gain from the SID to the AP is sufficient to send packets from the SID to the AP directly, then the AP may send a CTS packet to grant the *direct* channel access for the SID.

On the other hand, if the channel gain from the SID to the AP is not sufficient to send packets directly, then the AP broadcasts *another* CTS packet that requests for other IDs to help the packet transmission from the SID as relays. This request from AP to other IDs can be performed by embedding the request message into the CTS packet.

For obtaining the CSI at IDs, a certain RID can estimate the wireless channel from the SID to itself, i.e., SID-to-RID channel, by *overhearing* the RTS which is transmitted by the SID. With a similar way, the RID can also estimate the wireless channel from the AP to itself, i.e., AP-to-RID channel, by *overhearing* the CTS which is transmitted by the AP. With the assumption of channel reciprocity property, the RID can obtain its RID-to-AP channel. In addition, the AP can estimate the wireless channel from the SID to itself by receiving the RTS sent from the SID, while the SID can estimate the wireless channel from the AP to itself by receiving the CTS sent by the AP. It is worth noting that the AP does **not** need to know the channel state information from multiple RIDs to itself in the proposed technique. In short, the local CSI needs to be available at each RID.

Based on these RTS and CTS packets and the local CSIs from the SID to themselves or from themselves to the AP, each ID independently determines whether they will operate as an RID or not. In addition, energy constraint in each ID may also affect this decision. However, without loss of generality, we assume that all ID except for the SID are assumed to participate the packet relaying procedure in this paper.

This paper is focused on the scenario that SID is not able to communicate with the AP directly, Fig. 1 illustrates the considered R-IoT system after initialization procedure is over. The system consists of a SID, arbitrary number of RIDs and an AP, where the SID and all RIDs are equipped with single antenna whereas the AP has two antennas. Moreover, all RIDs operate with half-duplex (HD) decode-and-forward manner. It is assumed that local CSI can be obtained by a pilot signal and channel reciprocity in time-division duplexing.

2.1. First-hop operation

The SID broadcasts two symbols sequentially to all IDs which are candidates for RID. Note that, since all IDs decide independently whether they operate as RID, SID could not know how many RIDs. Then, the received signal at the k th ($k \in \{1, \ldots, K\}$) RID for the i th symbol ($i \in \{1, 2\}$) is given by

$$r_{k,i} = \sqrt{P_{\mathrm{t}}} g_k x_i + n_{k,i}, \tag{1}$$

where x_i and P_{t} denote the i th unit power transmit signal of the SID and the transmit power of the SID, respectively. Furthermore, g_k and $n_{k,i}$ denote the channel between the SID and k th RID and a noise of the k th RID in the i th symbol time, respectively. It is assumed that $g_k \in \mathbb{C}$ follows identically and independently distributed (i.i.d.) complex Gaussian distribution with zero mean and σ_1^2 variance, i.e., $g_k \sim \mathcal{CN}(0, \sigma_1^2)$, and g_k remains unchanged over two symbol times. Moreover, $n_{k,i}$ follows $\mathcal{CN}(0, N_0)$ for all k and i.

After receiving signals from the SID, each RID independently tries to decode them based on CSI. Let $\mathcal{D}$ be the decode set of RIDs that succeeded to decode symbols of the SID, $\mathcal{D}$ is defined as

$$\mathcal{D} \triangleq \left\{k \middle| \log_2\left(1 + \rho_{\mathrm{t}} |g_k|^2\right) \geq 2R\right\} = \{k|\, |g_k| \geq \rho_{\mathrm{th}}\}, \tag{2}$$

where $\rho_{\mathrm{t}} \triangleq P_{\mathrm{t}}/N_0$, R is the target transmission rate, and $\rho_{\mathrm{th}} = \sqrt{(2^{2R} - 1)/\rho_{\mathrm{t}}}$. Owing to HD operation, a required data rate of C-STLC needs to be $2R$ for each hop.

2.2. Second-hop operation

In the second hop, the RIDs belong to the decode set forward the signals encoded by STLC to the AP simultaneously. The STLC is a novel space–time coding technique that achieves the full-diversity in point-to-point SIMO channels when a transmitter knows the CSI. Specifically, the transmitter equipped with single antenna generates two transmit signals by encoding two independent symbols based on the CSI. During two time-slots, transmit signals are received by the receiver with two antennas. The receiver can decode two symbols through a simple linear combining technique. Based on the local CSI to AP, the STLC-coded two symbols of the κ th ($\kappa \in \mathcal{D}$) RID are given by

$$s_{\kappa,1} = \frac{h_{\kappa,1}^* x_1 + h_{\kappa,2}^* x_2^*}{\|\mathbf{h}_\kappa\|} \quad \text{and} \quad s_{\kappa,2} = \frac{h_{\kappa,2}^* x_1^* - h_{\kappa,1}^* x_2}{\|\mathbf{h}_\kappa\|}, \tag{3}$$

where $h_{\kappa,m}$ ($m \in \{1,2\}$) denotes the channel between the κ th RID and the m th antenna of AP, $\mathbf{h}_\kappa \triangleq \left[h_{\kappa,1}\ h_{\kappa,2}\right]^T$.

After encoding, RIDs transmit two STLC encoded signals, and the received signals at AP are given by

$$\begin{bmatrix} r_{1,1} & r_{1,2} \\ r_{2,1} & r_{2,2} \end{bmatrix} = \sum_{\kappa \in \mathcal{D}} \sqrt{\frac{P_\mathrm{t}}{N}} \mathbf{h}_\kappa \left[s_{\kappa,1}\ \ s_{\kappa,2}\right] + \begin{bmatrix} n_{1,1} & n_{1,2} \\ n_{2,1} & n_{2,2} \end{bmatrix}, \tag{4}$$

where $r_{m,l}$ ($m, l \in \{1,2\}$) and $n_{m,l}$ denote the received signal and the noise at the m th antenna of the AP at the l th symbol time, respectively. We assume that $h_{\kappa,m}$ and $n_{m,l}$ follow $\mathcal{CN}(0, \sigma_2^2)$ and $\mathcal{CN}(0, N_0)$, respectively, for all κ, m, and l. Moreover, $N \triangleq \mathbb{E}[|\mathcal{D}|] = K \exp(-\rho_\mathrm{th}/\sigma_1^2)$, where the term $|\mathcal{D}|$ denotes the cardinality of $\mathcal{D}$. Note that the transmit power of each RID is normalized by N, so that the total transmit power of the all RIDs is identical with P_t in average $\left(\text{i.e., } \mathbb{E}\left[\sum_{\kappa \in \mathcal{D}} P_\mathrm{t} |s_{\kappa,l}|^2 / N\right] = P_\mathrm{t}\right)$. Then, the AP combines the received STLC signals to obtain the original symbols of SID (x_1 and x_2) as follows [9]:

$$\begin{aligned} r_{1,1} + r_{2,2}^* &= \sum_{\kappa \in \mathcal{D}} \frac{\sqrt{P_\mathrm{t}}\, \|\mathbf{h}_\kappa\|}{\sqrt{N}} x_1 + n_{1,1} + n_{2,2}^*, \\ r_{2,1}^* - r_{1,2} &= \sum_{\kappa \in \mathcal{D}} \frac{\sqrt{P_\mathrm{t}}\, \|\mathbf{h}_\kappa\|}{\sqrt{N}} x_2 + n_{2,1}^* - n_{1,2}. \end{aligned} \tag{5}$$

Therefore, the event of decoding failure at AP $\mathscr{E}_\mathsf{AP}$ is defined as

$$\mathscr{E}_\mathsf{AP} \triangleq \left\{ \log_2 \left(1 + \frac{\rho_\mathrm{t}}{2N} \left(\sum_{\kappa \in \mathcal{D}} \|\mathbf{h}_\kappa\| \right)^2 \right) < 2R \right\}. \tag{6}$$

3. Performance analysis

In this section, we mathematically analyze the OP of the proposed C-STLC technique. We derive the expression of OP by exploiting the total probability theorem. Assuming that all channel coefficients are independent for the first and second hops, the OP of the symbol of SID at the AP is derived as follows:

$$\begin{aligned} P_o &= \sum_{d=0}^{K} P_\mathcal{D}(d) \times \Pr\{\mathscr{E}_\mathsf{AP} \mid |\mathcal{D}| = d\} \\ &= \sum_{d=1}^{K} P_\mathcal{D}(d) \times \Pr\left\{ \sum_{k \in \mathcal{D}} \|\mathbf{h}_k\| < \sqrt{2N}\rho_\mathrm{th} \mid |\mathcal{D}| = d \right\} \\ &= \sum_{d=1}^{K} P_\mathcal{D}(d) \times \Pr\left\{ \sum_{k=1}^{d} \|\mathbf{h}_k\| < \sqrt{2N}\rho_\mathrm{th} \right\}. \end{aligned} \tag{7}$$

Here, the probability that $|\mathcal{D}|$ is equal to d is given by

$$P_\mathcal{D}(d) = \binom{K}{d} \left(e^{-\frac{\rho_\mathrm{th}}{\sigma_1^2}} \right)^d \left(1 - e^{-\frac{\rho_\mathrm{th}}{\sigma_1^2}} \right)^{K-d}. \tag{8}$$

We define $\sum_{k=1}^{d} \|\mathbf{h}_k\|$ as a random variable (RV), Z_d. The conditional OP at the AP for a given d can then be equivalently derived from a cumulative density function (CDF) of Z_d.

From the definition, Z_d is given as follows:

$$Z_d = \sqrt{X_1 + X_2} + \sqrt{X_3 + X_4} + \cdots + \sqrt{X_{2d-1} + X_{2d}}, \tag{9}$$

where $X_1, \ldots, X_{2d}$ are the i.i.d. exponential RVs with σ_2^2 variance.

Unfortunately, the closed-form of PDF of RV Z_d for arbitrary d and σ_2^2 does not exist to the best of our knowledge. Thus, to obtain the final OP of the proposed C-STLC, we first obtain exact CDF of Z_d, where $d \in \{1, 2\}$ and approximated CDF of Z_d, where $d \geq 3$.

3.1. CDF of Z_d

3.1.1. CDF of Z_1

Based on the coordinate transformation, the PDF and CDF of Z_1 are, respectively, derived as follows:

$$f_{Z_1}(z) = \frac{2z^3}{\sigma_2^4} e^{-\frac{z^2}{\sigma_2^2}}; \quad F_{Z_1}(z) = 1 - \left(1 + \frac{z^2}{\sigma_2^2} \right) e^{-\frac{z^2}{\sigma_2^2}}, \tag{10}$$

which are similar to the chi distribution derived from the normal distribution with a non-unit variance.

3.1.2. CDF Z_2

To derive the exact PDF of Z_d, where $d \geq 2$, we need to compute $d-1$ times convolution of f_{Z_1}. By convolution theorem, it is well known that the Laplace transform (LT) of convolution is equal to multiplying the two LTs of original function before convolution. Based on this theorem, we can derive the PDF of Z_2 as follows:

$$f_{Z_2}(z) = f_{Z_1}(z) * f_{Z_1}(z) = \mathcal{L}^{-1}\left\{ \mathcal{F}^2(s) \right\}, \tag{11}$$

where $\mathcal{F}(s)$ denotes the LT of $f_{Z_1}(z)$ and $\mathcal{L}^{-1}$ denotes an inverse LT (ILT) operation. Here, $\mathcal{F}(s)$ is derived as follows:

$$\begin{aligned} \mathcal{F}(s) &\triangleq \mathcal{L}\left\{ f_{Z_1}(z) \right\} = \int_{-\infty}^{\infty} \frac{2z^3}{\sigma_2^4} e^{-\frac{z^2}{\sigma_2^2}} e^{-jsz} dz \\ &= 1 + \frac{\sigma_2^2 s^2}{4} - \frac{\sigma_2 \sqrt{\pi} s}{8} \left(6 + \sigma_2^2 s^2 \right) e^{\frac{\sigma_2^2 s^2}{4}} \operatorname{erfc}\left(\frac{\sigma_2 s}{2} \right). \end{aligned} \tag{12}$$

Let $\mathcal{G}(s) = e^{\frac{\sigma_2^2 s^2}{4}} \operatorname{erfc}\left(\frac{\sigma_2 s}{2}\right)$. Furthermore, the ILT of $\mathcal{G}(s)$ is given by [11]

$$\mathcal{L}^{-1}\{\mathcal{G}(s)\} = \frac{2}{\sqrt{\pi \sigma_2^2}} e^{-\frac{z^2}{\sigma_2^2}}. \tag{13}$$

We can easily obtain the ILT of $\mathcal{G}^2(s)$ by calculating the convolution of $\mathcal{L}^{-1}\{\mathcal{G}(s)\}$ with itself as follows:

$$\mathcal{L}^{-1}\left\{ \mathcal{G}^2(s) \right\} = \frac{2}{\sqrt{\pi \sigma_2^2}} e^{-\frac{z^2}{2\sigma_2^2}} \operatorname{erf}\left(\frac{z}{\sigma_2 \sqrt{2}} \right). \tag{14}$$

We derive $\mathcal{L}^{-1}\left\{ \mathcal{F}^2(s) \right\}$ by (13), (14), and a property of general derivative of one-side LT which is described as

$$\mathcal{L}\left\{ g^{(n)}(x) \right\} = s^n G(s) - \sum_{p=0}^{n-1} s^{n-p-1} g^{(p)}(0), \tag{15}$$

where $G(s)$ denotes the LT of an original function $g(x)$ and $g^{(n)}(x)$ denotes n th order derivative of function $g(x)$. By (13), (14), and (15), we obtain $\mathcal{L}^{-1}\left\{\mathcal{F}^2(s)\right\}$ which is the PDF of Z_2, denoted by $f_{Z_2}(z)$, as follows:

$$f_{Z_2}(z) = \frac{z}{16\sigma_2^2}\left(15 - \frac{4z^2}{\sigma_2^2} + \frac{z^4}{\sigma_2^4}\right)e^{-\frac{z^2}{\sigma_2^2}} - \frac{\sqrt{2\pi}}{32\sigma_2}\left(15 - \frac{9z^2}{\sigma_2^2} + \frac{3z^4}{\sigma_2^4} - \frac{z^6}{\sigma_2^6}\right)e^{-\frac{z^2}{2\sigma_2^2}}\operatorname{erf}\left(\frac{z}{\sigma_2\sqrt{2}}\right). \quad (16)$$

Then, the CDF of Z_2 is then given by

$$F_{Z_2}(z) = 1 - \frac{1}{16}\left(16 + \frac{z^2}{\sigma_2^2} + \frac{z^4}{\sigma_2^4}\right)e^{-\frac{z^2}{\sigma_2^2}} - \frac{\sqrt{2\pi}}{32}\left(\frac{15z}{\sigma_2} + \frac{2z^3}{\sigma_2^3} + \frac{z^5}{\sigma_2^5}\right)e^{-\frac{z^2}{2\sigma_2^2}}\operatorname{erf}\left(\frac{z}{\sigma_2\sqrt{2}}\right). \quad (17)$$

3.1.3. CDF of Z_d, where $d \geq 3$

We approximate the PDF of Z_d where $d \geq 3$ by the central limit theorem. Thus, the PDF of Z_d is approximated as Gaussian distribution. Firstly, the mean and the variance of Z_1 can be derived as $\mu_z \triangleq \mathbb{E}[Z_1] = 3\sqrt{\pi\sigma_2^2}/4$, and $\sigma_z^2 \triangleq \mathbb{E}\left[(Z_1-\mu_z)^2\right] = (2-9\pi/16)\,\sigma_2^2$, respectively.

The mean and variance of Z_d, where $d \geq 3$ are given by $d\mu_z$ and $d\sigma_z^2$, respectively [12]. Thus, the approximated CDF of Z_d for $d \geq 3$ can be expressed as follows:

$$F_{Z_d}(z) \approx \frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{z - d\mu_z}{\sqrt{2d\sigma_z^2}}\right)\right), \quad d \geq 3. \quad (18)$$

Finally, from (10), (17), and (18), we obtain the OP of cooperative STLC for arbitrary K as follows:

$$P_o \approx \sum_{d=1}^{K} P_{\mathcal{D}}(d)\, F_{Z_d}\left(\sqrt{2N}\rho_{\text{th}}\right) + \left(1 - e^{-\frac{\rho_{\text{th}}}{\sigma_1^2}}\right)^K. \quad (19)$$

4. Numerical results

In this section, we evaluate the performance of the proposed C-STLC technique through extensive computer simulations. In all simulations, $\sigma_1^2 = 0$ dB and $\sigma_2^2 = -10$ dB. We compared the proposed C-STLC and the existing cooperative relaying techniques in terms of OP. As the baseline, for the second hop, we considered two well-known schemes: BSR [4] and C-PS[1] [8]. In the BSR scheme, the RID with the largest $\|\mathbf{h}_\kappa\|^2$ was selected. On the other hand, in the C-PS scheme, the successful RIDs forward the signal by adjusting the phase of the signal to compensate the phase distortion $\angle\left(h_{\kappa,1}+h_{\kappa,2}\right)$.

In Fig. 2, we first validated our mathematical analysis on OP in (19), where the OP of C-STLC was shown for varying transmit signal-to-noise ratio (SNR) with different K and $R = 1.7$. As expected, the analysis matched exactly with the numerical result when $K = 2$ because we obtained the exact CDF of Z_2 in (17). It is worth noting that the analytical results on OP of C-STLC also match well with the numerical results when $K \geq 3$.

[1] The C-PS with modifications is considered as a reference technique of the proposed C-STLC in this paper.

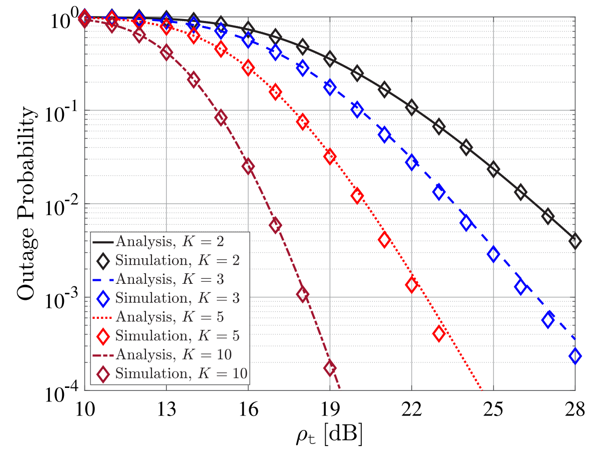

Fig. 2. OP performance of C-STLC according to ρ_t with various K.

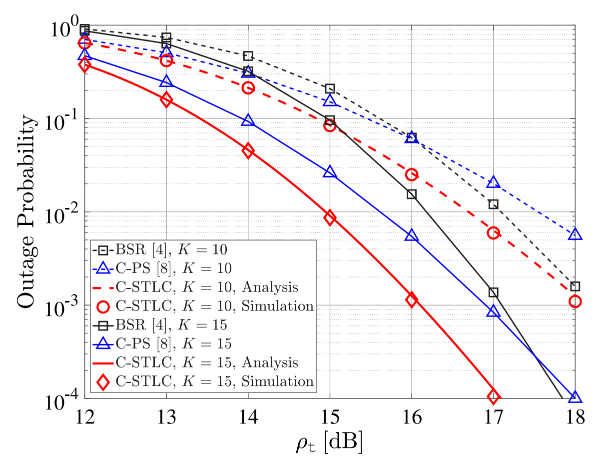

Fig. 3. OP performance of C-STLC, BSR, and C-PS according to ρ_t.

Fig. 3 shows the OP performance of three schemes for varying SNR, where $R = 1.7$ with different K. For all SNR values, the proposed C-STLC outperformed the conventional schemes. This is because C-STLC has the largest effective channel gain according to $|\mathcal{D}|$ in practical transmit SNR regimes. Especially, the performance gap between C-STLC and other techniques becomes larger as the number of RIDs is large. At some point (e.g. small K and high ρ_t), it seems like the performance gap between BSR and C-STLC will be reversed. However, since the R-IoT network, which requires low power consumption, is target of this paper, high power consumption of BSR for better performance might be a burden to IoT network.

5. Conclusion

In this paper, a novel *cooperative* space–time line code (C-STLC) scheme was proposed for relay-assisted internet of things (R-IoT) systems. In the proposed C-STLC, the access point does not need to know full channel state information and each relay IoT device (RID) operates with fully distributed manner, so that the signaling overhead of network is reduced. As a main result, we mathematically analyzed the outage probability (OP) performance of the proposed C-STLC and showed the analysis result matches well with simulation results. It was shown that the proposed C-STLC significantly outperforms the conventional cooperative relaying schemes in terms of OP especially with a large number of RIDs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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