Ultra-Reliable and Low-Latency Short-Packet Communications for Multihop MIMO Relaying

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Abstract—This work considers the multihop multiple-input multiple-output relay network under short-packet communications to facilitate not only ultra-reliability but also low-latency communications. We assume that the transmit antenna selection (TAS) scheme is utilized at the transmit side, whereas either selection combining (SC) or maximum ratio combining (MRC) is leveraged at the receive side to achieve diversity gains. For quasi-static Rayleigh fading channels and the finite-blocklength regime, we derive the approximate closed-form expressions of the end-to-end (e2e) block error rate (BLER) for both the TAS/MRC and TAS/SC schemes. The asymptotic performance in the high signal-to-noise ratio regime is derived, from which the comparison of TAS/MRC and TAS/SC schemes in terms of the diversity order, e2e BLER loss, and SNR gap is provided. The e2e latency and throughputs are also analyzed for the considered schemes. The correctness of our analysis is confirmed via Monte Carlo simulations.

Index Terms—Short-packet communication, ultra-reliable and low-latency communications, multihop relaying, multiple-input multiple-output, transmit and receive diversity.

I. INTRODUCTION

Fifth-generation (5G) networks will reinforce various foremost services, including massive Machine-Type Communications (mMTCs), enhanced Mobile Broadband (eMBB), and ultra-Reliable and Low-Latency Communications (uRLLCs) [1]. In particular, based on 5G ITU-R and IMT-2020, the 5G networks will fulfill the stringent requirements from (i) mMTC with one hundred times the network energy efficiency and three times the spectrum efficiency of IMT-Advanced, a traffic capacity of $10 - 100$ Mbps/m$^2$, user experienced data rates of 100 Mbps, and peak data rates of 10 – 20 Gbps; (ii) mMTCs with the connection density of $10^6$ devices/km$^2$; and (iii) uRLLC with very low latency of around 1 – 10 ms [2]. From the standpoint of uRLLC, the system needs to satisfy not only low latency, but also ultra-reliability, which refers to packet error rates lower than $10^{-5}$. Motivated by this, in [3], the fundamental short-packet communication (SPC) conception has been pioneeringly explored to meet the uRLLC requirements in or even beyond 5G [4] by shortening the frame length to as short as 100 channel uses (CUs), in contrast to the conventional systems with long blocklengths. Specifically, in [3], Polyanskiy et al. have contributed to obtaining the approximation of the maximum coding rate under the finite-blocklength (FBL) regime.

Besides that, the multiple-input multiple-output (MIMO) system can provide diversity gains to significantly improve reliability, whereas the multihop relay network is known to be an efficient solution to extend coverage, reduce transmit power, and improve reliability for data transmission over short distances. After the pioneering work in [3], SPC has recently received much attention, especially in state-of-the-art integration frameworks between SPC and MIMO/relaying system. In particular, Durisi et al. [5] considered a MIMO system for SPC and revealed that the traditional infinite-blocklength metrics would no longer accurately provide estimations for the maximum coding rate in the short-packet-size scenario. In [6] and [7], massive MIMO links supporting uRLLC transmissions were successfully leveraged by SPC. Meanwhile, [8] studied the physical-layer secrecy throughput in an uplink massive multi-user MIMO system using short-packet transmission. Subsequently, in [9], a full-duplex multi-user MIMO SPC network was considered in terms of secrecy throughput performance. Furthermore, [10] investigated MIMO systems in SPC along with non-orthogonal multiple access support to achieve the benefits of reliability, connectivity, spectral efficiency, and low latency. From the multihop relay network perspective under SPC, Li et al. [11] demonstrated that end-to-end (e2e) fountain coding is more suitable for multihop SPCs than random linear network coding. Meanwhile, Makki et al. [12] analyzed the e2e delay and throughput of multihop SPCs.

Although the various benefits of MIMO and multihop relay networks can be provided to SPC for uRLLCs, the comprehensive integrated framework of these schemes under SPC has not been defined. This paper first investigates the multihop MIMO relay network gains along with SPC to support uRLLCs. Our main contributions are summarized as follows:

- Typical diversity schemes, including transmit antenna selection (TAS), maximum ratio combining (MRC), and selection combining (SC), are utilized to exploit the full diversity gains of our proposed systems.
- Over quasi-static Rayleigh fading channels and FBL context, the e2e block error rate (BLER) performance...
is analyzed, from which the e2e latency and throughput are also investigated.

- Based on the asymptotic analysis in the high-SNR region, qualitative conclusions about the diversity orders, e2e BLER loss, and SNR gap between the TAS/MRC and TAS/SC schemes are made.
- Our theoretical analysis is verified by Monte Carlo simulations, which show that the e2e performance obtained via theoretical analysis agrees with that via simulation.
- The results confirm the benefits from the employment of MIMO and multihop relay network for SPC to meet the uRLLC requirements.

II. SYSTEM MODEL

We consider a multihop network under the SPC scheme with \( K \) selective decode-and-forward (SDF) relays named \( R_1, R_2, \ldots, R_K \), which assist the communication between one source terminal \( (R_0) \) and one destination \( (R_{K+1}) \) over Rayleigh fading channels. We assume that there is no direct link between the source and destination. The MIMO system under consideration consists of \( N_T \) transmit antennas and \( N_R \) receive antennas, which are installed in each relay node, whereas the source and destination nodes are equipped with only \( N_T \) transmit and \( N_R \) receive antennas, respectively. When the \( i \)th transmit antenna of the node \( R_{k-1} \) is chosen for transmission by the TAS scheme, the received signal at the \( j \)th antenna of the node \( R_k \) can be represented as

\[
y^{(i,j)}_k = \sqrt{P_{k-1} h^{(i,j)}_k} x + n^{(i,j)}_k,
\]

where \( P_{k-1} \) is the transmit power of the node \( R_{k-1} \), \( h^{(i,j)}_k \) is the fading coefficient from the \( i \)th transmit antenna to the \( j \)th receive antenna at the \( k \)th hop \((k = 1, K + 1, i = 1, N_T, \) and \( j = 1, N_R)\), \( x \) is a scalar complex baseband transmitted signal with zero mean and unit variance \( \mathbb{E}\{ |x|^2 \} = 1 \), and \( n^{(i,j)}_k \) is a zero-mean complex Gaussian noise signal with variance \( N_0 \).

We note that the TAS technique at the transmit side of each hop can achieve a significant reduction in power consumption and hardware cost because only a single radio-frequency (RF) chain is used. It is assumed that the receiver at each hop has the perfect channel-state information (CSI). At the transmit side, based on feedback information to the transmitter from the receiver, known as partial CSI feedback \( \mathcal{U}(x) \), the index of the best transmit antenna, which maximizes the received SNR, can be determined. Eventually, the transmitter employs only a single optimal antenna out of \( N_T \) antennas to transmit data. Meanwhile, the MRC and SC are considered at the receive side to achieve receive diversity at each hop.

For TAS/MRC, to achieve the spatial diversity gain at the receive side, the MRC scheme can be used \( \mathcal{U}(x) \), where the received signals from each channel are coherently combined. Therefore, the output SNR of the MRC combiner increases with the number of diversity branches. Subsequently, when we apply TAS and MRC simultaneously for each hop, the instantaneous SNR at the \( k \)th hop can be written as

\[
\gamma^{\text{TAS/MRC}}_k = \max_{i = 1, 2, \ldots, N_T} \sum_{j=1}^{N_R} \gamma^{(i,j)}_k.
\]

Accordingly, the cumulative distribution function (CDF) of \( \gamma^{\text{TAS/MRC}}_k \) can be obtained as

\[
F^{\text{TAS/MRC}}_{\gamma_k}(\gamma) = \left\{ 1 - \exp \left( -\frac{\gamma}{\gamma_k} \right) \sum_{n=0}^{N_R-1} \frac{1}{n!} \left( \frac{\gamma}{\gamma_k} \right)^n \right\}^{N_T}.
\]

For TAS/SC, when the SC scheme is employed at the receive side of each hop, the link with the highest received SNR is selected to perform the detection process \( \mathcal{U}(x) \). Once this approach is leveraged along with the TAS scheme, a single transmit antenna out of \( N_T \) antennas and a single receive antenna out of \( N_R \) antennas are jointly chosen. In this scheme, the output SNR can be expressed as \( \gamma^{\text{TAS/SC}}_k = \max_{i = 1, 2, \ldots, N_T} \gamma^{(i,j)}_k \). Accordingly, the CDF of \( \gamma^{\text{TAS/SC}}_k \) can be obtained easily as

\[
F^{\text{TAS/SC}}_{\gamma_k}(\gamma) = \left\{ 1 - \exp \left( -\frac{\gamma}{\gamma_k} \right) \right\}^{N_T N_R}.
\]

III. PERFORMANCE ANALYSIS

To evaluate the system performance of SPC, we derive the closed-form expression for the e2e BLER. The source encodes \( T \) information bits into a blocklength of \( \beta \) CUs, where the signals are transmitted from \( R_0 \) to \( R_{K+1} \) with the help of \( R_1, R_2, \ldots, R_K \) via quasi-static fading channels. For quasi-static fading channels, we assume that the channel fading coefficients are random, but remain constant during each transmission block and change independently at other blocks. The coding rate of the considered system for each time slot is given by \( R = \frac{T}{\beta} \). In contrast, in the context of the FBL scheme with the SPC, the blocklength employed should be minimized, but it still needs to be longer than 100 CUs. In this scenario, the maximum coding rate can be approximately expressed as

\[
R \approx C \left( \gamma^{X}_k \right) - \sqrt{\frac{V(\gamma^{X}_k)}{\beta Q^{-1}(\varepsilon^{X}_k)}}, \tag{4}
\]

where \( X \in \{ \text{TAS/MRC, TAS/SC} \} \) denotes one type of the diversity transmission schemes, \( \varepsilon^{X}_k \) represents the instantaneous BLER at the \( k \)th hop, \( C \left( \gamma^{X}_k \right) \) is the channel capacity, \( V(\gamma^{X}_k) \) is the channel dispersion measuring the stochastic variability of the channel relative to a deterministic channel for the same capacity \( C \), and \( Q^{-1}(\cdot) \) is the inverse function of the Q-function with \( Q(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} \exp \left( -\frac{u^2}{2} \right) du \).

From \( \text{(4)} \), the average BLER at each hop can be written as

\[
\varepsilon^{X}_k = \int_{0}^{\infty} Q \left( \frac{C \left( \gamma^{X}_k \right) - R}{\sqrt{V(\gamma^{X}_k)/\beta}} \right) f_{\gamma^{X}_k}(\gamma) d\gamma, \tag{5}
\]
where $f_{\gamma^X}(\cdot)$ denotes the probability density function of $\gamma^X_k$. Because of the complicated form of $Q(\cdot)$ in (5), the closed-form expression for the average BLER at each hop cannot be calculated directly. Fortunately, motivated by the work in [18 eq. (14)], an approximation approach of the $Q$-function can be leveraged to solve the problem in (5). In particular, we use the approximation $Q\left(\frac{c_1(\gamma^X_k) - R}{\sqrt{V(\gamma^X_k)}}/\beta\right) \approx \Psi \left(\frac{\gamma^X_k}{\beta}\right)$, with $\Psi \left(\frac{\gamma^X_k}{\beta}\right)$ represented as

$$
\Psi \left(\frac{\gamma^X_k}{\beta}\right) \approx \begin{cases} 
1, & \gamma^X_k \leq \varphi_L, \\
0.5 - \xi \sqrt{\beta} (\gamma^X_k - \tau), & \varphi_L < \gamma^X_k < \varphi_H, \\
0, & \gamma^X_k \geq \varphi_H,
\end{cases}
$$

(6)

where $\xi = [2\pi (2^2R - 1)]^{-1/2}$, $\tau = 2^R - 1$, $\varphi_H = \tau + 1/(2\xi \sqrt{\beta})$, and $\varphi_L = \tau - 1/(2\xi \sqrt{\beta})$. With this feasible approximation, the average BLER at each hop can be written as

$$
\varepsilon_{k}^{X} \approx \int_{0}^{\infty} \Psi \left(\frac{\gamma^X_k}{\beta}\right) f_{\gamma^X}(\gamma^X_k) d\gamma^X_k \exp^{-\gamma^X_k/\beta} \left[\int_{\varphi_L}^{\varphi_H} F_{\gamma^X}(\gamma) d\gamma \right]d\gamma^X_k,
$$

(7)

where step (a) is conducted by the partial integration method.

By inserting (a) into (7) and after some mathematical manipulations, the closed-form expression of the average BLER at each hop for the TAS/MRC scheme is given by

$$
\varepsilon_{k}^{TAS/MRC} \approx 1 + \xi \sqrt{\beta} \sum_{m=1}^{N_T} \sum_{l=1}^{N_R-1} \left(1 + \frac{1}{N_R} \right)m - S - \bar{\gamma}_k
$$

$$
\cdot \left\{ \mathcal{T} \left(S + 1, \frac{\varphi_L}{\bar{\gamma}_k}\right) - \mathcal{T} \left(S + 1, \varphi_L\right) \right\},
$$

(8)

where $S = \sum_{m=1}^{N_T} j_l$ and $\mathcal{T}(\alpha, z) = \int_{0}^{\infty} e^{-t \mathcal{Y} n} dt$ denotes the lower incomplete gamma function.

By inserting (a) into (7), the average BLER at each hop for the TAS/SC scheme can be written as

$$
\varepsilon_{k}^{TAS/SC} \approx 1 + \xi \sqrt{\beta} \sum_{m=1}^{N_T N_R} \left(1 + \frac{1}{N_R} \right)m - \bar{\gamma}_k \frac{\varphi_H}{m} - \left\{ \exp \left(-\frac{m}{\bar{\gamma}_k} \varphi_H\right) - \exp \left(-\frac{m}{\bar{\gamma}_k} \varphi_L\right) \right\}.
$$

(9)

For the given average BLERs at each hop in (8) and (9), we propose the following proposition to calculate the e2e BLERs via the SDF principle.

**Proposition 1:** Based on the SDF mechanism [19], only when a relay decodes the received data correctly, it forwards the data to the next hop. If the incorrect decoding occurs at a relay node, the BLERs for all later nodes become one, i.e., $\bar{\varepsilon}_n = 1 (\forall n > k)$, where $k$ is the index of the relay that performs erroneous decoding. Therefore, the e2e BLER for the multihop SDF network is given by

$$
\bar{\varepsilon}_{e2e}^{X} \approx \bar{\varepsilon}_1^{X} + (1 - \bar{\varepsilon}_1^{X}) \bar{\varepsilon}_2^{X} + \ldots + (1 - \bar{\varepsilon}_1^{X}) \ldots (1 - \bar{\varepsilon}_k^{X}) \varepsilon_{k+1}^{X} = \bar{\varepsilon}_1^{X} + \sum_{k=2}^{K+1} \left( \frac{1}{\bar{\nu}_k} \prod_{m=2}^{k} \left(1 - \bar{\varepsilon}_{m-1}^{X}\right) \right).
$$

(10)

**Proposition 2 (e2e latency and throughput):** Let $\mathcal{F}$ be the feedback delay in each hop, measured in CUs, and $\mathcal{D}(\beta)$ denote the delay for decoding a packet with the blocklength $\beta$ [20]. In practice, $\mathcal{D}(\beta)$ depends on the decoding scheme, the number of iterations in the decoder, etc. [20]. We consider the e2e latency in the retransmission scheme, where the retransmission continues until the packet is decoded correctly or the system reaches the maximum number of retransmission times, denoted by $\mathcal{L}$. As a result, the e2e packet transmission latency (measured in CUs) is expressed as

$$
\mathcal{L}_{e2e}^{X} = \frac{(1 - \bar{\varepsilon}_{e2e}^{X})^{L+1}}{(1 - \bar{\varepsilon}_{e2e}^{X})^{L+1}} \left[ \sum_{r=0}^{L} \left( \frac{\bar{\varepsilon}_{e2e}^{X}}{\bar{\varepsilon}_{e2e}^{X}} \right)^{r} \right],
$$

(11)

where $X$ denotes one type of transmission scheme, i.e., $X \in \{\text{TAS/MRC}, \text{TAS/SC}\}$. Here, $\mathcal{T}$ and $\mathcal{F}$ represent the average latency caused by e2e decoding success and failure, respectively, given by $\mathcal{T} = (K + 1) (\beta + \mathcal{D}(\beta))$ and $\mathcal{F} = (\beta + \mathcal{D}(\beta)) + \mathcal{F} \left( \frac{K+1}{k} \cdot \frac{1}{\mathcal{I}} \right)$.

Furthermore, the e2e throughput is defined as the ratio of the number of information bits successfully received at the destination to the average duration time, which is measured in bits per CU (BPCU). As a result, the e2e throughput for the considered system is given by

$$
\mathcal{J}_{e2e}^{X} = \frac{1}{\mathcal{L}_{e2e}^{X}} \left[ \frac{1 - \bar{\varepsilon}_{e2e}^{X}}{\mathcal{L}_{e2e}^{X}} \right].
$$

(13)

**IV. ASYMPTOTIC ANALYSIS**

We define $\gamma = P_S/N_0$ as an average SNR and assume that we allocate power for the source and relay nodes equally, i.e., $P_{k-1} = P_S/(K + 1)$, where $P_S$ is the total transmit power of the system. It is noted that $\bar{\gamma}_k = \frac{P_k}{N_0} \mathbb{E} \left[ \left| h_{k}^{(i,j)} \right|^2 \right] = c_k \bar{\gamma}$, where $c_k = \mathbb{E} \left[ \left| h_{k}^{(i,j)} \right|^2 \right] / (K + 1)$. Therefore, in the high-SNR regime with $\bar{\gamma} \rightarrow \infty$, we have $\bar{\gamma}_k \rightarrow \infty$.

In the high-SNR regime, we use (21) and (22) for (7). The asymptotic BLER at each hop for TAS/MRC can be given by

$$
\bar{\varepsilon}_{k}^{\infty \text{TAS/MRC}} = \frac{\xi \sqrt{\beta} \left( \varphi_H - \varphi_L \right)}{(N_R)^N R_k N_T R + 1}.
$$

(14)

For TAS/SC, when $\bar{\gamma}_k \rightarrow \infty$, we utilize $1 - \exp \left(-\frac{1}{\bar{\gamma}_k}\right) \sim \frac{1}{\bar{\gamma}_k}$ for (3). The asymptotic BLER at each hop for the TAS/SC
scheme is expressed as
\[
\hat{\varepsilon}_{\infty \text{TAS/SC}} = \frac{\xi \sqrt{\beta}}{\varepsilon_{\infty \text{TAS/SC}}} \left[ \varphi_H^{N_T N_R + 1} - \varphi_L^{N_T N_R + 1} \right].
\] (15)

In the same manner as Proposition 7, we invoke Proposition 10 for the average BLER at each hop such that given in (14) and (15). The value of \(\hat{\varepsilon}_{\infty \text{X}}\) is very small for \(\gamma_k \to \infty\), i.e., \(\hat{\varepsilon}_{\infty \text{X}} \ll 1\). Therefore, the asymptotic e2e BLER can be expressed approximately as \(\hat{\varepsilon}_{\infty \text{X}} \approx \sum_{k=1}^{K+1} \hat{\varepsilon}_k\).

**Proposition 3 (e2e diversity order, BLER loss, and SNR gap):** For the diversity order in the form of
\[
D_X = -\lim_{\gamma \to \infty} \frac{\log (\hat{\varepsilon}_{\infty \text{X}})}{\log (\gamma)},
\] (16)
the maximum diversity orders for both the TAS/MRC and TAS/SC schemes are achieved, i.e., \(D_X = N_T N_R\). For the BLER loss, we consider the ratio of the asymptotic e2e BLER for TAS/MRC to the asymptotic e2e BLER for TAS/SC as
\[
\frac{\hat{\varepsilon}_{\infty \text{TAS/MRC}}}{\hat{\varepsilon}_{\infty \text{TAS/SC}}} \approx \sum_{k=1}^{K+1} \frac{\hat{\varepsilon}_{\infty \text{TAS/MRC}}}{\hat{\varepsilon}_{\infty \text{TAS/SC}}} = \frac{1}{(N_R!)^{N_T}}.
\] (17)

To gain further insight, we can rewrite the asymptotic e2e BLER of \(X\) as \(\hat{\varepsilon}_{\infty \text{X}} \approx \left(\hat{G}_X \bar{\gamma}\right)^{-D_X}\), where \(\hat{G}_X = \left(\sum_{k=1}^{K+1} \frac{1}{c_k \gamma_k^{1/N_R}}\right)^{1/N_T}\) is the array gain, which represents the SNR gain in the e2e BLER curve with respect to \(\gamma^{-D_X}\). Here, \(\hat{G}_X\) is defined as
\[
\hat{G}_X = \begin{cases} 
\xi \sqrt{\beta} \left[ \varphi_H^{N_T N_R + 1} - \varphi_L^{N_T N_R + 1} \right], & \text{if } X = \text{TAS/MRC}, \\
\xi \sqrt{\beta} \left[ \varphi_H^{N_T N_R + 1} - \varphi_L^{N_T N_R + 1} \right] / (N_T N_R + 1), & \text{if } X = \text{TAS/SC}.
\end{cases}
\] (18)

Accordingly, the SNR gap between TAS/MRC and TAS/SC is represented by the ratio of their array gains, given by
\[
\frac{\hat{G}_{\text{TAS/MRC}}}{\hat{G}_{\text{TAS/SC}}} = \left[ \frac{\hat{G}_{\text{TAS/MRC}}}{\hat{G}_{\text{TAS/MRC}}} \right]^{N_T N_R} = (N_R!)^{-N_T}.
\] (19)

**Remark 1:** Although TAS/MRC and TAS/SC offer the same full diversity order, they have different array gains, which leads to the e2e BLER loss and SNR gap, as described in (17) and (19), respectively.

**V. SIMULATION RESULTS AND DISCUSSION**

In this section, we have performed Monte Carlo simulations to validate our theoretical results and evaluate the e2e performance of the proposed system. For channel settings, we consider the simplified path-loss model \(\xi\) with the average channel gain \(\mathbb{E}\{h^{(i,j)}_{k}\} = d_k^{-\eta}\), where \(d_k\) is the distance between two adjacent nodes and \(\eta = 3\) denotes the path-loss exponent. Assuming that we employ equal allocation for both the power and relay location configurations, e.g., \(d_k = D/(K+1)\) and \(P_{k-1} = P_S/(K+1)\), where \(D = 1\) is the normalized transmission distance.

Fig. 1 presents the comparison for various MIMO configurations, where \(K = 3\), \(T = 1024\) bits, and \(\beta = 128\) CUs.

![Fig. 1. e2e BLER versus the number of relays \(K\), where \(N_T = N_R = 2\), \(T = 1024\) bits, and \(\beta = 128\) CUs.](image)

**Remark 2:** We observe that the e2e BLER loss is lower for TAS/MRC compared to TAS/SC, and the SNR gap is smaller when using TAS/MRC. The SNR gap between TAS/MRC and TAS/SC is expressed approximately as \(\hat{G}_X \approx \sum_{k=1}^{K+1} \hat{\varepsilon}_k\).

In Fig. 2, we investigate the system performance versus the average SNR for various MIMO configurations. Fig. 2 shows that, as expected, better performance is achieved by employing more antennas, owing to higher diversity gains. It is also observed that for the two scenarios of \(N_T = 2, N_R = 4\) and \(N_T = 4, N_R = 2\), the TAS/SC has identical performance.
SNR of 0 implies that our analysis results for e2e BLER, presented in Proposition 3, respectively, which verifies our analytical correctness. Additionally, the analysis results also employ the SPC system.

For example, let us assume both the minimum-latency constraint and BLER performance. In contrast, for the TAS/MRC scheme, the MRC is employed at the receiver, and hence the employment of more receive antennas is more beneficial than that of more transmit antennas, which results in better performance for \((N_T = 2, N_R = 4)\) than for \((N_T = 4, N_R = 2)\).

In Figs. 1 and 2 we recognize that the simulation results are in good agreement with all the analysis results, which verifies our analytical correctness. Additionally, the analysis and simulation results converge to the asymptotic results at high SNRs in Fig. 2. It is worth noting that as the SNR increases, the e2e BLER loss between the TAS/MRC and TAS/SC schemes converges to \((N_R) / N_T\) and the SNR gap between them converges to \(10 \log \left( \left( \frac{N_R}{N_T} \right)^{\frac{1}{2}} \right) \) in dB, as presented in Proposition 2.

To observe the impact of the blocklength \(\beta\) on the system performance, we plot the e2e BLER as a function of blocklength \(\beta\) in Fig. 3. Fig. 3 shows that the increase in \(\beta\) leads to better system performance. We note that the main purpose of SPC is to maintain the blocklength as short as possible but it still employs more than 100 CUs to achieve both low latency and reliable communications. Considering this tradeoff, the value of \(\beta\) is chosen conservatively to satisfy both the minimum-latency constraint and BLER performance. For example, let us assume \(N_T = 2, N_R = 3\), an average SNR of 0 dB, and quality of service with a BLER of 10\(^{-5}\). In this scenario, \(\beta\) can be chosen as \(\beta \approx 460\) and \(\beta \approx 650\) CUs for the TAS/MRC and TAS/SC schemes, respectively, which implies that our analysis results for e2e BLER, presented in Section III, can be employed to optimize the SPC system.

To evaluate the e2e latency and throughput given in Proposition 2 we consider a linear decoding delay profile \(D(\beta) = \alpha \beta\), where \(\alpha\) is the constant decoding delay factor \(20\), which depends on different decoding schemes. In Fig. 4 for various decoding delay factors, the e2e performance is compared in terms of both the e2e latency and throughput. We also observe that TAS/MRC achieves lower latency and higher throughput compared to TAS/SC when \(K = 3\). In contrast, for \(K = 5\), the decoding error probability is very close to zero in both the TAS/MRC and TAS/SC schemes; hence, they have almost the same latency and throughput.

Fig. 5 depicts the e2e latency and throughput of the considered systems for various blocklengths \(\beta\). In Fig. 5, the e2e latency and very low e2e throughput were attained for short blocklengths. It is due to the fact that, with the short blocklength, the e2e BLER is high, which leads to the more frequent retransmissions. In contrast, when the blocklength is sufficiently long, the probability of retransmitting the packet converges to zero. In this scenario, increasing \(\beta\) leads to an increase in the e2e latency and a decrease in the e2e throughput. Therefore, choosing the optimal value for \(\beta\) is worth considering. In Fig. 5(a) and Fig. 5(b), it can be seen that for a given number of information bits \(T\), \(\beta = 330\) CUs and \(\beta = 420\) CUs are the optimal blocklength values for the TAS/MRC and TAS/SC schemes, respectively, which minimize the e2e latency and maximize the e2e throughput.

In multihop relay networks for uRLLCs, the number of relay nodes plays an important role. Fig. 6 shows the influence of \(K\) on the e2e latency and throughput performance. In Fig. 6 it
is observed that the e2e latency and throughput are minimized and maximized for \( K = 1 \), respectively. Intuitively, a larger number of relays leads to shorter hops, i.e., shorter distance between two relay nodes to improve the reliability, but it can suffer from a longer transmission time via relays and even e2e throughput degradation. Nonetheless, under the tradeoff consideration among e2e BLER, latency, and throughput, we can determine the optimal value of the number of relays. For example, for the environment shown in Fig. 6 \( K = 1 \) is the optimal value to achieve the highest e2e throughput and lowest e2e latency for both the TAS/MRC and TAS/SC schemes. For a CU duration of 3 \( \mu s \) \(^2\) and \( \alpha = 2 \), the e2e latencies for TAS/MRC and TAS/SC are 770 and 1030 CUs corresponding to 2.31 and 3.09 ms, respectively, which satisfy the low-latency constraint of uRLLCs (\( \leq 10 \text{ ms} \) \(^2\)).

### VI. CONCLUSIONS

In this work, we have investigated the MIMO SDF multihop relay network for the SPC scenario. Under the consideration of the FBL regime and quasi-static Rayleigh fading channels, the closed-form expressions for the e2e BLERs of the TAS/MRC and TAS/SC schemes are obtained in approximated forms, from which their asymptotic forms for high SNRs are derived. Based on the asymptotic analysis, the e2e diversity order, e2e BLER loss, and SNR gap are analyzed. Furthermore, the e2e latency and throughputs are also analyzed for the considered schemes. The simulation results demonstrate the gains from the employment of MIMO and multihop relay network for uRLLC requirements using SPC.

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