Modified ARQ-Based Cooperative Relaying Scheme for a Delay Tolerant Network

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***Abstract*—We use fixed relays deployed by network operators to reduce re-transmission (thereby reducing network power requirements) in addition to providing excellent end-to-end error performance in a revisit to automatic repeat request-based cooperative relaying. The new relaying scheme facilitates the creation of a connectivity suitable for delay tolerant internet-of-things (IoT)-type services.**

For IoT devices, link reliability and power efficiency are a major system design consideration. The proposed scheme operates in the following fashion. The source (e.g., a sensor) transmits for a certain time window. During this period, the source and the relays do not require per transmission acknowledgment (ACK) from the destination. At the end of a transmission window, the destination sends a 'group' ACK. If negative, relays are invited to help. Depending on the cooperation strategy, each relay transmits in either one transmission time slot or a few time slots, using a suitably chosen higher-order modulation constellation. If no error occurs, the source continues its transmission.

Furthermore, we devise a novel strategy for selecting the best relay for this new way of exploiting the benefits of multiple relays in a network. In the process, we reclaim the bandwidth expansion that comes with multi-relay system but still maintaining E2E bit error rate that is superior to that of a single relay cooperation. Numerical results that reveal the benefits of the new and modified ARQ cooperative relaying scheme are presented.

***Index Terms*—Cooperative relaying, IoT, Energy efficiency, Bit error rate (BER), Weibull fading.**

I. INTRODUCTION

Cooperative relaying techniques have received considerable attention in the literature and will continue to occupy an important part of advanced wireless network deployments. For instance, cooperative relaying is incorporated in the Third-Generation Partnership Project (3GPP) standard releases [1] and its capability to improve the performance of wireless links is well-documented variously in the literature, including [2] - [7].

Relaying can be implemented in full-duplexing or half-duplexing mode. Although full-duplex relaying (FDR) presents some implementation challenges, it offers superior multiplexing gains compared to the half-duplex relaying (HDR). In addition, ARQ-based relaying has been presented in the literature that emphasises its ability to extract further performance improvements by combining the relay cooperation strategy with ARQ protocol. This is the cooperative–ARQ (C-ARQ) relaying protocol where, a relay retransmits the source signal when the original transmission fails to be decoded correctly at the destination [2] thereby improving HDR performance. For example, the authors in [4] employed distributed space-time coding with ARQ-based relaying to increase the throughput metric.

Unfortunately, C-ARQ protocols suffer from some undesirable system or technology features or complexity [2]. One prominent of such features is the energy/power utilization. The energy consumption or efficiency of C-ARQ scheme is a function of the number of retransmissions from the network transmitters, e.g., the source and relays [9]. Additionally, excessive retransmission increases the interference floor of the network. And, if an IoT device (source) does the retransmissions, it drains its battery excessively, which reflects adversely on their expected up-to decades battery life-span.

Therefore, we adopt multiple fixed relays, which are network operator–deployed, in a novel twist to help reduce the number of transmissions in the network thereby helping to alleviate the power burden of IoT device. In addition, the IoT devices need to communicate reliably. Thus, the proposed novel scheme provides a superior end-to-end (E2E) bit error rate (BER) performance.

The main features of the proposed scheme and the contribution of this paper are listed as follows:

- This work extends and generalizes the single-relay work in [10] to multiple relay network.
- We devise a novel selection strategy to facilitate best relay selection that is appropriate for the new modified ARQ-based cooperative scheme. It should be mentioned that traditional best relay selection for multi-relay network re-

quires novel modification to allow for the implementation of the proposed twist to ARQ-based relay cooperation. This paper provides that new approach for best relay selection in multi-relay setting.

- Given the multi-relay scenario, we consider a number of relay signal processing at the destination; we examine maximal ratio combining and selection combining.
- The proposed scheme provides a reduction in the number of retransmissions in the network. Therefore, the relays do not pollute the network with frequent transmissions that would increase the interference level of the network.
- Furthermore, the scheme provides a reduction in signaling overhead. The reason being that acknowledgements are not sent per transmission with a significant importance in the massive machine type communication or IoT networks. In these networks, reducing signaling overheads is a desirable network operational requirement that could help improve network capacity, as discussed in [11].

II. THE MODIFIED ARQ-BASED COOPERATIVE RELAYING IN MULTI-RELAY NETWORK

The multi-relay network architecture shown in Fig. 1 is used to assess the performance of the modified ARQ-based relay cooperation. This is a generalization of the single-relay network treatment that is presented in [10]. Specialized further, the new treatment degenerates to the traditional multi-point relaying considerations as presented for example, in [1], [5], and [6]. The operation of the proposed scheme is as follows: In the first hop, the source broadcasts its signal to the destination and relays. The relays, equipped with L antennas, decode the signal using antenna selection diversity (see below); however, they do not transmit at this stage. The destination also decodes the received signal from the first hop but does not send an instant ACK. The source is allowed to continue to transmit. After a certain window of transmissions ($\mathcal{W}$) (four transmission cycles as depicted in Fig. 1), the destination interrupts to provide a "window-based" ACK. If no transmission error occurs, the source resumes its transmission of a new set of data. If there is an error, relaying is invoked.

The signal received at the destination can be expressed as

$$r_j^{\mathcal{S}-\mathcal{D}} = \alpha_j^{\mathcal{S}-\mathcal{D}} x_j + n_j^{\mathcal{D}}, \quad j = 1, 2, \cdots, \mathcal{W}. \tag{1}$$

Similarly, the signal received at the relays can be expressed as

$$r_j^{\mathcal{S}-\mathcal{R}_k} = \alpha_j^{\mathcal{S}-\mathcal{R}_k} x_j + n_j^{\mathcal{R}_k}, \quad j = 1, 2, \cdots, \mathcal{W}, \tag{2}$$

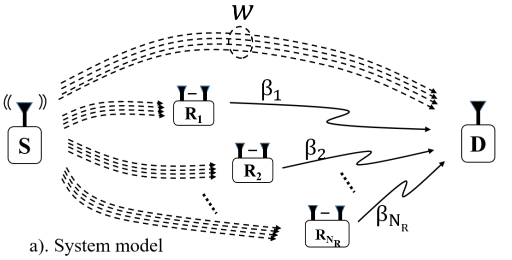
where j represents the transmission time instant, x_j represents the original source signal, $\alpha_j^{\mathcal{S}-\mathcal{D}}$ is the channel sample in the link $\mathcal{S}-\mathcal{D}$ between the source ($\mathcal{S}$) and the destination ($\mathcal{D}$), and $\mathcal{S}-\mathcal{R}_k$ is the link between $\mathcal{S}$ and the k-th relay, $k = 1, 2, \cdots, N_R$. The independent identically distributed (iid) Additive White Gaussian Noise (AWGN) at the destination and the relays are $n_j^{\mathcal{D}}$ and $n_j^{\mathcal{R}_k}$, respectively.

When relaying is invoked, the relays utilise spectrally-efficient modulation for their retransmission of the data that the source transmitted. Thus, the signal received at the destination can be expressed as

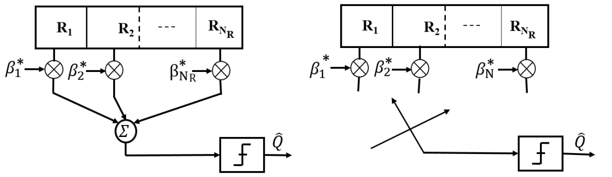
$$r_t^{\mathcal{R}_k-\mathcal{D}} = \beta_t^{\mathcal{R}_k-\mathcal{D}} \hat{x}_t^k + n_t^{\mathcal{R}_k}, \quad t = 1, 2, \cdots, \mathcal{W}_2, \tag{3}$$

where t is the transmission time instant, $\hat{x}_t^k$ is the regenerated signal by the k-th relay, $n_t^{\mathcal{R}_k}$ is the i.i.d AWGN, $\beta_t^{\mathcal{R}_k-\mathcal{D}}$ is the channel sample in the $\mathcal{R}_k-\mathcal{D}$ link, $\mathcal{W}_2 = \frac{\mathcal{W}}{\log_2(M)}$, and M is the constellation size of the modulation scheme employed in this link. Note that $\mathcal{W} = \log_2(M)$, indicates that one slot is used by each relay for its transmission in the second hop. However, relay transmissions can also be organized into multiple transmissions. It thus implies that x_j and $\hat{x}_t^k$ may not belong to the same constellation.

It is important to state that the scheme is designed around simplicity, even when relays are equipped with many antennas. The underlying operation is that each relay utilizes a single antenna for receiving and one antenna for transmission. The destination and the source are also one-antenna devices thereby facilitating low complexity and cost–a desirable feature of IoT devices.



a). System model



b). MRC-based relay combining c). Selection-based relay combining

Fig. 1. L-antennas multi-relay system model and destination processing schemes; maximal ratio combining or selection cooperation.

A. Channel Model

We employ the Weibull fading model to evaluate the performance of the proposed scheme. Weibull distribution, due to its versatility, has started attracting interest for modeling digital communication channels [12]. Its probability density function (PDF) is given as

$$f(x, K, \lambda) = \begin{cases} \frac{K}{\lambda}\left(\frac{x}{\lambda}\right)^{K-1} e^{-\left(\frac{x}{\lambda}\right)^K}, & x \geq 0, \\ \\ 0, & x < 0, \end{cases} \tag{4}$$

where $K > 0$ represents the shape parameter while $\lambda > 0$ is scaling parameter. Based on these parameters therefore different channel scenarios can be investigated. For example, when $K = 1$ the Weibull PDF simulates exponential fading, and when $K = 2$ and $\lambda = \sigma\sqrt{2}$, the model simulates the popular Rayleigh fading channel.

Before proceeding further, we provide some clarity on the channel representations. Let the first hop channel sample be expressed as $h_1(k,l,j)$ for the k-th relay's l-th antenna at the transmission instant j. Thus, in the above link equations, $\alpha_j^{\mathcal{S}-\mathcal{R}_k} = h_1(k,l^*,j)$. Similarly, for the second hop, $\beta_t^{\mathcal{R}_k-\mathcal{D}} = h_2(k,l^*,t)$, where $h_2(k,l,t)$ represents the second hop link channel and l^* represents the antenna that has the maximum channel gain at the instant of reception (in the first hop) or transmission (in the second hop).

B. *Generic Description*

As previously justified for simplicity appeal, each relay utilizes a single antenna to receive and one antenna to transmit. Therefore, to achieve this important distinction, the following pseudo-algorithms describe this aspect of the scheme:

```
• Antenna selection for relay to receive,
    – $\mathcal{L}_1 : j = 1$
    – $\mathcal{L}_2 : k = 1$
    – $\mathcal{L}_3 :$
          $l^* = \arg\max_{l \varepsilon L} h_1(k,l,j)$
    – $\mathcal{L}_4 : \alpha_j^{\mathcal{S}-\mathcal{R}_k} = h_1(k,l^*,j)$
    – $\mathcal{L}_5 : k = k+1$, if $k <= N_R$ Goto $\mathcal{L}_3$
    – $\mathcal{L}_6 : j = j+1$, if $j <= \mathcal{W}$ Goto $\mathcal{L}_2$
    – $\mathcal{L}_7 :$ End first hop transmission phase
• Antenna selection for relay to transmit,
    – $\mathcal{M}_1 : t = 1$
    – $\mathcal{M}_2 : kk = 1$
    – $\mathcal{M}_3 :$
          $l^* = \arg\max_{l \varepsilon L} h_2(kk,l,t)$
    – $\mathcal{M}_4 : \beta_t^{\mathcal{R}_{kk}-\mathcal{D}} = h_2(kk,l^*,t)$,
    – $\mathcal{M}_5 : kk = kk+1$, if $kk <= N_R$ Goto $\mathcal{M}_3$
    – $\mathcal{M}_6 : t = t+1$, if $t <= \mathcal{W}_2$, Goto $\mathcal{M}_2$
    – $\mathcal{M}_7 :$ End second hop transmission phase.
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In the following sections, we present the different scenarios for processing the signals from the relays at the destination.

III. MRC-BASED RELAY COOPERATION

Firstly, we consider a network configuration where the destination, upon its request for relays' transmission, utilizes all the transmissions from the relays to detect the $\mathcal{W}$ bits transmitted in the previous window. The destination employs the maximal ratio combining. For this scenario, we consider two cases as shown in Fig. 2 for noisy $\mathcal{S}-\mathcal{R}_k$ and Fig. 3 for noiseless $\mathcal{S}-\mathcal{R}_k$ links considering the channel scenario $K = 2, \lambda = 1$. We state here that an arbitrarily low error rate can be achieved in a noisy channel once the channel capacity is larger than the information transmission rate. We adopt the noiseless channel as a lower-bound setting reference. Such performance also exposes the possible obtainable performance assuming arbitrarily low error probability at the relay as depicted in Fig. 3. Note however that the proposed scheme does not rely on error-free source-relay channels.

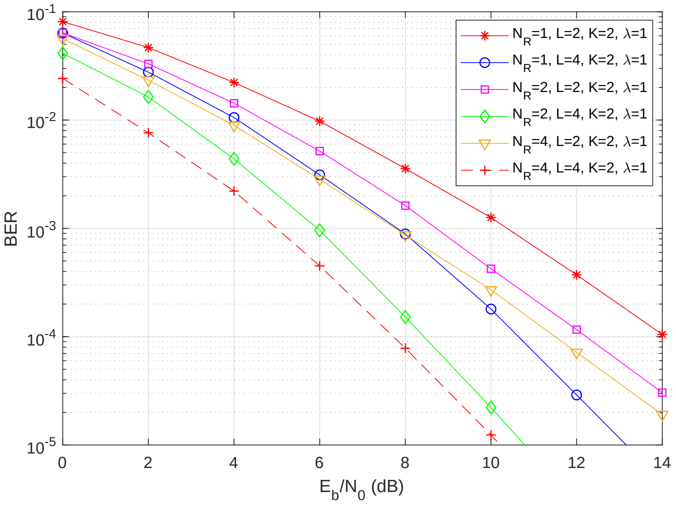

Fig. 2. BER performance for noisy S-R links for different number of relays and antennas, MRC-based relay combining for L antennas at a relay.

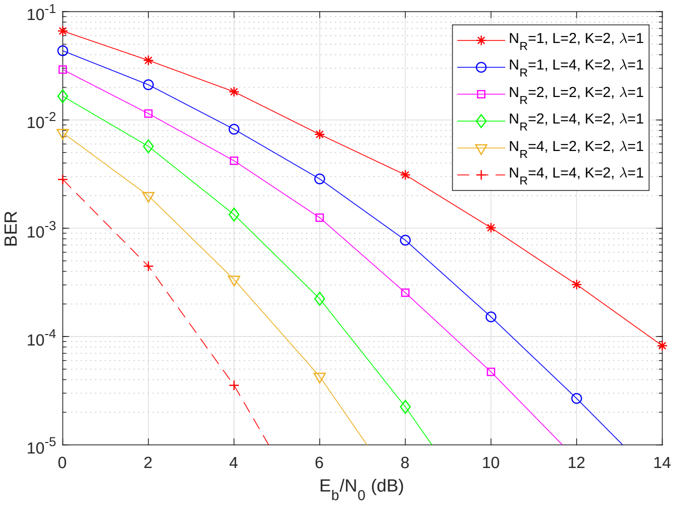

Fig. 3. BER performance for noiseless S-R links for different number of relays and antennas, MRC-based relay combining for L antennas at a relay.

Let us extract some important observations from Fig. 2 and Fig. 3. It is observed that the network setup $N_R = 2, L = 2$ yields a worse performance than that of $N_R = 1, L = 4$ (Fig. 2), which suggests the adverse effect of error propagation when relays, two in this case, are combined at the destination. It is also observed that 4 antennas with selection diversity at the relay provides sufficient error protection to enable the benefits of multi-relay over single relay.

The noisy channel scenario presents an important conundrum. If the S-R links are not sufficiently error protected, there is little value in engaging more relays at the destination. It simply makes more deployment sense investing in more antennas at a few relays, because that will provide performance returns in terms of E2E link error rate. In addition, it also saves time slots that the relays would need. And if the frequency of relaying is defined as the number of relays that transmit, this metric will also be adversely affected. Numerical results for other different configurations of $K = 1$ and $\lambda = 1$ are omitted due to space limitation, offer the same conclusions.

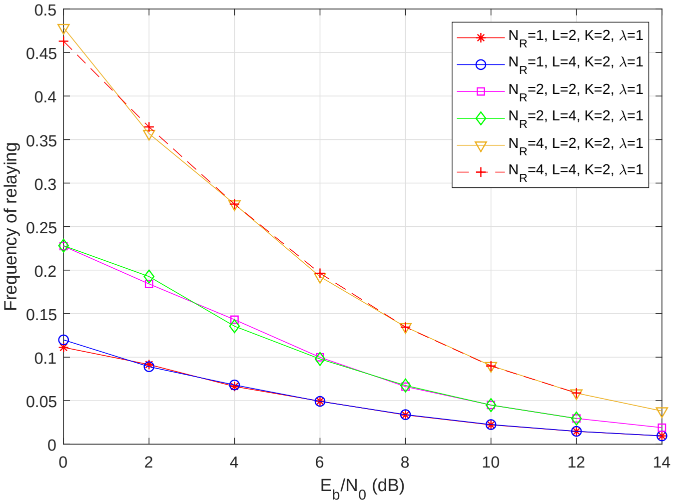

Fig. 4. Frequency of relaying for MRC-based relay combining for different number of relays with L antennas at a relay.

Figure 4, on the other hand, presents the frequency of relay retransmission. As expected, a significant increase in the number of relaying time is observed when all relays are engaged in the cooperation. We note that at sufficiently high SNRs (e.g., SNR $>$ 12 dB), the frequency of relaying for the multi-relay networks approaches that of a single relay cooperation. The fact that a multi-relay network incurs a higher number of re-transmissions helps underscore the importance of the best and single relay cooperation provided below for the proposed scheme.

IV. SELECTION-BASED RELAY COOPERATION

Usually spectrum expansion precludes the use of multi-relay system in the fashion we described above. To extract the benefits of relaying, we will be constrained to one relay transmitting, the best relay among a number of relays to bring the frequency of relaying down to that of a one-relay network. In the sections that follow we explore such relaying schemes and in the process devise a novel way to select the best relay. First, we consider scenario where the best relay is selected subject to the condition that the source - relay links are perfect. This is obviously an ideal assumption employed here just to help set the lower bound for any selection scheme. It is not the proposed scheme.

A. MaxSNR-based Relay Selection

Here, the destination employs the relay selection, where the relay with the best SNR (between the relay and destination) is selected for processing its signal. For this scenario too, we examine two cases as shown in Fig. 5 for noisy $\mathcal{S} - \mathcal{R}_k$ and Fig. 6 for noiseless $\mathcal{S} - \mathcal{R}_k$ links. Our objective here is to assess the proposed scheme for the gains that will be obtainable assuming that the relay operates error free. Therefore, the relay selection can be based on the $\mathcal{R}_k - \mathcal{D}$ links. Note, this particular scenario is clearly an ideal condition which we set in order to compare or benchmark the efficacy of the scheme proposed in this paper. The proposed selection scheme does not assume perfect S-R links.

We observe that employing a higher number of relays does not yield rich returns in terms of E2E error rate performance, and that the number of antennas at the relays provides the major limiting factor on the diversity order for the noisy source - relay scenario. Observe that in Figure 5, the curve for $N_R = 2, L = 4$ is parallel to that of $N_R = 4, L = 4$, and the curves for $N_R = 2, L = 2$ and $N_R = 4, L = 2$ are parallel, which signifies that they have the same diversity order. Figure 6 shows the convergence of the performance of $N_R = 2, L = 4$ and $N_R = 4, L = 2$. This is due to the assumption of perfect source-relay links; in reality the multi-relay scenario builds a giant single relay with the number antennas equal to $N_R \times L$.

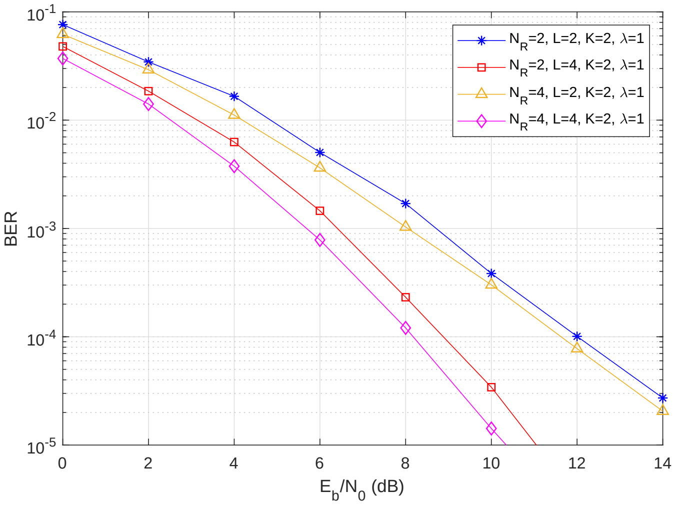

Fig. 5. BER performance for noisy S-R links, max SNR-based relay selection for L antennas at a relay

B. Novel, Practical and Best Relay Selection

Given that in practical relay network, the source - relay channels will not be perfect. Therefore, we embark on devising a methodology to perform best relay selection that considers both the source - relay and relay - destination channels. This is vital given that we are addressing a completely non-traditional multi-relay network cooperation and more importantly there is no such scheme available in the literature. The steps for selecting the best relay are outlined as follows:

- Recall, $h_1(k, l^*, j)$ represents the channel between the source and the k-th relay's best antenna at transmission instant j.
- Recall, $h_2(kk, l^*, t)$ represents the channel between the destination and the kk-th relay's best antenna at transmission instant t

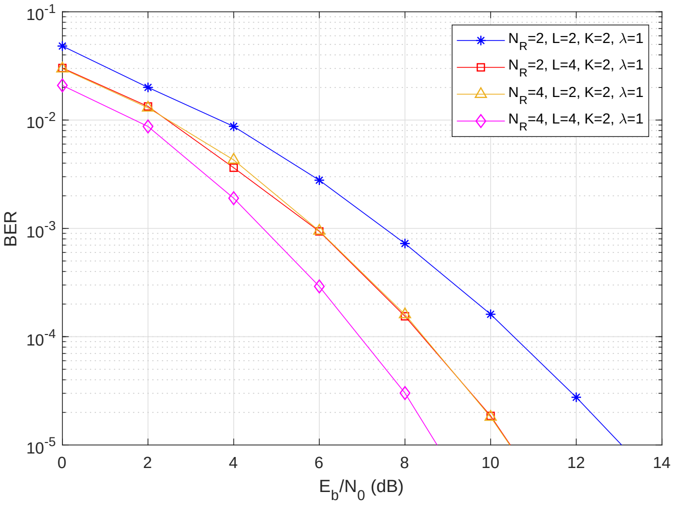

Fig. 6. BER performance for noiseless S-R links, max SNR-based relay selection for L antennas at a relay

- Perform the following calculation:

$$\begin{aligned}\gamma_k &= \frac{1}{\mathcal{W}}\sum_{j=1}^{\mathcal{W}} h_1(k,l^*,j) * h_1(k,l^*,j)^* \\ &= \frac{1}{\mathcal{W}}\sum_{j=1}^{\mathcal{W}} |h_1(k,l^*,j)|^2, \ \texttt{for } k=1,\cdots,N_R. \qquad (5)\end{aligned}$$

  This metric is defined to recognise the contribution or impact of each transmission window on the E2E performance. This metric also provides an avenue to be able to perform relay selection.
- Recall, $\beta_{kk} = |h_2(kk,l^*,1)|^2$, given that $t = 1$ for a single channel use in the second hop. That is $\mathcal{W}_2 = 1$, since $\mathcal{W}(=4) = \log_2(M = 16)$. That is, 16-QAM is the higher modulation constellation adopted in the second hop, while BPSK in the first hop.
- The relay selection can be implemented as follows:
  - Obtain the minimum of the backward and forward channels:

$$\Gamma_k = \min\{\beta_k, \gamma_k\}, \quad \texttt{for} \quad k = 1,\cdots,N_R. \qquad (6)$$

  - Select relay with maximum of all the minimums:

$$q^* = \max_{\arg \mathrm{k}} \Gamma_k. \qquad (7)$$

- Therefore, relay q^* will be the candidate relay to transmit at this instant of relays' involvement.

Some representative numerical results of the proposed novel best relay selection strategy are presented in Fig. 7, Fig. 8, and Fig. 9 for $K = 2, \lambda = 1$ for $N_R = 2$ and $N_R = 4$ and discussed as follows. It is observed that diversity gains are provided by the proposed scheme. The number of antennas at a relay has more impact on the performance of the relay network than the number of relays. This is not a particularly novel observation since the work in [7] already exposed this important relationship between the number of antennas and relays. What is however revealed in this current setup is the pronounced impact of the number of antennas. We see that four antennas at the relay in a 2-relay network significantly outperforms that of 4-relay with 2 antennas, in contrast to the observations in [7].

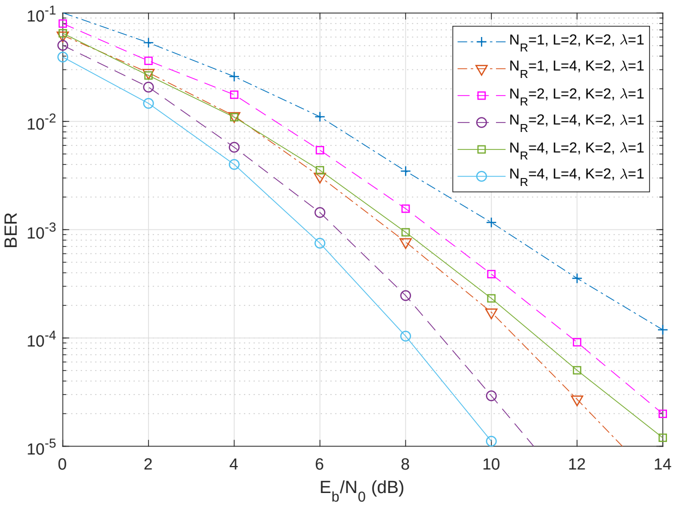

Fig. 7. BER performance of the practical relay selection cooperation for $L-$ antenna relay.

Fig. 8 and Fig. 9 present some comparative performances between the practical selection strategy and the scenarios where extreme assumptions are made, i.e., error-free source-relay links. We can deduce that the performance of the devised best relay selection for the new ARQ scheme will be lower bounded by the performance of the Max SNR R-D links scheme with perfect S-R links and upper bounded by the noisy S-R link. This fact is revealed in Fig. 8 and Fig. 9.

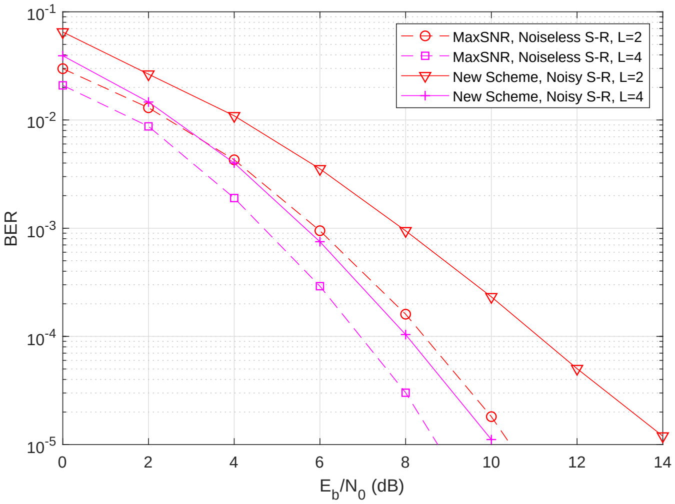

Fig. 8. BER comparison of the practical relay selection strategy and extreme assumption noiseless S-R links for $L-$ antenna relay, $N_R = 4$.

Fig. 8 and Fig. 9 for $N_R = 4$ and $N_R = 2$, respectively, show that the practical selection scheme provides comparable

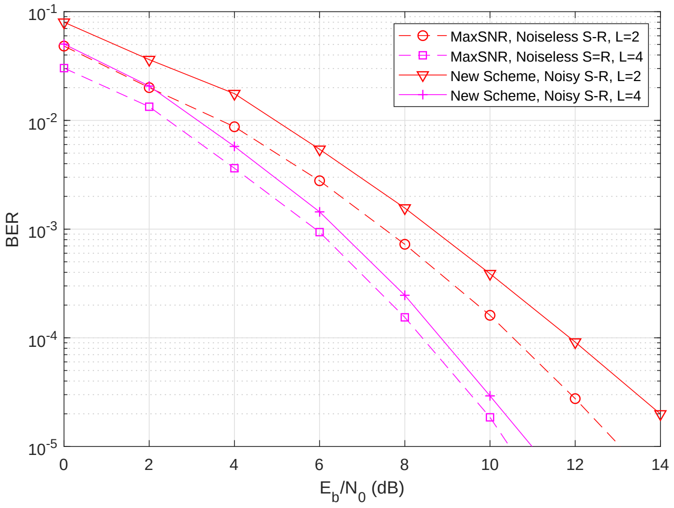

Fig. 9. BER comparison of the practical relay selection strategy and extreme assumption noiseless S-R links for $L-$ antenna relay, $N_R = 2$.

performance to the perfect source - relay link scenario, which is an impracticable and extreme assumption. For example, at a BER of 10^{-4} for $N_R = 4$ (Fig. 9), the new scheme is only about 0.5 dB inferior to the perfect channel conditions. For the SNR range, 8 dB $\leq$ SNR $\leq$ 10 dB, the reduction in frequency of relaying is significant comparing the curve for the single relay transmission to that of multi-relay where all relays are engaged (Fig. 4).

V. CONCLUSIONS

The paper presents a twist to the automatic repeat request–based cooperative relaying scheme that is suitable for delay tolerant applications. We employ multiple relays and devise a befitting best relay selection for the proposed scheme that provides excellent end-to-end bit error rate. In the proposed scheme, the source transmits for a certain time window without requiring instant acknowledgment from the destination. At the end of the transmission window, the destination sends a ‘group’ acknowledgement for either relays to assist if a single error occurs or source to continue to transmit if no error is detected. Depending on the cooperation strategy, each relay transmits in either one transmission time slot or a few time slots, using a suitably chosen higher-order modulation constellation. The relays transmit intermittently and in burst.

Since this is a novel proposal, we therefore devise a strategy for selecting the best (single) relay to transmit in the multi-relay network. The numerical results show that with just a few antennas at the relays, the new scheme provides both a reduction in the number of ARQ transmissions and a superior probability of bit error compared to the reference single relay cooperation. In addition, we reclaim the bandwidth expansion that comes with multi-relay system through the novel best relay selection strategy.

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