行政院國家科學委員會專題研究計畫 成果報告

OFDM 無線網路之合作通訊--子計畫三:合作式正交分頻多工系統之空時編解碼與訊號處理(2/2)

研究成果報告(完整版)

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行政院國家科學委員會補助專題研究計畫成果報告

OFDM無線網路之合作通訊–子計畫三:合作式正交分頻多工系統之空時編解碼與訊號處理(2/2)

伍紹勳

Abstract

合作式中繼通訊 "cooperative relaying" 是利用中繼站 "relay" 當做虛擬天線，以達到類似多重輸入-多重輸出 "MIMO: multiple-input multiple-output" 系統的效能，可用來增加傳輸的可靠度或是通道容量。 此外，配合自動重傳機制，亦能讓合作式通訊的功能作進一步的提升。首先我們在一個簡化的數學模型下， 利用選擇性的放大傳送 "selective amplified-and-forward: SAF" 中繼技術來協助系統之自動重傳"automatic retransmission request: ARQ"協定。分析的結果告訴我們當中繼端點收到超過一適當的通道品質之訊號才將此訊號放大轉送出去， 利用此 AF 中繼技術便可以得到相當的 ARQ 時間多樣性。基於上述分析，我們首先針對單一中繼端點， 提出一有效的 SAF 協定，來幫助系統達到完全的時間多樣性。接著，將此結果延伸到眾多中繼端點， 提出了兩個形式的投機式中繼協定"opportunistic relaying"，進而擴展在時間以及空間之多樣性。 此些協定我們可以統稱爲投機式選擇性 AF 中繼技術"opportunistic-selective AF relaying: OSAF"。 分析的結果顯示這兩各 OSAF 協定比起傳統 AF 中繼協助下之 ARQ 機制，均能提供更多的多樣性。另外，在 OSAF 協助下之 ARQ 機制的通吐率"throughput" 對於不同的通道環境，其效能表現也相當的穩健。

延續以上的結果，我們更延伸至 DF 中繼技術，討論投機分散式空時編碼"opportunistic distributed space-time coding"，根據分析的結果，讓所有尚未解調成功的中繼站持續聆聽來自傳送中之中繼站訊號，此舉亦能夠將系統的吞吐率顯著地提升。 儘管如此，在訊雜比極低或是極高的時候，即使不讓尚未解調成功的中繼站持續聆聽，也幾乎能夠輸出相同的性能，這樣的結果可以大大降低爲了讓中繼站彼此聆聽訊號所增加的協定設計複雜度。

Keywords

Selective amplified-and-forward, cooperative ARQ, opportunistic relaying, opportunistic DSTC.

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Abstract

Cooperative relaying is a distributed technology that uses relay stations to realize a virtual multiple-input multiple-output (MIMO) system. Motivated by the spatial diversity of MIMO and the temporal diversity of automatic retransmission request (ARQ), in this research project, we first develop cooperative ARQ protocols based on the amplified-and-forward (SAF) relaying method. Analysis shows that the temporal diversity of ARQs can be exploited with AF relaying only if the channel quality to the relay exceeds a threshold that depends on the source data rate requirement. Based on this analysis, an effective ARQ protocol is first developed from the concept of selective relaying to attain the full temporal diversity. Moreover, the notion of SAF relaying is further extended to systems with multiple relays to exploit the spatial and temporal diversities, incorporating the mechanism of opportunistic relaying. Two types of opportunistic-selective AF (OSAF) relaying methods are thus proposed for cooperative ARQs. Analysis shows that both OSAF protocols can offer much higher diversities than ARQ schemes with the typical AF relaying method. And the throughput of ARQs with OSAF is more robust to the variations of channel qualities and is close to their decode-and-forward (DF) counterparts.

In addition to ARQs with AF relaying, we also extend the study on ARQs based on the DF ODSTC. According to the simulation results, allowing the non-active relays to overhear the DSTC signal sent by one or two active relays yields significant advantage on the delay-limited throughput. Besides, the throughput enhancement becomes more pronounced when subject to a lower outage constraint. Nevertheless, in the extremely high or low SNR regimes, simple schemes without overhearing may provide almost the same performance offered by overhearing, despite its inferior diversities. Thus, it can greatly reduce the need for a complex protocol with overhearing.

Keywords

Selective amplified-and-forward, cooperative ARQ, opportunistic relaying, opportunistic DSTC.

I. Introduction

Cooperative communication has emerged as a new paradigm in wireless communications. Since the work of [1, 2], many cooperative ideas have been introduced to enhance the system capacity and/or transmission reliability, either through user cooperation or by signal relaying. They can be roughly categorized into the amplified-and-forward (AF) and decoded-and-forward (DF) methods. In view of the simplicity of AF relaying and its corresponding effect of noise enhancement, selective AF (SAF) relaying method has been considered in [3] to improve the power efficiency of typical AF relaying, or in [4] for multi-hop relaying and in [5] with phase feedbacks.

On the other hand, a host of cooperative schemes have been proposed to exploit the spatial diversity via distributed space-time coding (DSTC), *e.g.* [2,6]. The diversity order of the outage probability is shown to increase proportionally with the number of cooperative relays. Moreover, a full order of the cooperative diversity can be achieved even by using one out of a set of available relays opportunistically [7]. Motivated by the simplicity and effectiveness of opportunistic relaying, some more recent efforts have been made to investigate the opportunistic distributed beamforming [8] and DSTC [9].

For the AF scheme, to avoid the difficulty of synchronization among all participating relays and to prevent from the complexity of using distributed space-time coding or beamforming, opportunistic relaying (OR) has been introduced in [10] to exploit the spatial diversity offered by distributed relays. Inspired by the above results, we study herein effective opportunistic and selective AF methods for cooperative automatic retransmission request (ARQ) to exploit the spatial and temporal diversities via cooperative relaying.

According to our analysis, it shows that the temporal diversity of ARQs can be exploited with AF relaying only if the channel quality to the relay exceeds a threshold that depends on the source data rate requirement. Based on this result, an effective ARQ protocol is first proposed to employ the SAF relaying to attain the full temporal diversity. Moreover, by incorporating the OR mechanism, this SAF relaying scheme is further extended to exploit the spatial and temporal diversities in systems with multiple relays. Different from the opportunistic AF (OAF) in [10], the opportunistic selection methods studied herein only rely on the channel qualities to the destination, which prevents from the need of extra channel state information at the destination. Based on this opportunistic mechanism, two types of opportunistic-selective AF (OSAF) relaying methods are developed for cooperative ARQs. Analysis shows that both OSAF protocols can offer much higher diversities than ARQ schemes with the typical AF relaying method if proper thresholds are set for each hop along the relayings. Besides, numerical studies also demonstrate that the throughput of ARQs with OSAF is more robust to the variations of channel qualities and is close to their decode-and-forward counterparts.

Besides, for the DF scheme, in contrast to the rich results in the outage analysis for DSTC, the performance of automatic retransmission request (ARQ) is relatively less investigated for opportunistic DSTC (ODSTC). The average throughput of a cooperative hybrid-ARQ scheme has been reported in [6] for DSTC only. To study the effectiveness of ODSTC and the extra degrees of freedom via ARQs, in the beginning, the spatial and temporal diversities of cooperative ARQ via decode-and-forward (DF) ODSTC are investigated. Then, we analyze the delay-and outage-limited throughput to examine the effectiveness of each scheme at different SNRs. According to the numerical results, allowing the non-active relays to overhear the DSTC signal sent by one or two active relays yields significant advantage on the delay-limited throughput. Besides, the throughput enhancement becomes more pronounced when subject to a lower outage constraint. Nevertheless, in the high or low SNR regimes, simple schemes without overhearing may provide almost the same performance offered by overhearing, despite its inferior diversities. Thus, the need for a complex protocol with overhearing can be greatly reduced.

II. Cooperative ARQ with Selective AF Relaying

We introduce in this section the ARQ schemes with the assistance of SAF relaying evolved from the original AF in [11] and its variation in [4]. For the clearness of presentation, we first consider a system that consists of only one source, one destination and a single relay. The result of this system will then be extended to systems with multiple relays. Throughout the paper, the channel between any transmit and receive pair is considered flat Rayleigh and, for simplicity of analysis, the channel coefficients remain unchanged within a period of time and change randomly from period to period. This assumption, though rather optimistic in practice, allows us to proceed with the analysis based on the outage probability [12].

A. ARQ with selective AF relaying (ARQ-SAF)

Different from the typical AF relaying, the relay in this ARQ scheme first compares the instantaneous source-to-relay channel quality $\rho|h_{sr}|^2$ against a predetermined threshold, Δ, before retransmission. If $\rho|h_{sr}|^2$ is less than or equal to Δ, then the source will be asked to do the retransmission by itself, while, in the mean time, the relay keeps overhearing the signal during retransmissions. Once $\rho|h_{sr}|^2 > \Delta$, the relay proceeds with the retransmission using the AF relaying and will continue to use the same quantity for retransmission until it is decoded successfully at the destination or when the maximal number of ARQs is reached, namely no ARQ is further needed. The corresponding received SNR at the destination is given by

$$\mathrm{SNR}_d = \frac{\rho^2 |h_{sr}|^2 |h_{rd}|^2}{\rho |h_{sr}|^2 + \rho |h_{rd}|^2 + 1} \tag{1}$$

where h_{sr}, h_{sd}, and h_{rd} stand for the channel coefficients of source-to-relay (S-R), source-to-destination (S-D), and relay-to-destination (R-D), respectively, and are all complex Gaussian random variables with zero mean and variances equal to β_1, β_0 and β_2, respectively. Besides, without the loss of generality, the transmit SNR is assumed to be the same at the source and the relay, and is denoted by $\rho \triangleq \frac{E_s}{N_0}$.

III. The Outage Probability of ARQ-SAF

In this section, we will show that the threshold Δ for the selective AF relaying is crucial for ARQ schemes to attain their full diversities. In other words, the ARQ scheme with the simple AF relaying ($\Delta = 0$) is not able to benefit from diversity enhancement via retransmissions. The analysis is mainly based on the outage probability of the form

$$\Pr\{\log_2(\mathrm{SNR}+1) < R\} = \Pr\left\{\mathrm{SNR} < 2^R - 1\right\} \tag{2}$$

where R is the information rate in bits/sec per channel use. For convenience of expression, we define a number of notations for variables to be used frequently in the analysis. Specifically, we have $a \triangleq \rho|h_{sr}|^2$, $b \triangleq \rho|h_{rd}|^2$ and $w \triangleq \rho|h_{sd}|^2$, and denote the outage probability after n rounds of ARQs with scheme A by P_n^A, and the maximal number of ARQ rounds by $\mathcal{N}$. Besides, we also have $\delta_1 \triangleq 2^R - 1$, and redefine $\Delta \triangleq k\delta_1$ with $k \geq 0$. Finally, the diversity order d is defined as [12]

$$\xi \triangleq -\lim_{\rho \to \infty} \frac{\log P_n^A(\rho)}{\log \rho}. \tag{3}$$

Given Δ, the outage probability after n rounds of ARQs with the selective AF relaying can be expressed as

$$\begin{aligned} P_n^{\mathrm{SAF}} &= \Pr\{w < \delta_1\} \\ &\quad \times \sum_{l=0}^{n} \left[\left(\Pr\{a \leq \Delta\} \Pr\{w < \delta_1\}\right)^{n-l} F(\Delta, l) \right] \end{aligned} \tag{4}$$

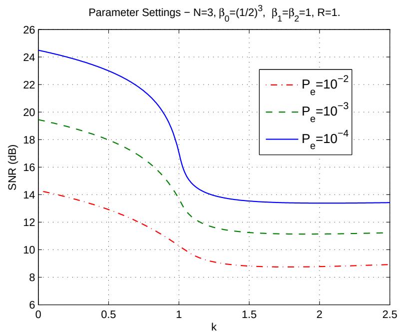

Fig. 1. The effect of $k = \frac{\Delta}{\delta_1}$ v.s. the SNR at a target $P_3^{\mathrm{SAF}} = P_e$.

where $(\Pr\{a \le \Delta\} \Pr\{w < \delta_1\})^{n-l}$ is the outage probability after $n-l$ consecutive retransmissions by the source, and $F(\Delta, l)$ stands for the outage probability of the subsequent l consecutive retransmissions by the relay, which are characterized by the joint probability of the outage events of

$$F(\Delta, l) = \Pr\left\{a > \Delta, \frac{ab_1}{a + b_1 + 1} < \delta_1, \dots, \frac{ab_l}{a + b_l + 1} < \delta_1\right\}, \text{for } l > 0 \tag{5}$$

with $F(\Delta, 0) \triangleq 1$. Since the R-D channel fades independently in each ARQ round, b_l is used to distinguish the corresponding channel quality in each ARQ round.

Apparently, the outage events in $F(\Delta, l)$ are correlated as the S-R channel quality "a" remains unchanged throughout the ARQs even if b_l are statistically independent. With some mathematical manipulations, it can be shown that the form of $F(\Delta, l)$ also depends on δ_1. For the conciseness of presentation, the result is summarized in the following lemma.

Lemma 1: Given Δ and R and, hence, δ_1, we have

$$F(\Delta, l) = e^{-\frac{\Delta}{\rho\beta_1}} + \begin{cases} \sum_{i=1}^{l} \mathcal{C}_i^l (-1)^i e^{-(\frac{1}{\rho\beta_1} + \frac{i}{\rho\beta_2})\delta_1} \Gamma(1, 0; \frac{i(\delta_1^2+\delta_1)}{\rho^2\beta_1\beta_2}) & , \Delta < \delta_1 \\ \sum_{i=1}^{l} \mathcal{C}_i^l (-1)^i e^{-(\frac{1}{\rho\beta_1} + \frac{i}{\rho\beta_2})\delta_1} \Gamma(1, \frac{\Delta-\delta_1}{\rho\beta_1}; \frac{i(\delta_1^2+\delta_1)}{\rho^2\beta_1\beta_2}) & , \Delta \ge \delta_1 \end{cases} \tag{6}$$

where $\Gamma(\alpha, x; b) = \int_x^\infty t^{\alpha-1} e^{-t-\frac{b}{t}} dt$ is the *generalized incomplete gamma function* [13], and $\mathcal{C}_i^l$ is the total number of combinations of picking i out of l distinct objects.

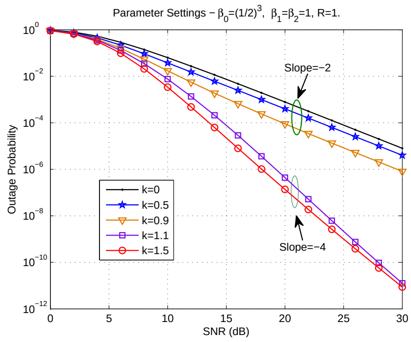

Fig. 2. Outage probabilities after three rounds of ARQ-SAFs (P_3^{SAF}), with thresholds $\Delta = k\delta_1$ in different k's.

Substituting (6) into (4) gives the closed form expression of (4). The relation between $\Delta \triangleq k\delta_1$ and the outage probability(4) is illustrated in Fig. 1. As can be seen in the figure, the required SNR for $P_3^{\text{SAF}} = P_e$ dramatically reduces around $k = 1$. This in fact results from the diversity loss for $k < 1$ shown in Fig. 2. The dependence of the diversity order on Δ is characterized in the following lemma. Due to the space limitation, the proof is not presented in the paper.

Lemma 2: If $\Delta > \delta_1$, then the diversity order of P_n^{SAF} in (4) is equal to $(n+1)$; whereas, if $\Delta < \delta_1$, it is equal to 2.

Lemma 2 shows that the full temporal diversity of ARQs can be achieved if a basic channel quality of Δ is met before the AF relaying. This gives an interesting reminiscence of the selective DF relaying in [11], even if the source signal is not decoded here before the AF retransmission.

The result of Lemma 2 also shows that the diversity order of ARQ with direct AF relaying (ARQ-AF) is equal to 2 as it is simply a special case of ARQ-SAF with $\Delta = 0$, which is always less than δ_1 for $R \geq 0$. According to Lemma 1, the corresponding outage probability for ARQ-AF is given by

$$P_n^{\text{AF}} = (1 - e^{-\frac{\delta_1}{\rho\beta_0}}) \times F(0, n). \tag{7}$$

IV. Cooperative ARQ with Opportunistic-Selective AF Relaying

In this section, we extend the notion of selective AF relaying to systems with multiple relays. Motivated by the opportunistic relay selection method in [10], we will discuss and analyze three protocols herein based on their outage probabilities. We assume there are M relays available in the system and denote the channel coefficient between the source and the relay j by $h_{j,sr}$ and the channel between the relay and the destination by $h_{j,rd}$. In addition, the channel coefficient between relay i and relay j is denoted by $h_{i,j}$. For simplicity of analysis, all channel coefficients are still assumed complex Gaussian random variables with zero mean. The variances of $h_{j,sr}$ for different j are the same and equal to β_1. Similarly, the variance of $h_{j,rd}$ is β_2, $\forall j = 1, \ldots, M$. Furthermore, the variance of $h_{i,j}$ is β_3, $\forall i, j = 1, \ldots, M$.

A. ARQ with opportunistic AF relaying

We first investigate the outage probability of ARQ with the opportunistic AF (ARQ-OAF) relaying method presented in [10]. The ARQ-OAF basically chooses the relay t in each round of ARQ that satisfies

$$t = \arg\max_{j\in\{1,\ldots,m\}} \left\{ \frac{\rho^2|h_{j,sr}|^2|h_{j,rd}|^2}{\rho|h_{j,sr}|^2 + \rho|h_{j,rd}|^2 + 1} \right\} \tag{8}$$

to directly amplify and forward the signal. Based on the previous results, the outage probability after n rounds of this OAF-based ARQs is provided in the following proposition.

Proposition 1: Given R and M, the outage probability after n rounds of ARQs with OAF is given by

$$P_n^{\text{OAF}} = (1 - e^{-\frac{\delta_1}{\rho\beta_0}}) \times (F(0, n))^M \tag{9}$$

and its diversity order is limited to $(M + 1)$, $\forall n = 1, \ldots, \mathcal{N}$.

Proof: : The detailed derivation for the outage probability is omitted here for space limitation. By Lemma 2, if $\Delta < \delta_1$, then $F(\Delta, n)$ is of the order of ρ^{-1} at high SNR. Thus, the diversity order of P_n^{OAF} is equal to $(M + 1)$. ■

In fact, the ARQ-OAF scheme offers the full cooperative diversity only for the first ARQ round. In the subsequent ARQs however, $a_j \triangleq \rho|h_{j,sr}|^2$ remain unchanged in the AF signal. Similar to the ARQ-AF scheme, this results in the loss of the temporal diversity as shown in Fig. 3. This motivates us to develop another two protocols based on the SAF relaying method in Section II to recover the diversity.

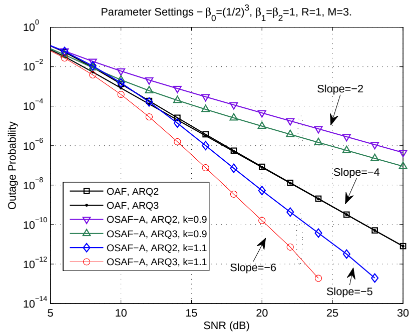

Fig. 3. Outage probabilities for ARQs with OAF and OSAF-A relayings. For OSAF-A with $\Delta = k\delta_1 \geq \delta_1$, the diversity orders increase by 1 with each round of ARQ. Otherwise, they are limited to 2.

B. ARQ with opportunistic-selective AF relaying

The essence of ARQ-SAF lies in setting a sufficiently high threshold that the relay is allowed for forwarding only if the S-R link quality, $\rho|h_{sr}|^2$, exceeds the threshold. By ensuring the quality of the received signal, the channel diversity in the subsequent ARQs can be exploited to reduce the outage probability. Inspired by this result, we define a qualified set $\mathcal{Q}$ of the relays whose $\rho|h_{j,sr}|^2 > \Delta$ for opportunistic AF relaying. In each ARQ, the relay in $\mathcal{Q}$ with the highest $\rho|h_{j,rd}|^2$ gets selected for AF relaying. In case of $\mathcal{Q} = \emptyset$, then the source will do the retransmission until $\mathcal{Q} \neq \emptyset$ or when no ARQ is further needed. We note that the relay selection method here is *unrelated* to the S-R channel quality any more, *i.e.* $h_{j,sr}$ is not needed at the destination.

Based on this opportunistic-selective AF (OSAF) relaying method, we discuss in the next section two types of ARQ schemes, referred to as the type A and B of ARQ-OSAF, respectively. The type-A scheme forms $\mathcal{Q}$ by overhearing the signals from the source only, while type-B continues to enlarge the cardinality of $\mathcal{Q}$ by overhearing the transmitted signals from relays in $\mathcal{Q}$ as well. Their performance are analyzed in the following two subsections.

B.1 ARQ with the type A of OSAF relaying (OSAF-A)

Under the assumption that all R-D channels have the same statistical property, every relay in $\mathcal{Q}$ has equal possibility to be chosen as the active relay for AF. With this simplified setting, the outage probability after n rounds of ARQs with OSAF-A can be expressed in the following compact form.

Proposition 2:

$$
\begin{aligned}
P_n^{\text{OSAF-A}} = \Pr\{w < \delta_1\} \times \sum_{l=0}^{n} \Big\{ \big[(\Pr\{a \le \Delta\})^M \\
\times \Pr\{w < \delta_1\} \big]^{n-l} \times \mathcal{G}(M, l) \Big\}
\end{aligned}
\tag{10}
$$

where $\mathcal{G}(M,l) \triangleq 1$ for $l = 0$; in addition, for $l > 0$, it follows

$$
\mathcal{G}(M, l) = \sum_{i=1}^{m} \mathcal{C}_{M-i}^{M} \left(\Pr\{a \le \Delta\}\right)^{M-i} \left(\frac{1}{i}\right)^{l} F^{(i)}(\Delta, l, i) \tag{11}
$$

in which for $i = 1, 2$, we have

$$
F^{(1)}(\Delta, l, r) \triangleq F(\Delta, l) \tag{12}
$$

$$
\begin{aligned}
F^{(2)}(\Delta, l, r) \triangleq \sum_{\zeta=0}^{l} \mathcal{C}_{\zeta}^{l} (e^{-\frac{\Delta}{\rho\beta_1}})^{q(l,\zeta)} \times F(\Delta, r \cdot \zeta) \\
\times F(\Delta, r \cdot (l - \zeta))
\end{aligned}
\tag{13}
$$

with $q(l,\zeta) = \delta[l-\zeta] + \delta[\zeta] - \delta[l+\zeta]$. While for $i > 2$, $F^{(i)}(\Delta, l, r)$ can be expressed as a recursive form of

$$
\begin{aligned}
F^{(i)}(\Delta, l, r) = \sum_{\zeta=0}^{l} \mathcal{C}_{\zeta}^{l} (e^{-\frac{\Delta}{\rho\beta_1}})^{q(l,\zeta)} \times F^{(i-1)}(\Delta, \zeta, r) \\
\times F(\Delta, r \cdot (l - \zeta))
\end{aligned}
\tag{14}
$$

Proof: Due to the space limitation, the proof is not included in the paper. Basically we make use of the Binomial Theorem and Lemma 1 to complete the proof. ■

As we have known from Lemma 2, different thresholds for ARQ-SAF will result in different outage probabilities or even diversity losses. For ARQ with OSAF-A, we also have similar results which are summarized in the next proposition.

Proposition 3: If the threshold Δ for ARQ-OSAF-A is large than δ_1, then the diversity order of $P_n^{\text{OSAF-A}}$ increases with n and is equal to $(M+n)$. However, if $\Delta < \delta_1$, then the diversity order of $P_n^{\text{OSAF-A}}$ is just equal to 2 regardless of the number of relays and the ARQ rounds.

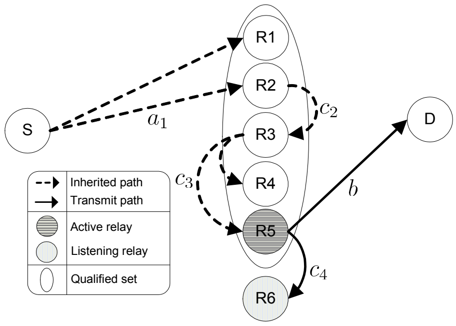

Fig. 4. An illustration for ARQs with the OSAF-B relaying.

Proof: : By Proposition 2 and Lemma 2, the diversity order of $P_n^{\text{OSAF-A}}$ could be easily verified. ■

The diversity orders of ARQ-OSAF-A can be verified with the outage probabilities presented in Fig. 3. Although only $\rho|h_{j,rd}|^2$ is considered for relay selection in OSAF-A, the OSAF relaying scheme is able to exploit the temporal diversity through ARQs if $\Delta > \delta_1$. Nevertheless, the diversity order only increases by 1 in each round after the first round of ARQ. This limitation is due to the worse case of $\mathcal{Q}$ in which only one relay is inside the set.

On the other hand for $\Delta < \delta_1$, the diversity order is limited to 2 due to the poor S-R channel qualities and the selection rule of OSAF. In comparison, the diversity order of ARQ-OAF is equal to $M+1$ as both $\rho|h_{j,sr}|^2$ and $\rho|h_{j,rd}|^2$ are required for the destination to choose the best relay according to (8).

B.2 ARQ with the type B of OSAF relaying (OSAF-B)

Based on the previous discussions on OSAF-A relaying, the key to further improve the diversity via ARQs is to increase the cardinality of $\mathcal{Q}$, denoted by $|\mathcal{Q}|$, through ARQs as well. This can be made possible only if the unqualified relays continue to overhear the signals transmitted by relays in $\mathcal{Q}$ during the process of ARQs. If conditions can be set on the link qualities, $\rho|h_{i,j}|^2$, between the transmitting and receiving relays to qualify and bring new relays into $\mathcal{Q}$, then the diversity may no longer be limited to the case of $|\mathcal{Q}| = 1$. This type of OSAF scheme is referred to as the ARQ with the OSAF-B relaying. The functioning of the protocol is illustrated in Fig. 4.

As shown in the figure, the active relay, R_5, of $\mathcal{Q}$ received the signal from R_3 in the previous ARQ and is currently forwarding the signal to the destination. The relay R_6 in the forbidden set, denoted by $\overline{\mathcal{Q}}$, overhears the signal from R_5. If $c_4 \triangleq \rho|h_{5,6}|^2$ exceeds a threshold, say Δ_4 with 4 being the number of hops before reaching the destination, then R_6 will be taken out of the forbidden set $\overline{\mathcal{Q}}$ and join the qualified set $\mathcal{Q}$. In the next round of ARQ, if any, the destination still chooses the relay in $\mathcal{Q}$ with the highest $\rho|h_{j,d}|^2$ for forwarding, even if the signal from R_6 has accumulated more noise through the hops from the source to R_2, R_3 and then R_5.

In general, for an active relay that forwards a signal already gone through p hops, the received SNR at the destination can be expressed as

$$\mathrm{SNR}_d = \frac{1}{\frac{1}{a_1} + \frac{1}{c_2} + \cdots + \frac{1}{c_p} + \frac{1}{b_*^{[q]}} + \left(\text{higher order terms}\right)} \tag{15}$$

where $b_*^{[q]}$ represents the highest $\rho|h_{j,d}|^2$ in $\mathcal{Q}$ with $q \triangleq |\mathcal{Q}|$. Since the higher order terms can be ignored in the high SNR regime, the denominator becomes simplified into the reciprocal sum of all the passed channel qualities. As a result, the corresponding outage probability at high SNR becomes

$$\lim_{\rho\to\infty} P_{out} = \lim_{\rho\to\infty} \Pr\left\{\frac{1}{b_*^{[q]}} > \frac{1}{\delta_1} - \left(\frac{1}{a_1} + \cdots + \frac{1}{c_p}\right)\right\}. \tag{16}$$

We next characterize the thresholds for (16) to achieve its full diversity. To this end, we first define a requirement on the reciprocal sum of $\frac{1}{a_1} + \cdots + \frac{1}{c_p}$.

Requirement 1 : Given a *fixed* and arbitrarily small positive number ϵ, for an active relay that forwards a signal already gone through p hops, the corresponding reciprocal sum satisfies $\frac{1}{a_1} + \frac{1}{c_2} + \cdots + \frac{1}{c_p} \leq \tau \triangleq \frac{1}{\delta_1} + \epsilon$.

For ARQ with OSAF-B relaying that satisfies Requirement 1, an upper bound can be obtained on the corresponding outage probability of (16), given by

$$\lim_{\rho\to\infty} P_{out} \leq \lim_{\rho\to\infty} \Pr\left\{b_*^{[q]} < \frac{1}{\epsilon}\right\}. \tag{17}$$

Based on this upper bound, we have the next two lemmas.

Lemma 3: If there exists a qualified set $\mathcal{Q}$ with $q = |\mathcal{Q}|$ and in $\mathcal{Q}$, every relay chosen by the destination according to the OSAF method satisfies Requirement 1, then the diversity order contributed by the relaying is q.

Lemma 4: Following Lemma 3, if the listening relays to be added into $\mathcal{Q}$ also satisfy Requirement 1, then the maximum diversity order that can be achieved for each ARQ is M.

Based on the above results, we arrive at a theorem for the diversity order of the ARQ-OSAF-B scheme.

Theorem 1: If all relays chosen according to OSAF-B out of $\mathcal{Q}$ satisfy Requirement 1, then the diversity order of the outage probability after n rounds of ARQ-OSAF-B is given by $(M \times n + 1)$.

Proof: By Proposition 3, at the first ARQ round, the OSAF-B scheme achieves a diversity order of $(M+1)$ as the first ARQ of OSAF-B is exactly the same to that of OSAF-A. For the subsequent rounds of ARQs, by Lemma 4, the diversity order increases by M with every extra ARQ round. As a result, the overall diversity of the outage probability is equal to $(M \times n + 1)$ after n rounds of ARQ-OSAF-B. ■

B.3 Threshold assignment for ARQ-OSAF-B

Apparently, for ARQ-SAF and ARQ-OSAF-A, the threshold Δ should be set greater than δ_1 according to Lemma 2 and Proposition 3, respectively. For ARQ-OSAF-B however, the source signal may go through multiple hops before arriving at the destination. Thus we need to define a threshold for each hop to control the channel quality of the entire relaying path. Since the maximal number of hops is limited to $\min[M, \mathcal{N}]$, we therefore define an array of thresholds as $[\Delta_1, \ldots, \Delta_i, \ldots, \Delta_{\min[M,\mathcal{N}]}]$ with Δ_i corresponding to the threshold for the i-th hop.

Fig. 5 demonstrates the outage probabilities for three different assignments of Δ_i with $M = 3$ and $\mathcal{N} = 3$. The thresholds are $[3\delta_1, 3\delta_1, 3\delta_1] + \epsilon/3$, $[2\delta_1, 4\delta_1, 8\delta_1]$ and $[1.5\delta_1, 8\delta_1, 15\delta_1]$, respectively, and all satisfy Requirement 1. As characterized by Theorem 1, all lead to the full diversity order at high SNR, while with small offsets among them.

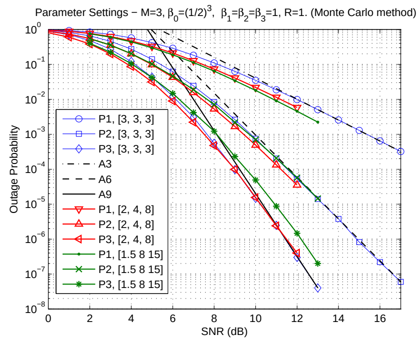

Fig. 5. Outage probabilities of ARQ-OSAF-B. The diversity contributed by $\Pr\{w < \delta_1\}$ is ignored here. Therefore, the full diversity becomes $(M \times i)$. Pi denotes the outage probability after i rounds of ARQs, and $[a, b, c]$ stands for the thresholds of $\delta_1 \times [a, b, c]$. Besides, A$j$ corresponds to the asymptotic line of diversity order j at high SNR.

V. Numerical Studies for AF relaying

We study herein the performance of the proposed OSAF schemes from the perspective of delay-limited (DL) throughput [14]. The DL throughput is defined as

$$\eta = R - \sum_{l=1}^{\mathcal{N}} \frac{R}{l \times (l+1)} P_{l-1} - \frac{R}{\mathcal{N}+1} P_{\mathcal{N}}. \tag{18}$$

According to this metric, we study the performance with the rate assignment obtained with

$$\max_{R \geq 0} \;\; \eta \quad \text{subject to } P_{\mathcal{N}} \leq P_e. \tag{19}$$

Two scenarios are considered in the study to characterize the effects of good and bad S-R channel qualities. The variances of the channel coefficients in Fig. 6 are assigned as $\beta_0 = (\frac{1}{2})^v$, $\beta_1 = 2^v$, and $\beta_2 = 1$, and the variances for Fig. 7 are $\beta_0 = (\frac{1}{2})^v$, $\beta_1 = (\frac{1}{2})^v$ and $\beta_2 = 1$. Besides, for opportunistic relayings, the variance β_3 for the channels between relays is set to 2^v. The path loss exponent v and the target outage probability P_e are set to 3 and 10^{-3}, respectively.

For comparisons, the results of DF relaying are also presented in the figures, which include those of ARQ-DF and ARQ-OSDF-B of the DF counterparts of ARQ-AF and ARQ-OSAF-B, respectively. It can be seen from Fig. 6 that the throughput of ARQ-OAF can approach that of the OSAF schemes since the S-R channel qualities are in

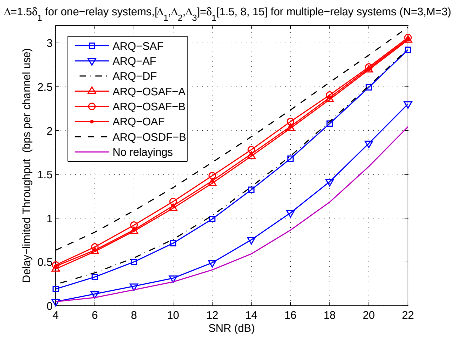

Fig. 6. The throughput of various ARQ schemes with $\beta_0 = (\frac{1}{2})^3$, $\beta_1 = 2^3$, and $\beta_2 = 1$ to simulate a good S-R channel condition.

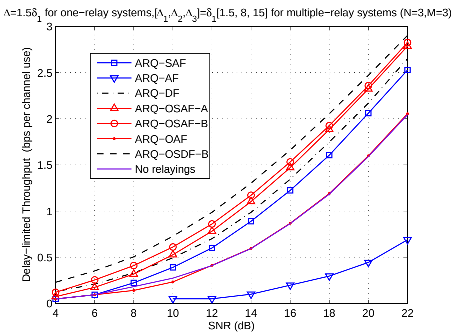

Fig. 7. The throughput of various ARQ schemes with $\beta_0 = (\frac{1}{2})^3$, $\beta_1 = (\frac{1}{2})^3$ and $\beta_2 = 1$ to simulate a poor S-R channel condition.

good condition. However, in poor S-R channel conditions as illustrated in Fig. 7, the performance of ARQ-OAF deteriorates significantly. Although the throughput of OSAF-A is slightly worse than that of OSAF-B, its performance is in fact pronounced considering its much simpler mechanism for relaying. In general, the ARQ schemes with OSAF relayings are more robust than the typical AF relaying, and their performance are very close to their DF counterparts.

VI. Cooperative ARQ with DF ODSTC

In this section, we consider a relay network with M relays to help re-transmit signals with DF ODSTC, and set β_0 as 1. If the signal is not successfully decoded at the destination, the relays that have decoded successfully will retransmit the data using DSTC, otherwise the source will rebroadcast the signal until either the destination or at least one relay is able to decode the signal. Throughout the paper, the set of relays that decode successfully is referred to as the decoding set and denoted by $\mathcal{DS}$. Again to focus on effective ARQ protocols for ODSTC, a perfect synchronization is assumed achieved among all relays. Under these assumptions, the channels between the transmitting relays and the destination can be viewed as a multiple-input single-output (MISO) channel, thus the corresponding mutual information follows [15]

$$I_d = \log\left(1 + \frac{P_{rd}}{N_0}\sum_{j\epsilon\mathcal{DS}} |h_{j,rd}|^2\right) \tag{20}$$

where P_{rd} is the received power at the destination for signals transmitted by relays in $\mathcal{DS}$, and $h_{j,rd}$ is the channel between the relay j and the destination and is $\sim \mathcal{CN}(0,1)$.

Similarly, for channels between the transmit and receive relays, the mutual information is given by

$$I_j = \log\left(1 + \frac{P_{rr}}{N_0}\sum_{i\epsilon\mathcal{DS}} |h_{i,j}|^2\right), j \notin \mathcal{DS}. \tag{21}$$

A. The Outage Probabilities for DF ODSTC

To proceed the analysis for ARQ protocols with ODSTC, we briefly review the ODSTC scheme below and give an exact expression for its outage probability.

Remind that $w \triangleq \rho|h_{sd}|^2 \sim$ Exp (λ), the outage probability for the direct source to destination channel link is given by

$$P_W(\delta_1) \triangleq P\{w < \delta_1\} = 1 - \exp\{-\lambda\delta_1\} \tag{22}$$

In cases of outage events, ODSTC opportunistically chooses at most i relays in $\mathcal{DS}$ to perform STC [9]. To distinguish from ordinary DSTC and to signify the use of i relays at most, we denote the protocol by ODSTCi. Define $X_j \triangleq \beta_2\rho|h_{j,rd}|^2 \sim \mathrm{Exp}(\lambda_2)$, $j \in \mathcal{DS}$. Let $\mathcal{X} \triangleq \{X_j | j \in \mathcal{DS}\}$. As ODSTCi chooses at most i elements of $\mathcal{X}$ that yield the highest capacity in (20), clearly $\min\{i, \mathcal{D}\}$, $\mathcal{D} \triangleq |\mathcal{DS}|$, of the largest elements in $\mathcal{X}$ will be chosen for STC. Therefore, sorting the elements of $\mathcal{X}$ in the ascending order into $\mathcal{X}' \triangleq \{X'_1, \ldots, X'_{\mathcal{D}}\}$ such that $X'_k \geq X'_j$ if $k > j$, the outage probability of ODSTCi conditioned on $\mathcal{D}$ is then given by

$$P_i(\delta|\mathcal{D}) \triangleq P\{\ \textstyle\sum_{j=\max\{1,d-i+1\}}^{d} X'_j < \delta \quad, \mathcal{D} \geq 1\ \} \tag{23}$$

where $\delta = 2^{\varepsilon R} - 1$ and εR is the code rate for DSTC. The outage probability (23) can be evaluated with a theorem quoted below from [16].

Theorem 2: [16] Let $\{X_1' < \cdots < X_Q'\}$ be the order statistics from Q *i.i.d.* exponential RVs with parameter ν. Define $Z_{Q,q} = \sum_{j=Q-q+1}^{Q} X_j', 1 \leq q \leq Q$. The complementary cumulative distributed function (CCDF) of $Z_{Q,q}$ is given by:

$$P\{Z_{Q,q} > z\} = \sum_{j=1}^{Q-q} a_j e^{\left(-\frac{Q-j+1}{q}\nu z\right)} \frac{1}{(q-1)!} \int_0^{z\nu} e^{(b_j y)} y^{(q-1)} dy + \sum_{k=0}^{q-1} e^{(-\nu z)} \frac{(\nu z)^k}{k!} \quad (24)$$

with $a_j \triangleq \frac{1}{Q-j+1} \frac{Q!}{q!} \frac{(-1)^{Q-q-j}}{(j-1)!(Q-q-j)!}$ and $b_j \triangleq \frac{Q-q-j+1}{q}$.

On the other hand, as $\beta_1 \rho |h_{j,sr}|^2 \sim \text{Exp}(\lambda_1)$, the probability mass function (PMF) of $\mathcal{D}$ is given by [2]

$$\mathcal{P}_{\mathcal{D}}(d) = C_d^M (e^{-\delta_1 \lambda_1})^d (1 - e^{-\delta_1 \lambda_1})^{M-d}. \quad (25)$$

Based on the above results, for transmission followed by an ARQ using ODSTCi, the outage probability follows

$$\mathbb{P}_i = P_W(\delta_1)^2 \mathcal{P}_{\mathcal{D}}(0) + P_W(\delta_1) \sum_{d=1}^{M} P_i(\delta|d) \mathcal{P}_{\mathcal{D}}(d). \quad (26)$$

We note that for ODSTC1, the outage probability degenerates to the case of opportunistic relaying (OR) in [7], while for ODSTCM, it is equal to DSTC in [2].

VII. The Coding Gain of DF ODSTC

In this section, we characterize the relative SNR advantage of ODSTCM against the ODSTCi schemes. To alleviate the complexity of analysis, we investigate this problem in the high SNR regime. Since the diversity gain is defined as

$$\xi \triangleq - \lim_{\rho \to \infty} \frac{\log \mathbb{P}_i}{\log \rho}. \quad (27)$$

Based on the fact that the diversity orders of the ODSTC1 and ODSTCM schemes are both $M + 1$ [2, 7], the diversity order of any ODSTCi scheme is also $M + 1$. Thus, the outage probability in the high SNR regime can be expressed as

$$\mathbb{P}_i \cong G(i) \cdot \rho^{-(M+1)} \quad (28)$$

where $G(i) \triangleq \lim_{\rho\to\infty} \mathbb{P}_i/\rho^{-(M+1)}$ and its properties are characterized in the following theorem.

Theorem 3: For DF-ODSTC$_i$ scheme, $i \in [1, M]$, operating at a rate R, we have

$$G(i) = \sum_{\mathcal{D}=1}^{M} \frac{C_{\mathcal{D}}^{M}}{\mathcal{D}!} \frac{\delta_1^{M-\mathcal{D}+1}\delta^{\mathcal{D}}}{\beta_2^{\mathcal{D}}\beta_1^{M-\mathcal{D}}} + \Delta(i) \tag{29}$$

where

$$\Delta(i) = \sum_{\mathcal{D}=i}^{M} \frac{\delta_1^{M-\mathcal{D}+1}\delta^{\mathcal{D}}C_{\mathcal{D}}^{M}}{\beta_2^{\mathcal{D}}\beta_1^{M-\mathcal{D}}} \left[\frac{i^{i-\mathcal{D}}}{i!} - \frac{1}{\mathcal{D}!}\right]. \tag{30}$$

Proof: The proof is omitted for space. ■

To characterize the SNR loss of the ODSTCi scheme against the SNR for the ODSTCM to achieve the same level of outage probability, $\mathbb{P}'$, at high SNR, we have $\mathbb{P}' = G(i)\rho_i^{-\xi} = G(M)\rho_M^{-\xi}$ and define the SNR loss of a ODSTCi scheme against the ODSTCM, $\forall i \in [1, M]$, as

$$\begin{aligned}
\mathcal{L}_i &\triangleq \log\{\rho_i\} - \log\{\rho_M\} = \frac{\log\{G(i)\} - \log\{G(M)\}}{M+1} \\
&= \frac{1}{M+1}\log\left\{1 + \frac{\Delta(i)}{G(M)}\right\}.
\end{aligned} \tag{31}$$

With some mathematical manipulations, we have two limiting values of $\mathcal{L}_i$ summarized in the following corollary.

Corollary 1: For $\forall i \in [1, M]$,

$$\mathcal{L}_i^{\beta_1\to\infty} = \frac{1}{M+1}\log\left\{\frac{M!}{i!i^{(M-i)}}\right\} \quad \text{as} \quad \beta_1 \to \infty. \tag{32}$$

On the other hand,

$$\mathcal{L}_i^{\beta_2\to\infty} = 0 \quad \text{as} \quad \beta_2 \to \infty. \tag{33}$$

Proof: The proof is omitted for space. ■

This shows that when β_1 is large, $\mathcal{L}_i$ becomes irrelevant of β_2 and δ and is only a function of i and M. While when β_2 becomes large ODSTCi severs as good as ODSTCM does.

Fig. 8 shows the outage probability for $i = 1, 2, 3$ and ODSTCM, which is denoted by the purple-star curve and always performs best among all the schemes. Nevertheless, in this example, the black-circle curve, which corresponds to the case of $i = 3$, is almost

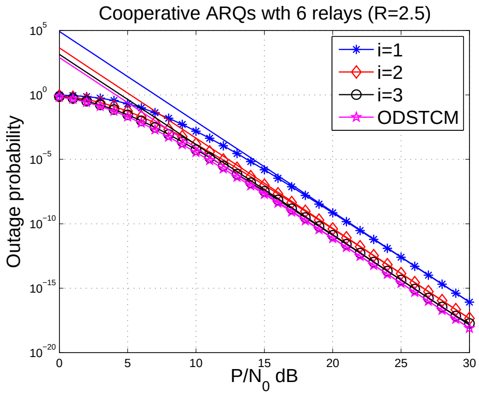

Fig. 8. The outage probabilities of the DF-ODSTCi protocols and their high SNR approximations, with M=6, R=2.5 and $\beta_1 = 10, \beta_2 = 1$.

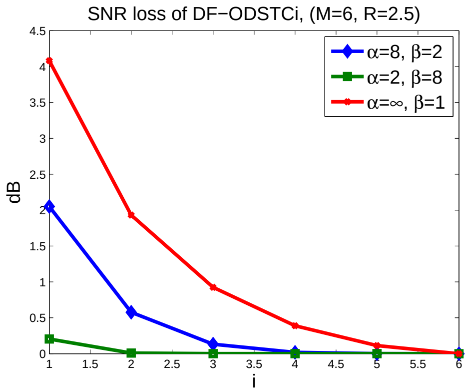

Fig. 9. The SNR losses of the ODSTCi at high SNR, with $i = 1, \cdots, M$, M=6, R=2.5.

undistinguishable from the purple one, ODSTCM scheme. It shows that the ODSTCi scheme performs closer to ODSTCM scheme with larger i. However, the SNR advantage for every scheme is also correlated with the links between the source, relays and destination. In Fig. 9, the red curve which corresponds to the case of $\beta_1 = \infty$, $\beta_2 = 1$ tells the fact that when the link quality between the source and relay is very good, using more relays is better. But to the blue one, $\beta_1 = 8$, $\beta_2 = 2$, using 4 relays is good enough in contrast to ODSTCM. Furthermore, for the case of $\beta_1 = 2$, $\beta_2 = 8$, the outage performance is limited to the case of $i = 2$. The reason is that the outage probability is limited by the case of $\mathcal{D} = 0$ or 1. The energy on the relays that fail to decode the signal are not able to be used to help enhance the performance, leaving the option of using more relays ineffective.

VIII. Cooperative ARQ Protocols using DF ODSTC

Based on ODSTCi presented in the above section, we study in this section the outage probabilities for three types of cooperative ARQ protocols. Each of them requires for different level of coordination between the source, relays and the destination.

A. Type-A Cooperative ARQ

As introduced earlier, whenever $\mathcal{DS} = \emptyset$, the destination will issue ARQs to the source. Once $\mathcal{DS} \neq \emptyset$, a straightforward method is to have the destination choose the best i relays for DSTC and then continues to use these relays in the subsequent ARQs if needed.

Therefore, Type-A ARQ essentially involves two kinds of STC schemes: the ODSTCi for ARQs until $\mathcal{D} \geq 1$ and the ordinary DSTC for the subsequent ARQs. For simplicity of presentation, we denote the n-th rounds of ARQs by ARQn and also refer to the initial direct transmission from the source to the destination as ARQ0. In addition, to facilitate the analysis, we define the probability for the following outage event involved in ARQs.

Definition 1: The outage probability of the DSTC conditioned on $\mathcal{D}$ is given by

$$P_{STCi}(\delta|\mathcal{D}) \triangleq P\left\{\sum_{\mu=1}^{i_{\mathcal{D}}} X_\mu < \delta,\ \mathcal{D} \geq 1\right\} = 1 - \sum_{y=1}^{i_{\mathcal{D}}-1} \frac{e^{-\delta\lambda_2}}{y!(\delta\lambda_2)^{-y}}$$

where $i_{\mathcal{D}} \triangleq \min\{i, \mathcal{D}\}$ and the subscript $STCi$ is used to signify the use of $i_{\mathcal{D}}$ relays for opportunistic relaying.

Following the above definitions of (23) and (25), respectively, it can be shown that the outage probability of the Type-A ARQ can be expressed in a closed form summarized in the following proposition.

Proposition 4: Given R, ε and M, the outage probability after n times Type-A ARQs is given by

$$\begin{aligned} &\mathbb{P}_{A,i}(n) = P_W(\delta_1)^{n+1}\mathcal{P}_{\mathcal{D}}^n(0) + P_W(\delta_1) \times \\ &\sum_{k=1}^{n}[P_W(\delta_1)\mathcal{P}_{\mathcal{D}}(0)]^{n-k}\sum_{d=1}^{M} P_i(\delta|d)\mathcal{P}_{\mathcal{D}}(d)P_{STCi}^{k-1}(\delta|d), \end{aligned} \tag{34}$$

$\forall i \in [1, M]$ with $\mathbb{P}_{A,i}(0) \triangleq P_W(\delta_1)$ in (22).

Proof: The proof is omitted for space. ■

B. Type-B Cooperative ARQ

A quick modification to improve the outage probability of the Type-A ARQ is to have the i active relays re-chosen from $\mathcal{DS}$ according to the channel strength in each phase of ARQ. Due to the re-selection mechanism, we know that $P_{STCi}(\delta|d)$ in (34) for Type-A ARQ should be replaced by $P_i(\delta|d)$ for all ARQn, $n \geq 1$. This gives the outage probability for the Type-B ARQ protocol, which is summarized in the following corollary.

Corollary 2: Given R, ε and M, the outage probability after n times Type-B ARQs is given by

$$\mathbb{P}_{B,i}(n) = P_W(\delta_1)^{n+1}\mathcal{P}_{\mathcal{D}}^n(0) + P_W(\delta_1) \sum_{k=1}^{n}[P_W(\delta_1)\mathcal{P}_{\mathcal{D}}(0)]^{n-k}\sum_{d=1}^{M} P_i^k(\delta|d)\mathcal{P}_{\mathcal{D}}(d), \tag{35}$$

$\forall i \in [1, M]$ with $\mathbb{P}_{B,i}(0) \triangleq P_W(\delta_1)$.

Comparing with Type-A ARQ, apparently, Type-B ARQ requires all relays in $\mathcal{DS}$ to keep the decoded data for retransmission before the end of ARQs. However, checking $P_i(\delta|d)$ in (35), one may soon find that the diversity order may often be dominated by the term $P_i^n(\delta|1)$, leaving the overall diversity order remaining to be $M + n$. This may cause the Type-B scheme rather ineffective, taking into account the extra efforts for the re-selection of relays in ARQs.

C. Type-C Cooperative ARQ

Checking (34) and (35), one may soon find that the diversity order for Type-A and B ARQ protocols is limited by the worst case of $\mathcal{D} = 1$. Thus, to resolve this diversity shortage problem, $\mathcal{DS}$ must be able to grow with ARQs. To this end, we have the relays not in $\mathcal{DS}$ continue to overhear the DSTC signals in ARQs and update their status to the destination to allow for being picked in the subsequent ARQs. As the cardinality of $\mathcal{DS}$ may increase now with ARQs, we define some parameters below.

Definition 2: Let $\mathcal{D}_0$ be the number of relays that are able to decode the signal send by the source.

The probability $\mathcal{P}_{\mathcal{D}_0}$ can be obtained by setting $\mathcal{D}_0 = \mathcal{D}$ in (25).

Definition 3: Let $\mathcal{D}_n$ be the number of increasing relays in the n-th subsequent ARQ after $\mathcal{D}_0 \geq 1$.

Define $\underline{\mathcal{D}}_n \triangleq \sum_{\ell=0}^{n} \mathcal{D}_\ell, \in [1, M]$ as the total number of relays in the $\mathcal{DS}$. The channels from the relays in $\mathcal{DS}$, which are particularly chosen to yield the highest mutual information at the destination, to a relay not in $\mathcal{DS}$ are still random. Define $V_{\mu,z} \triangleq \eta\rho|h_{\mu,z}|^2 \sim \text{Exp}(\lambda_3)$, for $\mu \in \mathcal{DS}$ and $z \notin \mathcal{DS}$. The outage probability for a relay z overhearing the ODSTCi signal send by relays in $\mathcal{DS}$ is given by

$$\begin{aligned} P_{OHi}(\delta|\underline{d}_n) &\triangleq P\left\{\sum_{\mu=1}^{i_{n+1}} V_{\mu,z} < \delta,\ \underline{d}_n \geq 1\right\} \\ &= 1 - \sum_{y=1}^{i_{n+1}-1} \frac{e^{-\delta\lambda_3}}{y!(\delta\lambda_3)^{-y}} \end{aligned} \tag{36}$$

where $i_{n+1} \triangleq \min\{i, \underline{d}_n\}$. Besides, as the source stops sending signal once $\mathcal{D}_0 \geq 1$. By (36), we have the outage probability of overhearing conditioned on $\underline{\mathcal{D}}_{n-1} = \underline{d}_{n-1}$ as

$$\begin{aligned} \mathcal{P}_{\mathcal{D}_n}(d_n|\underline{d}_{n-1}) = C_{d_n}^{M-\underline{d}_{n-1}}[1 - P_{OHi}(\delta|\underline{d}_{n-1})]^{d_n} \times \\ P_{OHi}(\delta|\underline{d}_{n-1})^{M-\underline{d}_{n-1}-d_n},\ n = 1, 2, \cdots. \end{aligned} \tag{37}$$

By induction, the outage probability for the Type-C ARQ protocol can be shown as follows.

Proposition 5: Given R, ε and M, the outage probability after n times Type-C ARQs for ODSTCi is given by

$$\begin{aligned} \mathbb{P}_{C,i}(n) = P_W(\delta_1)^{n+1}\mathcal{P}_{\mathcal{D}_0}^n(0) + \\ P_W(\delta_1)\sum_{k=1}^{n}[P_W(\delta_1)\mathcal{P}_{\mathcal{D}_0}(0)]^{n-k}\sum_{d_0=1}^{M}\sum_{d_1=0}^{M-d_0}\cdots\sum_{d_{k-1}=0}^{M-\underline{d}_{k-2}} \\ P_i(\delta|d_0)\mathcal{P}_{\mathcal{D}_0}(d_0)\prod_{\ell=1}^{k-1}P_i(\delta|\underline{d}_\ell)\mathcal{P}_{\mathcal{D}_\ell}(d_\ell|\underline{d}_{\ell-1}) \end{aligned} \tag{38}$$

with $\underline{d}_k \triangleq \sum_{q=0}^{k} d_q$ and $\mathbb{P}_{C,i}(0) \triangleq P_W(\delta_1)$.

As we can see from (23) that the diversity order of $P_i(\delta|\underline{d}_\ell)$ is $\underline{d}_\ell$, and from (37) that the diversity order of $\mathcal{P}_{\mathcal{D}_\ell}(d_\ell|\underline{d}_{\ell-1})$ is $(M - \underline{d}_\ell) \times \min\{i, \underline{d}_{\ell-1}\}, \ell \geq 1$. Considering the dominant term only, which has minimum diversity order, we may find that (38) is dominated by the second term when $k = n$, $d_0 = 1$ and $d_1 = \cdots = d_{n-1} = 0$, leading to a diversity order of $nM + 1$. This shows that the diversity can increase by M with each extra ARQ due to the aid of overhearing. Nevertheless, the complexity of this protocol is much higher too as all relays need to serve a user until the end of ARQs. On the other hand, for the Type-A protocol, even if the diversity order is inferior, the active relays are fixed in all subsequent ARQs, thus introducing less control overhead to the the system. It's a tradeoff between the theoretical performance and practical considerations. Therefore, an investigation on the expected throughput of each protocol will be done in the next section to examine the efficiency of each protocol in different channel conditions.

IX. Throughput analysis for DF ODSTC

To explore the efficiency of the proposed ARQ protocols, we characterize the delay-limited throughput of each protocol based on the outage formulas provided in Section VIII. In this paper, the throughput is denoted by $\eta_{\mathcal{T},i}(n)$, where the subscript $\mathcal{T}$ is used to distinguish from the above ARQ protocols. For example, $\eta_{A,i}(n)$ stands for the expected throughput after n times Type-A ARQs with ODSTCi.

As for ARQ0, it is straightforward to give the expected throughput as $R[1 - P_W(\delta_1)]$. With 1 round of ARQ, the throughput is given by

$$\begin{aligned}\eta_{\mathcal{T},i}(1) &= R[1 - P_W(\delta_1)] + \frac{R}{2} P_W(\delta_1)\mathcal{P}_{\mathcal{D}}(0)[1 - P_W(\delta_1)] \\ &\quad + \frac{\varepsilon R}{1+\varepsilon} \left\{ P_W(\delta_1) \sum_{d=1}^{M} \mathcal{P}_{\mathcal{D}}(d)[1 - P_i(\delta|d)] \right\}. \qquad (39)\end{aligned}$$

The second term in (39) denotes the expected throughput for the event that the source broadcasts again since neither the destination nor the relays are able to decode the signal in the first transmission, and the third term in (39) stands for the case that at least one relay is able to decode and forward the signal to the destination with a rate εR. Following the similar analysis, the delay-limited throughput for each type of ARQ protocol can be summarized in the theorem below.

Theorem 4: Given R, ε and M, after n times of ARQs, the expected throughput is given by

$$\eta_{\mathcal{T},i}(n) \triangleq \sum_{p=0}^{n} \sum_{q=1}^{n+1-p} \frac{\varepsilon R}{p + q\varepsilon} \mathbf{P}_{\mathcal{T}}(p, q) \qquad (40)$$

where $\mathbf{P}_{\mathcal{T}}(p,q)$ denotes the probability of the event corresponding to the effective rate $\frac{\varepsilon R}{p+q\varepsilon}$ and it is defined as

$$\mathbf{P}_{\mathcal{T}}(p,q) \triangleq [P_W(\delta_1)\mathcal{P}_{\mathcal{D}}(0)]^{q-1}\mathbf{P}_{\mathcal{T}}(p,1). \tag{41}$$

For each type of ARQ protocol, $\mathbf{P}_{\mathcal{T}}(p,1)$ are listed below

$$\begin{aligned}
\mathbf{P}_A(p,1) &\triangleq P_W(\delta_1)\sum_{d=1}^{M}\mathcal{P}_{\mathcal{D}}(d)P_i(\delta|d)[P_{STCi}(\delta|d)]^{p-2}\times \\
&\qquad\qquad\qquad [1-P_{STCi}(\delta|d)], && (42)\\
\mathbf{P}_B(p,1) &\triangleq P_W(\delta_1)\sum_{d=1}^{M}\mathcal{P}_{\mathcal{D}}(d)P_i(\delta|d)[P_i(\delta|d)]^{p-1}\times \\
&\qquad\qquad\qquad [1-P_i(\delta|d)], && (43)\\
\mathbf{P}_C(p,1) &\triangleq P_W(\delta_1)\sum_{d_0=1}^{M}\sum_{d_1=0}^{M-\underline{d}_0}\cdots\sum_{d_{(p-1)}=0}^{M-\underline{d}_{(p-2)}}\times \\
&\quad \mathcal{P}_{\mathcal{D}_0}(d_0)P_i(\delta|\underline{d}_0)\left\{\prod_{\ell=1}^{p-2}P_i(\delta|\underline{d}_\ell)\mathcal{P}_{\mathcal{D}_\ell}(d_\ell|\underline{d}_{\ell-1})\right\}\times \\
&\qquad \mathcal{P}_{\mathcal{D}_{(p-1)}}(d_{(p-1)}|\underline{d}_{(p-2)})[1-P_i(\delta|\underline{d}_{(p-1)})] && (44)
\end{aligned}$$

with $\mathbf{P}_A(1,1) \triangleq P_W(\delta_1)\sum_{d=1}^{M}\mathcal{P}_{\mathcal{D}}(d)[1-P_i(\delta|d)]$ and $\mathbf{P}_{\mathcal{T}}(0,1) \triangleq [1-P_W(\delta_1)]$.

Proof: The proof is omitted for space. ■

To examine the delay-limited throughput for different types of ARQ protocol, we adjust the rate according to SNR to achieve the best throughput under an outage constraint P_e, *i.e.*

$$\max_{\varepsilon,R}\eta_{\mathcal{T},i}(n)\ \ s.t.\ \mathbb{P}_{\mathcal{T},i}(n) \le P_e. \tag{45}$$

The optimal rate adaptation strategy is found by the following algorithm. Assumed that the SNR for all the relay-destination and source-destination channels can be estimated by the destination without any deviation, and remain unchanged during a block transmission time. Then the transmit nodes adjust the rate according to the feedback SNR. Therefore, we define $R \triangleq \gamma\log(1+\sigma\rho)$ and $\varepsilon R \triangleq \gamma\log(1+\sigma\beta_2\rho)$, where γ denotes the multiplexing gain, and σ stands for the SNR enhancement. As a result, the cost function in (45) turns

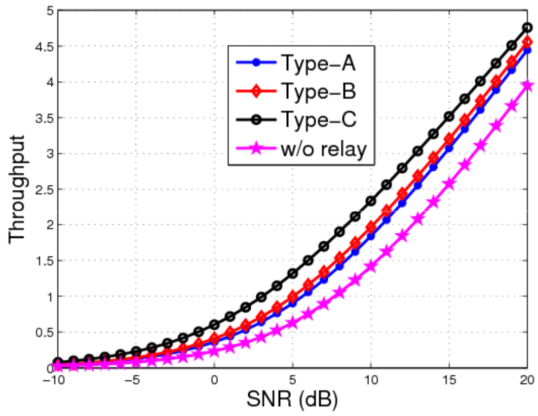

Fig. 10. The throughput for each type of protocol by ODSCT1 with the constraint $P_e = 0.001$ when $M = 3$, $\beta_1 = 2$, $\beta_2 = 8$ and $\beta_3 = 64$.

into

$$\max_{\gamma,\sigma} \eta_{\mathcal{T},i}(n) \;\; s.t. \;\; \mathbb{P}_{\mathcal{T},i}(n) \leq P_e. \tag{46}$$

In the beginning, we set $\gamma = 1$ and find the maximum σ to fit the outage constraint. However, the largest rate does not always lead to the maximum throughput. Therefore, given the σ obtained above, we exhaustively search the optimal γ to approach the maximum throughput and the results are shown in the following section.

X. Numerical Simulations for DF ODSTC

In this section, we set the channel condition as $\beta_1 = 2$ and $\beta_2 = 8$. This case is meaningful, especially when the direct link between the source and the destination has a poor SNR, *e,g,* $0 \sim 10$dB. $\beta_1 = 2$ stands for the case that the SNR for the link between the source and relays has a 3dB-gain in average to the direct link, and $\beta_2 = 8$ corresponds to an even better channel quality. In other words, when the source is hard to communicate with the destination directly, it needs some help from relays more eagerly.

Conditioned on the delay constraint, $n = 3$, and the outage constraint $P_e = 0.001$, Fig. 10 presents the maximum throughput for each type of ARQ protocol with ODSTC1 when $M = 3$, $\beta_1 = 2$, $\beta_2 = 8$ and $\beta_3 = 64$. The purple curve denotes the simple ARQs without relaying. In Fig. 10, the cooperative ARQ protocols provide significant throughput improvement not only when the link quality between the source and destination has good

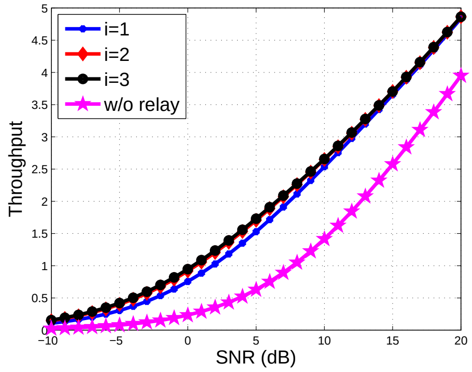

Fig. 11. The throughput of the Type-C protocol with the constraint $\mathbb{P}_{C,i}(3) \leq 10^{-3}$ when $M = 5$, $\beta_1 = 2$, $\beta_2 = 8$ and $\beta_3 = 27$.

SNR, but also when the quality is poor, *e.g.* SNR$=0 \sim 10$dB. Especially for Type-C ARQ, it performs the best because of the relay re-selection and overhearing.

However, in the extremely low or extremely high SNR regime, Fig. 10 also shows that the difference between each type of cooperative protocol is getting smaller. The reasons is that all the relays and the destination fail or succeed in decoding in probability. Thus, there is no need to always use the most complicate scheme, although it has superior diversity in outage analysis. Type-A ARQ, the simplest protocol, is also able to serve as good as Type-C ARQ does when the link quality between the source and destination is extremely poor or extremely good.

The effects of i are demonstrated in Fig. 11. As expected from Fig. 8 and Fig. 9, it is not always necessary to use as many relays as possible. In Fig. 11, for Type-C ARQ when $M = 5$, the black and red curves, which individually correspond to the case of $i = 3$ and $i = 2$, are almost undistinguishable. In other words, ODSTC2 is the relatively effective scheme under such channel condition.

Fig. 12 shows the effect of M on the throughput of different ARQ protocols by ODSTC1 at SNR$=5$dB. In contrast to Type-A ARQ, the advantage of Type-B ARQ increases with M. This is due to the fact that Type-B ARQ has better coding gain from the re-chosen mechanism, although they have the same diversity order. Besides, the performance of Type-C ARQ will saturate with M since ultra high diversity order does not give significant improvement in throughput anymore.

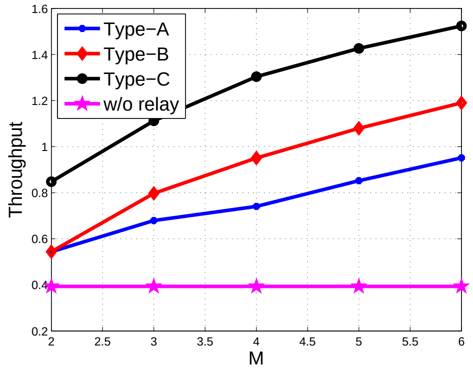

Fig. 12. The throughput for each type of protocol by ODSCT1 for different M when SNR= 5dB, $\beta_1 = 2$, $\beta_2 = 8$, $\beta_3 = 64$ and $P_e = 0.0001$.

In addition, compared with Fig. 10 when $M = 3$, the throughput enhancement against the direct transmission without cooperative relaying is more obvious when $P_e = 0.0001$. This also tells that the importance of the cooperative ARQ protocol is more critical if the outage constraint becomes stricter.

XI. Conclusion

A. *For AF relaying*

In this work, we proposed two types of opportunistic-selection AF relaying protocols to exploit the spatial and temporal diversity. And the numerical results showed that noth protocols can offer much higher diversities and more throughput advantage than ARQ schemes with the typical ARQ relaying method.

B. *For DF ODSTC*

The numerical results showed that the cooperative ARQ protocols provide significant throughput enhancement in contrast to the direct transmission without relaying. Besides, effective schemes can be obtained since it is not always necessary to use the most complicated protocol or as many relays as possible to achieve the best performance.

XII. Self Evaluation

The cooperative ARQ protocols developed throughout this project are quite practical yet effective and can be readily applied to the ARQ protocols for relay-assisted cellular networks like WiMAX or LTE. We are currently wrapping up the results and preparing two journal papers based on the SAF and ODSTC relaying methods developed in this research.

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行政院國家科學委員會補助國內專家學者出席國際學術會議報告

2009　年　　月　　日

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會議名稱	（中文）IEEE 個人、室內以及行動無線通訊會議 2009 （英文）IEEE Personal, Indoor and Mobile Radio Communications 2009		
發表論文題目	（中文）利用放大傳遞中繼方式之簡單合作式自動重傳請求協定 （英文）Simple Cooperative ARQ Protocols with Selective Amplify-and-Forward Relaying		

報告內容應包括下列各項：

一、參加會議經過

此次IEEE PIMRC於東京的The Westin Tokyo hotel招開，會議時間為9 月13 至16 日，會議第一天為workshop，第二到四天為technical programs。此次會議將報告場次分為口頭報告(oral section)以及海報報告(poster section)，我們於第二天的海報會場發表我們的論文，主題是「Simple Cooperative ARQ Protocols with Selective Amplify-and-Forward Relaying」，其主要議題為探討在AF中繼技術下如何有效率的協助系統進行重傳機制，我們提出三種不同的合作式協定，分別研究其特性以及效能，最後，我們以模擬系統的吞吐率(throughput)之結果來證明所提之協定均能提系統供相當的改善。

二、與會心得

綜觀此次會議內容，未來通訊學術研究將著重於以下主題

1. Cooperative network
2. 60GHz communications
3. Network MIMO
4. Cognitive wireless network

三、考察參觀活動(無是項活動者省略)

四、建議

五、攜回資料名稱及內容

PIMRC 2009 會議論文集電子檔案乙份。

六、其他