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Iterative Relay Scheduling with Hybrid ARQ under Multiple User Equipment (Type II) Relay Environments

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***Abstract*— In this work, we propose an iterative relay scheduling with hybrid ARQ (IRS-HARQ) scheme which realizes fast jump-in/successive relaying and subframe-based decoding under the multiple user equipment (UE) relay environments applicable to the next-generation cellular systems (e.g., LTE-Advanced and beyond). The proposed IRS-HARQ aims to increase the achievable data rate by iteratively scheduling a relatively better UE relay closer to the end user in a probabilistic sense, provided that the relay-to-end user link should be operated in an open-loop and transparent mode. The latter is due to the fact that not only there are no dedicated control channels between the UE relay and the end user but also a new cell is not created. Under this open-loop and transparent mode, our proposed protocol is implemented by partially exploiting the channel state information based on the overhearing mechanism of ACK/NACK for HARQ. Further, the iterative scheduling enables UE-to-UE direct communication with proximity that offers spatial frequency reuse and energy saving.**

***Index Terms*— UE relays, open-loop access link, dynamic decode-and-forward (DDF), iterative scheduling, hybrid ARQ, rateless codes, subframe decoding.**

I. Introduction

Next generation cellular standards (e.g., LTE-Advanced and beyond) [1] are defining two types of relaying strategies to increase the cell coverage (type I or infrastructure relay) [2]–[5] and data rate (type II or user equipment (UE) relay) [5]–[10] without creating undue inter-cell interference which is a prerequisite for implementing UE relays. In this work, under multiple type II relay environments, we will consider increasing the data rate of the end user near cell boundary or in indoor wireless environment especially with weaker signal quality from the serving base station (i.e., eNodeB). Note that, in the type II relay, the relay-to-destination ($\mathcal{R}-\mathcal{D}$) link must be operated in an open-loop and transparent mode because of the absence of the dedicated control channel [1]–[3]. However, $\mathcal{R}$ is required to notify some information (e.g., a short flag packet to indicate its presence to avoid any possible co-channel interference among relays, forwarding time and information that has been used for encoding, and so on) to $\mathcal{D}$ and other $\mathcal{R}$s since such information is a priori unknown at $\mathcal{R}$ due to the random nature of the source-to-relay ($\mathcal{S}-\mathcal{R}$) link gain caused by fading [3]–[5]. Consequently, $\mathcal{D}$ will not be able to distinguish between the two transmitted signals from $\mathcal{S}$ and $\mathcal{R}$ via conventional relaying protocols such as an opportunistic relaying [11], [12].

Recently, the dynamic decode-and-forward (DDF) protocol was proposed to overcome the main drawbacks of two distinguished conventional relaying protocols such as an amplify-and-forward (AF) and a decode-and-forward (DF) [6]. One of the main advantages of the DDF protocol is that fast jump-in relaying and decoding are possible at $\mathcal{R}$ and $\mathcal{D}$, respectively. However, the relaying with the conventional DDF protocol may not be directly applied to the type II relay because of the following main issues for the practical implementation. First, the term "user equipment" is referred as a mobile functioning (not fixed one) which causes variations in both large-scale and small-scale channel conditions. Second, the type II relay is battery powered so that UE-to-UE transmissions such as $\mathcal{R}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$ are typically in low power and short range. Third, the $\mathcal{R}-\mathcal{D}$ link is operated in an open-loop mode where each $\mathcal{R}$ link appears transparent to $\mathcal{D}$. Moreover, the $\mathcal{R}-\mathcal{D}$ link channel state information (CSI) is not fully, at most partially, available at $\mathcal{R}$. To overcome the above limitations in applying the DDF protocol to the type II relay, in [5] the modified dynamic decode-and-forward (MoDDF) protocol with two main subchannel/code selection methods such as in-phase and fixed random selections has been proposed. In this paper, we extend [5], especially focusing on the in-phase selection strategy in [5], to the multi-hop relaying scheme by proposing an iterative relay scheduling with hybrid automatic repeat request (IRS-HARQ) scheme under the multiple UE relay environments. As an additional benefit, the achievable data rate can be increased via UE-to-UE direct communication with proximity and this eventually offers spatial frequency reuse and energy saving.

A. Main Contributions

- In the type II relay, the channel gains over the backhaul and access ($\mathcal{S}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$) links are not available because the location of $\mathcal{R}$ is not fixed and there is no explicit control channel established over the access ($\mathcal{R}-\mathcal{D}$) link. For this reason, we consider the rateless code-based DDF protocol. The application of rateless codes has been advocated to accomplish DDF with flexible duration during the listening phase [13], [14]. Rateless

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code property of reconstructing the source data from any subset of encoded packets is particularly attractive for $\mathcal{R}$s overhearing the packets in between $\mathcal{S}$ and $\mathcal{D}$, given that the channel gains over the backhaul and access ($\mathcal{S}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$) links are not available. However, the successful decoding time at $\mathcal{R}$ and the forwarding time of its re-encoded message are unknown or continuously random over the continuous time. To avoid this timing uncertainty, a whole frame is segmented into a number of concatenated subframes and $\mathcal{R}$ attempts to decode the overheard message right after receiving each subframe [3]–[5], [15]. By adopting subframe-by-subframe decoding, the system can synchronize individual decoding and forwarding time on a subframe basis.

- If we consider the limited power and range of $\mathcal{R}$ as well as the limited CSI, it is desirable to select a route comprising a sequence of the candidate $\mathcal{R}$s in a probabilistic sense, such that the reliability over an open-loop access ($\mathcal{R}-\mathcal{D}$) link can be increased for successful retransmission. In general fading conditions, $\mathcal{R}$ closer to $\mathcal{S}$ is more likely to succeed in decoding earlier while $\mathcal{R}$ closer to $\mathcal{D}$ likely succeeds in decoding later. Meanwhile, $\mathcal{R}$ decoding later will likely yield a better $\mathcal{R}-\mathcal{D}$ link gain than that earlier. Based on these observations, we propose "iterative scheduling" of the candidate $\mathcal{R}$s closer to $\mathcal{D}$ in a probabilistic sense, one in each subframe. As such, $\mathcal{D}$ will probably see a better $\mathcal{R}-\mathcal{D}$ link gain in each subframe that will enable successful decoding earlier with increased data rate, especially for $\mathcal{R}$s operating in an open-loop mode over multiple $\mathcal{R}-\mathcal{D}$ uncertain links.
- To enable transparent and successive decoding at $\mathcal{D}$, the in-phase random code mapping (i.e., in-phase selection strategy proposed in [4], [5]) is employed on a single subchannel, which facilitates the iterative scheduling of the candidate $\mathcal{R}$s on a subframe basis.[1]

The rest of this paper is organized as follows. Section II presents the system and channel models including the overhearing mechanism and the relay scheduling scheme. We analyze the performance of the proposed scheme in terms of the achievable data rate in Section III and these results are illustrated and discussed in Section IV via some selected numerical examples.

II. System and Channel Models

A message comprises information bits including cyclic redundancy check (CRC) bits to allow $\mathcal{D}$ to check the correctness of the decoded message. Specifically, the information bits are assumed to be encoded by a rateless code, and to follow the in-phase selection strategy proposed in [5] as a subchannel/code selection scheme at $\mathcal{S}$ to form a frame [3]. The frame is then segmented into N concatenated subframes of same length as shown in [5, Fig 2] and transmitted sequentially. Subframe-based decoding is attempted at $\mathcal{R}$s and $\mathcal{D}$. Note that because the $\mathcal{S}-\mathcal{R}$ links are statistically independent, correct decoding of the received message at $\mathcal{R}$s can occur randomly at an arbitrary subframe index. As a result, the random decoding and forwarding time at $\mathcal{R}$s can be controlled on a subframe basis.

Further, we assume that all nodes ($\mathcal{S}$, $\mathcal{D}$, and $\mathcal{R}$s) employ a single antenna and all $\mathcal{R}$s operate in a half-duplex mode where the transmission occurs in two phases. In the first phase (i.e., listening phase), $\mathcal{S}$ broadcasts its message, and $\mathcal{D}$ and $\mathcal{R}$s receive it. If at least one relay successfully decodes before $\mathcal{D}$, the second phase (i.e., collaboration phase) starts. Before the listening phase ends, $\mathcal{S}$ schedules a $\mathcal{R}$ for retransmission according to the proposed relay scheduling scheme among candidate $\mathcal{R}$s ($\mathcal{R}_{\text{CAND}}$) which are the set of $\mathcal{R}$s that have correctly decoded a message. During the second phase, $\mathcal{S}$ becomes inactive and the scheduled $\mathcal{R}$ ($\mathcal{R}_{\text{SCH}}$) starts retransmitting the re-encoded message to both $\mathcal{D}$ and inactive $\mathcal{R}$s ($\mathcal{R}_{\text{INACT}}$) which do not succeed in decoding yet.

Iteratively, $\mathcal{S}$ schedules the next $\mathcal{R}$ on a subframe basis while each $\mathcal{R}_{\text{SCH}}$ forwards the overheard message successively in each subframe. Note that $\mathcal{R}_{\text{SCH}}$ forwards the re-encoded message on the same subchannel used by $\mathcal{S}$ using the same generating vectors as illustrated in [5], starting from the next subframe immediately after decoding correctly. When $\mathcal{D}$ succeeds in decoding, $\mathcal{D}$ informs it to $\mathcal{S}$ ($\mathcal{R}$s can overhear it), and then $\mathcal{S}$ or $\mathcal{R}_{\text{SCH}}$ terminates transmission or retransmission, respectively.

$\mathcal{R}_{\text{INACT}}$ keep gaining information for successfully decoding, upon which they compete for iterative scheduling on a subframe basis. Here, $\mathcal{R}_{\text{SCH}}$ employs a pre-determined sequence of subchannels (e.g., spreading codes/sequences for CDMA) and codes (i.e., generating vectors for the rateless code) [5]. Here, synchronized decoding at $\mathcal{R}$s and $\mathcal{D}$ can be realized via in-phase subchannel and code selection strategy in [5]. We assume that $\mathcal{S}$ priori shares these subchannel and code sequences information with $\mathcal{R}$s and $\mathcal{D}$. Then, $\mathcal{R}$, upon successful decoding, retransmits data to $\mathcal{D}$.

As a result, $\mathcal{D}$ and $\mathcal{R}$s can blindly search for the forwarded message based on the pre-determined subchannel sequence after receiving each subframe from $\mathcal{S}$ or $\mathcal{R}_{\text{SCH}}$. Note that at $\mathcal{D}$, information combining (IC) [5] is performed across subframes. Also note that we have considered HARQ type-II (or incremental redundancy HARQ). Thus, every retransmission contains different information from the previous one and then the information combining at $\mathcal{D}$ is performed.

Fig 1 illustrates an example of the mode of operation described above and how to accumulate information at $\mathcal{D}$.

For the analytical tractability, both the $\mathcal{S}-\mathcal{D}$ and $\mathcal{S}-\mathcal{R}-\mathcal{D}$ channels are assumed to be quasi-static independent and identically distributed (i.i.d.) Rayleigh fading channels, i.e., the fading coefficients remain constant over a frame and are independent from one frame to another. The length of subframes is assumed not to change for all subframes.

A. Overhearing Mechanism of ACK/NACK for HARQ

For a practical implementation, an overhearing mechanism based on the acknowledge/negative acknowledge

[1]With in-phase strategy in [5], $\mathcal{R}$, upon successful decoding the $(j-1)$-th subframe, starts retransmitting the first subframe on the same subchannel used by $\mathcal{S}$ using the same generating vectors as illustrated in [5, Fig 3].

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(ACK/NACK) messages is employed to partially estimate the $\mathcal{R}-\mathcal{D}$ link status at each candidate $\mathcal{R}$.

$\mathcal{R}$s periodically overhear the reference signals including ACK/NACK from $\mathcal{D}$ to $\mathcal{S}$ and exploit them to estimate the $\mathcal{R}-\mathcal{D}$ link quality. In time-division duplexing (TDD) mode, the channel reciprocity can be applied for acquiring CSI at the transmitter. The relative strength of the reference signal can be measured and quantized at $\mathcal{R}$s to check if their $\mathcal{R}-\mathcal{D}$ link quality is reliable (e.g., 1-bit limited or partial CSI feedback). This facilitates the iterative scheduling of $\mathcal{R}$s on a subframe basis to enhance the reliability of a route, namely a sequence of open-loop $\mathcal{R}-\mathcal{D}$ links. These $\mathcal{R}-\mathcal{D}$ link quality informations are transmitted to $\mathcal{S}$ over the control channel and then $\mathcal{S}$ will schedule $\mathcal{R}$ with an iterative relay scheduling scheme.

B. Iterative Relay Scheduling Scheme

In the proposed IRS-HARQ scheme, the system iteratively schedules a $\mathcal{R}$ as a serving node with relatively better $\mathcal{R}-\mathcal{D}$ link gain in each subframe based on partial CSIs from $\mathcal{R}_{\text{CAND}}$. Note that the iterative scheduling enables UE-to-UE direct communication based on proximity and this can result in energy saving.

In practice, the system may schedule a serving node by comparing partial CSIs of both newly nominated $\mathcal{R}_{\text{CAND}}$ and the current serving node ($\mathcal{S}$ or $\mathcal{R}_{\text{SCH}}$). Note that active but non-scheduled candidate $\mathcal{R}$s ($\mathcal{R}_{\text{NONSCH}}$) have no longer gain information from the serving node until the end of frame and, for energy efficiency, $\mathcal{R}_{\text{NONSCH}}$ clear their buffers by switching off until receiving the next frame from $\mathcal{S}$. Fig 2 illustrates the mode of operation of the considered scheduling strategies which are summarized as follows:

- Strategy I : If there is any new active $\mathcal{R}$s in any subframe, the best one among these newly nominated $\mathcal{R}_{\text{CAND}}$ is scheduled for retransmission and the current serving node stops retransmission regardless of the link gain of this node. In time-division duplexing (TDD) mode, the channel reciprocity can be applied for acquiring the (partial) CSI at the transmitter.
- Strategy II : The current serving node continues to keep retransmission mode unless there is a newly nominated $\mathcal{R}_{\text{CAND}}$ with better link gain compared to the link gain of the current serving node. If any new active $\mathcal{R}$ has better link gain than the current serving node, this relay is scheduled for retransmission and the current serving node stops retransmission.

The above iterative relay scheduling procedure is repeated until $\mathcal{D}$ sends ACK on a successful decoding to $\mathcal{S}$. While we manly propose the scheduling strategy II in this paper, the scheduling strategy I can be viewed as its suboptimal version. Given that $\mathcal{R}$s are for personal use, it may not be easy to use them as $\mathcal{R}$s to help other users for a long time period because it consumes considerable energy. Therefore, although the scheduling strategy II can provide the better performance, the scheduling strategy I can be made more feasible than scheduling strategy II especially when the UEs are utilized as mobile $\mathcal{R}$s.

III. Analysis of Achievable Rate

In this section, we analyze the achievable rate. For the analytical tractability, we evaluate the conditional average achievable rate of two proposed relay scheduling strategies as a function of the number of new $\mathcal{R}_{\text{CAND}}$ being active in each subframe.

Let R_k, $k=1,2,\cdots,N$, be the number of new $\mathcal{R}_{\text{CAND}}$ in the kth subframe, then for a given R_k, the conditional average achievable rate over a frame can be evaluated as

$$\overline{AR}_{Frame}=\sum_{k=1}^{N}\int_{0}^{\infty}\log\left(1+\gamma_k\right)f_{\gamma_k}\left(\gamma_k\right)d\gamma_k \tag{1}$$

where γ_k is an instantaneous SNR of a scheduled $\mathcal{R}$ in the kth subframe and $f_{\gamma_k}(\gamma_k)$ is the respective probability density function (PDF).

For the proposed IRS-HARQ scheme, the $\mathcal{R}-\mathcal{D}$ link of a scheduled $\mathcal{R}$ in each subframe has order statistics. Let γ_i, $i=1,2,\cdots,R_k$, denote R_k i.i.d. nonnegative random variables (RVs) of $\mathcal{R}-\mathcal{D}$ link gains. For the scheduling strategy I, the system sorts these RVs in descending order, then $\mathcal{R}$ with the largest one is scheduled for retransmission. For the scheduling strategy II, the system sorts the RVs of $\mathcal{R}_{\text{CAND}}$ in both current and previous subframes plus $\mathcal{S}$ in descending order, then $\mathcal{R}$ with the largest one is scheduled for retransmission. Therefore, for the scheduling strategy I, γ_k has the 1st ordered statistic among R_k while for the scheduling strategy II , γ_k has the 1st ordered statistic among R_{k_total} $(=R_1+\cdots+R_k+1)$.

For Rayleigh fading, we can write the PDF and the cumulative distribution function (CDF) of γ_i as

$$p_{\gamma_i}\left(x\right)=\frac{1}{\overline{\gamma}_i}\exp\left(-\frac{x}{\overline{\gamma}_i}\right) \tag{2}$$

and

$$P_{\gamma_i}\left(x\right)=1-\exp\left(-\frac{x}{\overline{\gamma}_i}\right), \tag{3}$$

respectively, where $\overline{\gamma}_i$ is the average SNR and the identical assumption gives $\gamma_i=\gamma$ and $\overline{\gamma}_i=\overline{\gamma}$.

In this section, we only consider the effect of multipath fading. However, subject to the path loss, the received power decays exponentially with the propagation distance, r, between the transmitter and the receiver. With the simplified path-loss model, the received signal power can be given as [16] as

$$P_{\text{Rx}}=\frac{P_{\text{Tx}}}{PL(r)} \tag{4}$$

where $PL(r)$ is the path loss and can be modeled as $PL(r)=Cr^a$ where C is a constant parameter and a is the path loss exponential, ranging from 2 to 6. By considering the effect of path loss, we can write the PDF of the received signal power at distance r over Rayleigh fading channel as

$$p_{P_i}\left(p|r\right)=\frac{1}{\overline{p}_i(r_i)}\exp\left(-\frac{p}{\overline{p}_i(r_i)}\right) \tag{5}$$

where $\overline{p}_i(r_i)$ is the average received signal power at distance r_i decided by path loss. Here, the average received signal power at distance r_i, $\overline{p}_i(r_i)$, has the role such as the different value of the average SNR. We will briefly consider this issue in the result section.

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In what follows, we derive closed-form expressions for both scheduling strategies I and II assuming Rayleigh fading.

A. Relay Scheduling Scheme : Strategy I

In this case, the system sorts the SNRs in descending order, then the relay with the largest one is scheduled for retransmission. As a result, the SNR of a scheduled $\mathcal{R}$ in the kth subframe, γ_k, has the 1st order statistic of a statistical sample. Therefore, with the help of [17], [18], especially by letting $L = R_k$ and $l = 1$ in [18, Eq. (3.1)], the PDF of γ_k can be written as

$$f_{\gamma_k}(\gamma) = R_k \left[1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right)\right]^{R_k - 1} \frac{1}{\overline{\gamma}} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right). \quad (6)$$

For a mathematical tractability, we need to consider two cases, 1) $k = 1$ and 2) $k \geq 2$ and for the latter, two subcases, i) $R_k \neq 0$ and ii) $R_k = 0$, separately. Then, (1) can be rewritten as

$$\overline{AR}_{Frame} = \sum_{k=1}^{N} \overline{AR}(k, \overline{\gamma}) \quad (7)$$

where $\overline{AR}(k, \overline{\gamma})$ is the conditional average achievable rate in the kth subframe.

1) For $k = 1$: In this case, the conditional average achievable rate can be written as

$$\overline{AR}(k, \overline{\gamma}) = \int_0^{\infty} \log(1 + \gamma) \frac{1}{\overline{\gamma}} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right) d\gamma. \quad (8)$$

From [19, Eq (4.337.2)] we can derive the following closed-form expression

$$\overline{AR}(k, \overline{\gamma}) = -\exp\left(\frac{1}{\overline{\gamma}}\right) \mathrm{Ei}\left(-\frac{1}{\overline{\gamma}}\right) \quad (9)$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral function [19, Eq. (8.21)].

2) For $k \geq 2$: In this case, we need to consider two subcases, i) $R_k \neq 0$ and ii) $R_k = 0$. For case i), the conditional average achievable rate can be written as

$$\begin{aligned}\overline{AR}(k, \overline{\gamma}) = &\int_0^{\infty} \log(1 + \gamma) R_k \left[1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right)\right]^{R_k - 1} \\ &\times \frac{1}{\overline{\gamma}} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right) d\gamma.\end{aligned} \quad (10)$$

For case ii), based on the mode of operation, $R_k = 0$ means that there is no active relay. Therefore, the conditional average achievable rate can be written as

$$\overline{AR}(k, \overline{\gamma}) = \overline{AR}(k - 1, \overline{\gamma}). \quad (11)$$

In (10), the multiple product term can be converted to the following multiple summation form, referring to [19, Eq. (1.111)]

$$\left[1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right)\right]^{R_k - 1} = \sum_{l=0}^{R_k - 1} \binom{R_k - 1}{l} (-1)^l \exp\left(-\frac{l}{\overline{\gamma}} \gamma\right). \quad (12)$$

Then, using [19, Eq. (4.337.2)], after applying (12) to (10) and then some manipulations, we can obtain the following closed-form expression for $R_k \neq 0$

$$\begin{aligned}\overline{AR}(k, \overline{\gamma}) = &\frac{R_k}{\overline{\gamma}} \sum_{l=0}^{R_k - 1} \binom{R_k - 1}{l} (-1)^{l+1} \left(\frac{\overline{\gamma}}{l + 1}\right) \\ &\times \exp\left(\frac{l + 1}{\overline{\gamma}}\right) \mathrm{Ei}\left(-\frac{l + 1}{\overline{\gamma}}\right).\end{aligned} \quad (13)$$

B. Relay Scheduling Scheme : Strategy II

In this case, the system sorts the SNRs of candidate relays in both current and previous subframes including $\mathcal{S}$ in descending order, then the relay with the largest one is scheduled for retransmission. Thus, the SNR of a scheduled relay in the kth subframe, γ_k, has the 1st order statistic of a statistical sample. Note that for the scheduling strategy II in practice, $\mathcal{S} - \mathcal{D}$ and $\mathcal{R} - \mathcal{D}$ links are non-identical, which is also considered below.

1) For Identical Case: Similar to the case of the scheduling strategy I, $f_{\gamma_k}(\gamma)$ can be written by replacing R_k with R_{k_total} as

$$f_{\gamma_k}(\gamma) = R_{k\_\mathrm{total}} \left[1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right)\right]^{R_{k\_\mathrm{total}} - 1} \frac{1}{\overline{\gamma}} \exp\left(-\frac{\gamma}{\overline{\gamma}}\right). \quad (14)$$

Then, with the help of (12), the following closed-form expression can be directly obtained

$$\begin{aligned}\overline{AR}_{Frame} &= \sum_{k=1}^{N} \int_0^{\infty} \log(1 + \gamma_k) f_{\gamma_k}(\gamma_k) d\gamma_k \\ &= \sum_{k=1}^{N} \frac{R_{k\_\mathrm{total}}}{\overline{\gamma}} \sum_{l=0}^{R_{k\_\mathrm{total}} - 1} \binom{R_{k\_\mathrm{total}} - 1}{l} \\ &\quad \times (-1)^{l+1} \left(\frac{\overline{\gamma}}{l+1}\right) \exp\left(\frac{l+1}{\overline{\gamma}}\right) \mathrm{Ei}\left(-\frac{l+1}{\overline{\gamma}}\right).\end{aligned} \quad (15)$$

2) For Non-identical Case: Now, we consider the more practical case that $\mathcal{S} - \mathcal{D}$ and $\mathcal{R} - \mathcal{D}$ links are non-identical. In this case, by adopting $K = R_{k\_\mathrm{total}}$ and $k = 1$ in [18, Eq. (6.47)], the PDF of γ_k can also be written as

$$\begin{aligned}f_{\gamma_k}(\gamma) = &\sum_{\substack{n_1, n_2, \cdots n_{R_{k\_\mathrm{total}}} \\ n_1 \neq n_2 \neq \cdots \neq n_{R_{k\_\mathrm{total}}}}}^{1, 2, \cdots, R_{k\_\mathrm{total}}} \frac{1}{\overline{\gamma}_{n_1}} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_1}}\right) \\ &\times \prod_{l=2}^{R_{k\_\mathrm{total}}} \left[1 - \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_l}}\right)\right]\end{aligned} \quad (16)$$

where $\sum_{\substack{n_1, n_2, \cdots n_{R_{k\_\mathrm{total}}} \\ n_1 \neq n_2 \neq \cdots \neq n_{R_{k\_\mathrm{total}}}}}^{1, 2, \cdots, R_{k\_\mathrm{total}}}$ means that $n_1, n_2, \cdots n_{R_{k\_\mathrm{total}}}$ are not equal to one another and take values from $1, 2, \cdots, R_{k\_\mathrm{total}}$.

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Applying (16) to (1) yields the following simplified result

$$\overline{AR}_{Frame} = \sum_{k=1}^{N} \sum_{\substack{n_1,n_2,\cdots n_{R_{k\_\text{total}}} \\ n_1 \neq n_2 \neq \cdots \neq n_{R_{k\_\text{total}}}}}^{1,2,\cdots,R_{k\_\text{total}}} \frac{1}{\overline{\gamma}_{n_1}} \times \int_0^\infty \log(1+\gamma) \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_1}}\right) \prod_{l=2}^{R_{k\_\text{total}}} \left[1-\exp\left(-\frac{\gamma}{\overline{\gamma}_{n_l}}\right)\right] d\gamma. \tag{17}$$

In (17), for $R_{k\_\text{total}} = 3$ and $R_{k\_\text{total}} = 4$, the expression of product of sums can be expressed as a simplified sum of products form by using the fact that multiplication distributes over addition as

$$\begin{aligned} &\prod_{l=2}^{3} \left[1-\exp\left(-\frac{\gamma}{\overline{\gamma}_{n_l}}\right)\right] \\ &= 1 + (-1) \sum_{j_1=2}^{3} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_1}}}\right) \\ &\quad + (-1)^2 \sum_{j_1=2}^{2} \sum_{j_2=j_1+1}^{3} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_1}}}\right) \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_2}}}\right) \end{aligned} \tag{18}$$

and

$$\begin{aligned} &\prod_{l=2}^{4} \left[1-\exp\left(-\frac{\gamma}{\overline{\gamma}_{n_l}}\right)\right] \\ &= 1 + (-1) \sum_{j_1=2}^{4} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_1}}}\right) \\ &\quad + (-1)^2 \sum_{j_1=2}^{3} \sum_{j_2=j_1+1}^{4} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_1}}}\right) \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_2}}}\right) \\ &\quad + (-1)^3 \sum_{j_1=2}^{2} \sum_{j_2=j_1+1}^{3} \sum_{j_3=j_2+1}^{4} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_1}}}\right) \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_2}}}\right) \\ &\qquad \times \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_3}}}\right). \end{aligned} \tag{19}$$

From the above simplified results, the multiple product term in (17) can be obtained as the following multiple summation form

$$\begin{aligned} &\prod_{l=2}^{R_{k\_\text{total}}} \left[1-\exp\left(-\frac{\gamma}{\overline{\gamma}_{n_l}}\right)\right] \\ &= 1 + \left[\sum_{l=1}^{R_{k\_\text{total}}-2+1} (-1)^l \sum_{j_1=2}^{R_{k\_\text{total}}-l+1} \cdots \sum_{j_l=j_{j-1}+1}^{R_{k\_\text{total}}} \times \prod_{m=1}^{l} \exp\left(-\frac{\gamma}{\overline{\gamma}_{n_{j_m}}}\right)\right]. \end{aligned} \tag{20}$$

Finally, using [19, Eq. (4.337.2)], after applying (20) to (17) and some manipulations, we can obtain the final closed-form expression as

$$\begin{aligned} &\overline{AR}_{Frame} \\ &= \sum_{k=1}^{N} \int_0^\infty \log(1+\gamma) f_{\gamma_k}(\gamma)\, d\gamma_k \\ &= \sum_{k=1}^{N} \sum_{\substack{n_1,n_2,\cdots n_{R_{k\_\text{total}}} \\ n_1 \neq n_2 \neq \cdots \neq n_{R_{k\_\text{total}}}}}^{1,2,\cdots,R_{k\_\text{total}}} \frac{1}{\overline{\gamma}_{n_1}} \Bigg[-\overline{\gamma}_{n_1} \exp\left(\frac{1}{\overline{\gamma}_{n_1}}\right) \mathrm{Ei}\left(-\frac{1}{\overline{\gamma}_{n_1}}\right) \\ &\quad + \sum_{l=1}^{R_{k\_\text{total}}-2+1} (-1)^{l+1} \sum_{j_1=2}^{R_{k\_\text{total}}-l+1} \cdots \sum_{j_l=j_{j-1}+1}^{R_{k\_\text{total}}} \\ &\quad \times \frac{\exp\left(\frac{1}{\overline{\gamma}_{n_1}} + \sum_{m=1}^{l} \frac{1}{\overline{\gamma}_{n_{j_m}}}\right)}{\left(\frac{1}{\overline{\gamma}_{n_1}} + \sum_{m=1}^{l} \frac{1}{\overline{\gamma}_{n_{j_m}}}\right)} \mathrm{Ei}\left(-\left(\frac{1}{\overline{\gamma}_{n_1}} + \sum_{m=1}^{l} \frac{1}{\overline{\gamma}_{n_{j_m}}}\right)\right) \Bigg]. \end{aligned} \tag{21}$$

IV. Results

We compare the proposed IRS-HARQ scheme with the conventional relay selection protocol under Rayleigh fading conditions in terms of the achievable rate. For the better illustration, we consider two basic conventional relaying modes; in mode 1, the first activated reliable relay is participated in retransmission over a frame while in mode 2, the first scheduled best relay with the highest $\mathcal{R}-\mathcal{D}$ link gain is participated in retransmission over a frame.

In Fig 3, for a given distribution of the new candidate relays, we can see that the simulation results obtained via Monte-Carlo simulation perfectly match with our analytical results for both relay scheduling strategies I and II.

Figs 4 - 6 show the average achievable rate [nats/sec/Hz] and the average switching rate over a frame as a function of subframe index. Here, we consider i) symmetric and ii) asymmetric cases for $\mathcal{S}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$ links where $\overline{\gamma}_{\text{SR}}$ and $\overline{\gamma}_{\text{RD}}$ are the average SNRs of the $\mathcal{S}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$ links, respectively, and R_T is total number of relays and T is a threshold for successful decoding. Note that the early termination occurs when the achievable rate is above the threshold. As anticipated, the proposed IRS-HARQ, where only relay scheduling strategy II is considered, provides the highest rate under above channel conditions by iteratively scheduling a relatively better $\mathcal{R}$ closer to $\mathcal{D}$ in each subframe while conventional modes 1 and 2 allow only the first scheduled single $\mathcal{R}$ to keep retransmission in all remaining subframes once it is scheduled.

In Figs 5 - 6, we can also observe that the rate increases as both $\mathcal{S}-\mathcal{R}$ and $\mathcal{R}-\mathcal{D}$ link gains are enhanced compared with Fig 4. Especially, for enhanced $\mathcal{S}-\mathcal{R}$ link gain in Fig 5, the possibility that a serving $\mathcal{R}$ is activated earlier becomes higher so that the possibility of this serving node participating in relaying quickly becomes higher. Eventually, it helps to accelerate the early termination because a serving $\mathcal{R}$ can provide the relatively higher data rate compared with $\mathcal{S}$ due to the proximity. Likewise, for enhanced $\mathcal{R}-\mathcal{D}$ link gain in Fig 6, increasing the probability that a serving $\mathcal{R}$ has a better

$\mathcal{R}-\mathcal{D}$ link gain also leads to the early termination at the end user.

For modes 1 and 2 in Fig 5, they show almost the same performance for the low subframe index since the time difference of activation point of a serving $\mathcal{R}$ between modes 1 and 2 is smaller. However, as subframe index increases, the performance of mode 2 eventually overtakes that of mode 1 and the performance gap increases because a serving relay node in mode 2 is likely to have a better $\mathcal{R}-\mathcal{D}$ link gain, which means that a serving relay node in mode 2 can transmit a relatively more data compared with that in mode 1. Note that in Fig 6, for the considered subframe index region, we can observe the performance of mode 1 is better than that of mode 2. However, as subframe index increases further, the performance of mode 2 may eventually overtake that of mode 1 because the serving $\mathcal{R}$ in mode 2 can provide the better transmission capacity compared with that in mode 1. Note also that the early termination reduces the frequency of redundant subframe transmission and decoding, resulting in energy saving. For instance, the proposed IRS-HARQ reduces 1 or 2 redundant subframes over a frame, which in turn saves the energy by about 15% in Fig 4 and $9\sim18\%$ in Figs 5 and 6, compared to the considered conventional relay protocols for symmetric and asymmetric cases, respectively.

In terms of the switching rate in Fig 7, it is desirable to keep it smaller since a large switching rate is undesirable for real implementation. Here, when compared to modes 1 and 2, the average switching rate of IRS-HARQ is about twice which is still reasonable.

In Fig 8, we consider the effect of the simplified path-loss model together with multipath fading by simply replacing the average SNR, $\overline{\gamma}_i$, with $\overline{p_i}(r_i)$ at distance r_i. Here, we consider four examples based on the different $\{R_k\}_{k=1}^{N}$ combinations where $\mathcal{R}$s are located gradually closer to $\mathcal{D}$ with $R_{k\_\text{total}}=17$, $N=10$, path-loss constant $C=0.1$, path-loss exponential $a=2$, distance from $\mathcal{S}$ and $\mathcal{D}$ $r_{\text{SD}}=600$ m, and transmission power from $\mathcal{S}$ and $\mathcal{R}$, $P_{\text{S}}=P_{\text{R}}=30$ dB. We can observe that the performance behavior is similar to that obtained from multipath fading only.

V. Conclusions

In this work, we proposed the iterative relay scheduling scheme under the multiple UE relay environments (i.e., IRS-HARQ scheme) applicable to the next-generation cellular systems (e.g., LTE-Advanced and beyond) by extending the previous work in [5], especially focusing on the in-phase selection strategy. With the proposed IRS-HARQ under the open-loop and transparent mode, we can iteratively schedule a relatively better UE relay closer to the end user in a probabilistic sense and it eventually leads increasing the achievable data rate. Under this open-loop and transparent mode, our proposed protocol can be implemented by partially exploiting the CSI based on the overhearing mechanism of ACK/NACK for HARQ. Further, the iterative scheduling enables UE-to-UE direct communication with proximity that offers spatial frequency reuse and energy saving, which can be one of the potential solutions in LTE UE relay-based public safety scenarios where the end user is out of coverage or the existing infrastructure becomes out of order [20], and so on.

Acknowledgments

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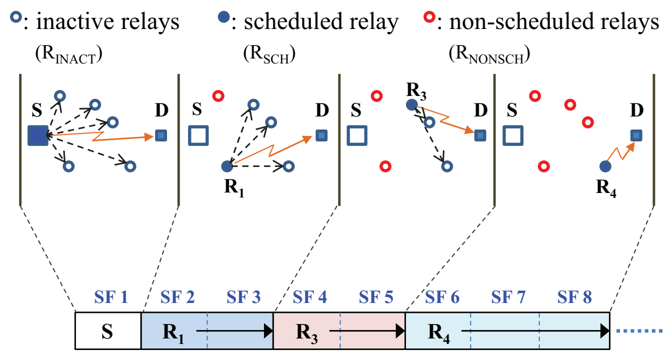
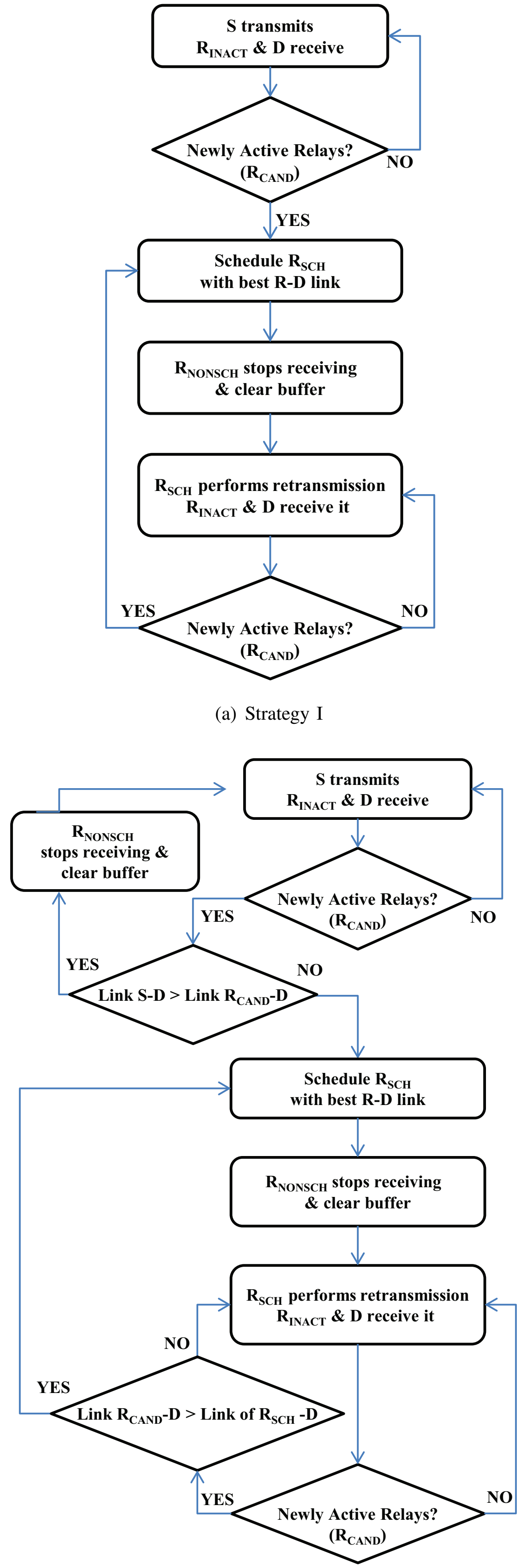


Fig. 1. Illustration of IRS-HARQ scheme (SF = subframe).



(a) Strategy I

(b) Strategy II

Fig. 2. Flowchart for iterative relay scheduling schemes.

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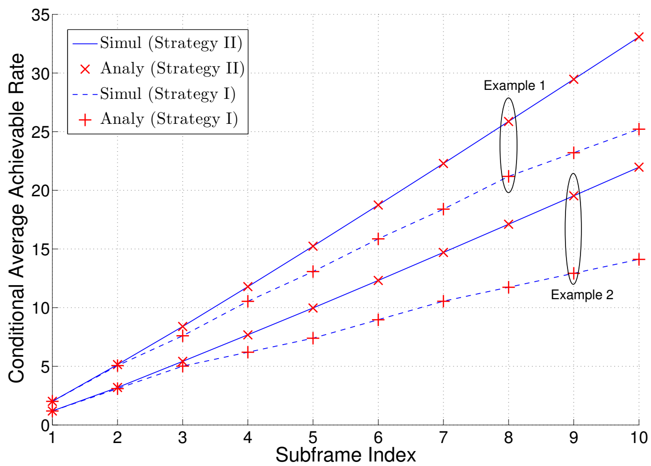

Fig. 3. Performance comparisons in terms of conditional average achievable rate over a frame between analytical and simulation results when $N = 10$, $\{R_k\}_{k=1}^{N} = \{0, 5, 2, 4, 2, 3, 2, 3, 1, 1\}$ with $\overline{\gamma} = 10$ dB (Example 1) and $\{R_k\}_{k=1}^{N} = \{0, 4, 4, 1, 1, 2, 2, 1, 1, 1\}$ with $\overline{\gamma} = 5$ dB (Example 2) over i.i.d. Rayleigh fading conditions.

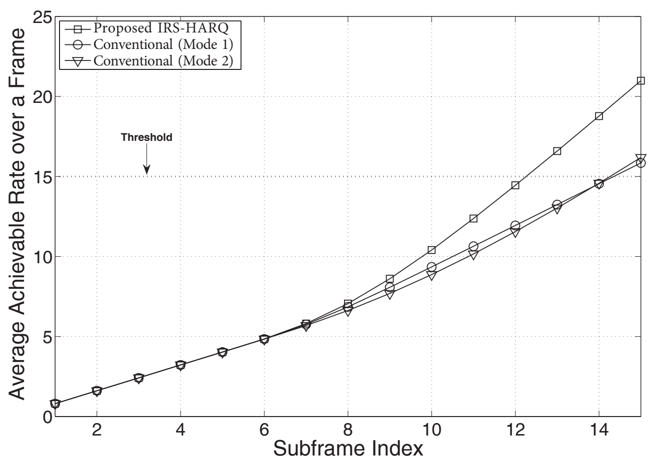

Fig. 4. Average achievable rate over a frame for the symmetric case ($\overline{\gamma}_{\rm SR} = \overline{\gamma}_{\rm RD} = 5$ dB) when $R_T = 10$, $N = 15$, and $T = 15$.

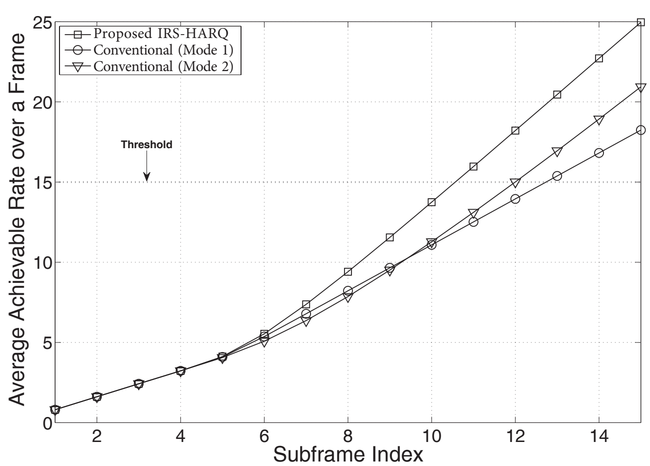

Fig. 5. Average achievable rate over a frame for the asymmetric case ($\overline{\gamma}_{\rm SR} = 10$ dB, $\overline{\gamma}_{\rm RD} = 5$ dB) when $R_T = 10$, $N = 15$, and $T = 15$.

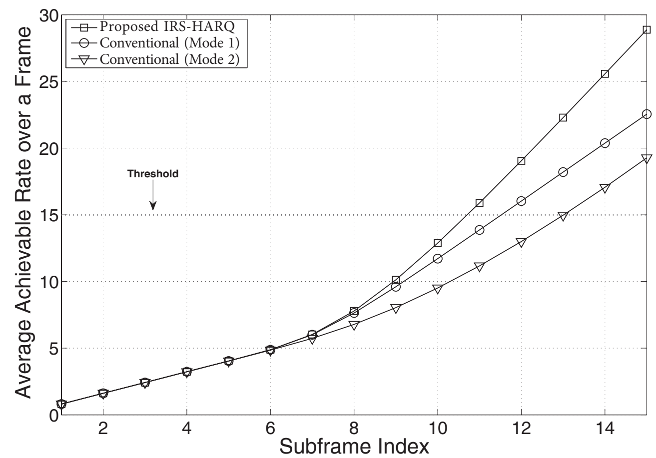

Fig. 6. Average achievable rate over a frame for the asymmetric case ($\overline{\gamma}_{\rm SR} = 5$ dB, $\overline{\gamma}_{\rm RD} = 10$ d B) when $R_T = 10$, $N = 15$, and $T = 15$.

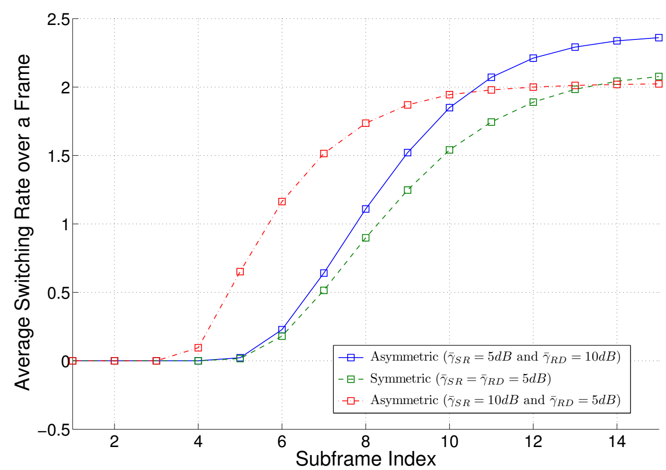

Fig. 7. Average switching rate of the IRS-HARQ scheme over a frame when $N = 15$ and $T = 15$.

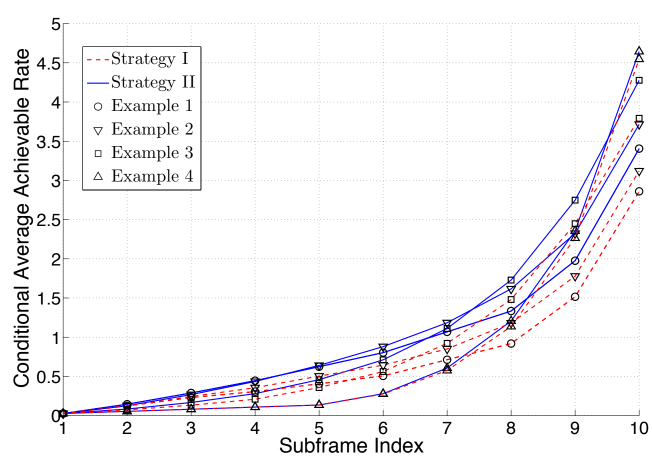

Fig. 8. Performance of conditional average achievable rate over a frame when $R_{k\_{\rm total}} = 17$, $N = 10$, and $P_{\rm S} = P_{\rm R} = 30$ dB in i.i.d. Rayleigh fading conditions with path loss ($C = 0.1$, $a = 2$, and $r_{\rm SD} = 600$ m).

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