Two-Level Distributed Opportunistic Scheduling in DF Relay Networks

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***Abstract*— We consider a distributed wireless network aided by decoded-and-forward relays. Multiple sources use contention for channel access. We investigate distributed opportunistic scheduling (DOS), which means that if a source wins the channel contention, it may give up its transmission opportunity if its channels over the two hops are not good. We propose a two-level DOS scheme which includes two-level decisions. Optimal rules in the two levels are theoretically derived.**

***Index Terms*— Opportunistic scheduling, relay networks.**

I. Introduction

Opportunistic scheduling in a multiple-user centralized network has been well investigated, in which a central coordinator collects all users' channel state information (CSI) and lets the user with the best channel quality to transmit. However, for a distributed network, it is challenging to achieve optimal distributed opportunistic scheduling (DOS) due to the unavailability of the global CSI of all users. This issue has been addressed in [1] using optimal stopping theory in a contention-based ad hoc network. It is shown that, when a user wins a contention, if its observed channel gain is less than an optimal threshold (which can be calculated off-line), it is optimal to give up the transmission opportunity; otherwise, it is optimal for the winner user to transmit its traffic. As extensions of [1], DOS with imperfect channel information is studied in [2], while DOS considering tradeoff between channel estimation accuracy and channel probing time is investigated in [3].

DOS is also investigated in relay networks [4]–[6] with multiple pairs of sources and destinations. The work in [4] investigates amplify-and-forward relay networks. In [5], a decode-and-forward (DF) relay network using channel contention is considered. When a source wins the contention (called a *winner source*), its channels to its destination and to its relay are probed, and a decision is made among three options: 1) to give up the transmission opportunity (in this paper, when we say a transmission opportunity is given up, it means that subsequently all sources start new channel contentions); 2) to transmit using direct link; or 3) to further probe the channel from the relay to the destination, and decide to transmit (either by direct link or by relay link) or to give up the transmission opportunity. The work in [5] focuses on whether or not to further probe the second hop. The work in [6] also considers a DF relay network. If a source wins the contention, its channel to its relay is probed, and a decision is made between two options: to give up the transmission opportunity; or to select a rate to transmit to the relay and let the relay wait for a good second-hop channel to transmit its received traffic to the destination (referred to as *relay-waiting*).

Works in [5] [6] consider two-level stopping. We have following observations. The further-probing option in [5] may be beneficial if the first hop and the second hop's instantaneous channel gains are both good. The relay-waiting option in [6] can be beneficial when the first hop and second hop's instantaneous channel gains are good and bad, respectively, since the source will first transmit to the relay (thus exploiting the good first-hop channel), and wait for the second hop to have a good channel. Motivated by these, we consider both further-probing and relay-waiting options. Note that the combination of further-probing and relay-waiting in our work is not simple. A simple combination could be: the winner source has three options: give-up, further-probing, and relay-waiting; and if one of the latter two options is selected, just follow the same method as in [5] or [6]. Different from this simple combination, we propose that, if further-probing is selected by the winner source, relay-waiting is considered as one option in the second-level decision process.

II. System Model

Consider K source-destination pairs and a number of DF relays. Each source-destination pair is pre-assigned a relay. As argued in [6], optimal DOS for the case with direct links can follow the same method in [1]. Thus, here we consider the case with no direct link between any source-destination pair. Channels in the two hops follow Rayleigh fading, with a common channel coherence time denoted τ_d. For source $i \in \{1, 2, ..., K\}$, the average received signal-to-noise ratio (SNR) of the channels from source i to its relay and from its relay to its destination are denoted as h_i and g_i, respectively.

A channel access procedure similar to [4]–[6] by using contention is adopted for the K sources. At a time slot, each source transmits to its relay a request-to-send (RTS) packet (which serves as probing packet of the source) with a predetermined probability p. If the slot is idle (i.e., no source transmits) or collided (i.e., two or more sources transmit), then all sources start a new channel contention in next slot after the idle slot or after a timeout period following the channel collision period. If there is only one source that transmits, then we say a successful contention happens. We call the process until a successful channel contention appears as *an observation* of the wireless system. Then an observation has a mean duration expressed as: $\tau_0 \triangleq \tau_R + \frac{(1-p)^K}{Kp(1-p)^{K-1}}\delta + \frac{1-(1-p)^K - Kp(1-p)^{K-1}}{Kp(1-p)^{K-1}}(\tau_R + \tau_{TO})$, where $\delta, \tau_R, \tau_{TO}$ are durations of a slot, an RTS transmission, and a timeout period.

When a source wins a successful contention, its relay can estimate the channel SNR of the first hop, denoted $\gamma_1(n)$

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(n is observation index), by RTS reception, and makes one from three possible decisions: 1) Give-up: the winner source gives up its transmission opportunity. 2) Relay-waiting: it is decided that the winner source transmits to its relay first, and then the relay waits for a good second-hop channel to send the received traffic. A first-hop transmission rate denoted R_n (no more than the first-hop channel capacity) is also decided. 3) Further-probing: the relay further probes the second-hop channel SNR. The above process is called *first-level decision*.

If the first-level decision is give-up, the decision is included in a clear-to-send (CTS) sent from the relay to the winner source (all other sources also overhear the decision).

If the first-level decision is relay-waiting, the decision is sent from the relay to the winner source by a CTS (the CTS also notifies other sources not to contend until the relay finishes its transmission to the destination). The winner source transmits with rate R_n and duration τ_d. Once the relay receives the traffic, it is proven in [6] that the relay should keep probing the second-hop channel until the achievable rate of a second-hop channel realization is not less than R_n and then transmit. In specific, the relay sends an RTS to the corresponding destination, and the destination feeds back a CTS which includes the second-hop CSI. If the second-hop achievable rate, denoted $\hat{R}$, satisfies $\hat{R} \geq R_n$, then the relay transmits with rate $\hat{R}$ and duration $(R_n/\hat{R})\tau_d$;[1] otherwise, the relay waits for τ_d duration and sends RTS again. This procedure is repeated until the second-hop channel achievable rate is not less than R_n and the relay transmits.

If the first-level decision is further-probing, the relay sends an RTS to the corresponding destination. The destination measures the second-hop channel SNR denoted $\gamma_2(n)$, and makes the *second-level decision* among three options: i) Give-up: the destination sends a CTS to notify the decision; ii) Relay-waiting (the same as the relay-waiting used in the first-level decision); iii) Direct-transmission ("direct" means there is no waiting between the two hops' transmissions): it is decided that the winner source sends to the relay and subsequently the relay sends to the destination, both with transmission rate $2R_{\text{direct}}(n)$ with duration $\tau_d/2$ (here $R_{\text{direct}}(n) \triangleq \frac{1}{2}\log_2\big(1 + \min(\gamma_1(n), \gamma_2(n))\big)$). A CTS is sent to the winner source to start the direct transmission.

It can be seen that for each transmission opportunity, it is eventually decided either to give up the opportunity and let all sources start new channel contentions and *observe* their channels, or to *stop* the channel observation process and transmit (by either direct-transmission or relay-waiting). Assume the system starts at time moment 0. Recall that an observation means a process until a successful contention. Denote Y_n as reward (i.e., amount of transmitted traffic) at observation n and T_n as the time duration from time moment 0 until the end of observation n plus transmission durations. And denote N as the "stopping" time, i.e., the transmission opportunities in observations $1, 2, ..., N-1$ are given up and the winner source of observation N stops and transmits. We also use N to denote the "stopping rule" (i.e., when to stop and how to stop?). We should derive the optimal stopping rule N^* for a maximal system throughput problem: $\sup_{N\geq 0}\mathbb{E}[Y_N]/\mathbb{E}[T_N]$ in which $\mathbb{E}[\cdot]$ denotes expectation. For this purpose, we can first solve a transformed problem with parameter $\lambda(>0)$ which means cost per time unit:

$$V(\lambda) = \sup_{N\geq 0}\mathbb{E}[Y_N] - \lambda\mathbb{E}[T_N]. \tag{1}$$

Then an optimal stopping rule of (1) with λ^* satisfying $V(\lambda^*) = 0$ is an optimal stopping rule of our maximal system throughput problem [7]. So next we focus on optimal stopping rule of (1) with λ^* (at the end of Section IV we will discuss how to determine value of λ^*).

III. Second-level Decision

In the n-th observation of the sources, denote $s(n)$ as the winner source, and $\gamma_1(n)$ as the first-hop SNR of the winner source. In this section, we consider that the first-level decision is further-probing. So the relay further probes the second-hop channel SNR denoted $\gamma_2(n)$. Then there are three options in the second-level decision: give-up, direct-transmission, and relay-waiting. The rewards of give-up and direct-transmission are $V(\lambda^*) = 0$ and $R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d$, respectively. Reward of relay-waiting is discussed next.

In relay-waiting, the winner source sends its traffic to its relay with a transmission rate R_n and duration τ_d. We denote $\Gamma_{s(n)} \triangleq 2^{R_n} - 1$. The probability density function of $\gamma_2(n)$ is $(1/g_{s(n)})e^{-\gamma_2(n)/g_{s(n)}}$. The second-hop channel is kept probed until a channel realization with achievable rate not less than R_n is found (or equivalently, the SNR of the second-hop channel realization is not less than $\Gamma_{s(n)}$). Thus, the number of times that the second-hop channel is probed follows a geometric distribution with mean value being $e^{\Gamma_{s(n)}/g_{s(n)}}$. So given $\gamma_1(n)$ and $\Gamma_{s(n)}$, the average reward of relay-waiting is given as $Y_w^{\gamma_1(n),\Gamma_{s(n)}}(n) = \log_2(1 + \Gamma_{s(n)})\tau_d - \lambda^*\tau_d - \lambda^*[e^{\Gamma_{s(n)}/g_{s(n)}}(\tau_d + \tau_R + \tau_C) + (\mathbb{E}[\frac{R_n}{\hat{R}}] - 1)\tau_d]$ in which subscript 'w' means "relay-waiting" and τ_C means CTS transmission duration. On the right handside of the expression, the second term is the time cost for data transmission from the winner source to its relay, and the third term is the time cost for transmission from the relay to the destination. Here $\mathbb{E}[\frac{R_n}{\hat{R}}]$ is the expectation of $\frac{R_n}{\hat{R}}$ under condition $\hat{R} \geq R_n$, expressed as $\mathbb{E}[\frac{R_n}{\hat{R}}] = e^{\Gamma_{s(n)}/g_{s(n)}}\log_2(1+\Gamma_{s(n)})\int_{\Gamma_{s(n)}}^{\infty}\frac{(1/g_{s(n)})e^{-x/g_{s(n)}}}{\log_2(1+x)}dx$. Since $Y_w^{\gamma_1(n),\Gamma_{s(n)}}(n)$ is a function of $\Gamma_{s(n)}$, it is desired to find the optimal $\Gamma_{s(n)} \in (0, \gamma_1(n)]$, denoted $\Gamma^*_{s(n)}$, that maximizes $Y_w^{\gamma_1(n),\Gamma_{s(n)}}(n)$.

Define function $\varphi(\gamma) \triangleq \log_2(1 + \gamma)\tau_d - \lambda^*\tau_d - \lambda^*[e^{\frac{\gamma}{g_{s(n)}}}(\tau_d + \tau_R + \tau_C) + (e^{\frac{\gamma}{g_{s(n)}}}\log_2(1 + \gamma)\int_{\gamma}^{\infty}\frac{(1/g_{s(n)})e^{-x/g_{s(n)}}}{\log_2(1+x)}dx - 1)\tau_d]$. So $Y_w^{\gamma_1(n),\Gamma_{s(n)}}(n)$ can be expressed as $\varphi(\Gamma_{s(n)})$. When $\gamma \in [0, \infty)$, denote $\gamma^{s(n)*}$ as the value of γ that maximizes $\varphi(\gamma)$, which can be calculated offline. Note that $\Gamma_{s(n)} \in (0, \gamma_1(n)]$. So we have $\Gamma^*_{s(n)} = \min(\gamma_1(n), \gamma^{s(n)*})$, and the corresponding maximal $Y_w^{\gamma_1(n),\Gamma_{s(n)}}(n)$ is given as

$$Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n) = \varphi(\min(\gamma_1(n), \gamma^{s(n)*})). \tag{2}$$

[1] In relay-waiting of [6], the relay transmits with rate R_n and duration τ_d. So here we actually use an enhanced version of the relay-waiting in [6], referred to as *enhanced relay-waiting*.

Overall, if further-probing is the first-level decision, then the second-level decision will be the one (among give-up, direct-transmission, and relay-waiting) that has the maximal reward. In other words, the reward after probing the second hop is $\max\left(0, R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d, Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)\right)$.

IV. First-level Decision

In the first-level decision, after channel SNR in the first hop ($\gamma_1(n)$) is obtained, the same as the second level, the reward of give-up is $V(\lambda^*) = 0$, and the reward of relay-waiting is $Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)$. The expected reward of further-probing is

$$Z_p^{\gamma_1(n)} = \mathbb{E}\Big[\max\Big(0, R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d, Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)\Big)\Big] - \lambda^*(\tau_R + \tau_C) \tag{3}$$

in which subscript 'p' means "further-probing", $\mathbb{E}[\cdot]$ means expectation with respect to second-hop channel SNR, and $\lambda^*(\tau_R + \tau_C)$ means the time cost in probing the second hop. Next we give detailed expression for $Z_p^{\gamma_1(n)}$, based on discussion in the preceding section.

A. when relay-waiting is worse than give-up in second-level decision

In this subsection, we consider that the first-hop channel SNR $\gamma_1(n)$ satisfies $\gamma_1(n) \in \mathcal{I}_1 \triangleq \{\gamma_1(n) \mid Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n) \leq 0\}$, which means that the relay-waiting strategy is worse than give-up in the second-level decision. Thus the second-level decision is give-up or direct-transmission. Then (3) can be rewritten as

$$Z_{p,\mathcal{I}_1}^{\gamma_1(n)} = \int_{\lambda^*}^{\infty} (x - \lambda^*)\tau_d dF_{R_{\text{direct}}(n)|\gamma_1(n)}(x) - \lambda^*(\tau_R + \tau_C)$$

where $F_{R_{\text{direct}}(n)|\gamma_1(n)}(\cdot)$ is conditional (on given $\gamma_1(n)$) cumulative distribution function (CDF) of $R_{\text{direct}}(n)$, given as

$$F_{R_{\text{direct}}(n)|\gamma_1(n)}(x) = \begin{cases} 1 - e^{-\frac{4^x-1}{g_{s(n)}}}, & x < \frac{1}{2}\log_2(1+\gamma_1(n)) \\ 1, & x \geq \frac{1}{2}\log_2(1+\gamma_1(n)). \end{cases}$$

Using integration by parts and some math manipulations, $Z_{p,\mathcal{I}_1}^{\gamma_1(n)}$ is given as

$$Z_{p,\mathcal{I}_1}^{\gamma_1(n)} = \begin{cases} \tau_d \int_{\lambda^*}^{\frac{1}{2}\log_2(1+\gamma_1(n))} e^{-\frac{4^x-1}{g_{s(n)}}} dx - \lambda^*(\tau_R + \tau_C), \\ \qquad\qquad \text{if } \lambda^* < \frac{1}{2}\log_2(1+\gamma_1(n)); \\ -\lambda^*(\tau_R + \tau_C), \qquad \text{if } \lambda^* \geq \frac{1}{2}\log_2(1+\gamma_1(n)). \end{cases}$$

B. when relay waiting is the best in second-level decision

Now we consider that $\gamma_1(n)$ satisfies $\gamma_1(n) \in \mathcal{I}_2 \triangleq \{\gamma_1(n) \mid Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n) > \max\left(0, \frac{1}{2}\log_2(1+\gamma_1(n))\tau_d - \lambda^*\tau_d\right)\}$, which means relay-waiting is the best among all three options in the second-level decision (noting that $\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d - \lambda^*\tau_d$ is an upper bound of reward of direct-transmission expressed as $R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d$). Therefore, (3) can be rewritten as $Z_{p,\mathcal{I}_2}^{\gamma_1(n)} = Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n) - \lambda^*(\tau_R + \tau_C)$.

C. other scenarios

Now we consider that $\gamma_1(n)$ satisfies $\gamma_1(n) \in \mathcal{I}_3 \triangleq \overline{\mathcal{I}_1 \cup \mathcal{I}_2} = \{\gamma_1(n) \mid \frac{1}{2}\log_2(1+\gamma_1(n))\tau_d - \lambda^*\tau_d \geq Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n) > 0\}$, which means that in the second-level decision, the reward of relay-waiting is larger than that of give-up, but smaller than the upper bound of reward of direct-transmission. Thus the second-level decision is relay-waiting or direct-transmission. We denote $Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)$ given in (2) by using a simple form Y^*. Then (3) becomes

$$\begin{aligned} Z_{p,\mathcal{I}_3}^{\gamma_1(n)} &= Y^*\Big(1 - e^{-\frac{2^{\frac{2(Y^*+\lambda^*\tau_d)}{\tau_d}}-1}{g_{s(n)}}}\Big) \\ &+ \Big(\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d - \lambda^*\tau_d\Big) e^{-\frac{\gamma_1(n)}{g_{s(n)}}} \\ &+ \int_{Y^*+\lambda^*\tau_d}^{\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d} (x - \lambda^*\tau_d) dF_{R_g\tau_d}(x) - \lambda^*(\tau_R + \tau_C). \end{aligned} \tag{4}$$

On the right handside of (4), there are four terms: the first term means that when $\gamma_2(n) < 2^{\frac{2(Y^*+\lambda^*\tau_d)}{\tau_d}} - 1$ (the probability of which is the expression in the brackets following Y^*), relay-waiting has larger reward than direct-transmission; the second term means that when $\gamma_2(n) > \gamma_1(n)$ (the probability of which is $e^{-\frac{\gamma_1(n)}{g_{s(n)}}}$), direct-transmission has larger reward given as $\left(\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d - \lambda^*\tau_d\right)$; the third term means that when $2^{\frac{2(Y^*+\lambda^*\tau_d)}{\tau_d}} - 1 \leq \gamma_2(n) \leq \gamma_1(n)$ (which equivalently means that $Y^* + \lambda^*\tau_d \leq R_g\tau_d \leq \frac{1}{2}\log_2(1+\gamma_1(n))\tau_d$ with $R_g \triangleq \frac{1}{2}\log_2(1+\gamma_2(n))$), direct-transmission has better reward given as $\int_{Y^*+\lambda^*\tau_d}^{\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d} (x - \lambda^*\tau_d) dF_{R_g\tau_d}(x)$ with $F_{R_g\tau_d}(\cdot)$ being the CDF of random variable $R_g\tau_d$.

Using integration by parts for the third term, and after some mathematical manipulations, (4) can be rewritten as

$$Z_{p,\mathcal{I}_3}^{\gamma_1(n)} = Y^* + \int_{Y^*+\lambda^*\tau_d}^{\frac{1}{2}\log_2(1+\gamma_1(n))\tau_d} e^{-\frac{2^{2x/\tau_d}-1}{g_{s(n)}}} dx - \lambda^*(\tau_R + \tau_C).$$

Overall, the expected reward of further-probing in first-level decision is given as $Z_p^{\gamma_1(n)} = Z_{p,\mathcal{I}_1}^{\gamma_1(n)} I_{\{\mathcal{I}_1\}} + Z_{p,\mathcal{I}_2}^{\gamma_1(n)} I_{\{\mathcal{I}_2\}} + Z_{p,\mathcal{I}_3}^{\gamma_1(n)} I_{\{\mathcal{I}_3\}}$ with $I_{\{\cdot\}}$ being an indicator function.

Thus, the first-level decision is to select the maximal reward from 0 (for give-up), $Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)$ (for relay-waiting), and $Z_p^{\gamma_1(n)}$ (for further-probing). And accordingly, the expected reward of Problem (1) is

$$\begin{aligned} V(\lambda^*) &= \textstyle\sum_{i=1}^{K} \frac{1}{K}\mathbb{E}_{h_i}[\max(0, Y_w^{\gamma_1(n),\Gamma^*_{s(n)=i}}(n), \\ & Z_p^{\gamma_1(n)})] - \lambda^*(\tau_0 + \tau_C) \end{aligned} \tag{5}$$

in which $\frac{1}{K}$ means the probability that user $i \in \{1, 2, ..., K\}$ is the winner source, the expectation $\mathbb{E}_{h_i}[\cdot]$ is with respect to the first-hop instantaneous channel SNR $\gamma_1(n)$ when the average first-hop SNR is h_i (i.e., when user i is the winner source), and $\lambda^*(\tau_0 + \tau_C)$ is the time cost in first-hop channel contention and probing.

Together with $V(\lambda^*) = 0$, we can numerically calculate the value of λ^* (the calculation can be done off-line). With the value of λ^*, for winner source $i \in \{1, 2, ..., K\}$, the rewards of the three options in the first-level decision can be

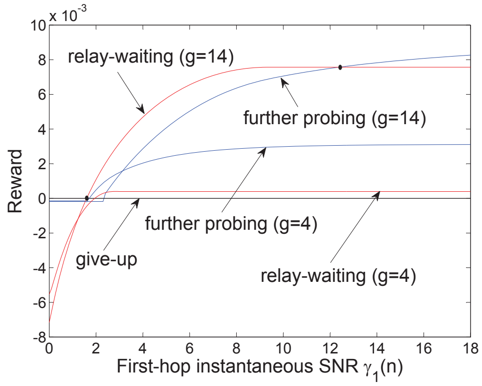

Fig. 1. Rewards of the three options in the first-level decision vs. $\gamma_1(n)$.

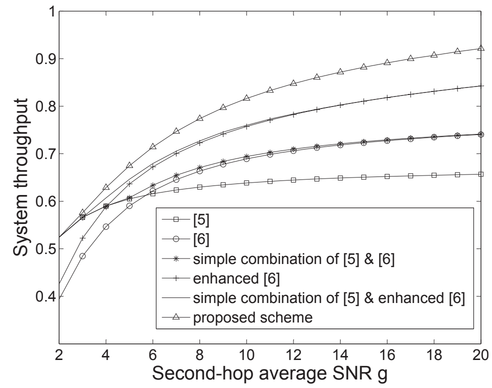

Fig. 2. Throughput vs. second hop average SNR g.

expressed as three non-decreasing curves in a "reward vs. first-hop instantaneous SNR $\gamma_1(n)$" plot. Based on the intersection points of the three curves, we have pure-threshold first-level decision for winner source i, to be illustrated in Section V.

V. Numerical/simulation Results and Conclusion

Consider $K = 15$ source-destination pairs. Other parameters are: $p = 0.1$, $\tau_d = 8$ms, $\tau_R = 103\mu$s, $\tau_C = \tau_{TO} = 106\mu$s, $\delta = 20\mu$s, $h_1 = h_2 = \ldots = h_{15} = 1$, and $g_1 = g_2 = \ldots = g_{15} = g$. For $g = 14$ or 4, Fig. 1 shows the rewards of the three options in the first-level decision of a winner source given as the three terms in the $\max(\cdot)$ function in (5). When $g = 14$, the two highlighted intersections give two thresholds of first-hop SNR: 1.60 and 12.38. So we have the following for first-level decision. 1) If $\gamma_1(n) < 1.60$, give-up is selected. 2) if $1.60 \leq \gamma_1(n) < 12.38$, relay-waiting is selected. 3) if $\gamma_1(n) \geq 12.38$, further-probing is selected in first-level decision, and we proceed to second-level decision, i.e., as discussed in Section III, after $\gamma_2(n)$ is probed, we select the maximal reward among 0 (for give-up), $R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d$ (for direct-transmission), and $Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)$ (for relay-waiting). When $g = 4$, the curve of further-probing is always better than the curve of relay-waiting in Fig. 1. This means relay-waiting is never selected in the first-level decision. However, it does not mean relay-waiting is useless. This is because relay-waiting is still an option in the second-level decision if the first-level decision is further-probing.

We conduct simulations to compare our proposed scheme with [5], [6], and the simple combination scheme of [5] and [6] as discussed in Section I (when simulating scheme in [5], direct links are not considered). We also simulate 1) "enhanced [6]", which is an enhanced version of the scheme in [6], in which the enhanced relay-waiting as discussed in Section II is implemented, and 2) a simple combination of [5] and enhanced [6]. The parameters are the same as used in Fig. 1, except that second-hop average SNR g varies from 2 to 20. The throughput of the schemes are shown in Fig. 2. The scheme in [5] performs better than the scheme in [6] with low g, but performs worse with high g. The enhanced relay-waiting can improve the system performance. Our proposed scheme outperforms all other schemes. Further, if $g = 4$, as aforementioned, relay-waiting is never selected in the first-level decision in our scheme. However, from Fig. 2, when $g = 4$, our proposed scheme achieves higher throughput than [5]. Our better performance than [5] comes from including relay-waiting in the second-level decision if the first-level decision is further-probing.

All the thresholds in our first-level decision can be numerically calculated off-line. So to perform first-level decision, a simple comparison of $\gamma_1(n)$ with the thresholds is needed. In our second-level decision, the calculations of $R_{\text{direct}}(n)\tau_d - \lambda^*\tau_d$ and $Y_w^{\gamma_1(n),\Gamma^*_{s(n)}}(n)$ in (2) are needed (noting that when (2) is calculated, the $\gamma^{s(n)*}$ is a fixed value for user $s(n)$, which can be obtained off-line), which are simple calculations. Note that the computation complexity is not a function of K (the number of user pairs), and thus, can be expressed as $O(1)$. For each of the other five schemes, the first-level and second-level decisions involve only simple comparisons/calculations. Their complexity (not a function of K) can also be expressed as $O(1)$. So the complexity of all above schemes are very low.

In summary, this paper proposes a new DOS strategy in DF relay networks, which takes the advantages of both further-probing and relay-waiting. Two-level decision problem is formulated. The first-level decision is a pure-threshold strategy. The second-level decision, if needed, is not pure-threshold. However, it requires very low computation complexity.

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