DOS/SP: Distributed Opportunistic Channel Access with Smart Probing in Wireless Cooperative Networks

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Abstract. This paper investigates optimal distributed opportunistic channel access in wireless cooperative networks with multiple relays deployed. While probing all potential relay channels could result in significant overhead and spectrum efficiency affected, distributed OCA strategies with smart relays probing is studied in this research. To achieve reliable communications of high efficiency, number of probed relays and way to use have to be carefully decided in a dynamic manner. Finding that the sequential channel probing and access are coupled, an optimal distributed OCA is much challenging, and main difficult lies in how to exploit multi-source diversity, multi-relay diversity and time diversity in full manner. To tackle this problem, an analytical framework is built based on theory of optimal sequential observation planned decision. This decision-theoretic approach integrates the design of MAC layer and physical layer, enabling smart probing and cooperative transmissions under multiple relays. Based on it, an optimal DOCA/SP strategy is proposed to maximize average system throughput, and the optimality is rigorously proved. The implementation is described, and through numerical and simulation results effectiveness is validated.

Keywords: Opportunistic scheduling · Smart relaying · Optimal sequential observation plan decision

1 Introduction

Recently wireless network harvests an unprecedented development in fulfilling rapidly increasing demands in various applications. These demands are from enhanced quality-of-service on system performance such as transmission reliability, throughput and energy efficiency. In fulfilling network management of multiple layers orderly and efficiently, joint design viewpoint is motivated, which has led to a cross-layer design concept, generally known as *opportunistic channel access*.

In a wireless network, the channel is usually shared by multiple users, and each individual user experiences time-varying channel condition. At a time

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instant, if channel quality of a user is poor, it is likely to drop the opportunity of accessing the channel and let others of good channel conditions access that channel. Whereas a myopic interest may be lost, more can be harvested in long run, as in the later if the user is in good channel condition, it transmits during channel access opportunities of others. In doing this, by letting nodes be aware of physical layer information, the MAC-layer mechanism coordinates channel access among multiple users more efficiently. Therefore, it is observed that, through opportunistic channel access (OCA), the average network throughput can be significantly enhanced.

In existing efforts, related works relevant to OCA are in two parts, centralized OCA (COCA) and distributed OCA (DOCA). Most of works tackle the COCA problem, where a centralized node, e.g., base station in a cellular network, can make channel-aware scheduling based on global channel state information (CSI) from all users [1,2]. In contrast, research on DOCA is still limited. In a distributed network, all users share the channel and contend for sensing and access. It is challenging to design an efficient strategy deciding how each user senses and accesses a shared channel using local and limited channel information. To address this difficulty, a study in novelty is carried out in [3] based on optimal stopping theory. Its basic idea is to let all users contend for channel access: if the winner has an achievable rate smaller than a threshold, it is optimal to *continue*, i.e., to give up access opportunity and re-contend the channel with others; otherwise, it is optimal to *stop*, i.e., to utilize the opportunity accessing the channel. Easy implementation benefits from such *pure-threshold* strategy. Extended from the work, the DOCA problem over an interference channel, which allows multiple nodes transmitting simultaneously, is investigated in [4], while the problem under delay constraints is also studied in [5] for real-time services.

To our best knowledge, a few works are concerned on DOCA for cooperative network, i.e. [6,7]. In particular, assuming channel state symmetry, two scenarios are investigated in [6]. In the first scenario, a dedicated relay node is considered, and each winner source determines whether to probe relay channel before transmission; in the second scenario, multiple un-dedicated relays are considered, and channel gain of the best relay is observed at a winner source. The best relay is used for cooperative transmission. By modeling this problem under two-level stopping approach, optimal strategies are proposed maximizing network throughput. In addition, different scenario is investigated in [7], and two cases are analysed. Particularly, in Case I a winner source knows all CSI of relays channels, and in Case II a winner source only knows a part. Maximizing the average network throughput, optimal DOCA strategies are proposed using optimal stopping theory and its extension.

As the contributions from these works, a trade-off problem is solved, and the balance is taken between the time spent in channel probing and transmission efficiency in channel access. Nevertheless, static probing pattern is considered in existing research as all relays are to probe once relay probing is decided. The flexibility in relay probing is much constrained and the benefit from multiple relays transmission is hardly obtained. Without channel symmetry, the contradiction is oblivious, as sufficient channel information offers increased transmission efficiency but results in heavy overhead. As the relay number becomes significant, a dilemma is faced. Therefore, it is naturally enlightened to design distributed scheduling strategy for managing channel probing and access of multiple sources and relays in an intelligent manner.

In this research, the DOCA problem with smart relays probing is thus investigated for distributed cooperative network, which is named as DOCA/SP problem. Within it, findings of optimal DOCA strategies, which determines how to probe two-hop channels (including both direct and relay channels), when to stop probing channels and how to access the channel, are pursued. The main contributions are listed as follows.

- An analytical framework is built up for the DOCA/SP problem based on optimal sequential observation planned decision (OSOPD) theory, and a decision-theoretic approach is proposed which guides the design of multi-source multi-relay OCA with smart channel probing in a distributed manner.
- Under the framework, an optimal DOCA/SP strategy is proposed which maximizes the average system throughput, and its optimality is rigorously proved.
- Implementations of the proposed strategy are presented enabling network operation, and through numerical simulations theoretic results are verified.

The rest of this paper is organized as follows. The network model and the protocol description of DOCA/SP are presented in Sect. 2. The analytical framework based on the OSOPD theory is established in Sect. 3, and based on it an optimal DOCA/SP strategy is derived in Sect. 4. Performance evaluation is provided in Sect. 5, followed by concluding remarks in Sect. 6.

2 Network and Protocol Model

2.1 Network Model

Supposed that in a distributed cooperative network there are K source-destination pairs, and L relays are employed to aid communications between sources and destinations, as shown in Fig. 1.

The source-destination pairs operate in a distributed manner, and a direct link between each pair is available. The sources contend to communicate with their destinations, and for transmission from a source to its destination, multiple relays are available aiding the transmission in decode-and-forward (DF) mode. The transmission power of a source and a relay is denoted as P_s and P_r, respectively. Channel reciprocity in terms of channel gain is assumed, and we denote the channel gain from the ith source to its destination (and vice versa) as h_i, the channel gain from the ith source to the jth relay (and vice versa) as f_{ij}, and the channel gain from the jth relay to the ith destination (and vice versa) as g_{ji}. It also assumes that $\sqrt{P_s}h_i$, $\sqrt{P_s}f_{ij}$ and $\sqrt{P_r}g_{ji}$ follow a Complex Gaussian distribution with zero mean and variance being σ_h^2, σ_f^2 and σ_g^2, respectively.

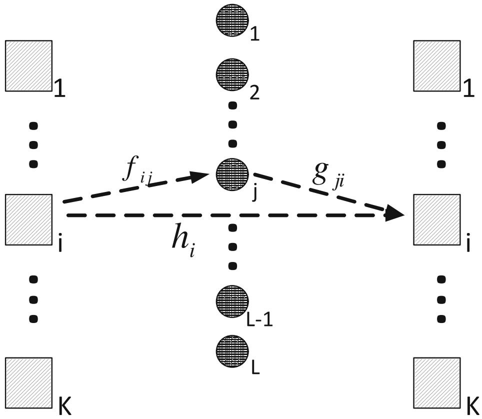

Fig. 1. Network model

In each source-to-destination transmission, say from the ith source to its destination, a relay, say the jth relay, aids the transmission. The maximal rate achieved as in [8] is that

$$\min\left(\log_2(1 + P_s|h_i|^2 + P_r|g_{ji}|^2), \log_2(1 + P_s|f_{ij}|^2)\right).$$

2.2 Basic Protocol Structure

Without delving into protocol details given in following sections, we present the basic protocol structure. In such network, all source-destination nodes follow a simplified carrier sensing multiple access with collision avoidance (CSMA/CA) mechanism and share a common channel for access. Similar mechanism is assumed in [7,9–11]. The DOCA/SP protocol, which describes the channel contention process of sources, is shown below.

At the beginning of a time slot with duration δ, each source independently contends to access the channel by sending a request-to-send (RTS) packet with probability p_0. In that time slot, there are three possible outcomes:

- **Idle:** If there is no source transmitting RTS in that slot (with probability $(1 - p_0)^K$), all sources continue to contend in next slot.
- **Collision:** If there are two or more sources transmitting RTSs (with probability $1-(1-p_0)^K - Kp_0(1-p_0)^{K-1}$), a collision happens. Then in the next slot after a CTS duration, all sources continue to contend.
- **Success:** If there is only one source, say Source i, transmitting RTS (with probability $Kp_0(1-p_0)^{K-1}$), this source is called *winner* of the channel contention.

As follows, we present the DOCA/SP protocol operation by steps upon successful channel contention slot.

On Receiving of the RTS from Source i: If the RTS from Source i is received by Destination i and each relay, the relays and Destination i can estimate the channel gain between Source i and itself. Then three options are available at the destination.

- *Stop:* If the channel gain of direct link is high enough, Destination i sends a CTS notifying that Source i transmits data to its destination without relaying.
- *Continue:* If the channel gain of direct link is low, Source i drops this transmission opportunity and re-contends the channel with other sources.
- *Defer:* Otherwise, Source i postpones by spending extra time for probing channels between relays and the destination, and makes subsequent decision.

Furthermore, we describe the subsequent operation when Destination i decides to defer.

1. *Send probing CTS:* Destination i decides the number of relays to probe, denoted by J, and sends a probing CTS notifying the J relays to probe second-hop channels.
2. *On receiving of the probing CTS:* If the relays receive a probing CTS, they take turns sending a probing RTS to Destination i, containing CSI of first-hop channels.
3. *On receiving of the RTS from relays:* After reception of the RTS from the relays, Destination i obtains channel gains from probed relays to itself, and collects the channel gains of both hops. Based on the information, through reward comparison between direct-link and relaying transmissions, referring to the traffic volume successfully transmitted, Destination i chooses a manner of higher reward to transmit.

Finally, Destination i decides to stop or continue.

- **Stop:** Destination i sends a CTS to Source i in designated manner as stated above.
- **Continue:** Destination i keeps silent, and other sources can detect an idle slot after the RTS-CTS exchange among Source i, the relays and Destination i. The idle slot tells other sources that Destination i decides to continue.

After a successful transmission, a new contention is started among all source nodes.

3 Decision Theoretical Approach Based on OSOPDT

In this section, based on *optimal sequential observation planned decision theory* (OSOPDT), the DOCA/SP problem is formulated as an OSOPD problem as in [12], and an analytic framework for finding optimal strategies is established, forming a whole course from observation to decision. On this basis, an optimal sequential observation plan decision rule is to be found maximizing the statistical average objective function, and further refined as an optimal strategy for the DOCA/SP problem.

3.1 Observation Process

As foundation of the analytic framework, sequential observation process is first formulated from dynamic process of multi-source channel contention and sequential probing of direct and relay channels. An observation is defined, associated with a sub-observation process.

Through problem analysis, an *observation process* is formed, and an observation starts from sources' channel contention and lasts until another channel contention. It is defined as the process of channel contention among all sources until a successful contention. In particular, for each observation, denoted as kth observation, a random time duration, denoted as $t_s(k)$ is spent until a winner source appears, denoted as $s(k)$. Channel gain in the direct link, denoted as $h_s(k)$, from itself to its destination is observed by the destination. In this respect, after kth observation, information denoted by $\mathscr{F}_k = \{s(k), h_{s(k)}(k), t_s(k)\}$ is obtained. As each round channel contention is independent, the number of contentions follows a geometric distribution with parameter $Kp_0(1-p_0)^{K-1}$. Among all the contentions for an observation, the last contention is successful, and its total duration is $\tau_{RTS}+\tau_{CTS}$. The quantities τ_{RTS} and τ_{CTS} are durations of an RTS and CTS, respectively. Any other contention is either an idle slot (with duration δ) or a collision (with duration τ_{RTS}). The mean of the duration of an observation is thus given as $\tau_o = \tau_{RTS}+\tau_{CTS}+\frac{(1-p_0)^K}{Kp_0(1-p_0)^{K-1}}\cdot\delta+\frac{1-(1-p_0)^K-Kp_0(1-p_0)^{K-1}}{Kp_0(1-p_0)^{K-1}}\cdot\tau_{RTS}$.

After each observation, by protocol structure described in Subsect. 2.2, the destination of winner source obtains CSI from the source to itself, and then has three options: to stop, defer or continue. The information obtained also depends on these options. In particular, for kth observation, the winner source $s(k)$ could obtain at maximum full information, denoted by

$$\mathscr{G}_k(L) = \{f_{s(k)1}(k), g_{1s(k)}(k), ..., f_{s(k)L}(k), g_{Ls(k)}(k)\},$$

where h, f and g with index (k) denote channel gain realizations after kth channel contention success, respectively. With the observation index $k = 1, 2, ..., \infty$, an observation information sequence $\{\mathscr{G}_k(L)\}_{k=1,2,...,\infty}$ is defined, and $\{\mathscr{F}_k \vee \mathscr{G}_k(L)\}_{k=1,2,...,\infty}$ represents all information observed through the whole course of a successful transmission[1].

3.2 Sub-observation Process

It is found that, for each observation from successful channel contention, relay channel information to obtain for each observation is dynamic, determined by relay probing decision. In particular, after kth observation, different information $\{\mathscr{G}_k(j)\}_{j=1,2,...,L}$ of relay channels may be observed, depending on number of probed relays. The following three cases exist, as observation process couples with decision on channel probing and access.

- If to stop, observation process ends and no further information is observed.

[1] The symbol $\vee$ represents the union of information.

- If to continue, the winner source re-contends the channel, and next observation will be after another success of multiple sources channel contention.
- If to defer, the winner source decides relays number to probe, and further observation occurs. Upon decision to probe J relays, first J relays are probed and information $\mathscr{G}_k(J)$ is observed at cost of an extra time $J \cdot \tau_{RTS} + \tau_{CTS}$. By obtaining extra CSI of relay channels, the destination calculates the maximal achievable rate using the relays, and access the channel during duration $\tau_d - \tau_{CTS} - J \cdot \tau_{RTS}$. The duration τ_d denotes the channel coherence time minus a CTS duration, as a CTS sent after channel gain estimation of the direct link and first-hop link. Thereafter, the source has to decide to either stop or continue.

Therefore, to model the dynamic decision process as stated above, a new observation process of finer granularity is required, enabling the smart probing decision after each observation. Motivated by that, for each observation, two *sub-observations* are defined. We use n to denote the sub-observation index. For kth observation, the first sub-observation, i.e. sub-observation $n = 2k - 1$ is defined, and information $\mathscr{F}_k$ is obtained. The second sub-observation, i.e. sub-observation $n = 2k$ is also defined, and at maximum full channel information $\mathscr{G}_k(L)$ is obtained. It is worth noting that, the second sub-observation is determined by decision of smart relay probing.

Along the index n, a sub-observation process is formed from the observations along index k, and decision process of smart relays probing can be analysed on this basis. Specially, after kth channel contention success, a winner source can decide if to stop or further probe. If to observe, the number J of relays to probe is optimized based on history information of the sub-observation process until time index $n = 2k - 1$. In details, a decision $J = 0$ means not probing relay and letting sources re-contend the channel, while $J > 0$ means probing J relays, obtaining observation information $\mathscr{G}_k(J)$.

3.3 Observation Plan and Objective Function

Based on built-up sub-observation process, we are finding out an optimal sequential plan decision rule, based on which an optimal DOCA/SP strategy is derived.

We define a *sequential observation plan*, denoted by $\mathbf{a} = (a_1, a_2, ..., a_n)$ for $n \in \mathbb{N}$. The plan $\mathbf{a}$ represents a sequence with respect to the sub-observation process. Its domain is that

$$\mathbb{A} \triangleq \Big\{(a_1, a_2, ..., a_j) : j \in \mathbb{N}, a_{2k-1} = 1, a_{2k} \in \{0, 1, 2, ..., L\}, \forall k \leq \lceil \frac{j}{2} \rceil \Big\}.$$

The symbol $\mathbb{N}$ denotes a set including all positive integers and 0[2]. For the plan, $a_{2k-1} = 1$ means that, at sub-observation $n = 2k - 1$, sources contend the channel, and a source wins the channel and obtains CSI of the direct link. $a_{2k} \in \{0, 1, ..., L\}$ means that, at sub-observation $n = 2k$, the winner source has to

[2] When $j = 0$, the sequence $(a_1, a_2, ..., a_j)$ does not exit, and is denoted as $()$.

decide whether to probe relay channels ($a_{2k} > 0$) or not ($a_{2k} = 0$). To probe relays, how many channels to observe is further to decide, i.e. $a_{2k} \in \{1, 2, ..., L\}$. An instance of an observation plan is $(a_1, a_2, ..., a_{2k+1}) = (1, 2, 1, 1, ..., 1, 0, 1)$.

Moreover, an observation plan associates with observed information. Until nth sub-observation, the information obtained by a plan $\mathbf{a} = (a_1, a_2, ..., a_n)$ is denoted as $\mathscr{B}_{\mathbf{a}}$. In it, for $n = 2k-1$, the information is[3] $\mathscr{B}_{\mathbf{a}} = (\vee_{m=1}^{k} \mathscr{F}_m) \vee \big(\vee_{m=1}^{k-1} \mathscr{G}_m(a_{2m})\big)$, and for $n = 2k$, the information is $\mathscr{B}_{\mathbf{a}} = (\vee_{m=1}^{k} \mathscr{F}_m) \vee \big(\vee_{m=1}^{k} \mathscr{G}_m(a_{2m})\big)$.

Based on observation plan and information observed, reward function is defined reflecting the system throughput of DOCA/SP. In particular, after nth sub-observation, observation plan $\mathbf{a}$ is experienced, and a reward is obtained after a successful transmission, which refers to the maximal total traffic volume sent by the winner source in the transmission round. We denote the reward by $Y_{\mathbf{a}}$, which is a deterministic function based on information $\mathscr{B}_{\mathbf{a}}$. Meanwhile, a time cost $T_{\mathbf{a}}$ is also spent, referring to the total waited time from the first observation until nth sub-observation plus the data transmission duration. If it is to stop after the observation plan $\mathbf{a}$, an instantaneous system throughput $Y_{\mathbf{a}}/T_{\mathbf{a}}$ is obtained.

Based on definitions above, we define the optimal DOCA/SP strategy and formulate the statistical optimization problem as follows. Symbol N aligning with previous work [7] denotes an DOCA/SP strategy. Notably, such strategy differs from the stopping rule in the research before. Particularly, under optimal stopping theory, the problem on when to stop barely matters, in which the stopping rule N takes a integer value. However, in our research an optimal strategy of a sequence plan is to find, and the optimal rule takes a plan $\mathbf{a}$.

Following an DOCA/SP strategy N, after each round successful transmission, a traffic volume Y_N and time cost T_N are obtained. In the long term, by the law of large number, the time average system throughput will converge in full probability (i.e. almost surely) to the statistical average throughput, satisfying that

$$\lim_{t\to\infty} \frac{Y_N(1) + Y_N(2) + \cdots + Y_N(t)}{T_N(1) + T_N(2) + \cdots + T_N(t)} \xrightarrow{a.s.} \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]}.$$

Here $\mathbb{E}[\cdot]$ means expectation.

In the following section, the goal is to find an optimal DOCA/SP strategy N^* which attains the maximal average system throughput[4] $\sup\limits_N \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]}$.

4 Optimal DOCA/SP Strategy

In this section, an optimal DOCA/SP strategy for the distributed cooperative network is derived, maximizing the average system throughput in steps under the analytic framework in Sect. 3. The procedure is as follows. The objective

[3] The symbol $\vee_{m=1}^{n}$ can be understood as the union of information.

[4] Note that the supreme may not be attainable, while the maximum is defined as the attainable supreme.

function of fractional form is first transformed into a price-based function, upon which an optimal rule is then derived. Taking advantage of special traits of the practical problem, analysis is carried out, refining the optimal rule into an optimal DOCA/SP strategy. At last, implementation of the strategy is investigated guaranteeing feasibility and practicability.

4.1 Equivalent Transformation

Recognizing that the average throughput maximization problem is analytically intractable, it is transformed into another problem of a price-based objective function. We use $Z_{\mathbf{a}}(\lambda)$ and $Z_N(\lambda)$ to denote transformed rewards $Y_{\mathbf{a}} - \lambda T_{\mathbf{a}}$ and $Y_N - \lambda T_N$, respectively. The argument λ is the price charged on the time spent. For a given price $\lambda > 0$, a strategy for the transformed objective function is denoted by $N(\lambda)$, and an optimal strategy is denoted as $N^*(\lambda)$. The relation between the original and transformed problems is given below.

Lemma 1. *A strategy $N^*(\lambda^*)$ maximizing the expected reward $\mathbb{E}[Z_N(\lambda^*)]$ such that $\sup_N \mathbb{E}[Z_N(\lambda^*)] = 0$ is optimal which achieves the maximal average system throughput. The price λ^* is the maximal average system throughput, and uniquely exists satisfying $\sup_N \mathbb{E}[Z_N(\lambda^*)] = 0$.*

In accordance with the lemma above, the main train for solving the DOCA/SP problem is enlightened. For a given price $\lambda > 0$, an optimal strategy is first acquired achieving $\sup_N \mathbb{E}[Z_N(\lambda)]$. Then, by replacing λ with λ^*, the strategy $N^*(\lambda^*)$ is a solution for the DOCA/SP problem.

4.2 Optimal Sequential Plan Decision Rule

Based on the framework described in Sect. 2, an optimal observation plan decision rule is derived in this subsection. After kth channel contention success, at sub-observation $n = 2k-1$, the instantaneous reward $Y_{\mathbf{a}}$ is $\tau_d R_d(k)$, which refers to the traffic volume sent in direct link at rate $R_d(k) = \log_2\left(1 + P_s|h_{s(k)}(k)|^2\right)$.

And at sub-observation $n = 2k$, if relay(s) probed, i.e. $a_n > 0$, the instantaneous reward $Y_{\mathbf{a}}$ is $(\tau_d - \tau_{CTS} - a_n \cdot \tau_{RTS}) \cdot \max\left\{R_d(k), R_r(k)/2\right\}$. It refers to the maximal traffic volume transmitted over both direct and relay channels. The symbols $R_d(k)$ and $R_r(k)$ denote transmission rates by direct and relaying transmission, respectively. For instance, under single relay transmission, say a transmission from Source i to its destination and jth relay is used, the rate $R_r(k)$ is calculated as

$$\min\left\{\log_2(1 + P_s|h_i(k)|^2 + P_r|g_{ji}(k)|^2), \log_2(1 + P_s|f_{ij}(k)|^2)\right\}.$$

For multiple relays transmission, the rate $R_r(k)$ denotes the maximal achievable rate. It is attained through optimal multi-relay selection based on instantaneous channels conditions.

On the other hand, if the winner source does not probe relay, i.e. $a_n = 0$, the reward is defined as $Y_{\mathbf{a}} = -\infty$. In this case, the winner source will not let the source transmit, but drops transmission opportunity and re-contending the channel with other sources.

Correspondingly, the time cost until sub-observation n is calculated as

$$T_{\mathbf{a}} = \sum_{l=1}^{k} t_s(l) + \sum_{l=1}^{k-1} \big(\mathbb{I}[a_{2l} > 0] \cdot \tau_{CTS} + a_{2l} \cdot \tau_{RTS}\big) + \tau_d.$$

It denotes the total time spent if a source transmits.

To avoid abasement, several notations and relations are provided as necessary. For an arbitrary observation sequence $\mathbf{a} = (a_1, a_2, ..., a_j)$ and an integer m, $(\mathbf{a}, m)$ denotes a prolonged sequence $(a_1, a_2, ..., a_j, m)$. A relation between any two sequential plans is specified as that: for plans $\mathbf{a}$ and $\mathbf{b}$, $\mathbf{b} \geq \mathbf{a}$ means $b_i = a_i$ for $\forall 1 \leq i \leq |\mathbf{a}|$. We also denote $A_{\mathbf{a}}$ as the set of actions following the plan $\mathbf{a}$.

For a plan $\mathbf{a}$, we define $V_{\mathbf{a}} = \sup\limits_{j \in A_{\mathbf{a}}} \mathbb{E}[U_{(\mathbf{a},j)} | \mathscr{B}_{\mathbf{a}}]$ and $U_{\mathbf{a}} = \sup\limits_{\mathbf{b} \geq \mathbf{a}} \mathbb{E}[Z_{\mathbf{b}} | \mathscr{B}_{\mathbf{a}}]$. In particular, $V_{\mathbf{a}}$ represents the maximal average reward if not stop at plan $\mathbf{a}$ conditioned on observed information. $U_{\mathbf{a}}$ represents the maximal average reward conditioned on observed information. Notably, for an observation plan with $|\mathbf{a}| = 0$ (i.e. without making any channel probing), the expected reward $U_{\mathbf{a}}$ (i.e. $U_{()}$) is denoted as U_0 and $U_0 = \sup\limits_{N} \mathbb{E}[Z_N]$.

Based on definitions as above, an optimal rule is derived in Theorem 1.

Theorem 1. *For any price $\lambda > 0$, an optimal sequential plan decision rule is in form that: starting from $|\mathbf{a}| = 0$, at sub-observation n, it is optimal to stop with $N^* = \mathbf{a}$ when $Z_{\mathbf{a}} \geq V_{\mathbf{a}}$, or continue otherwise. Furthermore, if continue at $n = 2k - 1$, it is optimal to update sequential plan by $\mathbf{a} = (\mathbf{a}, J^*)$ where $J^* := \min\{0 \leq j \leq L : U_{(\mathbf{a},j)} = V_{\mathbf{a}}\}$. If continue at $n = 2k$, sequential plan is updated by $\mathbf{a} = (\mathbf{a}, 1)$.*

4.3 Further Analysis on the Optimal Rule

Based on the optimal rule, we derive an optimal strategy for DOCA/SP problem in the distributed cooperative network. By observing the optimal rule, threshold functions are crucial, with respect to which statistical characteristics of the system model is studied to solve. Bellman equations are used to calculate these thresholds.

For a sequential plan $\mathbf{a}$, thresholds $V_{\mathbf{a}}$ and $U_{\mathbf{a}}$ can be calculated from Bellman Equation [12, Chapter 2]. In particular, thresholds $V_{\mathbf{a}}$ and $U_{\mathbf{a}}$ satisfy that

$$U_{\mathbf{a}} = \max\{Z_{\mathbf{a}}, V_{\mathbf{a}}\} = \max\big\{Z_{\mathbf{a}}, \sup_{j \in A_{\mathbf{a}}} \mathbb{E}[U_{(\mathbf{a},j)} | \mathscr{B}_{\mathbf{a}}]\big\}. \quad (1)$$

Since the action set $A_{\mathbf{a}}$ for plan $\mathbf{a}$ depends on length of $\mathbf{a}$, Bellman Equation has two expressions, which are analysed respectively as follows.

Expression 1: For an odd length $|\mathbf{a}| = 2k-1$, Eq. (1) is rewritten as

$$U_{\mathbf{a}} = \max\big\{Z_{\mathbf{a}}, \max_{j\in\{0,1,\ldots,L\}} \mathbb{E}[U_{(\mathbf{a},j)}|\mathscr{B}_{\mathbf{a}}]\big\}. \tag{2}$$

Expression 2: For an even length $|\mathbf{a}| = 2k$, Eq. (1) is rewritten as

$$U_{\mathbf{a}} = \max\big\{Z_{\mathbf{a}}, \mathbb{E}[U_{(\mathbf{a},1)}|\mathscr{B}_{\mathbf{a}}]\big\}. \tag{3}$$

In accordance with expressions above, thresholds are represented by observed information $\mathscr{B}_{\mathbf{a}}$. Recalling that such information includes information on sources' channel contention, direct link and relays channel gains, and using the relation between two expressions, Expression 2 is analyzed in advance below.

Based on $U_{\mathbf{a}}$ in Expressions 1 and 2, the threshold $V_{\mathbf{a}}$ is derived by its definition.

Based on expressions analysis, thresholds $\{U_{\mathbf{a}}, V_{\mathbf{a}}\}$ in Theorem 1 are represented. According to Theorem 1, an optimal strategy is derived as follows.

Theorem 2. *For a given price $\lambda > 0$, an optimal strategy has the structure that: after kth successful channel contention with $k \in \mathbb{N}$, at sub-observation $2k-1$,*

- *if the immediate reward $\tau_d R_d(k) - \lambda\tau_d \geq M_j\big(R_d(k)\big)$ for all $j = 1, 2, ..., L$ and $\tau_d R_d(k) - \lambda\tau_d \geq U_0$, stop and transmit over direct link.*
- *if the expected reward $U_0 > \max\big\{\tau_d R_d(k) - \lambda\tau_d, \max_{j=1,2,\ldots,L} M_j\big(R_d(k)\big)\big\}$, continue without probing relays and skip to sub-observation $2k+1$.*
- *otherwise, continue by probing J^* relays with $J^* = \min\big\{j \in \{1, 2, ..., L\} : M_j\big(R_d(k)\big) = \max_{l=1,2,\ldots,L} M_l\big(R_d(k)\big)\big\}$.*

then, at sub-observation $2k$,

- *if the immediate reward $\big(\tau_d - \tau_{CTS} - J^* \cdot \tau_{RTS}\big)\max\big\{R_d(k), R_r(k)/2\big\} \geq U_0 + \lambda\big(\tau_d - \tau_{CTS} - J^* \cdot \tau_{RTS}\big)$, then stop;*
- *otherwise, to continue.*

Optimal Multi-relay Relaying Transmission. The procedure of multi-relay transmission is as follows. After each time channel contention success and relays probing, channel gains of direct and 2-hop channels are obtained by the winner source. A two-phase time division relaying transmission is used. Particularly, after kth successful channel contention, and for $J \in \{1, 2, ..., L\}$ relays under distributed beam-forming, the maximal transmission rate $R_r(k)$ or more specifically denoted by $R_r^J(k)$. Therein, $\{\gamma_1 \geq \gamma_2 \geq \cdots \geq \gamma_J\}$ are descending ordered, from channel gains in the fist-hop $\{|f_{s(k)1}(k)|^2, |f_{s(k)2}(k)|^2, ..., |f_{s(k)J}(k)|^2\}$. And after ordering, channel gains in the second hop are permuted, and channel gains are regenerated, denoted by $\{|g_{\sigma_1 s(k)}|^2, |g_{\sigma_2 s(k)}|^2, ..., |g_{\sigma_J s(k)}|^2\}$. The permutation function σ maps the index j to σ_j. Also, for $u = 1, 2, ..., J$, sets are denoted that $A_u = \big[\gamma_u \leq \sum_{j=1}^{u} P_r|g_{\sigma_j s(k)}(k)|^2 + P_s|h_{s(k)}(k)|^2\big]$ and $B_u = \big[\gamma_u \leq \sum_{j=1}^{u-1} P_r|g_{\sigma_j s(k)}(k)|^2 + P_s|h_{s(k)}(k)|^2\big]$. The operator $\bar{(\cdot)}$ denotes the supplement set.

Reward and Threshold Relationship. Based on the maximal rate as above, threshold comparison given in Theorem 2 is further studied. To simplify the optimal strategy in terms of complexity, relations between the instantaneous reward and thresholds are analysed. In this regard, we investigate thresholds properties.

Firstly, the monotonicity of threshold functions $M_j(R_d)$ for $j = 1, 2, ..., L$ are considered. When j relays are probed, the expected reward $M_j(R_d(k))$ conditioned on direct-link channel gain $|h_{s(k)}(k)|^2 = h_s$ is calculated as

$$M_j(R_d) = \mathbb{E}\big[\max\big\{(\tau_d - \tau^j)\cdot\max\{\log_2(1+h_s), R_r^j(k)/2\} - \lambda\tau_d, U_0 - \lambda\tau^j\big\}\big]. \quad (4)$$

Since R_r increases with h_s and two-hop channel gains of relay channels are independent of R_d, function $M_j(R_d)$ is strictly increasing over h_s.

As follows, we investigate the monotonicity of threshold functions $M_j(h_s) - \big(R_d(h_s)\tau_d - \lambda\tau_d\big)$ for $j = 1, 2, ..., L$. They represent difference between the expected reward by probing j relays channels and the immediate reward by direct channel transmission. It is rewritten as

$$\begin{aligned} &M_j(h_s) - \big(R_d(h_s)\tau_d - \lambda\tau_d\big) = \\ &\mathbb{E}\big[\max\big\{(\tau_d - \tau^j)\max\big\{0, R_r(h_s)/2 - R_d(h_s)\big\} - R_d\big(h_s\big)\tau^j, \\ &\qquad U_0 + \lambda(\tau_d - \tau^j) - R_d(h_s)\tau_d\big\}\big]. \end{aligned} \quad (5)$$

By observing the right-side of (5), it suffices to prove decreasing monotonicity of $\frac{1}{2}R_r(h_s) - R_d(h_s)$.

When j relays are probed, there are in total 2^j combinations, which are used for cooperative transmission. We use notations $\mathcal{J}_l$ to denote lth combination with $l \in \{1, 2, ..., j\}$. The difference between rates in relaying and in direct transmission, is calculated as

$$\begin{aligned} &\frac{1}{2}R_r(h_s) - R_d(h_s) = \frac{1}{2}\cdot\max_{l=1,2,\ldots,2^j} \\ &\log_2\frac{1+\min\big(\min\limits_{m\in\mathcal{J}_l} P_s|f_{s(k)m}|^2, \sum\limits_{m\in\mathcal{J}_l} P_r|g_{ms(k)}|^2 + P_s h_s\big)}{(1+P_s h_s)^2}. \end{aligned}$$

It is observed that the above function is decreasing over h_s. And in the right-side of (5), other components are subtracted by either $R_d(h_s)\tau^j$ or $R_d(h_s)\tau_d$ which increases with h_s. And the decreasing monotonicity of (5) over h_s is proved.

Based on the monotonicity properties, the relation between thresholds $\{M_j(R_d)\}$, $j = 1, ..., L$, rewards $R_d(h_s)\tau_d - \lambda\tau_d$ and U_0 is then investigated to refine the optimal strategy into a channel-gain threshold-based strategy.

In particular, when[5] $h_s \to -\infty$, for a number $j \in \{1, 2, ..., L\}$ of probed relays, by Eq. (4) we have $\lim_{h_s \to -\infty} M_j\big(h_s\big) = U_0 - \lambda \tau^j$, and when $h_s \to \infty$, we have $\lim_{h_s \to \infty} M_j(R_d) = \infty$.

Therefore, using increasing monotonicity, there exists a unique threshold, denoted as h_j^* such that $M_j(h_j^*) = U_0$ for $j \in \{1, 2, ..., L\}$. For $h_s \geq h_j^*$, we have $M_j(R_d) \geq U_0$, while for $h_s < h_j^*$, we have $M_j(R_d) < U_0$.

Moreover, when $h_s \to -\infty$, for $j \in \{1, 2, ..., L\}$ we have

$$\lim_{h_s \to -\infty} M_j(R_d) - \tau_d R_d(h_s) + \lambda \tau_d = \infty,$$

and when $h_s \to \infty$, we have

$$\lim_{h_s \to \infty} M_j(R_d) - \tau_d R_d(h_s) + \lambda \tau_d = -\infty.$$

Therefore, by the decreasing monotonicity, there exits a unique threshold $h_j^\dagger$ such that $M_j(h_j^\dagger) = \tau_d R_d(h_j^\dagger) - \lambda \tau_d$. For $h_s \geq h_j^\dagger$, we have $M_j(R_d) \leq \tau_d R_d - \lambda \tau_d$, while for $h_s < h_j^\dagger$, we have $M_j(R_d) > \tau_d R_d - \lambda \tau_d$.

As specified above, quantities $\{h_j^*, h_j^\dagger\}_{j=1,2,...,L}$ are interactions of the reward and threshold functions over the direct channel gain h_s, which are pure channel-gain based thresholds.

4.4 Refined Optimal Strategy for Transformed Problem

Using channel-gain based thresholds, the optimal strategy in Theorem 2 can be significantly simplified, and an optimal strategy of threshold-based structure is derived in Theorem 3.

Theorem 3. *For a price $\lambda > 0$, an optimal strategy for the transformed problem is of channel-gain based threshold structure as follows.*

Structure 1: *If $\min_{j=1,2,...,L} h_j^* \leq \max_{j=1,2,...,L} h_j^\dagger$, after kth successful channel contention where $k \in \mathbb{N}$, each winner source obtains direct link channel gain h_s and operates as that:*

- *if $h_s \leq \min_{j=1,2,...,L} h_j^*$, it is optimal to give up transmission and re-contend with other sources.*
- *if $h_s \in \big(\min_{j=1,2,...,L} h_j^*, \max_{j=1,2,...,L} h_j^\dagger\big)$, it is optimal to probe number of relays such that*
  $J^* := \min\big\{1 \leq j \leq L : M_j(R_d) = \max_{l=1,2,...,L} M_l(h_s)\big\}$. Then, if J^* relay(s) are probed, when $(\tau_d - \tau^{J^*}) \max\{R_d(h_s), \frac{1}{2} R_r(h_s)\} \geq U_0 + \lambda(\tau_d - \tau^{J^*})$, it is optimal to stop, or continue otherwise.

[5] It notes that, since $h_s \geq 0$ always holds, the negative value is not valid. However, the analysis makes sense for checking the monotonic property and obtaining theoretic bounds for $M_j\big(R_d\big)$.

– *if* $h_s \geq \max_{j=1,2,\ldots,L} h_j^\dagger$, *it is optimal to transmit directly without relaying.*

Structure 2: *If* $\min_{j=1,2,\ldots,L} h_j^* > \max_{j=1,2,\ldots,L} h_j^\dagger$, *the optimal strategy degrades into a simple form as that: after* k*th successful channel contention where* $k \in \mathbb{N}$, *it operates as that:*

– *if* $\tau_d R_d(h_s) - \lambda\tau_d \leq U_0$, *it is optimal to transmit in direct link.*
– *otherwise, to continue.*

The maximal expected reward U_0 *is uniquely determined by the equation that*

$$U_0 = \mathbb{E}\big[\max\big\{\tau_d R_d - \lambda\tau_d, U_0, \max_{j=1,2,\ldots,L} M_j(R_d)\big\}\big] - \lambda\tau_o.$$

Based on above theorem, we denote $h^* \triangleq \min_{j=1,2,\ldots,L} h_j^*$ and $h^\dagger \triangleq \max_{j=1,2,\ldots,L} h_j^\dagger$, respectively. They are determined by channel characteristics and number of relays to probe. Correspondingly, we also denote $\max_{j=1,2,\ldots,L} M_j(R_d)$ as $M^*(R_d)$.

Unique existence of channel-gain thresholds in Theorem 3 is guaranteed by the following Lemma.

Lemma 2. *For any price* $\lambda > 0$, *the array of solution* $\{U_0, h^*, h^\dagger\}$ *satisfying threshold relation* $h^* \leq h^\dagger$ *is unique if it exits; moreover, the solution* U_0 *is unique if* $h^* > h^\dagger$.

As the relation of h^* and $h^\dagger$ reflects structure of the optimal strategy as shown in Theorem 3, the decision criteria is given in Theorem 4. The function $M^*\big(y, r\big)$ is equivalently transferred from $M^*\big(R_d(h_s)\tau_d, r\big)$, where y represents the immediate reward $R_d(h_s)\tau_d - \lambda\tau_d$.

With F_0 denoted as cumulative distribution function (CDF) of h_s following an exponential distribution, a special factor r_0 uniquely exists, such that

$$r_0 = r_0 \cdot F_0\big(R_d^{-1}(\frac{r_0}{\tau_d} + \lambda)\big) + \int_{R_d(x)-\lambda=r_0/\tau_d}^{\infty} \big(R_d(x)\tau_d - \lambda\tau_d\big) dF_0(x) - \lambda\tau_o. \quad (6)$$

Theorem 4. *If* $M^*(r_0, r_0) > r_0$, $h^* \leq h^\dagger$ *satisfies and by the optimal strategy each winner source will probe relay(s) when* $h_s \in (h^*, h^\dagger)$; *otherwise,* $h^* > h^\dagger$ *satisfies and the optimal strategy degrades to a simple form where relay probing is discarded.*

4.5 Optimal DOCA/SP Strategy and Its Implementation

Optimal DOCA/SP Strategy. By replacing the price λ by λ^* such that $U_0(\lambda^*) = 0$, an optimal DOCA/SP strategy is obtained.

For a given price $\lambda > 0$, we solve the following equation to derive expected reward $U_0(\lambda)$:

$$U_0(\lambda) = \mathbb{E}\big[\max\big\{\tau_d R_d - \lambda\tau_d, U_0(\lambda), M^*(R_d)\big\}\big] - \lambda\tau_o. \tag{7}$$

Decision criteria $M^*(r_0(\lambda), r_0(\lambda)) > r_0(\lambda)$ by Theorem 4 needs to determine, and depending on the optimal strategy structure, two cases exist in calculating value of $U_0(\lambda)$:

- if criteria satisfied, $U_0(\lambda)$ is calculated through solving the equations, where a unique solution $\{U_0(\lambda), h^*(\lambda), h^\dagger(\lambda)\}$ is guaranteed;
- otherwise, $U_0(\lambda)$ is equal to $r_0(\lambda)$ satisfying Eq. (6).

For both cases, unique existence of $U_0(\lambda)$ is guaranteed by Lemma 2.

Then, being a specific λ such that $U_0(\lambda) = 0$, the maximal average throughput λ^* is uniquely calculated in accordance with Lemma 1. Replacing price λ with λ^*, an optimal DOCA/SP strategy is derived, and it operates as follows.

In such a distributed network with multiple DF relays, all sources randomly contend the channel. After the kth channel contention success, a source, say Source $s(k)$ wins the channel, and obtains direct link channel gain h_s, then

- if $M^*\big(r_0(\lambda^*), r_0(\lambda^*)\big) > r_0(\lambda^*)$,
  - if $h_s \le h^*(\lambda^*)$, it gives up the transmission opportunity and re-contends the channel with other sources.
  - if $h_s \in \big(h^*(\lambda^*), h^\dagger(\lambda^*)\big)$, it spends an extra duration τ^{J^*} to probe the first $J^* := \min\big\{j \in \{1, 2, ..., L\} : M_j(R_d) = \max_{l=1,2,...,L} M_l(h_s)\big\}$ relays. After probing those relays, if $\max\{R_d, \frac{1}{2}R_r(k, J^*)\} \ge \lambda^*$, the winner source transmits in cooperation; otherwise, it gives up the transmission opportunity and re-contends the channel with other sources. When the source transmits, a factor value is embedded in the CTS from the destination used for beam-forming[6]. Then, following procedure is used for channel access of duration $\tau_d - \tau^{J^*}$:
    1. in the first-half duration, the winner source transmits data to all relays and the destination;
    2. in the second-half duration, the relay(s) able to decode the transmitted data forwards its received data to the destination by signal processing using optimal beam-forming.
  - if $h_s \ge h^\dagger(\lambda^*)$, it transmits over direct link without spending extra time to probe relays.
- if $M^*\big(r_0(\lambda^*), r_0(\lambda^*)\big) \le r_0(\lambda^*)$,
  - if $R_d \ge \lambda^*$, it transmits directly.
  - otherwise, it gives up the transmission opportunity and re-contends the channel with other sources.

[6] The factor is norm of beam forming vector in the second hop.

5 Performance Evaluation

This section uses computer simulation results to validate the results above. Consider 5 source-destination pairs and multiple relays in the distributed cooperative network. Channels from sources to each relay, from sources to destinations experience i.i.d. Rayleigh fading, while channels from the relays to destinations also experience i.i.d. Rayleigh fading. Channel contention parameters of source nodes are set as $p_0 = 0.3$, $\delta = 25$ µs, $\tau_{RTS} = \tau_{CTS} = 50$ µs.

The average system throughput of proposed DOCA/SP strategy for the distributed cooperative network is verified. The average received signal-to-noise ratio (SNR) of direct link is σ_h^2, the average received SNR of first-hop and second-hop relay channels are σ_f^2 and σ_g^2, respectively. We consider a scenario where $\sigma_f^2 = 4 \cdot \sigma_h^2$, $\sigma_g^2 = 2 \cdot \sigma_h^2$. By simulating based on various values on the main impact factors, the analytical system throughput and system throughput achieved by the proposed DOCA/SP strategy is compared. Firstly, when the average SNR σ_h^2 varies from 2dB to 8dB, the two-line result in the top of Table 1 shows the numerically calculated (shown as 'analytical') and simulated (shown as 'simu') system throughput achieved by the proposed strategy. Secondly, we consider the scenario where $\sigma_h^2 = 5\,\text{dB}$, $\sigma_f^2 = 30\,\text{dB}$ and $\sigma_g^2 = 20\,\text{dB}$. By varying the number of relays from single ($L = 1$) to multiple relays ($L = 7$), the two-line result in the middle of Table 1 show the numerically calculated and simulated system throughput. Thirdly, scenario with $\sigma_h^2 = 5$ dB, $\sigma_f^2 = 30$ dB, $\sigma_g^2 = 20$ dB and $L = 6$ is considered. When channel coherence time τ_d increases from 1 ms to 4 ms, the two-line result in the bottom of Table 1 show the numerically calculated and simulated system throughput. In these three scenarios, it can be seen that the analytical and simulation results match well, confirming accuracy of the analysis of the proposed strategy. As the analytical results are the optimal value, the optimality of proposed strategy s is verified. And it is also found that: (1) the average system throughput increases when SNR increases; (2) average system throughput increases when channel coherence time increases; (3) average system throughput increases if more relays are deployed.

Table 1. System throughput match

σ_h^2	2 dB	4 dB	6 dB	8 dB
analytical	1.7673	2.1626	2.6834	3.2790
simu	1.7646	2.1634	2.6823	3.2749
Duration of τ_d	1 ms	2 ms	3 ms	4 ms
analytical	2.4957	3.1688	3.4989	3.6853
simu	2.4998	3.1644	3.4904	3.6860
Number of relays	1	3	5	7
analytical	2.9521	3.3583	3.4790	3.5016
simu	2.9569	3.3574	3.4776	3.4979

To check performance enhancement by the proposed strategy, we compare system performance with alternative strategies. Two strategies are investigated: (1) No-wait strategy: a winner source has full CSI, including CSI of direct link and all relays channels, and it always transmits using the best achievable rate; (2) Optimal-single-relay (OSR) strategy: it is similar to our proposed strategy with two major differences. Each winner source will probe all relays when defer is selected, and rather than multiple relays selection, best single-relay selection is used for relaying transmission.

In simulation, we consider a scenario where relay channels statistics are $\sigma_f^2 = 6 \cdot \sigma_h^2$ and $\sigma_g^2 = 3 \cdot \sigma_h^2$. For a fixed duration of τ_d (i.e. τ_d = 1 ms, 2 ms, 3 ms, 4 ms), when the direct-link average SNR σ_h^2 varies from 1 dB to 5 dB, the *stopping gain* is calculated, expressed by the ratio of performance increase by the proposed optimal strategy when compared with the average system throughput of No-wait strategy. The results are shown in Table 2. It is seen that the optimal strategy has obvious benefit in improving system throughout. Moreover, a trend shows that, when the average SNR of direct channel increases, the stopping gain decreases.

Figure 2 shows average system throughput of our proposed strategy and those of the OSR strategy. It is shown that, for the scenario with single relay deployed, the proposed optimal strategy is equivalent to the OSR strategy, and thus the same performance is obtained. For fixed number of relays from $L = 3$ to $L = 7$, the proposed OCA strategy performs better than that of OSR strategies. Particularly, the performance enhancement by the proposed strategy becomes larger when relays being deployed increase. Such phenomenon can be explained as follows. Through multiple relays selection transmission optimization, the proposed strategy exploits relays channels information better. Operated under the proposed strategy, each winner source dynamically selects the best number of relays to probe and transmit. By doing this, trade-off between channel information exploitation and overhead in such information collection is well balanced. In Fig. 2, when more relays are deployed for opportunistic transmission, average system throughput of the proposed optimal strategy remains increasing. However, as relays increase, the system throughput of the OSR strategy shows an opposite trend. The OSR strategy under scenario $L = 5$ performs better than $L = 7$, which is explained that, using the single best-relay selection, there is a sharper trade-off between relay channel exploitation and information overhead. It means that, overhead for probing most L relays channels dominates the benefit of system throughput.

Table 2. Stopping gain on average throughput

Duration of τ_d	1 dB	2 dB	3 dB	4 dB	5 dB
1 ms	84.81%	65.31%	49.10%	38.22%	33.28%
2 ms	49.12%	36.56%	24.98%	16.16%	10.77%
3 ms	52.26%	33.61%	25.45%	13.53%	8.15%
4 ms	56.47%	40.50%	24.50%	15.03%	11.14%

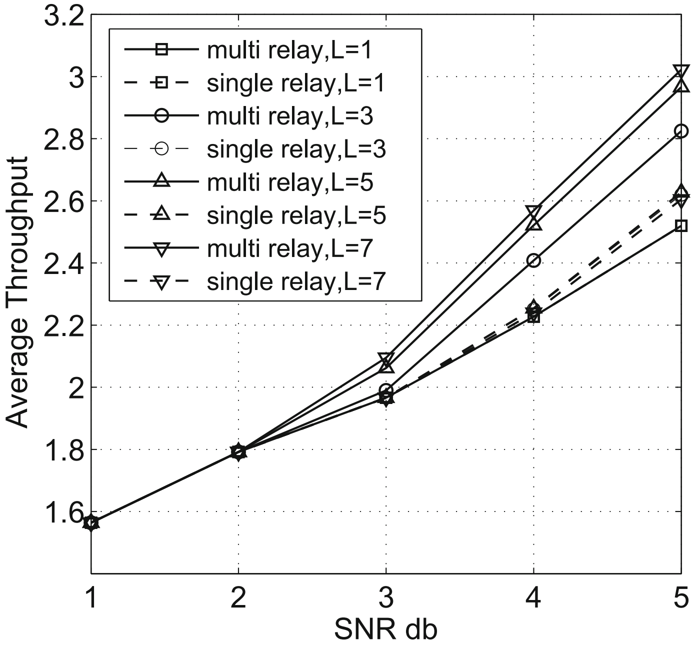

Fig. 2. Comparison between our proposed and OSR strategy

6 Conclusion

In a wireless ad-hoc cooperative network with multiple relaying, independent channel fading is experienced between all source-destination pairs and multiple relays being deployed. To improve the spectrum efficiency, a joint and efficient exploitation of the multi-source diversity, multi-relay cooperative diversity and time diversity is desired, and thus opportunistic channel access managing multiple sources and relays transmission is motivated. To harvest the full exploitation of these diversities, the DOCA problem with smart relays probing is investigated in this research. With regards to the problem, an optimal DOCA/SP strategy is proposed with its optimality rigorously proved, and the implementation is also presented. The findings will imply a novel view of jointly cross-layer design for opportunistic channel sensing and access for distributed cooperative networks.

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