Distributed Opportunistic Channel Access with Optimal Single Relay Under Delay Constraints

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Abstract. In this paper, we study distributed scheduling with different delay constraints for each user in a heterogeneous collaborative network with multiple relays, and the relay assists transmission under AF mode and DF mode, respectively. Considering the case that the winner source has full CSI, that is, the winner source in a contention has CSI of links from itself to relays and from relays to its destination. After research, it is found that this is a pure threshold strategy. In it, the threshold selection of each user is regarded as a non-cooperative game, and the existence of Nash equilibrium is proved. This paper maximizes the throughput by using the optimal stopping theory, and validates the correctness through numerical and simulation results.

Keywords: Delay constraints · Heterogeneous collaborative network · Optimal stopping theory

1 Introduction

With the rapid development of the times, modern society has increasingly higher requirements for the communication quality of wireless networks, which leads to the increasingly serious problem of insufficient spectrum resources. In order to solve this problem, while vigorously developing a new blank spectrum, it is a better solution to efficiently improve the spectrum efficiency.

In traditional wireless network, MAC layer and physical layer are designed independently. Therefore, most of the research [1–3] achieve multi-user collaboration focuses on single layer. The physical layer is only responsible for solving the channel fading problem, while the MAC layer only considers how to avoid collision when multiple users share the channel, and does not consider the channel state information of the physical layer users. According to the viewpoint of joint design, the transmission opportunity can be used for channel transmission more efficiently, so a concept of cross-layer design is produced, i.e. the MAC layer controller dynamically schedules multiple users for channel access according to the channel state information sensed in the physical layer. This special channel access mode is called opportunistic channel access.

B. Li et al. (Eds.): IoTaaS 2020, LNICST 346, pp. 599–610, 2021.
https://doi.org/10.1007/978-3-030-67514-1_47

In the past work, opportunistic scheduling strategies have been studied in both centralized [4–6] and distributed networks [4,7–9], but in practical applications, many video applications and voice applications have different delay requirements, and some have extremely low tolerance for time. Specifically, when the effective time of real-time video data packet is reduced to zero, it will become a useless data packet and be discarded immediately, Which seriously reduces the video quality. Moreover, with time delay constraints, the system is prevented from endlessly searching for better channel conditions, thus affecting QoS performance.

In this paper, we study the optimal stopping strategy with delay constraints based on two different relay forwarding models, namely, amplify-and-forward network and decode-and-forward network. The rest of this paper is organized as follows. System model under delay constraints is described in Sect. 2. DOS is studied under AF mode and DF mode respectively in Sect. 3, and an optimal DOS strategy is derived in Sect. 4, Performance evaluation is provided in Sect. 5. Finally, the summary is shown in Sect. 6.

2 System Model

In a wireless network, K source-destination communication pairs (also called users) with L relays under amplify-and-forward (AF) mode and decode-and-forward (DF) mode are considered in a distributed manner. There is no direct link between the source and the destination, and it can only be assisted by the relay. Each user senses and accesses the channel in a competitive manner, as shown in Fig. 1.

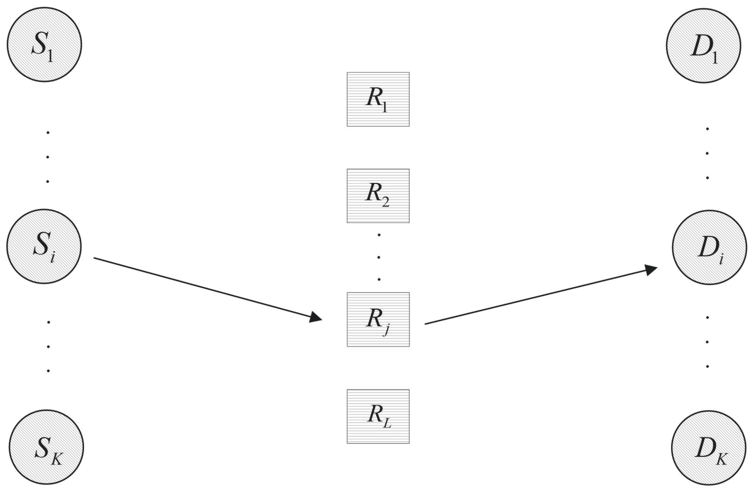

Fig. 1. Relay network model

Opportunistic channel access by multiple pairs proceeds as follows. At beginning of a time slot[1] with duration δ , each source $i = 1,2,...,K$ independently contends for the channel by sending a request-to-send (RTS) packet with probability p_i. There are three situations to consider during this period:

- Idle: If there is no source transmitting RTS in this time slot (with Probability $\prod_{i=1}^{K} (1 - p_i)$), all sources continue to contend in the next time slot.
- Collision: If there are two or more sources transmitting RTS (with Probability $1 - \prod_{i=1}^{K} (1 - p_i) - \sum_{i=1}^{K} p_i \prod_{k \neq i} (1 - p_k)$), a collision happens, and all sources continue to contend in the next time slot.
- Success: If there is only one source, say Source i, transmitting RTS packet(with Probability $\sum_{i=1}^{K} p_i \prod_{k \neq i} (1 - p_k)$, the source is called winner of the channel contention and obtain the channel access opportunity.

When the channel competition is successful, by receiving the RTS of the winner source i, all relays can estimate the CSI between source i and itself, then the relay send RTS to the destination, and the destination replies with a CTS packet after receiving it. At this time, each relay can estimate the CSI between itself and the destination, and the relay sends CTS packets containing information from the source i to relay and relay to destination i to the winner source in turn. At this point, the source i obtains all CSI information. After that, source i has two decisions:

- to *stop*: Source i selects the optimal relay that can reach the maximum rate, and sends the data packet to the optimal relay j^*. Relay j^* forwards the data packet to the destination i, the duration is the channel coherence time τ_d;
- to *continue*: Source i will give up the access opportunity, and a new contention is started among all sources.

After the winner source decides to stop, that is, the channel successfully access, all the source will start one new round of channel contention.

The successful channel contention is regarded as one channel sense. For the nth successful channel sense, let t_n denote the time spent, and the number of channel contentions to be experienced during this period follows a geometric random distribution. There are two cases of time overhead corresponding to channel contention: when the slot is idle due to no user competing for the channel, the time spent is the minimum slot $t_n = \delta$; When there is user competition, the time spent is $t_n = \tau_{RTS}$, that is, the time of using RTS packet for user probe channel. The time expectation of single channel sense t_n is given as $\tau_1 = (\tau_{RTS} + \tau_{CTS}) + \frac{\prod_{i=1}^{K} (1-p_i)}{p_s} \cdot \delta + \frac{(1-\prod_{i=1}^{K} (1-p_i) - \sum_{i=1}^{K} p_{s,i})}{p_s} \cdot \tau_{RTS}$, where $p_s = \sum_{i=1}^{K} p_{s,i}$ denote the probability of successful user contention, and $p_{s,i}$ is the probability that user i contend successfully, satisfying $p_{s,i} = p_i \prod_{k \neq i} (1 - p_k)$.

[1] The time slot is the shortest unit by which the channel availability is sensed.

After each channel access, the winner source will obtain the CSI of the two-hop channel, then calculate the maximum achievable rate and select the best single relay among all relays, and then decide whether to transmit. If it decides to stop, the winner source will transmits through the optimal relay, and if it decides to continue, the winner source will contend for the channel again with other sources.

3 Distributed Opportunistic Scheduling Under Constraints

Based on the optimal stopping theory, the problem of channel access can be modeled as a classical optimal statistical rate of return problem. To simplify the expression, R_n is the mean of achievable transmission rate at the nth observation, given as

$$R_n = \sum_{i=1}^{K} \frac{1}{K} \mathbb{I}[s(n) = i] \max_{j \in \{1,\ldots,L\}} \log_2(1 + \gamma_i). \tag{1}$$

where $\mathbb{I}[\cdot]$ means an indicator function. Specifically, when relay is selected to help with AF mode, $\gamma_i = \max_{j \in \{1,\ldots,L\}} \frac{P_s P_r |f_{ij}(n)|^2 |g_{ji}(n)|^2}{1+P_s|f_{ij}(n)|^2+|g_{ji}(n)|^2}$, and with DF relay mode, $\gamma_i = \max_{j \in \{1,\ldots,L\}} \{P_r|g_{ji}(n)|^2, P_s|f_{ij}(n)|^2\}$.

According to the stopping method, after every successful channel contention, source-destination communication pairs will have two choices: utilize the current channel opportunity for data transmission, or give up this channel to allow others to contend again. Assuming that data transmission is successfully completed t times under this method, let $\{N_1 N_2, ..., N_t\}$ denote the stop time corresponding to multiple transmissions, R_{N_l} denote the information rate of the lth channel access, τ_d denote the time of single channel access, T_{N_l} denote the time spent of lth channel access. Based on Renewal's theorem and the law of large numbers, time-averaged system throughput converges to its statistical value, satisfying

$$\frac{\sum_{l=1}^{t} R_{N_l} \tau_d}{\sum_{l=1}^{t} T_{N_l}} \rightarrow \frac{\mathbb{E}[R_N \tau_d]}{\mathbb{E}[T_N]} \quad a.s.$$

where $\frac{\mathbb{E}[R_N \tau_d]}{\mathbb{E}[T_N]}$ is the statistical rate of return of a typical statistical model. The random variables R_N and T_N both depend on the optimal stop time N in this problem.

Considering channel opportunistic access under different user delay constraints, we further analyze the impact of delay constraint conditions on the optimal access method and performance of different users. Specifically, in the optimization problem model, T_N is used to denote the channel access time of each user. According to QoS service requirements, Each user's time expectation needs to satisfy the delay sensitivity constraint condition of $\mathbb{E}[T_N] \leq T_{th}$, and T_{th} denotes the constraint condition of the average service delay. For the method of not waiting for access, the expected access time $\mathbb{E}[T_{N_0}]$=$\tau_1 + \tau_d$. For $N > 0$,

$\mathbb{E}[T_N] \geq \tau_1 + \tau_d$ is satisfied, Therefore, there is no feasible solution to the above problem when the delay constraint $T_{th} < \tau_1 + \tau_d$.

The optimization problem of statistical throughput of the system can be regarded as the maximum reward problem, mainly seeking the optimal stopping method N^* and the maximum network throughput λ^*, the details are as follows:

$$N^* = \arg\max_{N \in Q_T} \frac{\mathbb{E}[R_N \tau_d]}{\mathbb{E}[T_N]}, \lambda^* = \sup_{N \in Q_T} \frac{\mathbb{E}[R_N \tau_d]}{\mathbb{E}[T_N]}. \tag{2}$$

where $Q_T = \{N : N \geq 1, \mathbb{E}[T_N] \leq T_{th}\}$.

4 Optimal Stopping Strategy

For each user i, the maximum-expected-rate-of-return problem can be equivalently transformed into a standard form of maximum expected return rate. In particular, in order to get N^* of each user, it is necessary to find the optimal strategy that can obtain the maximum expected return

$$V^*(\lambda) = \sup_{N \in Q} \mathbb{E}\big[R_N \tau_d - \lambda T_N\big]$$
$$s.t. \;\; \mathbb{E}[T_N] \leq T_{th}. \tag{3}$$

For the optimization problem of the difference objective function under the delay constraint, the Lagrange duality problem is defined as follows:

$$L^*(\lambda) = \min_{\alpha \geq 0} L(\alpha, \lambda) = \min_{\alpha \geq 0} \big\{V^*(\lambda, \alpha) + \alpha T_{th}\big\}. \tag{4}$$

where $L(\alpha, \lambda)$ is the Lagrangian function, $V^*(\lambda, \alpha) = \sup_{N > 0} \mathbb{E}\big[R_N \tau_d - (\lambda + \alpha) T_N\big]$, α is the Lagrangian multiplier.

The following lemma establishes the relationship between the original optimization problem, the equivalent transformation problem and the dual problem.

Lemma 1. *The above problem satisfies relationship is as follows:*

1) *The inequality relation $V^*(\lambda) \leq L^*(\lambda)$ is satisfied between the maximum value $V^*(\lambda)$ of the objective function of the equivalent transformation optimal problem (3) and the maximum value $L^*(\lambda)$ of the dual optimization problem;*
2) *When the user channel fading follows the Rayleigh model and channel access is performed at the maximum transmission rate, the channel statistical model has sufficient continuity, and there is a strong duality between the equivalent transformation optimization problem (3) and the Lagrange duality problem (4). For any coefficient $\lambda > 0$, $V^*(\lambda) = L^*(\lambda)$.*
3) *When the coefficient $\lambda = \lambda^*$, and λ^* satisfies $V^*(\lambda) = 0$, the optimal solution of the original problem (2) is $\lambda^* = \frac{\mathbb{E}[R_{N^*} \tau_d]}{\mathbb{E}[T_{N^*}]}$, the optimal channel access method is $N^* = N^*(\alpha^*, \lambda^*)$ and α^* is the optimal coefficient solution of the dual problem.*

We assume that the average delay constraint satisfies $T_{th} \geq \tau_1 + \tau_d$, based on the optimal stopping theory and Lagrange duality method, the optimal stopping method under delay constraint is analyzed as follows.

Theorem 1. *The optimal method N^* for distributed channel access has a pure threshold structure. That is to say, after the user contends successfully, the winner source will make the current optimal choice according to the real-time sensed channel quality, access the channel or give up the opportunity. Specifically, when the time delay constraint T_{th} is less than the time delay limit T^*_{th}, the winner source will judge whether the channel achievable rate R_n is higher than the fixed threshold λ_{th} at this time, if it is satisfied, access the channel and transmit at the information rate R_n. Otherwise, the winner source give up the channel opportunity and contend with other users again. Similarly, when the delay T_{th} is higher than the delay limit T^*_{th}, the winner will judge whether the channel reachable rate R_n is higher than the threshold λ^*, and then make a corresponding decision. Therefore, according to the relationship between delay constraints T_{th} and constraint limits T^*_{th}, the optimal channel access method N^* for the optimization problem with delay constraints can be divided into the following two structures:*

1) when time constraints $T_{th} < T^*_{th}$, the optimal access method N^* satisfies

$$N^* = \min\{n \geq 1 : R_n \geq \lambda_{th}\}, \quad \lambda_{th} = F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th} - \tau_d}\Big).$$

.

2) when time constraints $T_{th} \geq T^*_{th}$, the optimal access method N^* satisfies

$$N^* = \min\{n \geq 1 : R_n \geq \lambda^*\}, \quad \lambda^* \ satisfies \ \mathbb{E}\big[(R_n - \lambda^*)^+\big] = \lambda^* \tau_1/\tau_d,$$

where $T^*_{th} = \frac{\tau_1}{1 - F_R(\lambda^*)} + \tau_d$.

Proof. To analyze the Lagrange duality problem, the cost coefficient $\lambda > 0$ and the Lagrange multiplier $\alpha > 0$ are given, the optimal stopping method $N^*(\alpha, \lambda)$ to reach $L(\alpha, \lambda)$ is

$$N^*(\alpha, \lambda) = \min\big\{n \geq 1 : R_n \tau_d \geq V^*(\alpha, \lambda) + (\lambda + \alpha)\tau_d\big\}, \tag{5}$$

where $V^*(\alpha, \lambda)$ satisfies the equation

$$\mathbb{E}\big[\max\big(R_n - (\lambda + \alpha) - V^*(\alpha, \lambda)/\tau_d, 0\big)\big] = (\lambda + \alpha)\tau_1/\tau_d. \tag{6}$$

Using the strong duality between the original problem and the dual problem, the optimal solution $N^*(\lambda)$ of the equivalent problem (3) and the optimal solution α^* of the dual problem (4) satisfy Karush-Kuhn-Tucker(KKT) conditions as follows:

$$\begin{cases} \alpha^* \cdot (\mathbb{E}[T_{N^*(\lambda)}] - T_{th}) = 0, \\ N^*(\lambda) = \arg \max\limits_{N(\lambda)>0} \mathbb{E}\big[R_{N(\lambda)}\tau_d - (\lambda + \alpha^*)T_{N(\lambda)}\big], \\ \mathbb{E}[T_{N^*(\lambda)}] \leq T_{th}, \\ \alpha^* \geq 0. \end{cases} \tag{7}$$

The following analyzes the Lagrange multiplier optimal solution α^*, including $\alpha^* > 0$ and $\alpha^* = 0$. Since the optimal solution α^* exists for any cost coefficient λ, and there is a direct mapping relationship between the λ and the revenue function $V^*(\alpha^*, \lambda)$, replacing λ with λ^* that satisfies the $V^*(\alpha^*, \lambda) = 0$ can simplify the KKT condition, i.e. let $\alpha^* = \alpha^*(\lambda^*)$.

For the first case, i.e. $\alpha^* = 0$, the Lagrangian function $L(\alpha^*, \lambda^*) = 0$ can be expressed as

$$\mathbb{E}\big[\max\big(R_n - \lambda^*, 0\big)\big] = \lambda^* \tau_1 / \tau_d. \tag{8}$$

According to KKT condition and expression (5), the optimal stopping method $N^*(\lambda^*) = N^*(0, \lambda^*)$

$$N^*(0, \lambda^*) = \min\big\{n \geq 1 : R_n \geq \lambda^*\big\}, \tag{9}$$

where λ^* satisfies Eq. (8), which is the expected value of maximum throughput without delay constraints.

The time expectation of access method $N^*(0, \lambda^*)$ is

$$\mathbb{E}[T_{N^*(0,\lambda^*)}] = \frac{\tau_1}{1 - F_R(\lambda^*)} + \tau_d \leq T_{th}.$$

For the second case, i.e. $\alpha^* > 0$, according to KKT condition (7), $\mathbb{E}[T_{N^*(\lambda^*)}] = T_{th}$ can be obtained. Since $N^*(\lambda^*) = N^*(\lambda^*, \alpha^*)$, $N^*(\lambda^*, \alpha^*)$ satisfies the expression (5) of the access method, $V^*(\lambda^*, \alpha^*)$ satisfies the Eq. (6). The access time expectation of the optimal stopping method $N^*(\alpha^*, \lambda^*)$ is

$$\mathbb{E}\big[T_{N^*(\lambda^*,\alpha^*)}\big] = \frac{\tau_1}{1 - F_R\big((\lambda^* + \alpha^*) + V^*(\alpha^*, \lambda^*)/\tau_d\big)} + \tau_d.$$

According to KKT condition, the following equation can be derived

$$\frac{\tau_1}{1 - F_R\big((\lambda^* + \alpha^*) + V^*(\alpha^*, \lambda^*)/\tau_d\big)} = T_{th} - \tau_d. \tag{10}$$

In addition, $V^*(\lambda^*, \alpha^*)$ satisfies the equation

$$\mathbb{E}\big[\max\big(R_n\tau_d - (\lambda^* + \alpha^*)\tau_d - V^*(\alpha^*, \lambda^*), 0\big)\big] = (\lambda^* + \alpha^*)\tau_1. \tag{11}$$

and

$$L(\alpha^*, \lambda^*) = V^*(\lambda^*, \alpha^*) + \alpha^* T_{th} = 0. \tag{12}$$

Based on the Eq. (10) and (12), it can be obtained

$$(\lambda^* + \alpha^*) - \alpha^* T_{th}/\tau_d = F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th} - \tau_d}\Big). \tag{13}$$

Combined with Eqs. (11) and (12), it can be derived that

$$\mathbb{E}\big[\max\big(R_n\tau_d - (\lambda^* + \alpha^*)\tau_d + \alpha^* T_{th}, 0\big)\big] = (\lambda^* + \alpha^*)\tau_1. \tag{14}$$

Substituting Eq. (13) into Eq. (14), we can get

$$\mathbb{E}\Big[\max\Big(R_n - F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th} - \tau_d}\Big), 0\Big)\Big] = (\lambda^* + \alpha^*)\tau_1/\tau_d. \tag{15}$$

Based on Eqs. (13) and (15), we can find that the optimal solution α of Lagrange dual problem satisfies

$$\begin{aligned}\mathbb{E}\Big[\max\Big(R_n - F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th} - \tau_d}\Big), 0\Big)\Big]\tau_d/\tau_1 \\ - F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th} - \tau_d}\Big) = \alpha^* T_{th}/\tau_d > 0.\end{aligned} \tag{16}$$

It can be seen from the observation that the left function $\mathbb{E}\big[\max(R_n - x, 0)\big]\tau_d/\tau_1 - x$ of Eq. (16) is a monotonically decreasing function with $x \geq 0$. According to Eq. (8), when $F_R^{-1}\Big(1 - \frac{\tau_1}{T_{th}-\tau_d}\Big) < \lambda_0^*$, i.e. $T_{th} < \frac{\tau_1}{1-F_R(\lambda_0^*)} + \tau_d$, inequality (16) is valid and λ_0^* satisfies $\mathbb{E}\big[\max\{R_n - \lambda_0^*, 0\}\big] = \lambda_0^*\tau_1/\tau_d$.

The corresponding optimal stopping method $N^*(\alpha^*, \lambda^*)$ at this time is

$$N^*(\alpha^*, \lambda^*) = \min\big\{n \geq 1 : R_n \geq \lambda_{th}\big\}, \tag{17}$$

where $\lambda_{th} = F_R^{-1}\big(1 - \frac{\tau_1}{T_{th}-\tau_d}\big)$.

When $F_R^{-1}\big(1 - \frac{\tau_1}{T_{th}-\tau_d}\big) \geq \lambda_0^*$, i.e. $T_{th} \geq \frac{\tau_1}{1-F_R(\lambda_0^*)} + \tau_d$, the inequality (16) is invalid, which contradicts the precondition with $\alpha^* > 0$.

Combining the two cases of $\alpha^* > 0$ and $\alpha^* = 0$, the optimal stopping method has two structures according to the different limits of the time constraint T_{th}: when $T_{th} \geq \frac{\tau_1}{1-F_R(\lambda_0^*)} + \tau_d$, Lagrange optimal solution satisfies $\alpha^* = 0$, the expression of access method $N^*(0, \lambda^*)$ is shown in (9), λ^* satisfies the Eq. (8). when $T_{th} < \frac{\tau_1}{1-F_R(\lambda_0^*)} + \tau_d$, the Lagrangian optimal solution satisfies $\alpha^* > 0$, and the optimal method $N^*(\alpha^*, \lambda^*)$ is shown in Expression (17).

Theorem 1 shows that the optimal channel access method exhibits different method structures according to different delay limits T_{th}^*. As the two methods are threshold structures, and the thresholds λ_{th} and λ^* of the method can be obtained by offline calculation, the optimal channel access method has good engineering feasibility.

In summary, the throughput performance of the optimal access method proposed in this paper is as follows:

1) when delay constraint $T_{th} < T_{th}^*$, the average throughput of the optimal access method N^* is:

$$\frac{E[R_{N^*}\tau_d]}{E[T_{N^*}]} = \frac{\tau_d}{T_{th}} F_R^{-1}(1 - \frac{\tau_1}{T_{th} - \tau_d}) + \frac{\tau_d}{\tau_1}(1 - \frac{\tau_d}{T_{th}}) E[\max(R_n - F_R^{-1}(1 - \frac{\tau_1}{T_{th} - \tau_d}), 0)]$$

2) when delay constraint $T_{th} \geq T_{th}^*$, the average throughput λ^* of the optimal access method N^* satisfies

$$E[(R_n - \lambda^*)^+] = \lambda^* \tau_1 / \tau_d$$

.

5 Performance Evaluation

In this section, system performance for our proposed strategy is investigated through computer simulations. We consider a wireless cooperative network with 5 source-destination pairs under the help of multiple relays, the channels from the source to each relay station, from the relay to the destination all experience i.i.d Rayleigh fading. In it, The channel contention parameters of the source are set as follows, the contention probability $p_i = [0.2, 0.25, 0.3, 0.35, 0.4]$, $i \in \{1, 2, 3, 4, 5\}$, the mini-slot duration $\delta = 20\,\mu$s, RTS transmission and CTS transmission duration is $\tau_{RTS} = \tau_{CTS} = 50\,\mu$s, the average SNR of the relay channel for the first hop and the second hop are σ_f^2 and σ_g^2, respectively.

Based on AF relay forwarding mode, we first investigate the influence of various average SNR configurations. As shown in Fig. 2, channel coherence time

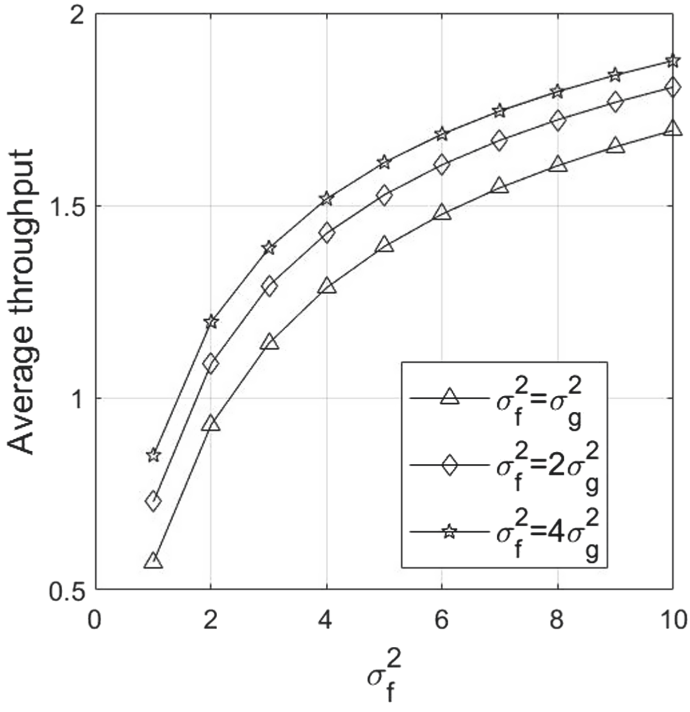

Fig. 2. Performance influence from SNR under AF mode

$\tau_d = 2\,\mathrm{ms}$, the first-hop average SNR σ_f^2 is from 1 dB to 10 dB, and the second-hop average SNR $\sigma_g^2 = \sigma_f^2$, $\sigma_g^2 = 2 \cdot \sigma_f^2$ and $\sigma_g^2 = 4 \cdot \sigma_f^2$, respectively. We can see that the average throughput increases with the increase of the first-hop average SNR σ_f^2 in the horizontal view, and the average throughput is also improved when the ratio σ_g^2/σ_f^2 increases in the vertical view. Secondly, we studied the influence of τ_d on system throughput as shown in Fig. 3, we can see clearly that the system throughput increases greatly with the increase of τ_d.

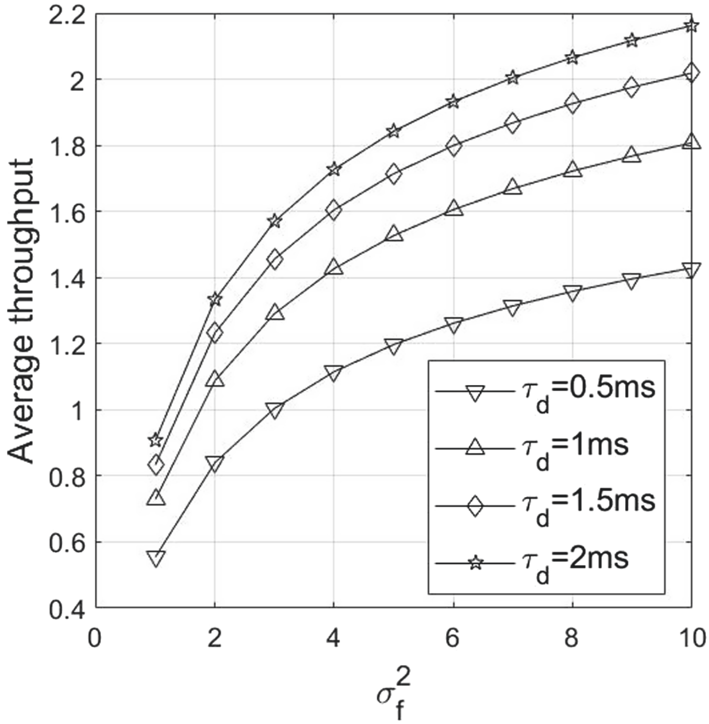

Fig. 3. Performance influence from τ_d under AF mode

Based on DF relay forwarding mode, we also studied the impact of different SNR on the system throughput. In Fig. 4, we can see that the system throughput increases with the increase of σ_f^2. At the same time, with the increase of τ_d, the system throughput also increases significantly.

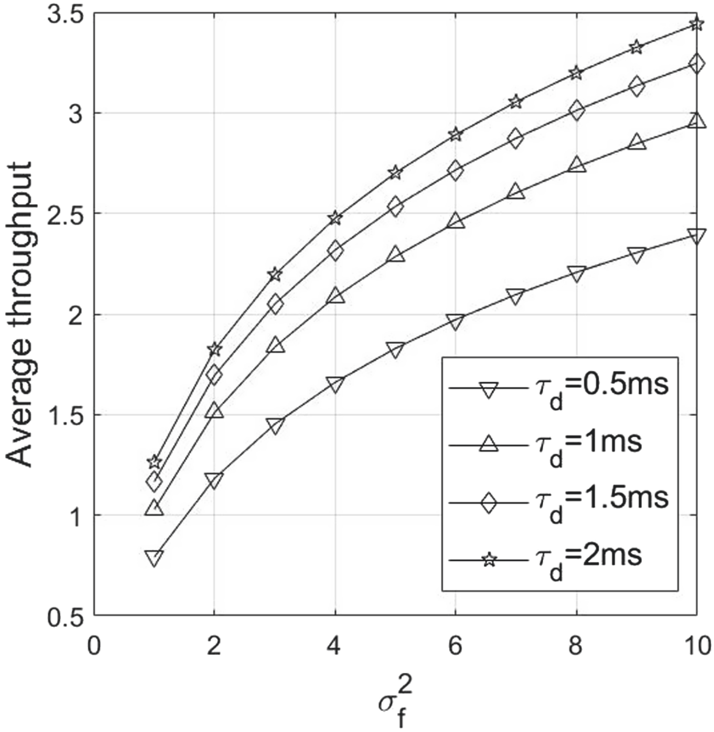

Fig. 4. Performance influence from τ_d under DF mode

6 Conclusion

In this paper, the problem of multi-user channel access in a wireless ad-hoc cooperative network with multiple relaying and no direct link is studied, in which all channels experience independent channel fading. Based on the modeling and analysis of the optimal stopping theory, this paper proposes an optimal single relay strategy with delay constraints, which makes full use of multi-relay cooperative diversity and dynamically determines the channel access time to improve the system performance. The approximate expression of the maximum throughput expectation of the policy system is given in this paper, and all thresholds can be calculated off-line and easy implementation is available. Finally, the optimality of the policy is strictly proved by calculation and simulation.

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