Distributed Opportunistic Wireless Channel Access in Decode-and-Forward Relay Networks

by

Shuai Zhou

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Department of Electrical and Computer Engineering
University of Alberta

Abstract

In wireless networks, opportunistic scheduling has been extensively studied for its ability to improve spectrum utilization efficiency by exploiting time-varying nature of the radio environment. Most of existing works focus on opportunistic scheduling in centralized networks, in which a central scheduler collects the instantaneous channel state information (CSI) for all links and scheduling is based on global information. For distributed networks, no such central scheduler exits. The scheduling decision is made by each individual user. However, each user only has its own CSI without knowing the CSI of other users. The unique characteristic of distributed networks makes the scheduling in distributed networks more challenging.

The main goal of this thesis is to develop an opportunistic scheduling strategy in distributed networks with decode-and-forward (DF) relays without direct link. Two cases are considered: 1) the winner source has full CSI (CSI of source-relay link and relay-destination link), 2) the winner source has partial CSI (CSI of source-relay link only). For the first case, a pure threshold scheduling strategy is proposed. Specifically, when the minimum of the detected signal-to-noise ratio (SNR) of the source-relay link and relay-destination link exceeds a certain threshold, it is optimal for the winner source to transmit data at the highest achievable rate; otherwise, the

winner source should give up the transmission opportunity and let all sources re-contend the channel. For the second case, the scheduling strategy is also threshold-based. In specific, when the detected SNR of the source-relay link exceeds a certain threshold, it is optimal for the winner source to transmit data at a rate determined by the detected first hop SNR and the expectation of second hop channel conditions. After the relay receives the data, the optimal strategy is probing the second hop until the second-hop channel condition is good enough to be able to forward the received data to the destination. The threshold is calculated by the statistics of the channel using the optimal stopping rule.

Extensive simulation demonstrates the efficiency of the proposed strategies in this thesis.

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A	number of idle minislots during an observation
B	number of collisions during an observation
$\mathcal{C}$	the set that $\mathbb{E}[T_N] < \infty$
$\mathbb{E}[\cdot]$	expectation of random variable
$f_f(\cdot)$	PDF of the first hop detected SNR
$f_{f^1}(\cdot)$	PDF of r_n^f under the condition that $r_{1(n)} \leq r_n^f \leq x_{(n)}^*$
$F_f(\cdot)$	CDF of the first hop detected SNR
$f_g(\cdot)$	PDF of the second hop detected SNR
$f_{g^1}(\cdot)$	PDF of r_g^n under the condition that $r_g^n \geq r_n$
$f_{g^2}(\cdot)$	PDF of r_g^n under the condition that $r_g(n) \geq x_{(n)}^*$
$F_g(\cdot)$	CDF of the second hop detected SNR
$f_{r_{min}}(\cdot)$	PDF of r_{min}
$F_{r_{min}}(\cdot)$	CDF of r_{min}
K	number of source-destination pairs
N	stopping time
N^*	optimal stopping time
p	probability that a source sends a RTS in a minislot
Pr$[\cdot]$	probability of an event
r_n	$2^{R_n} - 1$
r_n^f	detected first-hop SNR of the nth probing
r_n^g	detected second-hop SNR of the nth probing
r_{min}	$\min\{r_n^f, r_n^g\}$
$r_{1(n)}$	lower threshold when $\lambda = \lambda_n$

R_n	the first hop transmission rate
S_l	strategy that a relay has up to l chances of channel probings
T_n	time until the nth observation plus the subsequent transmission time following the nth observation
$U(\lambda)$	net reward
$U^*(\lambda)$	optimal net reward
$V^l(\lambda)$	the net reward of strategy S_l
Y_n	reward by stopping at time n
δ	minislot duration
λ	"cost" per unit of time
λ^*	optimal rate of return
ρ_f	average SNR of the first hop
ρ_g	average SNR of the second hop
τ_{CTS}	CTS duration
τ_d	channel coherence time
τ_{RTS}	RTS duration
τ_1	duration of an observation
τ_2	$\tau_{RTS} + \tau_{CTS} + \tau_d$

List of Abbreviations

Acronyms	Definition
AF	amplify-and-forward
CDF	cumulative density function
CDMA	code division multiple access
CSI	channel state information
CSMA	carrier sense multiple-access
CSMA-CA	carrier sense multiple-access with collision avoidance
CTS	clear-to-send
DF	decode-and-forward
FCC	Federal Communications Commission
FDMA	frequency division multiple access
M-LWDF	Modified Largest Weighted Delay First
PDF	probability density function
RTS	request-to-send
SNR	signal-to-noise ratio
TDMA	time division multiple access

Chapter 1

Introduction

Wireless communications are one of the most rapid development sciences which have great impact on the human life and social progress in the past decades. Compared with wired communications, wireless communications use the electromagnetic signals that can propagate in free space to exchange information without the need of arrangement of wire. However, with the popularity of smart phones and tablet computers, great expansion of mobile Internet applications drives increasing demands for higher data transmission rate and better data transmission quality.

To meet the increasing demands, one possible solution is to explore new spectrum with large bandwidth. However, only limited frequency bands are suitable for wireless communications, from few hundred megahertz to several gigahertz. Under current spectrum regulatory framework, almost all available spectrum has been licensed to various wireless applications already. Therefore, to achieve higher data transmission rate and guarantee the service quality, the only way is to improve spectrum utilization efficiency. There are three main problems that affect the spectrum utilization efficiency.

In the first place, large portion of the licensed spectrum is underutilized. Under the current spectrum regulatory framework, the spectrum is regulated by government agencies such as Federal Communications Commission (FCC). According to FCC's Spectrum Policy Task Force [1], large portion of the licensed spectrum is not utilized efficiently.

Secondly, channel fluctuation reduces the utilization efficiency greatly. Channel fluctuation includes path loss, shadowing and multi-path fading. Path loss is caused by dissipation of the power. Shadowing is caused by large obstacles such as buildings between the source and destination. Multi-path fading is caused by the different travel paths of the signal from the transmitter to the receiver.

Thirdly, wireless channels may be utilized by users with bad channel conditions. Different users experience different channel conditions at the same time. If a channel is assigned to a user with bad channel condition, the spectrum utilization efficiency is poor, since the user can achieve only a very small transmission rate.

For the first problem, the most promising solution is cognitive radio [2]–[9]. According to [5], "Cognitive Radio" is an intelligent radio. Based on interaction with the environment, it can change transmitter parameters. It enables unlicensed users (secondary users) to utilize the portion of the spectrum that is currently underutilized by the licensed users (primary users) in an opportunistic way.

For the second problem, the common solution is Multiple-Input Multiple-Output (MIMO) technology [10]–[13]. MIMO is a technology that employs multiple transmit antennas and multiple receive antennas to transmit signal in order to improve the quality of communication. It fully utilizes the space diversity to suppress channel fading effects and enhance the spectrum utilization efficiency. As an alternative solution, cooperative communications can also achieve high spectrum utilization efficiency since the destination can receive signal from the source as well as relays.

For the third problem, it is already well investigated in cellular networks. In cellular networks, a central controller such as the base station collects the channel state information (CSI) of all users and chooses the users with favorable channel conditions. However, in distributed networks, the central controller does not exist, and the users need to make the scheduling decision in a distributed way. Each user only has its own CSI without CSI of other users, and thus, it is challenging to make the scheduling decision with such limited information to optimize the system performance. Recently, a few works have developed threshold-based scheduling strategies using the tool of optimal stopping rule [14]–[20].

1.1 Thesis Motivations and Contributions

In distributed networks such as ad-hoc networks, all sources gain the transmission opportunity by channel contention. Usually, sources that have data to transmit send request-to-send (RTS). If multiple sources send RTS at the same time, they collide with each other. When only one source transmits RTS, its destination can receive the RTS successfully and sends back clear-to-send (CTS). Then the source begins to transmit data to its destination no matter the channel condition is good or not. When the channel condition is bad, only small transmission rate can be achieved and the channel is not fully utilized. One solution is letting the source give up the transmission opportunity when the channel condition is bad, and letting all other sources re-contend the channel so that sources with good channel conditions have higher chance to transmit. However, each user in a distributed network only has the CSI of its own channel. Then a problem arises: how to distinguish the good and bad channel conditions only based on a user's own CSI?

A recent work [14] uses the optimal stopping theory to solve the problem and a pure threshold strategy is proposed. When a destination receives a RTS from its source, the destination estimates the signal-to-noise ratio (SNR) of the channel from its source to itself. Then the destination sends back to the source a CTS, in which the SNR information is included. If the SNR is greater than a threshold, then the source transmits data to destination; otherwise, the source gives up the transmission opportunity and letting all sources begin a new round of channel contention. In the long term, all sources will benefit from the strategy since only users with good channel conditions transmit, and thus, the wireless channel is utilized efficiently. The threshold is the critical point that the net reward of transmission equals the net reward of giving up the transmission opportunity, and it can be calculated based on the statistics of the channels.

In a similar way, work [19] proposes a threshold-based strategy for the decode-and-forward (DF) relay networks. Each source has a destination and a relay. When a source has data to transmit, it sends RTS to its relay and destination. After getting the CTS feedbacks from the relay and destination, the source knows the CSI for its links to the relay and to the destination. Then the source has a first decision with three choices:

- give up transmission opportunity
- transmit with direct link (the link between the source and the destination)
- continue to probe the channel between the relay and destination

If the last option is chosen, after probing the second hop (relay-destination link), the source has a second decision with two choices: to give up transmission opportunity, or transmit (by direct link or relay link, whichever has higher achievable transmission rate). The probing overhead to get CSI for making the first decision of the source is: one RTS transmission duration (broadcast from source to relay and destination), and two CTS transmission durations (from relay to source, from destination to source).

The channel probing can be done in a different way. First, the source broadcasts a RTS. By RTS reception, the relay and the destination can estimate the source-relay link SNR and source-destination link SNR, respectively. Then the relay sends a CTS to the source, and the information of the source-relay link SNR is also included in the CTS. The CTS is overheard by the destination, and the destination can estimate the relay-destination link SNR by CTS reception. After that, the destination sends to the source a CTS, which includes information of the source-destination link SNR and relay-destination link SNR. When the source gets the CTS from the destination, it has SNR information for the source-destination link, the source-relay link, and relay-destination link. The total probing time is still one RTS transmission duration and two CTS transmission durations. Thus, it takes the same time as the first decision of [19] to probe the channel, but gets the CSI of the source-destination link, the source-relay link, and the relay-destination link (for the work in [19], to make the first decision, the source does not have the CSI of relay-destination link). With more information than the work in [19], the source can calculate the end-to-end achievable rate, and the two-hop network can be viewed as a virtual single-hop network with the end-to-end achievable rate treated as the peer-to-peer achievable rate. Thus, the source can decide whether to transmit or to give up the transmission opportunity, by following the same way as in a single-hop ad-hoc network in [14].

Now we examine the work of [19] without direct link. After a relay receives a RTS from its source, it estimates the SNR of the source-relay link. Then it either sends a CTS to the source to notify the source of giving up the transmission opportunity or decides to further probe the second hop. If the relay decides to further probe the second hop, it sends a RTS to the destination. By reception of the RTS, the destination estimates the SNR of the relay-destination link, and sends back to the relay a CTS that contains the relay-destination link SNR information. Then the relay decides whether to skip the transmission opportunity or to take the transmission opportunity, and notifies the source of the decision by a CTS feedback. If the decision is to take the transmission opportunity, then the source transfers data to the relay and subsequently the relay re-transmit data to the destination, and in both process, the transmission rate is the minimum of the achievable rates of the two hops. If the decision is to skip the transmission opportunity, then all sources begin a new round of channel contention.

The above strategy have two disadvantages. 1) When the first hop's channel condition is good but the second hop's channel condition is bad, it wastes time probing the second hop. 2) When the channel conditions of both hops are good, the maximum total data transmission time in the two hops is channel coherence time (the maximum duration within which the detected CSI is valid). So the data transmission time in each hop is only half of the channel coherence time.

To address the above two disadvantages, we propose a new strategy. After a relay receives the RTS from its source, based on the estimation of the first-hop SNR, the relay sends back a CTS to inform the source of a transmission rate or notify the source of giving up the transmission opportunity. If it is decided that the source should transmit, after the relay receives the data from the source, it begins to probe the second hop, and based on the detected CSI of the second hop, it either transmits the data or waits for a channel coherence time and probes again until the second-hop channel condition is good enough to forward the data.

In our strategy, if the first-hop channel condition is good and second-hop channel condition is bad, the relay may wait channel coherence time and probe again rather than giving up the transmission opportunity. By this way, the good channel condition in the first hop is utilized. And the data transmission time in each hop is channel coherence time.

1.2 Thesis Outline

The thesis is organized as follows. In Chapter 2, channel access methods are introduced and related works on opportunistic scheduling are surveyed. The case when a winner source (i.e., a source that wins the channel contention) has full CSI (i.e., first-hop and second-hop CSI) is studied in Chapter 3. The case when the winner source has partial CSI (i.e., first-hop CSI) is explored in Chapter 4 and Chapter 5. Chapter 6 concludes the thesis and discusses the future work that can be done based on the work in this thesis.

Chapter 2

Background and Literature Review

2.1 Wireless Channel Access Schemes

Multiple access refers to the situation where multiple users expect to communicate simultaneously using the same medium. There are two broad categories of multiple access techniques: conflict-free multiple access and non-conflict-free multiple access. The main idea in conflict-free multiple access is partitioning of the medium into separate orthogonal channels that are dedicated to particular users. The commonly used conflict-free multiple access methods are frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). In non-conflict-free multiple access, users that expect to transfer data are either uncoordinated or only partially coordinated. The completely uncoordinated strategy is called random access. Common random access protocols are Aloha, carrier sense multiple access (CSMA), and variants of CSMA.

2.1.1 Aloha

Aloha was first developed by a research group from University of Hawaii in the late 1960s and early 1970s for satellite communications [21]–[23]. Aloha is a packet-switching system. A slot is the time duration for transmitting one packet. Vulnerable period is the maximum interval over which two packets can overlap and destroy each other. In the system of pure Aloha, a user can transmit data whenever it wants. If, within the time-out period, the user receives an acknowledgment from the destination, then the user knows that no conflict occurs; otherwise the user assumes a collision occurs and waits for a random delay time to transmit again. The vulnerable period of pure Aloha is two slot durations. In slotted Aloha system, time is slotted into segments whose duration is the transmission time of a single packet (we assume constant-length packets). Users can transmit only at the beginning of a slot. Since two frames can either completely overlap or do not overlap at all, the vulnerable period of slotted Aloha is only one slot time.

2.1.2 CSMA

In CSMA, a user senses the channel before data transmission. If the channel is idle, the user begins to transmit its data; otherwise, several actions can be taken based on the corresponding protocols [24]. For non-persistent CSMA, if a user senses a busy channel, the user waits a random time, and senses the channel again, and repeats above procedure. In p-persistent CSMA case, if a user senses a busy channel, the user waits until the channel goes idle, and then transmits with a probability p in each subsequent minislot.

2.1.3 CSMA-CA

In carrier sensing multiple access with collision avoidance (CSMA-CA), a station senses the channel before transmission. If the channel is busy, the station picks up a random back-off time to schedule a reattempt [25]. After a channel busy period, a station that has scheduled a reattempt monitors the medium and decrements its back-off timer by one when the channel has been idle for one minislot. The back-off timer is suspended if the channel becomes busy (which means other stations are transmitting), and the back-off timer is resumed when the channel becomes idle again. The station is allowed to transmit when its back-off timer expires (i.e., reaches zero). When a station has successfully completed a frame transmission and has another frame to transmit, the station must execute the back-off procedure again.

2.2 Opportunistic Scheduling

Opportunistic scheduling takes advantage of variations of channel conditions of different users. It gives some priority to users with good channel conditions to improve the overall system throughput. It is easy to be implemented in centralized networks where a central controller collects CSI of all users. However, only limited progress is made in distributed networks.

2.2.1 Opportunistic Scheduling in Centralized Networks

In centralized networks, a central scheduler collects the CSI for all links and scheduling is made based on the global information. The major idea is to schedule users with good channel conditions to transmit over the wireless channels.

A scheduling algorithm which takes advantage of channel fluctuations by giving some form of priority to users with better channels is proposed in [26], which takes into considerations the data rate and packet delay for each user. A Modified Largest Weighted Delay First (M-LWDF) scheduling strategy is formulated and both the rate requirement and the delay requirement can be satisfied by adjusting some parameter.

Since the diversity gains increase with the range of channel fluctuations, work [27] proposes to use multiple transmit antennas to increase channel fluctuations in order to fully exploit the multiuser diversity gain in wireless communications networks. The transmit power and phase of different antennas are randomized. By assigning the common resource to user with good channel conditions, the overall system throughput can be improved a lot.

In [28], the opportunistic transmission scheduling scheme takes consideration of fairness requirement. The scheduling scheme is developed under a certain resource allocation constraint for a time-slotted system, where a number between 0 and 1 is assigned to each user representing the long-term fraction of time allocated to the user. In this scheduling scheme, each user is guaranteed a certain portion of resource and the performance improves 20% - 150% compared with a scheduling scheme that does not take advantage of the channel fluctuation.

2.2.2 Opportunistic Scheduling in Distributed Networks

In distributed networks, such as ad-hoc networks, no central controller exists to collect the CSI of all users. So the distributed users need to make the scheduling decision. However, each user only has its own CSI without CSI of other users, thus it is challenging to make the scheduling decision with such limited information.

A distributed opportunistic scheduling scheme for a single-hop ad hoc network is developed in [14]. All sources use random access to contend the channel. Sources with data to transmit send RTS. If the destination receives the RTS successfully, it estimates the SNR of the link and sends back a CTS with the SNR information embedded in. If the detected SNR is below some threshold, then the source would skip the transmission opportunity and all sources begin a new round of channel contention; otherwise, the source transmits with the highest achievable rate. By giving up the transmission opportunity when the channel conditions are poor, sources with good channel conditions might get the transmission opportunity. Each source benefits from this strategy in the long run by getting more chances to transmit when its channel conditions are good. In [14], the optimal stopping theory is introduced to get the optimal threshold. It is promising that the threshold can be calculated only based on the statistics of the channel conditions which make the scheduling strategy easy to implement.

One issue with the distributed opportunistic scheduling is that the system may waste a long time probing the channel when the channel conditions are bad. This may seriously affect the delay requirement of real time communications with stringent delay requirement. A scheduling scheme that maximizes the throughput under delay constraint is developed in [17]. Under network wide average delay constraint, the optimal scheduling problem can be converted a constrained optimal stopping problem. A threshold-based strategy is developed , i.e. only when the achievable rate is above a threshold, the user can transmit.

Cooperative communication [29]–[36] has emerged as a promising technique for enhancing communication efficiency. There are two popular relaying strategies: decode-and-forward (DF) relaying and amplify-and-forward (AF) relaying. In DF relaying, the relay decodes the received data and then forwards the re-encoded signal to the destination, while in AF relaying, the relay scales up or down the received signal before forwarding. Several works focus on distributed opportunistic scheduling in wireless relay networks (see e.g. [19] [20]). In wireless relay networks, the scheduling problem boils down to tradeoff between throughput gains from cooperative networking and time cost caused by probing to establish cooperative relaying.

An optimal scheduling strategy in DF relay network is developed in [19]. In the system model, data transmission can be achieved by direct link (from source to destination) or relay link (from source to relay and from relay to destination). To achieve higher data transmission rate, after the source gets the SNR of the source-destination link and source-relay link, it needs to decide whether to use the relay link or not (i.e., to probe the relay-destination link or not). It is proved that in the case with dedicated relays the optimal strategy is a pure threshold structure (i.e. it is optimal to probe the relay-destination link when the SNR of the source-relay link is greater than some threshold). Based on the statistical information, the thresholds can be calculated, which makes the scheduling scheme easy to implement in a distributed manner.

The optimal stopping strategy for wireless networks with AF relay is investigated in [20], where the scheduling rule for the source and the relay are studied together. Two cases are considered: 1) when the winner source has CSI of source-relay link and relay-destination link, the optimal stopping strategy has a pure-threshold structure; 2) when the source does not have the CSI of relay-destination link, the stopping rule for the source is threshold-based. For the relay, the threshold is based on the first-hop transmission rate.

2.2.3 Optimal Stopping Theory

The theory of optimal stopping [37] deals with problems of choosing the best time to stop in order to maximize the reward. A player observes a sequence of random variables (usually the distribution of the random variable is known). After each observation the player needs to make a decision: 1) go on observation; or 2) stop observation and get a reward based on the observed random variable. Usually there is a cost associated with each observation. The goal is to maximize the long-term reward.

One common example is house selling problem. A seller has a house to sell, and each day he can get an offer (the observed random variable). Assume the seller knows the distribution of the offers. After getting an offer the seller either rejects the offer and waits for new ones later; or stops waiting and accepts the offer. If he/she chooses to stop, the reward is the money he/she gets and the cost can be considered as daily advertisement fee. The goal is to maximize the amount of money the seller gets.

In mathematical way, let X_1,X_2...denote a sequence of offers whose joint distribution is known, c denote daily advertisement fee and $\{y_1(X_1), y_2(X_1, X_2), ...,$ $y_\infty(X_1, X_2, ...)\}$ the money the seller can get. Here the seller is not allowed to recall the past offers, so $y_n(X_1, ..., X_n) = X_n - nc$ is the money the seller gets if he/she chooses to stop at the nth day. The goal is to choose the optimal stopping time N in order to maximize the expected return $\mathbb{E}[Y_N]$ (Y_N is the reward by stopping at the Nth day), with $\mathbb{E}[\cdot]$ representing mathematical expectation.

To solve this problem, the first thing is to check whether the optimal stopping rule exists. Two inequalities must be satisfied to guarantee the existence of the optimal stopping rule.

$$\mathbb{E}[\sup_n Y_n] < \infty$$

$$\lim \sup_{n\to\infty} Y_n \leq Y_\infty \, a.s.$$

where Y_∞ is the reward if the player never stops, and "a.s." is the short form for "almost surely". The first inequality means that even if the player is able to know everything in the future, he/she can only get a finite return.

However, in some cases, people are more interested in maximizing the average return per unit of time if the optimal stopping problem is repeated in time. A different perspective on house selling problem can be used to illustrate this point. If the seller has many houses to sell, it might be more attractive for him to sell a house per month with an average earning of \$1,000 per sale than to sell only one house in a year with a earning \$10,000. More typical application is in wireless communication system. Consider a system with many users sharing the wireless channel and contending for the channel access if they have data to transmit. After the successful contention of a user, let us call it a winner source. The winner source can estimate the CSI and the achievable transmission rate. The winner source either transmits with the achievable rate and gets the throughput as reward, or gives up the transmission opportunity so that other sources with better channel conditions get the transmission opportunity. The scheduling scheme is about to make the right decision for each winner source in order to maximize the system throughput.

Put in mathematical way, let T_n denote the total time spent to reach stage n, Y_n denote the throughput realized by stopping (stop probing and begin to transmit) at stage n. The stopping rule N is responsible for making the decision whether to stop or not. The goal is to find the optimal stopping rule N^* in order to maximize $\mathbb{E}[Y_N]/\mathbb{E}[T_N]$ (rather than to maximize $\mathbb{E}[Y_N]$). To avoid triviality, we assume that $0 < T_1 \leq T_2 \leq T_3 \cdots a.s.$ and $\mathbb{E}[T_N] < \infty$. This problem is hard to solve. So typically it is transformed into an ordinary stopping rule problem. Let λ denote the "cost" per unit of time, and $U^*(\lambda) = \sup_{N(\lambda)\geq 0} \mathbb{E}[Y_{N(\lambda)} - \lambda T_{N(\lambda)}]$ ($N(\lambda)$ is the stopping rule when the cost per unit of time is λ). If we find a λ^* such that $U^*(\lambda^*) = 0$, then an optimal stopping rule that maximizes $\mathbb{E}[Y_N - \lambda T_N]$ is also an optimal stopping rule that maximizes $\mathbb{E}[Y_N]/\mathbb{E}[T_N]$ (proof can be found in [37]).

Chapter 3

Distributed Opportunistic Scheduling in Wireless Relay Networks with Full CSI

In this chapter, we investigate the opportunistic scheduling in distributed wireless networks with DF relay, where the winner source (the source that wins the channel contention) has full CSI, specifically, the winner source has the CSI of source-relay link (first hop) and relay-destination link (second hop). A pure threshold-structure optimal stopping rule is developed, to be specific, when the minimum of the detected SNRs of the first hop and second hop exceeds a certain threshold, it is optimal for the winner source to transmit data at the highest achievable transmission rate (i.e., the minimum of the achievable transmission rates of the two hops); otherwise, the winner source should give up the transmission opportunity.

3.1 System Model

Consider multiple source-destination pairs, each with a dedicated DF relay. There are no direct links between sources and destinations. Assume the source-relay links and relay-destination links follow independent and identically distributed Rayleigh fading with the average SNR being ρ_f and ρ_g, respectively. Additionally, we assume that channel coherence time is same for the first hop and second hop, denoted as τ_d.

The channel contention process is as follows. At a minislot (with duration δ), each source sends a RTS to its relay with a probability p. For each minislot, there are three possible outcomes:

- No RTS is transmitted. This minislot is an idle minislot.
- Only one source transmits a RTS. So the source wins transmission opportunity and we call it a winner source.
- More than one source transmit multiple RTSs. So the RTSs collide with each other. No RTS is transmitted successfully, and no source wins transmission opportunity.

We assume that there are M source-destination pairs. Let τ_{RTS} and τ_{CTS} denote the RTS duration and CTS duration, respectively. Define an *observation* as as the interval from the starting point of the channel contention until a winner source appears (i.e., its RTS is successfully received by its relay). Then the duration of an observation is given by $\tau_1 = A\delta + \tau_{RTS} + B\tau_{RTS}$, where A is the number of minislots that no source transmits RTS, $\mathbb{E}[A] = \frac{(1-p)^M}{Mp(1-p)^{M-1}}$ ($\mathbb{E}[\cdot]$ means expectation), and B is the number of collisions during an observation, $\mathbb{E}[B] = \frac{1-(1-p)^M-Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}}$. So the average duration of an observation can be expressed as $\mathbb{E}[\tau_1] = \frac{(1-p)^M}{Mp(1-p)^{M-1}} \cdot \delta + \tau_{RTS} + \frac{1-(1-p)^M-Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}}\tau_{RTS}$.

After the relay of the winner source receives the RTS successfully and gets the first hop CSI, the relay transmits a RTS to the destination (the RTS also notifies other source not to transmit). After the destination receives the RTS, it estimates the CSI of the second hop and sends this information within a CTS back to the relay. After the relay receives the CTS from the destination, it has full CSI of the two hops and has two choices:

- if the channel conditions of both hops are good, the relay sends back a CTS to notify the winner source of the transmission decision and the transmission rate which is the minimum of the achievable rates of the two hops;

- if the channel condition of either hop is bad, the relay sends back a CTS to the winner source to notify the decision. This CTS also notifies all sources to start a new channel contention.

The threshold to distinguish good and bad channel conditions will be discussed later.

If the first choice is selected, after the winner source receives the CTS from the relay, it begins to transmit data to the relay. After the relay gets the data, it decodes the data, re-encodes it, and forwards to the destination. Here data is transmitted at the same rate for both hops, which is the minimum of the achievable rates of the two hops.

3.2 Optimal Stopping Strategy

We call the winner source of the nth observation as the nth winner source. For the nth winner source, denote the detected SNR of the source-relay link and relay-destination link as r_n^f and r_n^g , respectively. If the nth winner source stops (i.e., it is decided that the nth winner should utilize the transmission opportunity, and thus, the nth winner first transmits with rate $R_n = \log_2(1 + \min\{r_n^f, r_n^g\})$ with duration $\tau_d/2$, and subsequently its relay transmits with rate R_n with duration $\tau_d/2$), let T_n denote the time duration from observation 1 until observation n plus the time used for transmissions in the two hops after observation n, and let Y_n denote the total amount of traffic that is sent by the winner source and received by its destination. Let N denote the stopping time, i.e., the winner sources of the first $N-1$ observations skip the transmission opportunity and the winner source in the Nth observation stops and begins to transmit data.

Define

$$\mathcal{C} \triangleq \{N : N \geq 1, \mathbb{E}[T_N] < \infty\}. \tag{3.1}$$

The average rate of return is given by $\mathbb{E}[Y_N]/\mathbb{E}[T_N]$. The optimal stopping time

N^* is defined as the one that can maximize the average rate of return

$$N^* \triangleq arg \max_{N \in \mathcal{C}} \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]}. \tag{3.2}$$

The optimal rate of return λ^* is

$$\lambda^* \triangleq \sup_{N \in \mathcal{C}} \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]}. \tag{3.3}$$

As we mentioned in Chapter 2, the problem of maximizing average rate of return per unit of time can be converted to an ordinary optimal stopping problem that maximizes the net reward $U(\lambda) = Y_N - \lambda T_N$, where λ denotes the "cost" per unit of time. The optimal net return is defined as

$$U^*(\lambda) = \sup_{N(\lambda) \in \mathcal{C}} \mathbb{E}[Y_{N(\lambda)} - \lambda T_{N(\lambda)}]. \tag{3.4}$$

Theorem 3.1. There exists an optimal rule for Problem (3.4).

Proof. It follows from [37] that optimal $N(\lambda)$ exists for Problem (3.4) if the following two conditions are satisfied:

$$\mathbb{E}[\sup_n R_n \tau_d / 2 - \lambda T_n] < \infty \tag{3.5}$$

$$\lim_{n \to \infty} \sup R_n \tau_d / 2 - \lambda T_n = -\infty. \tag{3.6}$$

Denote A_i and B_i as the number of idle minislots and the number of collisions duration observation i. For the first condition, we have

$$
\begin{aligned}
&\mathbb{E}[\sup_n R_n\tau_d/2 - \lambda T_n] \\
=&\mathbb{E}[\sup_n R_n\tau_d/2 - \lambda(\sum_{i=1}^{n} A_i\delta + \sum_{i=1}^{n} B_i\tau_{RTS})] \\
&- \lambda(n\tau_{RTS} + 2n\tau_{CTS} + \tau_d) \\
=&\mathbb{E}[\sup_n R_n\tau_d/2 - \lambda n\mathbb{E}[A_i]\delta - \lambda n\mathbb{E}[B_i]\tau_{RTS}] \\
&- \mathbb{E}[\sup_n \lambda\sum_{i=1}^{n}(A_i - \mathbb{E}[A_i])\delta + \lambda\sum_{i=1}^{n}(B_i - \mathbb{E}[B_i])\tau_{RTS}] \\
&- \lambda(n\tau_{RTS} + 2n\tau_{CTS} + \tau_d).
\end{aligned}
\tag{3.7}
$$

It is reasonable to assume that the second moment of R_n exists. It then follows from the maximal inequalities in [37] that the first term of the right-hand side of (3.7) is less than ∞. The second term of the right-hand side of (3.7) equals zero according to law of large numbers and the last term is also finite. Thus the first condition is satisfied.

For the second condition: it is clear that $\lim\sup_{n\to\infty} R_n\tau_d/2 - \lambda T_n = -\infty$ since $n \to \infty \Rightarrow T_n \to \infty$ and $R_n\tau_d$ is finite. Thus the second condition is satisfied. So, both (3.5) and (3.6) are satisfied and the existence of the optimal stopping rule is proven.

□

For Problem (3.4), the net reward for the first choice (i.e., stop and transmit) is $U(\lambda) = R_n\tau_d/2 - \lambda\tau_{CTS} - \lambda\tau_d$. $\lambda\tau_{CTS}$ is the time cost for the relay sending back a CTS to the winner source and $\lambda\tau_d$ is the time cost for data transmission (both first hop and second hop data transmission time are equal to $\tau_d/2$, so the total transmission time is τ_d).

The net return of the second choice (i.g., give up) is $U(\lambda) = -\lambda\tau_{CTS} + U^*(\lambda)$, i.e., after paying the cost $\lambda\tau_{CTS}$ to send back a CTS to the winner source, all the sources will begin a new contention and can get the optimal net return $U^*(\lambda)$ if all the sources follow the optimal stopping rule.

The optimal rule is to select the choice that has higher net reward, so only when the net reward of transmission is greater than or equal to the net reward of giving up the transmission opportunity, the relay will choose to stop:

$$N^*(\lambda) = \min\{n \geq 1 \, : R_n\tau_d/2 - \lambda\tau_d \geq U^*(\lambda)\}. \tag{3.8}$$

$U^*(\lambda)$ satisfies the following optimality equation (from [37]):

$$\mathbb{E}[\max\{R_n\tau_d/2 - \lambda\tau_{CTS} - \lambda\tau_d \, , U^*(\lambda) - \lambda\tau_{CTS}\}] - \lambda\tau_1 = U^*(\lambda) \tag{3.9}$$

where $\lambda\tau_1$ is the sink cost, i.e. the cost that has already occurred for whichever choice that is made.

Based on [37], optimal solution of the Problem (3.4) with $\lambda = \lambda^*$ satisfying $U^*(\lambda^*) = 0$ is an optimal solution of Problem (3.2). The optimal "cost" per unit of time λ^* is also the optimal rate of return of Problem (3.2). So next we focus on $\lambda = \lambda^*$.

Letting $\lambda = \lambda^*$ and combining with $U^*(\lambda^*) = 0$, Eq. (3.9) can be simplified as:

$$\mathbb{E}[R_n\tau_d/2 - \lambda^*\tau_d]^+ = \lambda^*\tau_1 + \lambda^*\tau_{CTS} \tag{3.10}$$

in which we denote $[x]^+ = \max\{x, 0\}$.

Based on (3.10), we can find out value of λ^* numerically. Then from (3.8) and the facts $U^*(\lambda^*) = 0$ and $R_n = \log_2(1+\min\{r_n^f, r_n^g\})$, the optimal rule for Problem (3.2) is given as

$$N^*(\lambda^*) = \min\{n \geq 1 \, : \min\{r_n^f, r_n^g\} \geq 4^{\lambda^*} - 1\}. \tag{3.11}$$

In other words, if the minimum of the detected SNRs of the two hops is less than $4^{\lambda^*} - 1$, then the source should give up the transmission opportunity; otherwise, the source should transmit with rate R_n.

3.3 Iterative Algorithm for Calculating λ^*

It is not easy to get a closed-form solution of (3.10). So the solution (i.e., value of λ^*) should be found by numerical methods. Reference [37] provides us an iterative algorithm that gives a good approximation of the optimal rate of return λ^*.

First we need to take an initial guess of λ, then by the following formula (3.12) we can get a good approximation of λ^*.

$$\lambda_{n+1} = \frac{\mathbb{E}[Y_{N(\lambda_n)}]}{\mathbb{E}[T_{N(\lambda_n)}]}. \tag{3.12}$$

Now we explain how to develop the iterative algorithm using (3.12). Suppose we already know λ_n, then the optimal stopping rule (3.8) becomes

$$N(\lambda_n) = \min\{n \geq 1 \,:\, \min\{r_n^f, r_n^g\} \geq 4^{\lambda_n} - 1\}. \tag{3.13}$$

This means when $\min\{r_n^f, r_n^g\} \geq 4^{\lambda_n} - 1$, the winner source would stop to transmit. The expectation of total time until transmission using the stopping rule (3.13) is

$$\mathbb{E}[T_{(n)}] = \frac{\tau_1 + \tau_{RTS} + 2\tau_{CTS}}{1 - F_{r_{min}}(4^{\lambda_n} - 1)} + \tau_d \tag{3.14}$$

where $r_{min} = \min\{r_n^f, r_n^g\}$, $F_{r_{min}}(r) = \text{Pr}(\min\{r_n^f, r_n^g\} < r) = 1 - e^{-r\frac{\rho_f + \rho_g}{\rho_f \cdot \rho_g}}$ is the CDF of r_{min} (Pr$(\cdot)$ means probability of an event), $\frac{1}{1-F_{r_{min}}(4^{\lambda_n}-1)}$ is the average number of observations until stopping (i.e., when $r_{min} \geq 4^{\lambda_n} - 1$), $\tau_1 + \tau_{RTS} + 2\tau_{CTS}$ is the time for channel contention, the RTS transmission from relay to destination, CTS transmission from destination to relay, and CTS transmission from relay to winner source (the RTS transmission time from winner source to the relay is included in τ_1).

The expectation of data throughput per transmission using the stopping rule

(3.13) is

$$\mathbb{E}[Y_{(n)}] = \frac{\tau_d}{2}\int_{4^{\lambda_n}-1}^{\infty} \log_2(1+r_{min}) f_{r_{min}}(r_{min}) dr_{min} \tag{3.15}$$

where $f_{r_{min}}(r) = \frac{\rho_f+\rho_g}{\rho_f \cdot \rho_g} e^{-r\frac{\rho_f+\rho_g}{\rho_f \cdot \rho_g}}$ is the PDF of r_{min} and can be obtained as the derivative of $F_{r_{min}}(r)$.

Thus, the iterative algorithm calculating λ^* is as follows

- step 1: Take an initial guess λ_0
- step 2: Calculate the threshold through (3.13)
- step 3: Calculate $\mathbb{E}[Y_{(n)}]$ and $\mathbb{E}[T_{(n)}]$ through (3.15) and (3.14)
- step 4: Calculate $\lambda_{(n+1)} = \frac{\mathbb{E}[Y_{(n)}]}{\mathbb{E}[T_{(n)}]}$ and go back to step 2, until the difference between the λ calculated this time and that in the last time is less than a certain small number.

3.4 Numerical Results

Consider 18 source-destination pairs. Other parameters are [38] : the probability that a source sends a RTS in a minislot $p = 0.1$, channel coherence time $\tau_d =$ 8ms, RTS transmission duration $\tau_{RTS} = 103\mu$s, CTS transmission duration $\tau_{CTS} =$ 106μs, minislot duration $\delta = 20\mu$s, first-hop average SNR $\rho_f = 1$.

Fig. 3.1 is the performance of the iterative algorithm when the second-hop average SNR $\rho_g = 2$. The iterative algorithm converges quickly under different initial values.

Fig. 3.2 is the optimal threshold under different second-hop average SNR. When the minimum of the first hop and second-hop SNR exceeds the threshold, it is optimal for a winner source to transmit data; otherwise, the winner source should give up the transmission opportunity and let all sources re-contend the channel.

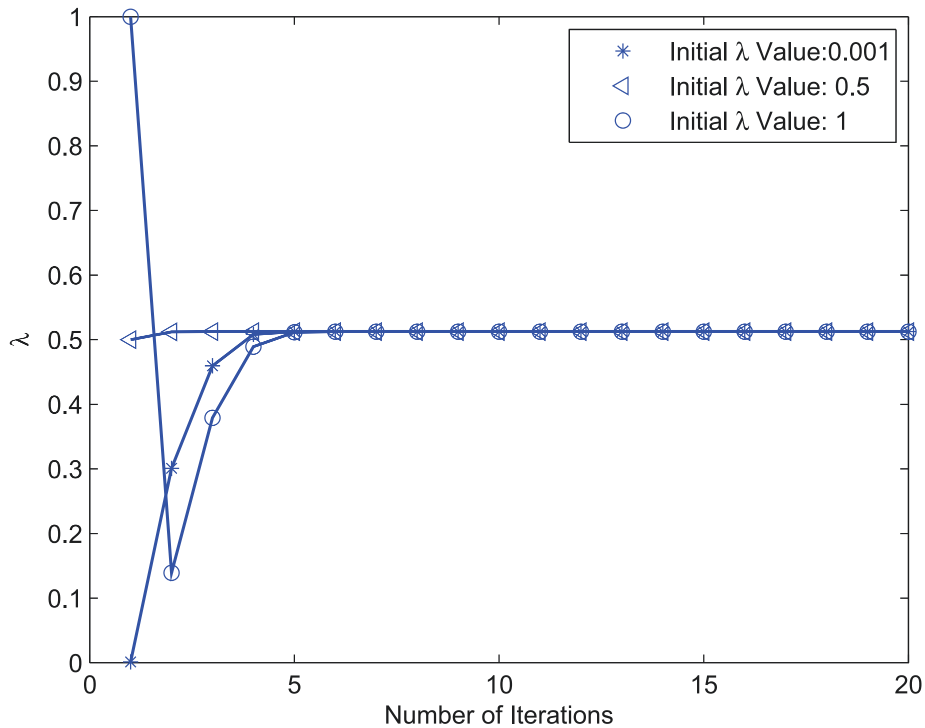

Fig. 3.1. Convergence performance of the iterative algorithm.

Fig. 3.3 shows the simulation results of average throughput with the proposed strategy, theoretical results (i.e., values of λ^*) of average throughput with the proposed strategy, and simulation results of average throughput without any strategy (i.e., a winner source never gives up) under different second-hop average SNR. It can be seen from Fig. 3.3 that our theoretical results agree with the simulation results very well. The average throughput with the proposed strategy is about 70% more than that without any strategy.

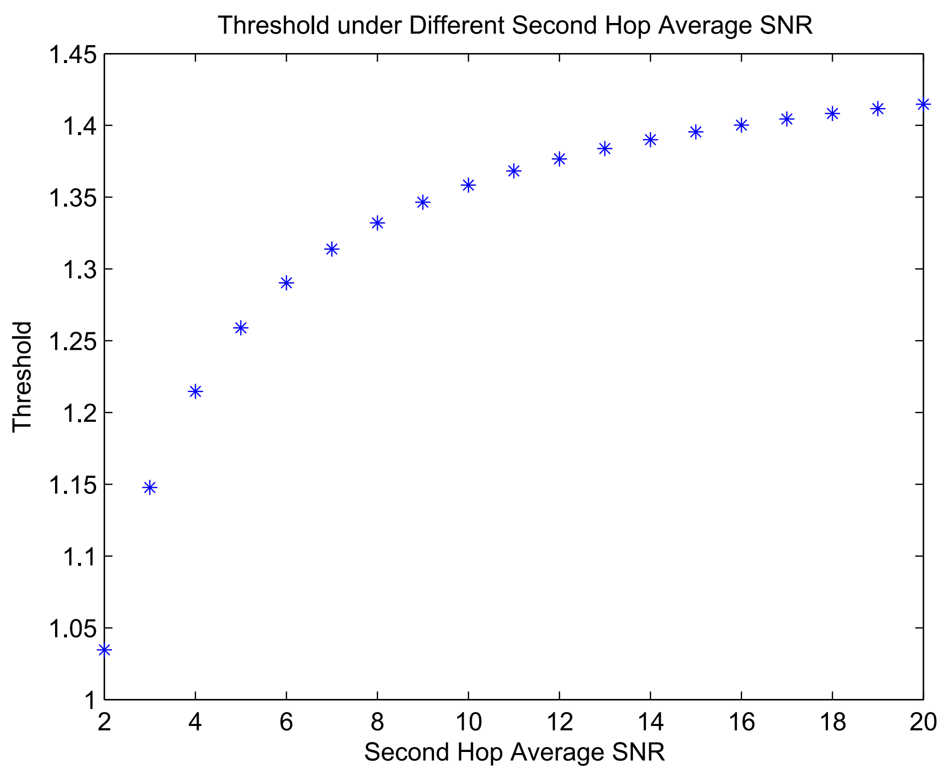

Fig. 3.2. Threshold under different second-hop average SNR.

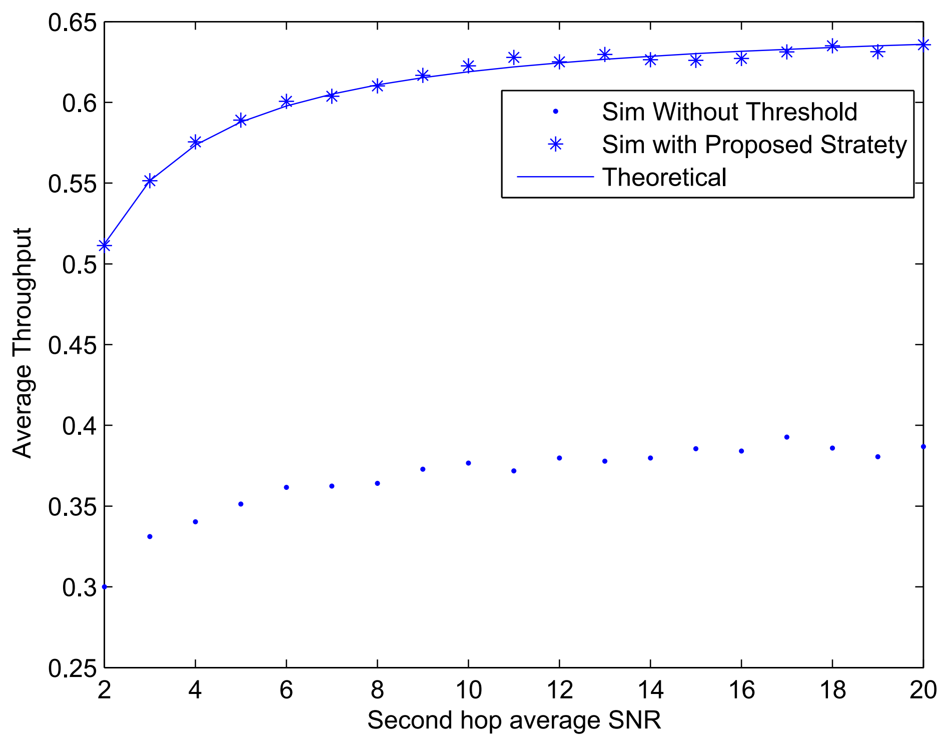

Fig. 3.3. Simulation and theoretical results.

Chapter 4

Distributed Opportunistic Scheduling in Wireless Relay Networks with Partial CSI

In this chapter, we investigate the opportunistic channel access in distributed wireless networks with DF relay, where the winner source has partial CSI, specifically, the winner source only has the CSI of source-relay link. The optimal stopping rule for the first hop is threshold-based. For the second hop, provided that the relay has already received the data from the winner source, it is proven that the only best choice for the relay is to keep probing the second hop until the second hop achievable transmission rate is higher than the first hop transmission rate. That is to say, the relay needs to wait until the second hop channel condition is good enough to be able to transmit the received data to the destination. Thus, if the first hop transmission rate is high and a huge amount of data is transmitted to the relay, it might take the relay a long time to probe the second hop to get a good second hop channel condition to transmit the data to the destination. To solve this problem, we derive a higher threshold for the first-hop transmission rate, i.e., if the first hop achievable rate is above the threshold, then the source only transmits at the threshold rate.

4.1 System Model

Consider a distributed DF relay network that includes a number, M, of source-destination pairs. Each source-destination pair has a relay assigned. There do not exist direct links between each source-destination pair. Assume channels in the first hop (i.e., from sources to their relays) follow independent and identically distributed (i.i.d.) Rayleigh fading with average received SNR being ρ_f, while the channels in the second hop (i.e., from relays to destinations) follow i.i.d. Rayleigh fading with average received SNR being ρ_g.

The M sources use a channel contention procedure as follows. At a minislot (the duration of which is denoted as δ), each source sends a RTS with probability p to its relay. So at each minislot, if no source transmits, i.e., the minislot is idle (the probability is $(1-p)^M$), then all sources start a new channel contention in next minislot; if more than one source send RTS (the probability is $1-(1-p)^M - Mp(1-p)^{M-1}$), it means that transmissions of the sources collide with each other, and thus, all the sources start a new channel contention following the collision; if only one source sends RTS (with probability $Mp(1-p)^{M-1}$), then we call the source *a winner source*. Define *an observation* as the interval from the starting point of the channel contention until a winner source appears (i.e., its RTS is successfully received by its relay). The average duration of an observation can be calculated as $\tau_1 = \frac{(1-p)^M}{Mp(1-p)^{M-1}} \cdot \delta + \frac{1-(1-p)^M - Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}} \tau_{RTS} + \tau_{RTS}$, in which τ_{RTS} is RTS duration.

At the end of an observation (say, observation n), the winner source's relay can estimate the channel SNR from the winner source to itself by the RTS reception, and it decides from two options: 1) option *give-up*: to give up the transmission opportunity, and notify the source of the decision by sending back a CTS. This CTS is also received by other sources. Thus, subsequently all sources can start a new contention. 2) option *stop*: to *stop* the process and utilize the transmission opportunity, and send back a CTS to notify the decision. In the CTS, a transmission rate denoted R_n is also indicated for transmission from the winner source to the relay. Then the winner source transmits for duration of a channel coherence time denoted as τ_d by using transmission rate R_n. The optimal value of R_n is derived in Section 4.3.

For observation n, if the winner source stops, denote reward Y_n as the total amount of traffic that is sent by the winner source and received by its destination, and denote T_n as the time duration from observation 1 until observation n plus the time used for transmissions in the two hops. Denote N as the *stopping time*, i.e., the winner sources in the first $N-1$ observations do not stop, and the winner source in the Nth observation stops. We target at an optimal stopping time denoted as N^*, which makes the system achieve the maximal system throughput, i.e.,

$$N^* = \arg\sup_{N\geq 0} \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]} \tag{4.1}$$

where $\mathbb{E}[\cdot]$ means expectation. N^* is also referred to as *optimal stopping strategy*. Based on [37, Chapter 6], we can transform problem (4.1) into a problem that maximizes net reward $Y_N - \lambda T_N$ with $\lambda > 0$. In specific, for $\lambda > 0$, an optimal strategy denoted $N^*(\lambda)$ should be found, which maximizes expected reward of the transformed problem:

$$U^*(\lambda) = \sup_{N(\lambda)\geq 0} \{\mathbb{E}[Y_{N(\lambda)}] - \lambda \mathbb{E}[T_{N(\lambda)}]\}. \tag{4.2}$$

Then if we find a λ^* such that $U^*(\lambda^*) = 0$, then an optimal strategy of problem (4.1) is in the form of $N^*(\lambda)$ with $\lambda = \lambda^*$ [37].

Next we find optimal strategy for problem (4.2), which includes two parts: the optimal second-hop strategy and optimal first-hop strategy, discussed in the subsequent two sections.

4.2 Strategy for the Second Hop

Consider observation n. Here we first try to find the optimal strategy for the second hop, i.e., we assume the winner source stops and transmits to its relay with rate R_n. For the second hop, the relay should find out its best strategy. The relay first sends a RTS to the destination, and the destination estimates the second-hop channel SNR denoted r_g and feedbacks a CTS that includes the channel SNR information, referred to as a *channel probing*. If the achievable second-hop transmission rate, given as $\log_2(1 + r_g)$, is not less than R_n, then the relay transmits to the destination by using transmission rate R_n with duration τ_d; otherwise, the relay may decide to give up or to continue channel probing. If the relay decides to give up, all sources start a new channel contention. If the relay decides to continue channel probing, then the relay waits for channel coherence time τ_d and has a new RTS-CTS exchange with the destination (a new channel probing), and transmits if the achievable second-hop transmission rate is not less than R_n, or decides to give up or to continue channel probing otherwise. This procedure is repeated until the relay either transmits or gives up. It can be seen that there are a sequence of decisions in the second hop, which makes the optimal second-hop strategy challenging. To address the challenge, we review second-hop strategies from a new perspective, as follows.

Denote S_l as the second-hop strategy that the relay can have up to l channel probings of its channel to the destination. So if the relay cannot find a second-hop channel realization with achievable rate not less than R_n within l channel probings, the relay is forced to give up. Denote $V^l(\lambda)$ (which is a function of λ) as the net reward of strategy S_l. Therefore, the optimal second-hop strategy should achieve net reward $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], ..., \mathbb{E}[V^\infty(\lambda)]\}$.

The net reward expectation of strategy S_1 is

$$\begin{aligned}\mathbb{E}[V^1(\lambda)] &= \Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) \\ &\quad + \Pr[r_g^1 < r_n](-\lambda(\tau_{RTS} + \tau_{CTS})) \\ &= (1 - F_g(r_n))(R_n\tau_d - \lambda\tau_2)+ \\ &\quad F_g(r_n)(-\lambda(\tau_{RTS} + \tau_{CTS}))\end{aligned} \tag{4.3}$$

where $\Pr[\cdot]$ means probability of an event, τ_{CTS} is CTS transmission duration, $\tau_2 =$

$\tau_{RTS} + \tau_{CTS} + \tau_d$ is the time cost for probing and transmission in the second hop, $F_g(\cdot)$ is the cumulative distribution function (CDF) of the second-hop channel SNR (the subscript g stands for the second hop), r_g^1 is the second-hop channel SNR in the first channel probing, $r_n \triangleq 2^{R_n} - 1$ is the minimum required SNR of the second hop for achievable transmission rate R_n.

The net reward expectation of strategy S_∞ is

$$\begin{aligned} &\mathbb{E}[V^\infty(\lambda)] \\ =&\text{Pr}[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) + \text{Pr}[r_g^1 < r_n](\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_2) \\ =&(1 - F_g(r_n))(R_n\tau_d - \lambda\tau_2) + F_g(r_n)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_2). \end{aligned} \tag{4.4}$$

From (4.3) and (4.4), we have

$$\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^1(\lambda)] = F_g(r_n)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d). \tag{4.5}$$

4.2.1 Case with $\mathbb{E}[V^\infty(\lambda)] \geq \lambda\tau_d$

If $\mathbb{E}[V^\infty(\lambda)] \geq \lambda\tau_d$, then from (4.5) we have $\mathbb{E}[V^\infty(\lambda)] \geq \mathbb{E}[V^1(\lambda)]$. Now we compare $\mathbb{E}[V^\infty(\lambda)]$ with $\mathbb{E}[V^l(\lambda)]$, $l \geq 1$.

We have

$$\begin{aligned} \mathbb{E}[V^l(\lambda)] = &\text{Pr}[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) + \text{Pr}[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - 2\lambda\tau_2) + ... \\ &+ \text{Pr}[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - l\lambda\tau_2) \\ &+ \text{Pr}[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l < r_n](-(l-1)\lambda\tau_2 - \lambda(\tau_{RTS} + \tau_{CTS})) \end{aligned} \tag{4.6}$$

in which $r_g^1, r_g^2, ..., r_g^l$ are channel SNRs of 1st, 2nd, ..., lth channel probing of the relay. $\mathbb{E}[V^\infty(\lambda)]$ can be expressed as

$$\begin{aligned}\mathbb{E}[V^\infty(\lambda)] = \; & \text{Pr}[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_2) \\ & + \text{Pr}[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - 2\lambda\tau_2) + ... \\ & + \text{Pr}[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - l\lambda\tau_2) \\ & + \text{Pr}[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l < r_n](\mathbb{E}[V^\infty(\lambda)] - l\lambda\tau_2).\end{aligned}$$

So

$$\begin{aligned}\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^l(\lambda)] & = \text{Pr}[r_g^1 < r_n, ..., r_g^{l-1} < r_n, r_g^l < r_n](\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \\ & = (F_g(r_n))^l(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \geq 0\end{aligned} \tag{4.7}$$

which means the optimal second-hop strategy should be: the relay keeps probing the second-hop channel until the achievable rate is not less than R_n.

4.2.2 Case with $\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$

If $\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$, from (4.5) we have $\mathbb{E}[V^\infty(\lambda)] < \mathbb{E}[V^1(\lambda)]$. Now we compare $\mathbb{E}[V^1(\lambda)]$ with $\mathbb{E}[V^l(\lambda)]$, $l > 1$.

$$\begin{aligned}\mathbb{E}[V^1(\lambda)] - \mathbb{E}[V^l(\lambda)] & = -(\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^1(\lambda)]) + (\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^l(\lambda)]) \\ & \overset{(a)}{=} -F_g(r_n)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) + (F_g(r_n))^l(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \\ & = F_g(r_n)\big(-1 + (F_g(r_n))^{l-1}\big)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \overset{(b)}{>} 0\end{aligned}$$

in which (a) comes from (4.5) and (4.7), and (b) comes from $F_g(r_n) < 1$ and $\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$. Thus, the optimal second-hop strategy should be: the relay probes the second-hop channel only once, and transmits if the achievable transmission rate is not less than R_n, or gives up otherwise.

Overall, for the second hop, depending on comparison of $\mathbb{E}[V^\infty(\lambda)]$ with $\lambda\tau_d$, the relay should either probe the second-hop channel once, or keep probing the second-hop channel until the achievable second-hop rate is not less than R_n.

4.3 Strategy for the First Hop

Based on optimal strategy in the second hop, now we derive optimal strategy for the first hop. In the first hop, at observation n, once the RTS of the winner source (i.e., the source that wins channel contention) is received by its relay, and the first-hop channel SNR denoted r_n^f is estimated, then the decision is either give-up or stop (i.e., to transmit), whichever has higher reward. If the decision for the first hop is give-up, then the net reward is $-\lambda\tau_{CTS}$ (since a CTS is needed to notify the decision); if the decision for the first hop is to transmit with rate R_n, the net reward is $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], \ldots, \mathbb{E}[V^\infty(\lambda)]\} - \lambda(\tau_{CTS} + \tau_d)$, in which $\tau_{CTS} + \tau_d$ is time cost in the first hop: the relay uses a CTS to notify the source of the decision and the source transmits with τ_d duration (noting that the time cost in the subsequent second hop is included in $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], \ldots, \mathbb{E}[V^\infty(\lambda)]\}$).

First consider $\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$ for the second hop. Then based on discussion in Section 4.2.2, $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], \ldots, \mathbb{E}[V^\infty(\lambda)]\} = \mathbb{E}[V^1(\lambda)]$, so the net reward of transmission in first hop is $\mathbb{E}[V^1(\lambda)] - \lambda(\tau_{CTS} + \tau_d)$. Since $\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$, from (4.5) we have

$$\begin{aligned}\mathbb{E}[V^1(\lambda)] &= (1 - F_g(r_n))\mathbb{E}[V^\infty(\lambda)] + F_g(r_n)\lambda\tau_d \\ &< (1 - F_g(r_n))\lambda\tau_d + F_g(r_n)\lambda\tau_d = \lambda\tau_d\end{aligned} \tag{4.8}$$

which leads to $\mathbb{E}[V^1(\lambda)] - \lambda(\tau_{CTS} + \tau_d) < -\lambda\tau_{CTS}$. In other words, the net reward of transmission in the first hop is less than the net reward of give-up in the first hop, and thus, the winner source will always give up in the first hop. Therefore, when we calculate the net reward of transmission in the first hop, we can ignore "$\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$". Thus, we focus on $\mathbb{E}[V^\infty(\lambda)] \geq \lambda\tau_d$, and based on discussion in Section 4.2.1, we have $\max\{\mathbb{E}[V^1(\lambda)], \mathbb{E}[V^2(\lambda)], \ldots, \mathbb{E}[V^\infty(\lambda)]\} = \mathbb{E}[V^\infty(\lambda)]$.

So the net reward of transmission (stopping) in the first hop is

$$
\begin{aligned}
&\mathbb{E}[V^{\infty}(\lambda)] - \lambda(\tau_{CTS} + \tau_d) \\
\overset{(c)}{=} & R_n \tau_d - \frac{1}{1 - F_g(r_n)} \lambda \tau_2 - \lambda(\tau_{CTS} + \tau_d) \\
\overset{(d)}{=} & \log_2(1 + r_n)\tau_d - \lambda \tau_{CTS} - \lambda \tau_d - \lambda e^{\frac{r_n}{\rho_g}} \tau_2
\end{aligned}
\tag{4.9}
$$

in which (c) comes from $\mathbb{E}[V^{\infty}(\lambda)] = R_n \tau_d - \frac{1}{1-F_g(r_n)} \lambda \tau_2$ which is from (4.4), and (d) is from $F_g(r_n) = 1 - e^{-\frac{r_n}{\rho_g}}$ (Rayleigh fading) and $r_n \triangleq 2^{R_n} - 1$. The net reward (4.9) is not a monotonically increasing function of r_n. So we need to set up an optimal r_n that makes the net reward maximal.

Define function $\phi(x) = \log_2(1 + x)\tau_d - \lambda \tau_{CTS} - \lambda \tau_d - \lambda e^{\frac{x}{\rho_g}} \tau_2$, which is a concave function. To find the optimal x, denoted x^*, that maximizes $\phi(x)$, we can solve $\frac{d\phi(x)}{dx} = 0$, which leads to

$$
\frac{\tau_d}{(1 + x^*) \ln 2} = \frac{\lambda}{\rho_g} e^{\frac{x^*}{\rho_g}} \tau_2. \tag{4.10}
$$

x^* can be calculated from (4.10) numerically. So r_n should be set to x^* if feasible. However, it may not be feasible to set r_n to be x^* since r_n should be no more than the first-hop channel SNR r_n^f. Thus, overall we should set $r_n = \min\{r_n^f, x^*\}$ and $R_n = \log_2(1 + \min\{r_n^f, x^*\})$.

Recall that an optimal stopping strategy of problem (4.2) with λ^* satisfying $U(\lambda^*) = 0$ is an optimal stopping strategy of problem (4.1). So next we focus on optimal stopping strategy of problem (4.2) with λ^*. Maximal expected reward $U(\lambda^*)$ of problem (4.2) should satisfy an optimality equation [37]:

$$
\begin{aligned}
\mathbb{E}\Big[\max \Big\{ & \log_2(1 + \min\{r_n^f, x^*\})\tau_d - \lambda^*(\tau_{CTS} + \tau_d \\
& + e^{\frac{\min\{r_n^f, x^*\}}{\rho_g}} \tau_2), \; U(\lambda^*) - \lambda^* \tau_{CTS} \Big\} \Big] - \lambda \tau_1 = U(\lambda^*).
\end{aligned}
$$

Since $U(\lambda^*) = 0$, the optimal equation is rewritten as

$$\mathbb{E}\Big[\max\Big\{\log_2(1+\min\{r_n^f,x^*\})\tau_d - \lambda^*(\tau_{CTS}+\tau_d + e^{\frac{\min\{r_n^f,x^*\}}{\rho g}}\tau_2),\ -\lambda^*\tau_{CTS}\Big\}\Big] = \lambda^*\tau_1 \quad (4.11)$$

from which λ^* can be calculated numerically.

Accordingly, the optimal stopping strategy in the first hop is given as

$$N^*(\lambda^*) = \min\Big\{n \geq 1:\ \log_2(1+\min\{r_n^f,x^*\})\tau_d - \lambda^*(\tau_{CTS}+\tau_d+e^{\frac{\min\{r_n^f,x^*\}}{\rho g}}\tau_2) \geq -\lambda^*\tau_{CTS}\Big\} \quad (4.12)$$

in which x^* can be calculated from (4.10) with $\lambda = \lambda^*$.

The left handside of the inequality in (4.12) is a non-decreasing function of r_n^f. Denote $\hat{r}_f$ as the solution of r_n^f for $\log_2(1+\min\{r_n^f,x^*\})\tau_d - \lambda^*(\tau_{CTS}+\tau_d+e^{\frac{\min\{r_n^f,x^*\}}{\rho g}}\tau_2) = -\lambda^*\tau_{CTS}$. Then the optimal stopping strategy in the first hop is rewritten as $N^*(\lambda^*) = \min\big\{n \geq 1:\ r_n^f \geq \hat{r}_f\big\}$. Thus, at observation n, if the fist-hop channel SNR r_n^f is less than the threshold $\hat{r}_f$, the winner source gives up; otherwise, the winner source stops, i.e., transmits with rate $R_n = \log_2(1+\min\{r_n^f,x^*\})$, and subsequently the relay keeps probing the second-hop channel until an achievable rate not less than R_n. The values of $\hat{r}_f$ and x^* can be calculated offline, and thus, the optimal strategy is a pure-threshold strategy, with very low computational complexity.

4.4 Iterate Algorithm for Calculating λ^*

It is hard to get an analytical closed-form solution from eq. (4.11). Similar to Chapter 3, we will use an iterative algorithm [37] to get a good approximation of optimal rate of return λ^*.

Suppose we already know λ_n, then the optimal stopping rule (4.12) becomes

$$N(\lambda_n) = \min\{n \geq 1, \log_2(1 + \min(r_n^f, x_{(n)}^*))\tau_d - \lambda_n e^{\frac{\min(r_n^f, x_{(n)}^*)}{\rho_g}} \tau_2 \\ \geq \lambda_n \tau_d\} \tag{4.13}$$

where $x_{(n)}^*$ is the threshold get from (4.10) by letting $\lambda = \lambda_n$. Suppose when $r_n^f = r_{1(n)}$, we have $\log_2(1 + \min(r_n^f, x_{(n)}^*))\tau_d - \lambda_n e^{\frac{\min(r_n^f, x_{(n)}^*)}{\rho_g}} \tau_2 = \lambda_n \tau_d$. In other words, $r_{1(n)}$ is the threshold for the first-hop SNR, i.e., when the first-hop SNR is greater than the threshold, the winner source begins to transmit data to its relay.

The expectation of throughput per transmission using the stopping rule (4.13) is

$$\begin{aligned}
\mathbb{E}[Y_{(n)}] &= \frac{F_f(x_{(n)}^*) - F_f(r_{1(n)})}{1 - F_f(r_{1(n)})} \tau_d \int_{r_{1(n)}}^{x_{(n)}^*} \log_2(1 + r) \frac{f_f(r)}{F_f(x_{(n)}^*) - F_f(r_{1(n)})} dr \\
&+ \frac{1 - F_f(x_{(n)}^*)}{1 - F_f(r_{1(n)})} \tau_d \log_2(1 + x_{(n)}^*) \\
&= e^{\frac{r_{1(n)}}{\rho_f}} \tau_d \int_{r_{1(n)}}^{x_{(n)}^*} \log_2(1 + r) \frac{1}{\rho_f} e^{-\frac{r}{\rho_f}} dr + e^{\frac{r_{1(n)}}{\rho_f} - \frac{x_{(n)}^*}{\rho_f}} \tau_d \log_2(1 + x_{(n)}^*) \\
&= [\frac{1}{\rho_f} e^{\frac{r_{1(n)}}{\rho_f}} \int_{r_{1(n)}}^{x_{(n)}^*} \ln(1 + r) e^{-\frac{r}{\rho_f}} dr + e^{\frac{r_{1(n)}}{\rho_f} - \frac{x_{(n)}^*}{\rho_f}} \ln(1 + x_{(n)}^*)] / \ln 2 * \tau_d \\
&= [\frac{1}{\rho_f} e^{\frac{r_{1(n)}}{\rho_f}} (-\rho_f) \int_{r_{1(n)}}^{x_{(n)}^*} \ln(1 + r) d e^{-\frac{r}{\rho_f}} + e^{\frac{r_{1(n)}}{\rho_f} - \frac{x_{(n)}^*}{\rho_f}} \ln(1 + x_{(n)}^*)] / \ln 2 * \tau_d \\
&= \{e^{\frac{r_{1(n)}}{\rho_f}} [\ln(1 + r_{1(n)}) e^{-\frac{r_{1(n)}}{\rho_f}} - \ln(1 + x_{(n)}^*) e^{-\frac{x_{(n)}^*}{\rho_f}} + \int_{r_{1(n)}}^{x_{(n)}^*} e^{-\frac{r_{1(n)}}{\rho_f}} \frac{1}{1 + r} dr] \\
&+ e^{\frac{r_{1(n)}}{\rho_f} - \frac{x_{(n)}^*}{\rho_f}} \ln(1 + x_{(n)}^*)\} / \ln 2 * \tau_d \\
&= \{e^{\frac{r_{1(n)}}{\rho_f}} [\ln(1 + r_{1(n)}) e^{-\frac{r_{1(n)}}{\rho_f}} - \ln(1 + x_{(n)}^*) e^{-\frac{x_{(n)}^*}{\rho_f}} + e \cdot (ei(-x_{(n)}^* - 1) \\
&- ei(-r_{1(n)} - 1))] + e^{\frac{r_{1(n)}}{\rho_f} - \frac{x_{(n)}^*}{\rho_f}} \ln(1 + x_{(n)}^*)\} / \ln 2 * \tau_d
\end{aligned} \tag{4.14}$$

where $F_f(\cdot)$ is the CDF of the first-hop SNR r_n^f. Here $\frac{F_f(x_{(n)}^*) - F_f(r_{1(n)})}{1 - F_f(r_{1(n)})}$ is the probability that r_n^f satisfies $r_{1(n)} \leq r_n^f \leq x_{(n)}^*$. $f_f(\cdot)$ is the PDF of r_n^f, $\frac{f_f(r)}{F_f(x_{(n)}^*) - F_f(r_{1(n)})}$ is the PDF of r_n^f under the condition that $r_{1(n)} \leq r_n^f \leq x_{(n)}^*$, so $\tau_d \int_{r_{1(n)}}^{x_{(n)}^*} \log_2(1 +$

$r)\frac{f_f(r)}{F_f(x^*_{(n)})-F_f(r_{1(n)})}dr$ is the average throughput if r^f_n satisfies $r_{1(n)} \leq r^f_n \leq x^*_{(n)}$. $\frac{1-F_f(x^*_{(n)})}{1-F_f(r_{1(n)})}$ is the probability that $r^f_n > x^*_{(n)}$, $\log_2(1+x^*_{(n)})$ is the average throughput if $r^f_n > x^*_{(n)}$. $ei(x) = \int_{-\infty}^{x} \frac{e^t}{t}dt$.

The expectation of time cost per transmission using the stopping rule (4.13) is

$$\begin{aligned}
\mathbb{E}[T_{(n)}] &= \frac{\tau_1 + \tau_{CTS}}{1 - F_f(r_{1(n)})} + \tau_d \\
&+ \frac{F_f(x^*_{(n)}) - F_f(r_{1(n)})}{1 - F_f(r_{1(n)})}\tau_2 \int_{r_{1(n)}}^{x^*_{(n)}} \frac{1}{1 - F_g(r)} \frac{f_f(r)}{F_f(x^*_{(n)}) - F_f(r_{1(n)})} dr + \\
&\frac{1 - F_f(x^*_{(n)})}{1 - F_f(r_{1(n)})}\tau_2 \frac{1}{1 - F_g(x^*_{(n)})} \\
&= (\tau_1 + \tau_{CTS})e^{\frac{r_{1(n)}}{\rho_f}} + \tau_d \\
&+ e^{\frac{r_{1(n)}}{\rho_f}}\tau_2 \int_{r_{1(n)}}^{x^*_{(n)}} e^{\frac{r}{\rho_g}} \frac{1}{\rho_f} e^{-\frac{r}{\rho_f}} dr + e^{\frac{-x^*_{(n)}+r_{1(n)}}{\rho_f}} \tau_2 e^{\frac{x^*_{(n)}}{\rho_g}} \\
&= (\tau_1 + \tau_{CTS})e^{\frac{r_{1(n)}}{\rho_f}} + \tau_d \\
&+ e^{\frac{r_{1(n)}}{\rho_f}}\tau_2 \frac{1}{\rho_f} \frac{\rho_f * \rho_g}{\rho_f - \rho_g}(e^{\frac{\rho_f - \rho_g}{\rho_f * \rho_g} * x^*_{(n)}} - e^{\frac{\rho_f - \rho_g}{\rho_f * \rho_g} * r_{1(n)}}) + \tau_2 e^{\frac{-x^*_{(n)}+r_{1(n)}}{\rho_f} + \frac{x^*_{(n)}}{\rho_g}}.
\end{aligned} \tag{4.15}$$

here $\frac{1}{1-F_f(r_{1(n)})}$ is the average number of observations until the first-hop SNR $r^f_n \geq r_{1(n)}$. $\tau_1 + \tau_{CTS}$ is the time for channel contention and the relay sends back a CTS. $\tau_2 \int_{r_{1(n)}}^{x^*_{(n)}} \frac{1}{1-F_g(r)} \frac{f_f(r)}{F_f(x^*_{(n)})-F_f(r_{1(n)})}dr$ is the time cost for waiting and data transmission in the second hop if the first-hop SNR satisfies $r_{1(n)} \leq r^f_n \leq x^*_{(n)}$. $\tau_2 \frac{1}{1-F_g(x^*_{(n)})}$ is the time cost of waiting and data transmission in the second hop if the first-hop SNR $r^f_n > x^*_{(n)}$.

Thus, the iterative algorithm is as follows:

- step 1: Take an initial guess λ_0
- step 2: Calculate x^* and $r_{1(n)}$ through (4.10) and (4.13)
- step 3: Calculate $\mathbb{E}[Y_{(n)}]$ and $\mathbb{E}[T_{(n)}]$ through (4.14) and (4.15)
- step 4: Calculate $\lambda_{(n+1)} = \frac{\mathbb{E}[Y_{(n)}]}{\mathbb{E}[T_{(n)}]}$ and go back to step 2, until the difference bewteen the λ calculated this time and last time is less than a certain small number.

4.5 Numerical Results

Consider 18 source-destination pairs. Other parameters are [38]: the probability that a source sends a RTS in a minislot $p = 0.1$, channel coherence time $\tau_d = 8$ms, RTS transmission duration $\tau_{RTS} = 103\mu$s, CTS transmission duration $\tau_{CTS} = 106\mu$s, minislot duration $\delta = 20\mu$s, first-hop average SNR $\rho_f = 1$.

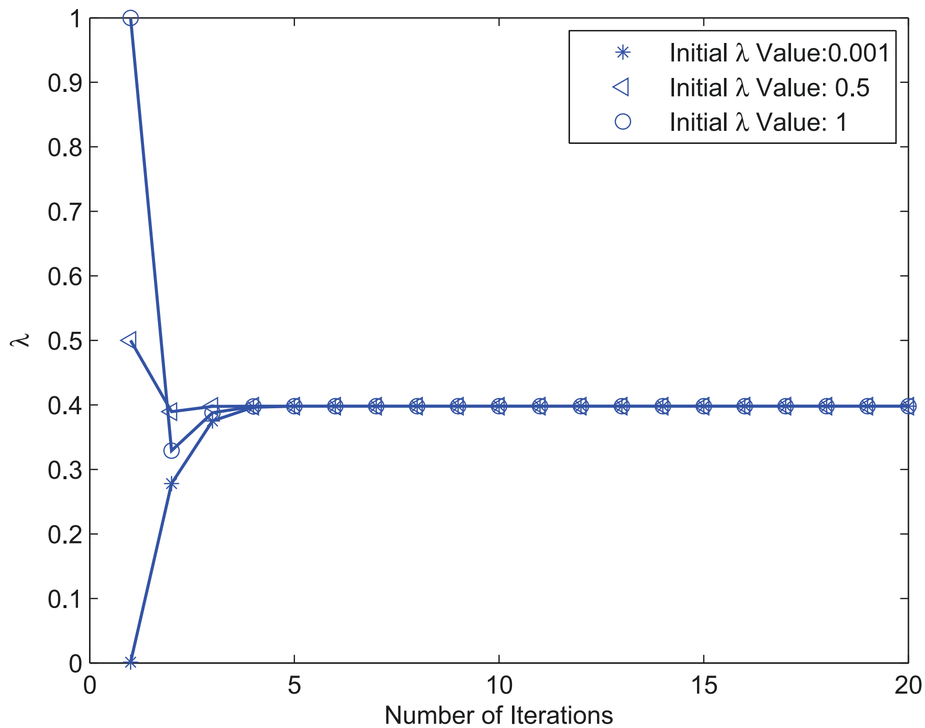

Fig. 4.1. Convergence performance of the iterative algorithm.

Fig. 4.1 shows the performance of the iterative algorithm when the second-hop average SNR is $\rho_g = 2$. It can be seen that the iterative algorithm converges quickly under different initial values.

Fig. 4.2 is the upper and lower thresholds for the first-hop SNR, calculated from (4.10) and (4.12), respectively, under different second-hop average SNR. For example, when the second-hop average SNR is 10, the lower threshold is 2.0327 and the upper threshold is 7.9523, i.e., when the detected first-hop SNR is less than 2.0327,

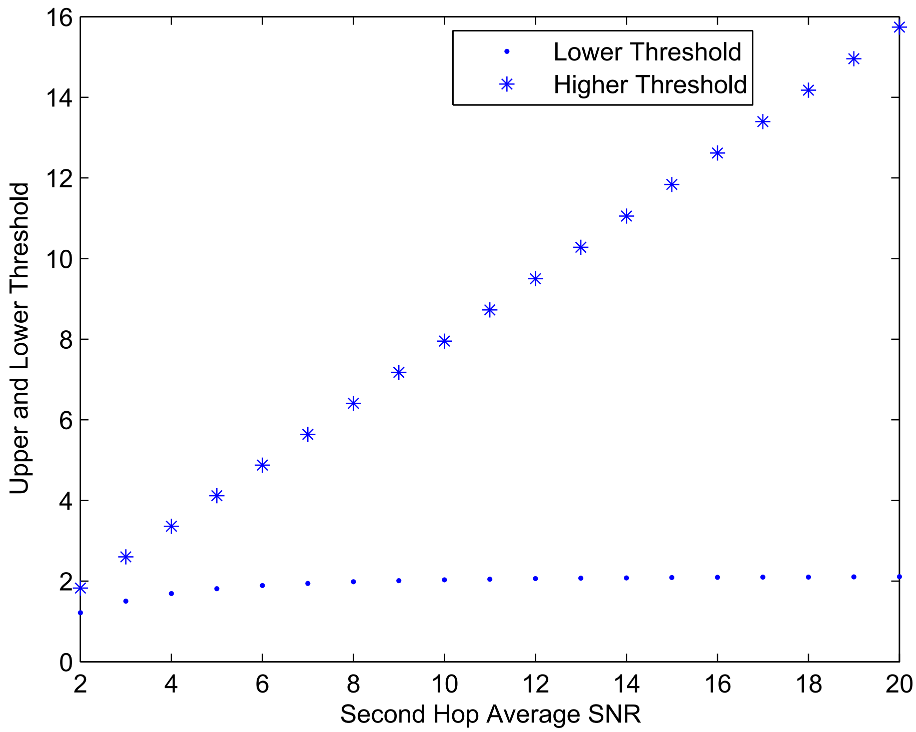

Fig. 4.2. Thresholds under different second-hop average SNR.

the source will give up the transmission opportunity; when the detected first-hop SNR is between 2.0327 and 7.9523, the source will transmit its data at its full channel capacity; when the detected first-hop SNR is greater than 7.9523, the source will transmit its data at rate $\log_2(1 + 7.9523)$.

Fig. 4.3 shows the simulation results of average throughput with the proposed strategy, theoretical results of average throughput with the proposed strategy, and simulation results of average throughput without any strategy (i.e., after probing the first-hop, a winner source always transits to its relay using the full first-hop channel capacity, and then the relay keeps waiting until a good enough second-hop channel condition is found) under different second-hop average SNR. It can be seen from Fig. 4.3 that our theoretical results agree with the simulation results very well. The average throughput with the proposed strategy is about 40% more than that without any strategy when the second-hop average SNR is low; when the second-

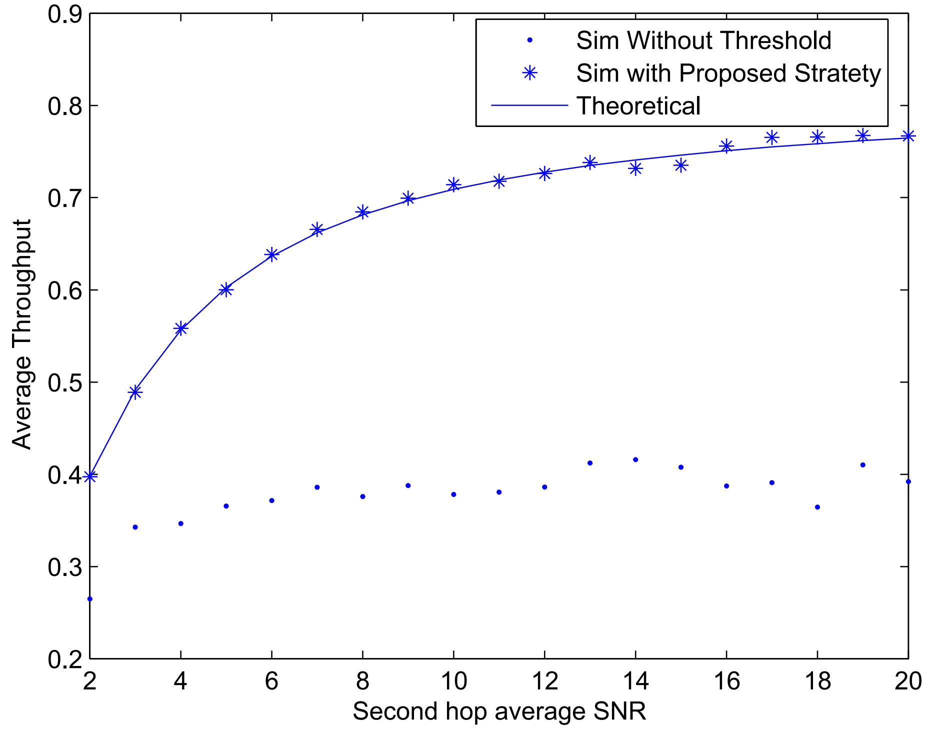

Fig. 4.3. Simulation and theoretical results.

hop average SNR is high, average throughput with the proposed strategy is almost twice that without any strategy.

Chapter 5

Distributed Opportunistic Scheduling in Wireless Relay Networks with Partial CSI–Further Improvement

In Chapter 4, we assume that the data transmission time and rate are equal in both hops, i.e., the second hop transmission rate is equal to the first hop transmission rate even when the second hop achievable rate is higher than the first hop transmission rate. This leads to resource waste and low channel utilization efficiency. In this chapter, we assume that when the second hop achievable rate is higher than the first hop transmission rate, the relay will transmit data at the second-hop achievable rate in order to reduce transmission time and improve the channel utilization efficiency.

5.1 System Model

The system model is almost the same as that in Chapter 4. The only difference is the choice for the relay after probing the second hop. Specifically, if the detected second-hop SNR r_g satisfies $\log_2(1 + r_g) \geq R_n$ or equivalently, $r_g \geq r_n$ (R_n is the first hop transmission rate, and $R_n = \log_2(1 + r_n)$), then the relay transmits the received data at rate $\log_2(1 + r_g)$ rather than R_n; otherwise, the relay either waits for channel coherence time and probes again or abandons the received data.

Similar to Chapter 4, for observation n, if the winner source stops, denote reward Y_n as the total amount of traffic that is sent by the winner source and received by its destination, and denote T_n as the time duration from observation 1 until observation n plus the time used for transmissions in the two hops. Denote N as the *stopping time*. Our goal is still to find the optimal stopping time N^* that can maximize the average rate of return

$$N^* \triangleq arg \max_{N \in \mathcal{C}} \frac{\mathbb{E}[Y_N]}{\mathbb{E}[T_N]}. \tag{5.1}$$

This problem can be converted to an ordinary optimal stopping problem that maximizes the net reward $U(\lambda) = Y_N - \lambda T_N$, where λ denotes the "cost" per unit of time. The optimal net return is defined as

$$U^*(\lambda) = \sup_{N(\lambda) \in \mathcal{C}} \mathbb{E}[Y_{N(\lambda)} - \lambda T_{N(\lambda)}]. \tag{5.2}$$

5.2 Optimal Strategy

As defined in Chapter 4, S_l is the second hop strategy that the relay can have up to l chances of channel probings and $V^l(\lambda)$ is the net reward of strategy S_l. Since the transmission time for the second hop is a random variable and is determined by the first hop transmission rate and the detected SNR of the second hop, the expectation of net reward of strategy S_1 is:

$$
\begin{aligned}
&\mathbb{E}[V^1(\lambda)] \\
=&Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n](-\lambda(\tau_{RTS} + \tau_{CTS})) \\
=&(1 - F_g(r_n))(R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ F_g(r_n)(-\lambda(\tau_{RTS} + \tau_{CTS}))
\end{aligned} \tag{5.3}
$$

where $r_g^n\,(n = 1, 2, 3...)$ is the second-hop SNR of the nth probing, $f_{g^1}(r) = \frac{f_g(r)}{1-F_g(r_n)} = \frac{1}{\rho_g}e^{-\frac{r-r_n}{\rho_g}}$ is the PDF of the second hop detected SNR r_g^n under the condition that $r_g^n \geq r_n$, and $f_g(r)$ is the PDF of r_g^n. $\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr$ is the average time for data transmission in the second hop.

The expectation of net reward of strategy S_∞ is given by

$$
\begin{aligned}
&\mathbb{E}[V^\infty(\lambda)] \\
=&Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n](\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_2) \\
=&(1 - F_g(r_n))(R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ F_g(r_n)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_2).
\end{aligned} \tag{5.4}
$$

From (5.3) and (5.4) we have

$$
\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^1(\lambda)] = F_g(r_n)(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \tag{5.5}
$$

which is same as (4.5).

The expectation of net reward of strategy S_l is given by

$$
\begin{aligned}
&\mathbb{E}[V^l(\lambda)] \\
=&Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - \lambda\tau_2 - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \\
&\lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) + \dots \\
&+ Pr[r_g^1 < r_n, \dots, r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - (l-1)\lambda\tau_2 \\
&- \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n, \dots, r_g^{l-1} < r_n, r_g^l < r_n](-(l-1)\lambda\tau_2 - \lambda(\tau_{RTS} + \tau_{CTS})).
\end{aligned}
\tag{5.6}
$$

$\mathbb{E}[V^\infty(\lambda)]$ can be expressed as

$$
\begin{aligned}
&\mathbb{E}[V^\infty(\lambda)] \\
=&Pr[r_g^1 \geq r_n](R_n\tau_d - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n, r_g^2 \geq r_n](R_n\tau_d - \lambda\tau_2 - \lambda\tau_{RTS} - \lambda\tau_{CTS} - \\
&\lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) + ... \\
&+ Pr[r_g^1 < r_n, \dots, r_g^{l-1} < r_n, r_g^l \geq r_n](R_n\tau_d - (l-1)\lambda\tau_2 \\
&- \lambda\tau_{RTS} - \lambda\tau_{CTS} - \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr) \\
&+ Pr[r_g^1 < r_n, \dots, r_g^{l-1} < r_n, r_g^l < r_n](\mathbb{E}[V^\infty(\lambda)] - l\lambda\tau_2).
\end{aligned}
\tag{5.7}
$$

From (5.6) and (5.7) we have

$$
\begin{aligned}
&\mathbb{E}[V^\infty(\lambda)] - \mathbb{E}[V^l(\lambda)] \\
=&Pr[r_g^1 < r_n, \dots, r_g^{l-1} < r_n, r_g^l < r_n](\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d) \\
=&(F_g(r_n))^l(\mathbb{E}[V^\infty(\lambda)] - \lambda\tau_d)
\end{aligned}
\tag{5.8}
$$

which is the same as (4.7).

Therefore, similar to Chapter 4, we can prove that S_∞ is the best strategy for the relay if the expectation of net reward of S_∞ is not less than $\lambda\tau_d$; otherwise S_1 is the best strategy.

For the first hop, using the same method in Chapter 4, it can be proven that when $\mathbb{E}[V^\infty(\lambda)]-\lambda\tau_d < 0$, the net reward of transmission in the first hop must be less than the net reward of give-up in the first hop, and thus, the winner source will always give up the transmission opportunity in the first hop. Therefore, when we calculate the net reward of transmission in the first hop, we can ignore "$\mathbb{E}[V^\infty(\lambda)] < \lambda\tau_d$". Thus, we focus on $\mathbb{E}[V^\infty(\lambda)] \geq \lambda\tau_d$. Then, the net reward for data transmission in the first hop is:

$$\begin{aligned}U(\lambda) =&\mathbb{E}[V^\infty(\lambda)] - \lambda(\tau_{CTS} + \tau_d)\\ =&R_n\tau_d - (\frac{1}{1-F_g(r_n)} - 1)\lambda\tau_2 - \lambda\tau_{RTS} - \lambda\tau_{CTS}\\ &- \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}f_{g^1}(r)dr - \lambda(\tau_{CTS}+\tau_d)\\ =&\log_2(1+r_n)\tau_d - \lambda\tau_{CTS} - \lambda e^{\frac{r_n}{\rho_g}}\tau_2\\ &- \lambda\int_{r_n}^{\infty}\frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)}\frac{1}{\rho_g}e^{-\frac{r-r_n}{\rho_g}}dr\end{aligned} \tag{5.9}$$

The net reward for transmission is not a monotonically increasing function of r_n. So we should choose an optimal r_n from the available range $(0,\, r_f(n)]$ that maximizes the net reward.

Define function

$$\begin{aligned}\varphi(x) =&\log_2(1+x)\tau_d - \lambda\tau_{CTS} - \lambda e^{\frac{x}{\rho_g}}\tau_2\\ &- \lambda\int_{x}^{\infty}\frac{\log_2(1+x)\tau_d}{\log_2(1+r)}\frac{1}{\rho_g}e^{-\frac{r-x}{\rho_g}}dr.\end{aligned} \tag{5.10}$$

Assume x^* maximizes $\varphi(x)$. In order to maximize the net reward, when $r_n^f < x^*$, we have $r_n = r_n^f$; when $r_n^f \geq x^*$, we have $r_n = x^*$. In short, $r_n = \min(r_n^f, x^*)$ and it follows that $R_n = \log_2(1+\min(r_n^f, x^*))$

Now, the optimal stopping rule is

$$N(\lambda^*) = \min\{n \geq 1,\, \log_2(1+r_n)\tau_d - \lambda\tau_{CTS} - \lambda e^{\frac{r_n}{\rho_g}}\tau_2 \\ - \lambda \int_{r_n}^{\infty} \frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)} \frac{1}{\rho_g} e^{-\frac{r-r_n}{\rho_g}} dr \geq U^*(\lambda^*) - \lambda^*\tau_{CTS}\} \tag{5.11}$$

i.e., the optimal stopping time is the first time that the net reward of transmission is not less than the net reward of give-up.

Note that $U^*(\lambda^*) = 0$ from [37] and $r_n = \min(r_n^f, x^*)$ so the optimal stopping rule (5.11) can be simplified as

$$N(\lambda^*) = \min\{n \geq 1,\, \log_2(1+\min(r_n^f, x^*))\tau_d - \lambda e^{\frac{\min(r_n^f, x^*)}{\rho_g}}\tau_2 \\ - \lambda \int_{\min(r_n^f, x^*)}^{\infty} \frac{\log_2(1+\min(r_n^f, x^*))\tau_d}{\log_2(1+r)} \frac{1}{\rho_g} e^{-\frac{r-\min(r_n^f, x^*)}{\rho_g}} dr \geq 0\}. \tag{5.12}$$

The optimal rate of return λ^* can be found by solving the optimality equation

$$\mathbb{E}[\max\{\log_2(1+r_n)\tau_d - \lambda\tau_{CTS} - \lambda e^{\frac{r_n}{\rho_g}}\tau_2 \\ - \lambda \int_{r_n}^{\infty} \frac{\log_2(1+r_n)\tau_d}{\log_2(1+r)} \frac{1}{\rho_g} e^{-\frac{r-r_n}{\rho_g}} dr,\, U^*(\lambda^*) - \lambda^*\tau_{CTS}\}] - \lambda^*\tau_1 = U^*(\lambda^*). \tag{5.13}$$

Note that $U^*(\lambda^*) = 0$, and $r_n = \min(r_n^f, x^*)$ so the optimality equation (5.13) can be simplified as

$$\mathbb{E}[\log_2(1+\min(r_n^f, x^*))\tau_d - \lambda e^{\frac{\min(r_n^f, x^*)}{\rho_g}}\tau_2 \\ - \lambda \int_{\min(r_n^f, x^*)}^{\infty} \frac{\log_2(1+\min(r_n^f, x^*))\tau_d}{\log_2(1+r)} \frac{1}{\rho_g} e^{-\frac{r-\min(r_n^f, x^*)}{\rho_g}} dr]^+ = \lambda^*(\tau_1 + \tau_{CTS}). \tag{5.14}$$

5.3 Iterative Algorithm for Calculating λ^*

The iterative algorithm to calculate λ^* is similar to that in Chapter 4. First we need to take an initial guess of λ. Suppose we already know λ_n. Then the optimal stopping rule (5.12) becomes

$$\begin{aligned}N(\lambda_n) = \min\{n \geq 1,\ &\log_2(1+\min(r_n^f, x^*_{(n)}))\tau_d - \lambda e^{\frac{\min(r_n^f, x^*_{(n)})}{\rho_g}}\tau_2 \\ &- \lambda_n \int_{\min(r_n^f, x^*_{(n)})}^{\infty} \frac{\log_2(1+\min(r_n^f, x^*_{(n)}))\tau_d}{\log_2(1+r)} \frac{1}{\rho_g} e^{-\frac{r-\min(r_n^f, x^*_{(n)})}{\rho_g}} dr \geq 0\}\end{aligned} \tag{5.15}$$

where $x^*_{(n)}$ is the one that can maximize $\varphi(x)$ when $\lambda = \lambda_n$.

The expectation of throughput per transmission using the stopping rule (5.15) is

$$\begin{aligned}\mathbb{E}[Y_{(n)}] =& \frac{F_f(x^*_{(n)}) - F_f(r_{1(n)})}{1-F_f(r_{1(n)})}\tau_d \int_{r_{1(n)}}^{x^*_{(n)}} \log_2(1+r) f_{f^1}(r) dr \\ &+ \frac{1-F_f(x^*_{(n)})}{1-F_f(r_{1(n)})}\tau_d \log_2(1+x^*_{(n)})\end{aligned} \tag{5.16}$$

where $r_{1(n)}$ is the threshold get from (5.15) which is the minimum required SNR that the reward of transmission is not less than the reward of give-up.

The expectation of time cost per transmission using the stopping rule (5.15) is

$$\begin{aligned}\mathbb{E}[T_{(n)}] =& \frac{\tau_1 + \tau_{CTS}}{1-F_f(r_{1(n)})} + \tau_d \\ &+ \frac{F_f(x^*_{(n)}) - F_f(r_{1(n)})}{1-F_f(r_{1(n)})}\tau_2 \int_{r_{1(n)}}^{x^*_{(n)}} \frac{1}{1-F_g(r)} f_{f^1}(r) dr \\ &+ \frac{1-F_f(x^*_{(n)})}{1-F_f(r_{1(n)})}\tau_2 \frac{1}{1-F_g(x^*_{(n)})} - \tau_d \\ &+ \frac{F_f(x^*_{(n)}) - F_f(r_{1(n)})}{1-F_f(r_{1(n)})} \int_{r_{1(n)}}^{x^*_{(n)}} \int_{r_1}^{\infty} \frac{\log_2(1+r_1)\tau_d}{\log_2(1+r_2)} f_{g^1}(r) dr_2 f_{f^1}(r) dr_1 \\ &+ \frac{1-F_f(x^*_{(n)})}{1-F_f(r_{1(n)})} \int_{x^*_{(n)}}^{\infty} \frac{\log_2(x^*_{(n)}+1)\tau_d)}{\log_2(1+r2)} f_{g^2}(r) dr_2.\end{aligned} \tag{5.17}$$

Here $\frac{\tau_1+\tau_{CTS}}{1-F_f(r_{1(n)})} + \tau_d$ is the time cost in channel contention, re-contention and data transmission in the first hop. $f_{f^1}(r) = \frac{f_f(r)}{F_f(x^*_{(n)})-F_f(r_{1(n)})}$ is the PDF of first-hop SNR under the condition that $r_{1(n)} \leq r_n^f \leq x^*_{(n)}$. $\frac{F_f(x^*_{(n)})-F_f(r_{1(n)})}{1-F_f(r_{1(n)})}\tau_2 \int_{r_{1(n)}}^{x^*_{(n)}} \frac{1}{1-F_g(r)} f_{f^1}(r) dr + \frac{1-F_f(x^*_{(n)})}{1-F_f(r_{1(n)})}\tau_2 \frac{1}{1-F_g(x^*_{(n)})} - \tau_d$ is the time cost for the second hop channel probing and waiting until the achievable transmission rate is not less than R_n. $f_{g^1}(\cdot)$ and $f_{g^2}(\cdot)$ are the PDF of the second hop detected SNR under the condition that $r_g(n) \geq r_1$ and $r_g(n) \geq x^*_{(n)}$, respectively. The last two parts are the average data transmission time when $r_{1(n)} \leq r^f_n \leq x^*_{(n)}$ and when $r^f_n \geq x^*_{(n)}$, respectively.

Thus, the algorithm is as follows

- step 1: Take an initial guess λ_0
- step 2: Calculate x^* and $r_{1(n)}$
- step 3: Calculate $\mathbb{E}[Y_{(n)}]$ and $\mathbb{E}[T_{(n)}]$ through (5.16) and (5.17)
- step 4: Calculate a new $\lambda = \frac{\mathbb{E}[Y_{(n)}]}{\mathbb{E}[T_{(n)}]}$ and go back to step 2, until the difference between the λ calculated this time and the last time is less than a certain small number.

5.4 Numerical Results

Consider 18 source-destination pairs. Other parameters are [38]: the probability that a source sends a RTS in a minislot $p = 0.1$, channel coherence time $\tau_d = 8$ms, RTS transmission duration $\tau_{RTS} = 103\mu$s, CTS transmission duration $\tau_{CTS} = 106\mu$s, minislot duration $\delta = 20\mu$s, and first-hop average SNR $\rho_f = 1$.

Fig. 5.1 is the performance of the iterative algorithm when the second-hop average SNR $\rho_g = 2$. The iterative algorithm converges quickly under different initial values.

Fig. 5.2 shows the upper and lower threshold under different second-hop average SNR. For example, when the second-hop average SNR is 10, the lower threshold is 1.6741 and the upper threshold is 6.6610. So when the detected first-hop SNR is less than 1.6741, the source will give up the transmission opportunity; when the detected first-hop SNR is between 1.6741 and 6.6610, the source will transmit data at its full channel capacity; when the detected first-hop SNR is greater than 6.6610, the source will transmit data at rate $\log_2(1 + 6.6610)$.

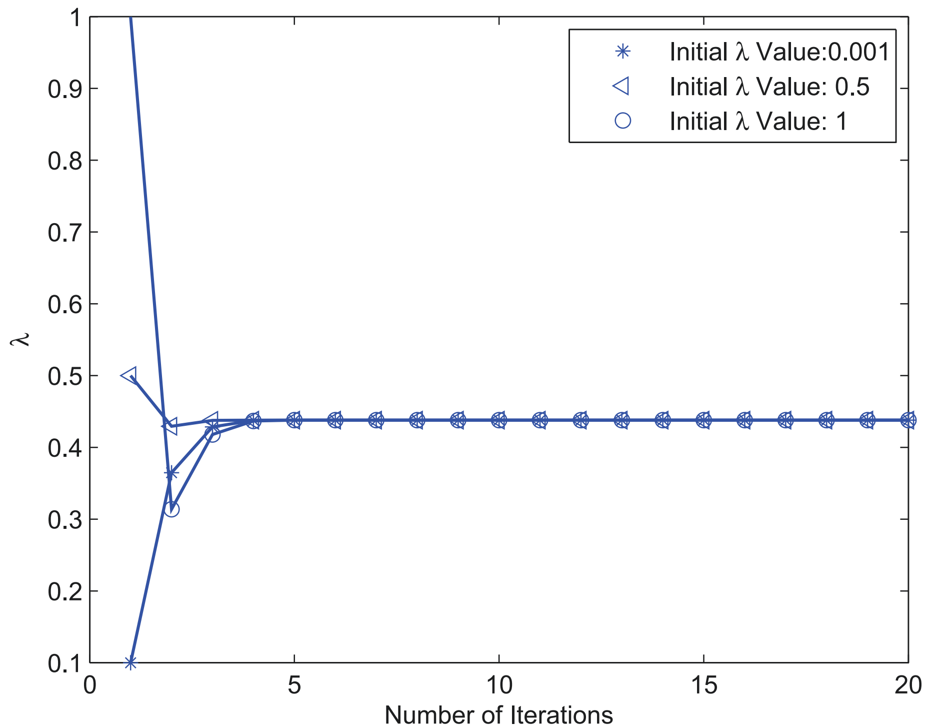

Fig. 5.1. Convergence performance of the iterative algorithm.

Fig. 5.3 shows the simulation results of average throughput with the proposed strategy, theoretical results of average throughput with the proposed strategy, and simulation results of average throughput without any strategy (the same as the case without any strategy in numerical results of Chapter 4) under different second-hop average SNR. It can be seen from Fig. 5.3 that our theoretical results agree with the simulation results very well. The average throughput with the proposed strategy is about 60% more than that without any strategy when the second-hop average SNR is low; when the second-hop average SNR is high, average throughput with the proposed strategy is more than twice that without any strategy.

Fig. 5.4 shows the simulation result of different scheduling strategies. Sim 1 is for the case without any strategy, and Sim 2 refers to the simulation results with strategy proposed in [19]. Sim 3, Sim 4, and Sim 5 refer to the simulation results for our strategies in Chapter 3, Chapter 4, and Chapter 5, respectively.

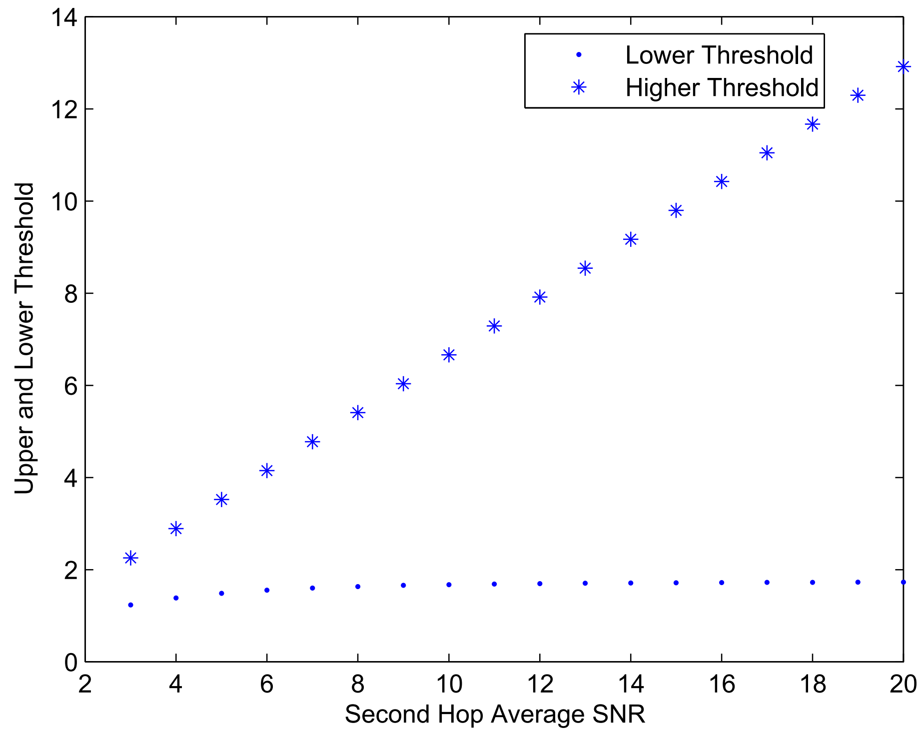

Fig. 5.2. Thresholds under different second-hop average SNR.

Not surprisingly, the average throughput without any strategy performs the worst among all the strategies.

The strategy in [19] is always better than our strategy in Chapter 3 because in the strategy of [19], after probing the first hop, if the channel condition is bad, the winner source will give up the transmission opportunity; but in our strategy in Chapter 3, the decision is made after finishing probing the two hops.

Our Strategy in Chapter 5 always performs better than our strategy in Chapter 4. This is because high transmission rate in the second hop can be achieved in our strategy in Chapter 5.

Our strategy in Chapter 5 performs worse than the strategy in [19] when the second-hop average SNR is low, and performs better when the second-hop average SNR is high. There are two main differences between these two strategies:

- In our strategy in Chapter 5, data transmission in the first hop is separate

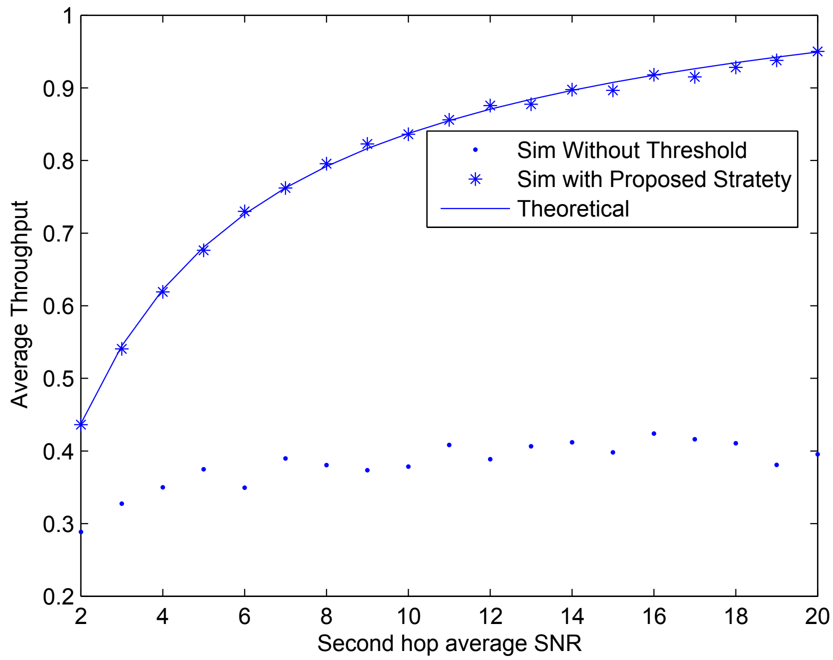

Fig. 5.3. Simulation and theoretical results.

from the transmission in the second hop, and thus, the transmission time in each hop is up to the channel coherence time. In the strategy of [19], data transmission is successive in the two hops and must be finished in channel coherence time. In this way, our strategy has more transmission time per transmission in each hop.

- The strategy of [19] probes the second hop before data transmission. In our strategy, the first hop transmission is based on the expectation of the second hop, and the relay begins to probe the second hop after it has received the data from the source.

When the second-hop average SNR is low, it is relatively hard for the second hop to get an achievable rate greater than that in the first hop, and we can say the second hop is unstable compared with the first hop. The strategy of [19] has the advantage by probing before transmission and can fully utilize the second hop, while our strategy may suffers from more waiting time in the second hop. However, when

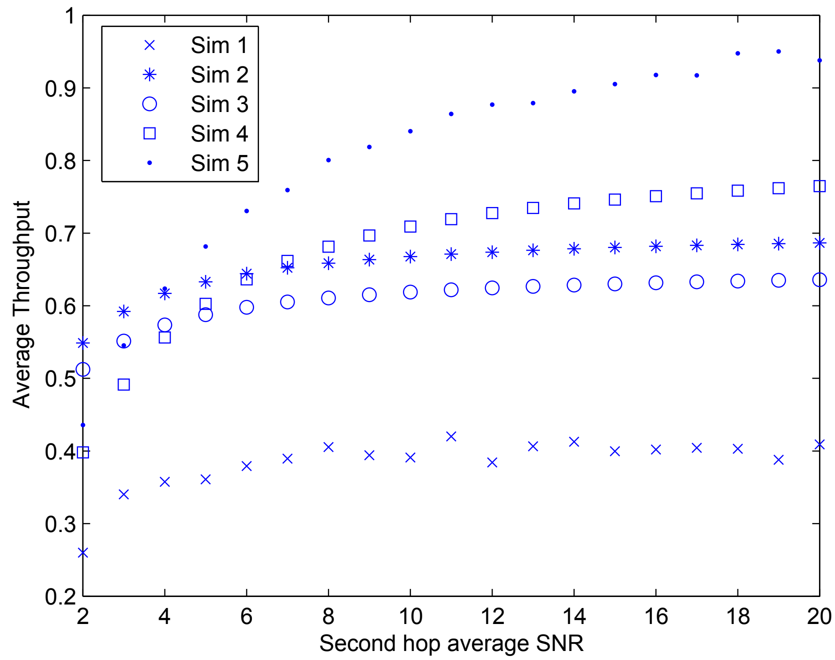

Fig. 5.4. Simulation result comparison.

the second-hop average SNR is high, it is relatively easy for the second hop to get an achievable rate higher than that in the first hop. For our strategy, the effect of possible more waiting time in the second hop is negligible, and the benefit of more transmission time in each hop dominates. Thus, our strategy can achieve higher system throughput.

Chapter 6

Conclusion and Future Work

This chapter summarizes the contributions of the thesis. The future work that can be done based on the thesis is also discussed.

6.1 Conclusion

In this thesis, we have proposed a distributed opportunistic scheduling scheme for ad-hoc networks with dedicated DF relays without direct links (source-destination links). Two cases are considered: 1) the winner source has full CSI (CSI of source-relay link and relay-destination link), 2) the winner source has partial CSI (CSI of source-relay link). All sources use random access to contend the channel, and the source that wins the transmission opportunity is called winner source.

For the first case, the winner source probes the source-relay link and relay-destination link successively and decides to transmit or give up the transmission opportunity after getting the full CSI. A pure threshold-structure optimal stopping rule is developed for this case, to be specific, when the minimum of the detected SNRs of the source-relay link and relay-destination link exceeds a certain threshold, it is optimal for the winner source to transmit data; otherwise, the winner source should give up the transmission opportunity and let all sources re-contend the channel.

For the second case, the winner source only probes the source-relay link and then decides to transmit or give up the transmission opportunity. If the first one (i.e., to transmit) is chosen, after the relay receives the data, it begins to probe the second hop and has three choices: 1) to transmit; 2) to wait for channel coherence time and probe again and repeat the procedure; 3) to abandon the data.

First we consider a simple situation: the second hop transmission rate equals the first hop transmission rate when the second hop channel is good enough. In this situation, under the condition that the relay has received the data from the source, it is proven that the best decision for the relay is either 1) probing just once or 2) keeping probing until the channel condition is good. However, it is proven that the net reward of transmission in the first hop is always less than the net reward of giving up transmission opportunity in the first hop when the decision 1) is better than decision 2). In other words, when the net reward of transmission in the first hop is greater than the net reward of giving up transmission opportunity in the first hop, the source chooses to transmit, and the only best choice for the relay is keeping probing the second hop until the channel condition is good; when the net reward of transmission in the first hop is less than the net reward of giving up transmission opportunity in the first hop, the source gives up the transmission opportunity (the decision for relay is not needed).

A pure threshold structure stopping rule is developed for this situation. The rule contains two thresholds, a low threshold and an upper threshold. When the first hop detected SNR is smaller than the lower threshold, the source will give up the transmission opportunity; when the SNR is between the lower threshold and the upper threshold, the source transmits at full channel capacity; when the SNR is higher than the upper threshold, the source transmits at a rate based on the upper threshold.

Then a complicated situation is considered: the second hop can transmit at its full channel capacity when its achievable transmission rate is not less than the first hop transmission rate. In this situation the second hop transmission time is a random variable determined by the first hop transmission rate and the second hop detected SNR. We prove that the decision rule has the same structure as that of the simple situation but the average throughput is higher especially when the second-hop average SNR is high.

Through simulation, we can see that the average throughput of the three proposed strategies in this thesis are at least 40% more than that without scheduling strategy. Compared with the strategy in [19], the last two proposed strategies perform better when the second-hop average SNR is high.

6.2 Future Work

In this paper, we assume that the first hop transmission time equals channel coherence time when the source has partial CSI. Thus when the channel condition of the first hop is very good, a winner source would not transmit at its full channel capacity because if so, the large volume of data transmitted in the first hop would lead to a longer waiting time for the relay to get a good enough second-hop channel condition to forward the data to the destination. If the winner source could transmit using the full first-hop channel capacity but with less transmission time, we expect that the performance could be improved. However, the derivation of the optimal stopping rule would be much more complicated, which deserves further investigation.

References

[1] FCC, "Spectrum policy task force report," Nov 2002.

[2] J. Mitola, "Cognitive radio–an integrated agent architecture for software defined radio," 2000.

[3] J. Mitola and G. Q. Maguire Jr, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, 1999.

[4] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[5] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks*, vol. 50, no. 13, pp. 2127–2159, 2006.

[6] H. Jiang, L. Lai, R. Fan, and H. V. Poor, "Optimal selection of channel sensing order in cognitive radio," *IEEE Transactions on Wireless Communications*, vol. 8, no. 1, pp. 297-307, Jan. 2009.

[7] R. Fan and H. Jiang, "Channel sensing-order setting in cognitive radio networks: A two-user case," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 4997-5008, Nov. 2009.

[8] R. Fan and H. Jiang, "Optimal multi-channel cooperative sensing in cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 3, pp. 1128-1138, Mar. 2010.

[9] Z. Zhang, H. Jiang, P. Tan, and J. Slevinsky, "Channel exploration and exploitation with imperfect spectrum sensing in cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 3, pp. 429-441, Mar. 2013.

[10] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of mimo communications-a key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198–218, 2004.

[11] D. Gesbert, M. Shafi, D.-s. Shiu, P. J. Smith, and A. Naguib, "From theory to practice: an overview of mimo space-time coded wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 281–302, 2003.

[12] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, "Capacity limits of mimo channels," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 5, pp. 684–702, 2003.

[13] J.-P. Kermoal, L. Schumacher, K. I. Pedersen, P. E. Mogensen, and F. Frederiksen, "A stochastic mimo radio channel model with experimental validation," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 6, pp. 1211–1226, 2002.

[14] D. Zheng, W. Ge, and J. Zhang, "Distributed opportunistic scheduling for ad hoc networks with random access: an optimal stopping approach," *IEEE Transactions on Information Theory*, vol. 55, no. 1, pp. 205–222, 2009.

[15] D. Zheng, M.-O. Pun, W. Ge, J. Zhang, and H. V. Poor, "Distributed opportunistic scheduling for ad hoc communications with imperfect channel infor-

mation," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5450–5460, 2008.

[16] W. Ge, J. Zhang, J. E. Wieselthier, and X. Shen, "Phy-aware distributed scheduling for ad hoc communications with physical interference model," *IEEE Transactions on Wireless Communications*, vol. 8, no. 5, pp. 2682–2693, 2009.

[17] S.-S. Tan, D. Zheng, J. Zhang, and B. Zeidler, "Distributed opportunistic scheduling for ad-hoc communications under delay constraints," *in Proceedings of IEEE INFOCOM* , pp. 1 – 9, 2010.

[18] P. Thejaswi, J. Zhang, M.-O. Pun, H. V. Poor, and D. Zheng, "Distributed opportunistic scheduling with two-level probing," *IEEE/ACM Transactions on Networking*, vol. 18, no. 5, pp. 1464–1477, 2010.

[19] X. Gong, T. Chandrashekhar, J. Zhang, and H. V. Poor, "Opportunistic cooperative networking: To relay or not to relay?" *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 2, pp. 307–314, 2012.

[20] Z. Zhang and H. Jiang, "Distributed opportunistic channel access in wireless relay networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 9, pp. 1675–1683, 2012.

[21] N. Abramson, "The aloha system: another alternative for computer communications," in *Proceedings of the November 17-19, 1970, Fall Joint Computer Conference*. ACM, 1970, pp. 281–285.

[22] N. Abramson, *Multiple Access Communications: Foundations for Emerging Technologies*. IEEE Press, 1995.

[23] C. Namislo, "Analysis of mobile radio slotted aloha networks," *IEEE Transactions on Vehicular Technology*, vol. 33, no. 3, pp. 199–204, 1984.

[24] L. Kleinrock and F. A. Tobagi, “Packet switching in radio channels: Part i–carrier sense multiple-access modes and their throughput-delay characteristics,” *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, 1975.

[25] F. A. Tobagi and V. Bruce Hunt, “Performance analysis of carrier sense multiple access with collision detection,” *Computer Networks*, vol. 4, no. 5, pp. 245–259, 1980.

[26] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, R. Vijayakumar, “Providing quality of service over a shared wireless link,” *IEEE Communications Magazine*, vol. 39, no. 2, pp. 150–154, 2001.

[27] P. Viswanath, D. N. C. Tse, and R. Laroia, “Opportunistic beamforming using dumb antennas,” *IEEE Transactions on Information Theory*, vol. 48, no. 6, pp. 1277–1294, 2002.

[28] X. Liu, E. K. P. Chong, and N. B. Shroff, “Opportunistic transmission scheduling with resource-sharing constraints in wireless networks,” *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 2053–2064, 2001.

[29] M. O. Hasna and M. S. Alouini, “End-to-end performance of transmission systems with relays over Rayleigh-fading channels,” *IEEE Transactions on Wireless Communications*, vol. 2, no. 6, pp. 1126–1131, Nov. 2003.

[30] M. Hasna and M.-S. Alouini, “Harmonic mean and end-to-end performance of transmission systems with relays,” *IEEE Transactions on Communications*, vol. 52, no. 1, pp. 130–135, Jan. 2004.

[31] J. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[32] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3037-3063, Sep. 2005.

[33] B. Wang, J. Zhang, and L. Zheng, “Achievable rates and scaling laws of power-constrained wireless sensory relay networks,” *IEEE Transactions on Information Theory*, vol. 52, no. 9, pp. 4084-4104, Sep. 2006.

[34] R. Fan and H. Jiang, “Average rate maximization in relay networks over slow fading channels,” *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3865-3881, Oct. 2011.

[35] S. Atapattu, Y. Jing, H. Jiang, and C. Tellambura, “Relay selection schemes and performance analysis approximations for two-way networks,” *IEEE Transactions on Communications*, vol. 61, no. 3, pp. 987-998, Mar. 2013.

[36] S. Atapattu, Y. Jing, H. Jiang, and C. Tellambura, “Relay selection and performance analysis in multiple-user networks,” *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 8, pp. 1517-1529, Aug. 2013.

[37] T. Ferguson, *Optimal stopping and applications*, Available online: http://www.math.ucla.edu/~tom/Stopping/Contents.html, Mathematics Department, UCLA.

[38] L. Huang, H. Jiang, Z. Zhang, and Z. Yan, “Optimal Traffic Scheduling Between Roadside Units in Vehicular Delay Tolerant Networks,” *IEEE Transactions on Vehicular Technology*, vol. 64, no. 3, pp. 1079-1094, Mar. 2015.