行政院國家科學委員會專題研究計畫成果報告

廣義的機會式通訊：無線行動網路中之競爭、合作與感知

子計畫三：感知無線行動網路之協力式擇路協定及服務品質控制
期末報告

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摘要

近年的研究說明了靜態的頻帶分配是造成頻帶使用缺少效率的主因，為了增進頻帶使用率，可動態偵測且使用認證頻帶的感知無線電(Cognitive Radio, CR)因應而生。如何提供有效率的頻帶換手在感知無線電中是個很重要的議題。現存的頻帶換手(Spectrum Handoff)方法假定感知無線電使用者(CR User)可以正確的偵測每一個頻帶以便找到適合的頻帶進行換手。然而，這個假設在實際的情況下是不實際的，因為感知無線電使用者偵測頻帶所花費的時間將會太高而影響主要使用者(Primary User)的品質。本研究團隊藉由部分可知的環境下的馬可夫決策過程(Partial Observable Markov Decision Process, POMDP)之幫助，可以透過探測部分的頻帶來估測整個網路環境。研究團隊提出以 POMDP 為基準的頻帶換手機制(POMDP-based Spectrum Handoff, POSH)，其目的為藉由部分的通道狀態來找出最適合進行換手的頻帶。此外，我們亦針對多人的感知無線電使用者情況下設計出機會式多人頻帶換手機制(POMDP-based multi-user spectrum handoff, M-POSH)，用以解決多人的頻帶競爭問題。藉由 POSH 及 M-POSH 機制所選出的頻帶，可達到在每次換手時感知無線電使用者所需等待的時間(Waiting Time)最短，依據模擬結果顯示出此方法可有效率地讓感知無線電使用者在每次頻帶換手時達到最少的等待時間。

另一方面，由於通訊環境的不穩定，例如多重路徑衰弱通道（Multipath Fading Channel）的影響，各式各樣的分集技術（Diversity）因此而被提出以維持傳輸的品質。近幾年來，協力式通訊（Cooperative Communication）亦被提出來成為一種新的通訊模式，利用周遭的鄰近節點來提升自我的分集增益（Cooperative Diversity），進而改善點對點之間的通訊品質。於協力式通訊系統中，來源節點（Source Node）與目標節點(Destination Node)間的傳輸，將引進中繼節點(Relay Node)的協助，因而使目標節點得以取得多份相同的封包。進一步地，目標節點將這些相同的封包重新整合與解碼，有機會地降低接收端的位元錯誤率，以達到通訊可信度上的提升。從實體層（Physical Layer）的角度上來評論，協力式通訊於接收可靠度的表現，似乎扮演著重要的角色。然而，在實作複雜度的限制下，半工傳輸（Half-Duplex）是現今大部分通訊系統的假設，因而，協力式通訊的模式往往便需要兩個階段才能完成，導致在傳輸時間上延伸變得是無可避免的。因此，若改由整體網路的吞吐量（Network Throughput）觀點來思考，協力式通訊不見得會帶來所期待的效能。在本研究中，我們將以 IEEE 802.11 媒介接取控制技術為基礎，佐以模擬驗證，利用

二維的馬可夫鏈（Two Dimensional Markov Chain）的數學分析來探討協力式通訊於網路吞吐量的表現。在媒介接取控制的考量下，適當地找尋協力式通訊的使用時機。基於此模式的思考，本研究團隊提出兩個可針對通訊環境變化而適應性的選擇應採取傳統點對點通訊系統或協力式通訊技術。全通訊頻道狀態標協力式(Full-CSI based Cooperative, FCC)協定利用完整的通訊頻道訊息來決定中繼點選擇及要採取那一種傳輸技術。但其所造成的通訊負擔會跟隨中繼點數量增加而上升。因此，本研究團隊提出位元競爭式協力式(Bitwise Competition based Cooperative, BCC)協定來有效率的決定適當的中繼點來做為資料傳輸。依據模擬結果顯示出本研究團隊提出 BCC 協定優於傳統點對點通訊，可有效率地增加網路整體傳輸的吞吐量。

Abstract

Recent studies have been conducted to indicate the ineffective usage of licensed bands due to static spectrum allocation. In order to improve spectrum utilization, cognitive radio (CR) is therefore suggested to dynamically exploit the opportunistic primary frequency spectrums. How to provide efficient spectrum handoff has been considered a crucial issue in the CR networks. Existing spectrum handoff algorithms assume that all the channels can be correctly sensed by the CR users in order to perform appropriate spectrum handoff process. However, this assumption is impractical since excessive time will be required for the CR user to sense the entire spectrum space. In this paper, the partially observable Markov decision process (POMDP) is applied to estimate the network information by partially sensing the frequency spectrums. A POMDP-based spectrum handoff (POSH) scheme is proposed to determine the optimal target channel for spectrum handoff according to the partially observable channel state information. Moreover, a POMDP-based multi-user spectrum handoff (M-POSH) protocol is proposed to exploit the POMDP policy into multi-user CR networks by distributing CR users to frequency spectrums opportunistically. By adopting the policies resulted from the POSH and M-POSH algorithms for target channel selection, minimal waiting time at each occurrence of spectrum handoff can be achieved. Numerical results illustrate that the proposed spectrum handoff protocols can effectively minimize the required waiting time for spectrum handoff in the CR networks.

On the other hand, cooperative communication has been developed as a new communication strategy that incorporates a relay node to assist direct point-to-point transmission. By exploiting cooperative diversity, different types of techniques have been proposed to improve transmission reliability from the physical layer perspective. However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance network throughput in view of the medium access control (MAC) performance. In this research, system throughput of combined direct/cooperative communication is evaluated by exploiting the proposed analytical model based on the IEEE 802.11 MAC protocol. The feasibility of adopting either cooperative or direct communication is also studied in the analytical model. In terms of network throughput, whether to adopt cooperative schemes depends on the tradeoff between cooperative transmission delay and channel condition of direct communication. Moreover, two cooperative MAC protocols are proposed to determine the circumstances to activate cooperative communication according to the channel conditions. The full-CSI based cooperative (FCC) MAC protocol is introduced to choose both the transmission scheme and the relay node according to the full channel information. However, the overhead caused by the FCC scheme can degrade the throughput performance as the number of available relays is significantly increased. Therefore, the bitwise competition based cooperative (BCC) MAC protocol is utilized to efficiently determine a feasible relay node for data transmission. Simulations are performed to validate the effectiveness of proposed analytical models and cooperative MAC protocols. It is observed that the proposed BCC scheme can outperform both the FCC protocol and conventional direct transmission with enhanced system throughput.

Publications:

1. Rui-Ting Ma, Yu-Pin Hsu, Kai-Ten Feng, and Li-Chun Wang, "Stochastic Spectrum Handoff Protocols for Partially Observable Cognitive Radio Networks," major revision, *IEEE Transactions on Vehicular Technology.*
2. Chun-Chieh Liao, Yu-Pin Hsu and Kai-Ten Feng, "Analysis and Determination of Cooperative MAC Strategies from Throughput Perspectives," major revision, *ACM Wireless Networks*.
3. Rui-Ting Ma, Yu-Pin Hsu, and Kai-Ten Feng, "A POMDP-based Spectrum Handoff Protocol for Partially Observable Cognitive Radio Networks," in *Proceedings of IEEE Wireless Communication and Networking Conference (WCNC 2009)*, Apr. 2009, Budapest, Hungry.
4. Chun-Chieh Liao, Yu-Pin Hsu and Kai-Ten Feng,” Performance Analysis of Cooperative Communications from MAC Layer Perspectives,” in *Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications* (*PIMRC*), Cannes, France, Sept. 2008.

Stochastic Spectrum Handoff Protocols for Partially Observable Cognitive Radio Networks

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Abstract

Recent studies have been conducted to indicate the ineffective usage of licensed bands due to static spectrum allocation. In order to improve spectrum utilization, cognitive radio (CR) is therefore suggested to dynamically exploit the opportunistic primary frequency spectrums. How to provide efficient spectrum handoff has been considered a crucial issue in the CR networks. Existing spectrum handoff algorithms assume that all the channels can be correctly sensed by the CR users in order to perform appropriate spectrum handoff process. However, this assumption is impractical since excessive time will be required for the CR user to sense the entire spectrum space. In this paper, the partially observable Markov decision process (POMDP) is applied to estimate the network information by partially sensing the frequency spectrums. A POMDP-based spectrum handoff (POSH) scheme is proposed to determine the optimal target channel for spectrum handoff according to the partially observable channel state information. Moreover, a POMDP-based multi-user spectrum handoff (M-POSH) protocol is proposed to exploit the POMDP policy into multi-user CR networks by distributing CR users to frequency spectrums opportunistically. By adopting the policies resulted from the POSH and M-POSH algorithms for target channel selection, minimal waiting time at each occurrence of spectrum handoff can be achieved. Numerical results illustrate that the proposed spectrum handoff protocols can effectively minimize the required waiting time for spectrum handoff in the CR networks.

Keywords: Cognitive radio, partially observable Markov decision process (POMDP), spectrum handoff, channel selection.

I. Introduction

According to the research conducted by FCC [1; 2], a large portion of the auctioned of frequency spectrum remains idle at any given time and location. It has been indicated that the spectrum shortage problem is primarily resulted from the spectrum management policy rather than the physical scarcity of frequency spectrum. Consequently, a great amount of research is devoted to cognitive radio (CR) in recent years [3–6]. The CR user, i.e. the secondary user, is capable of sensing the channel condition and can adapt its internal parameters to access the licensed channels while these channels are not being utilized by the primary users. The IEEE 802.22 [7; 8], considered as a realistic implementation of the CR concept, is an emerging standard that allocates analog TV spectrum for broadband services. Since there is no promise for a CR user to finish its transmission on a certain spectrum, a mechanism called spectrum handoff has been introduced to allow the CR user to select another channel to maintain its data transmission. Consequently, the main objective for spectrum handoff is to select a feasible target channel which the CR user can be switched into in order to retain its on-going transmissions. The performance of spectrum handoff will primarily be dominated by the feasibility of conducting channel selection.

Target channel selection can be categorized into two different types of schemes according to their sensing strategies [9], i.e. the pre-sensing and post-sensing methods. The pre-sensing scheme indicates that the secondary user will sense the frequency spectrums and consequently choose a sequence of selected target channels before the beginning of its data transmission. Once the secondary user is interrupted by the primary user, the secondary user will be switched into a channel which was determined in sequence in the pre-sensing phase. In general, pre-sensing techniques can reduce the waiting time for spectrum handoff since the target channel is selected based on a pre-determined channel list. However, since the stochastic characteristics of channel can vary drastically in realistic environments, the pre-determined channel list can become infeasible to be adopted in target channel selection for spectrum handoff. The channel reservation scheme as proposed in [10] conducts pre-sensing by exploiting the balance between blocking probability and forced termination in order to reserve idle channels for spectrum handoff. Analytical models have been studied in [11; 12] to illustrate the beneficial aspects of pre-sensing strategy. However, those reserved idle channels can not be ensured available at the time for spectrum handoff. As a result, the performance of pre-sensing strategies can not be guaranteed especially under fast-fading channel environments.

On the other hand, the post-sensing techniques is implemented while the secondary user is forced to terminate its transmission by the primary user. The CR user will start to sense the spectrum in order to verify if there are available channels that can be accessed and consequently becomes its target channel. Compared to the pre-sensing approaches, a more feasible and accurate channel can be selected by exploiting the post-sensing schemes since the target channel is determined at the time while the secondary user is interrupted. Nevertheless, the post-sensing methods in general require excessive time in spectrum sensing, especially under crowded network traffic. This situation is not permissible in spectrum handoff since the allowable time duration is considered limited for the CR user to vacate its current channel for the primary user. Furthermore, it is assumed in most of the existing pre-sensing and post-sensing strategies that all the channels within the network can be correctly sensed, which is not realistic in practice. In other words, the transition probabilities of all the channel states are not always available to the CR users within the network. The algorithm in [13] was proposed to estimate the transition probability by adopting the maximum likelihood function. However, the converging speed for the estimation algorithm becomes intolerably slow under small value of transition probability.

In this paper, without the necessity of obtaining all the correct channel information, the partially observable Markov decision process (POMDP) [14–17] is utilized to reveal the network information by partially sensing the available frequency channels. A POMDP-based spectrum handoff (POSH) mechanism is proposed as a post-sensing strategy in order to acquire the policy such that optimal channel can be obtained with the minimal waiting time at each occurrence of spectrum handoff. The transition probabilities for the channel states are derived in this paper by considering the channel as an M/G/1 system with given packet arrival rate and service rate. In order to observe the behavior of spectrum handoff, analytical models for the proposed POSH protocol and other existing channel selection schemes are derived, validated, and compared via simulations. Furthermore, practical considerations on the required phases for channel selection is also discussed and compared between the spectrum handoff schemes. It is demonstrated via simulations that reduced waiting time can be obtained from the proposed POSH protocol comparing with other existing schemes.

Furthermore, multiple CR users can exist concurrently and access the licensed spectrums in a

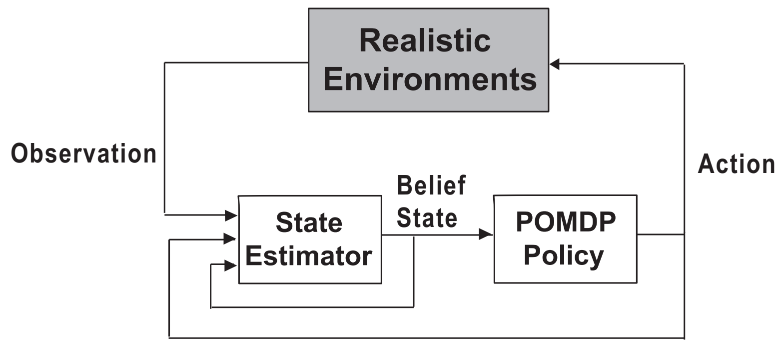

Fig. 1. The schematic diagram of the POMDP framework.

more realistic environment. Unlike the single user scenario, a specific frequency spectrum can be simultaneously chosen by more than one CR users as the target channel in multi-user scenarios. Therefore, it is crucial to provide channel selection policy by considering information from other CR users, and also to alleviate the overhead while multiple CR users are contending for the target channel. In this paper, a POMDP-based multi-user spectrum handoff (M-POSH) protocol is proposed to extend the original POSH scheme into the multi-user CR networks. In addition to merely observing the primary user's traffic, the M-POSH scheme also monitors the required information from CR users in the network. A negotiation procedure is employed to facilitate the determination process for a feasible CR user to operate within a specific target channel. In comparison with other existing protocols, the proposed M-POSH scheme can effectively minimize the waiting time for spectrum handoff.

The rest of this paper is organized as follows. Section II briefly summarizes the concept of POMDP approach. The proposed POSH scheme is modeled and derived in Section III. Performance analysis of the POSH protocol associated with practical considerations is conducted in Section IV. Considering the network scenario with multiple CR users, the M-POSH protocol is proposed in Section V. Section VI illustrates the performance evaluation for both the proposed POSH and M-POSH approaches; while the conclusions are drawn in Section VII.

II. POMDP FRAMEWORK

A Markov decision process (MDP) refers to a discrete time stochastic control process that conducts decision-making based on the present state information $s_k \in \boldsymbol{S}_k$, where $\boldsymbol{S}_k$ represents the entire state space at the kth time slot. Considering the realistic case that not all the current states are obtainable, the partially observable Markov decision process (POMDP) [14] is utilized to determine the decision policy based on the partially available information and the observations from external environment. The schematic diagram of POMDP framework is illustrated in Fig. 1. In general, optimization techniques are exploited in order to obtain the solution for the POMDP-based problem.

A. Observation

Since not all the states are directly observable within the POMDP setting, a set of observations $z_k \in \boldsymbol{Z}_k$ is essential to provide an indication about which state the environment should be located. The observations can be considered with probabilistic nature, where an observation function o is defined as a probability distribution over all possible observations z_k for each action a_k and resulting states s_{k+1}, i.e.

$$o(s_{k+1}, a_k, z_k) = P_r(z_k | a_k, s_{k+1}) \tag{1}$$

$\forall z_k \in \boldsymbol{Z}_k, a_k \in \boldsymbol{A}_k, s_{k+1} \in \boldsymbol{S}_{k+1}$ where $\boldsymbol{A}_k$ stands for the action set at the kth time slot. The parameter a_k denotes the action chosen by the POMDP formulation and s_{k+1} is the resulting state after executing action a_k. Considering the MDP case, a policy is determined to map from the current state to the corresponding action since the present state of MDP is fully observable. On the other hand, the POMDP can only map from the latest observation to the corresponding action (as shown in Fig. 1), which is considered insufficient to represent the history of the process. Therefore, the belief state is utilized to reveal the statistic distribution of current state information, which will be explained in the next subsection.

B. Belief State

The concept of belief state, i.e. the information state, is developed to reveal the state of environment and help to behave truly and effectively in a partially observable world. The belief state $b(\boldsymbol{S}_k)$ is a statistic distribution over the state space $\boldsymbol{S}_k$; while $b(s_k)$ corresponds to the probability of state s_k with $\sum_{s_k \in \mathbf{S}_k} b(s_k) \leq 1$. It is noticed that the belief state comprises a sufficient statistical information for the past history, including all the actions and observations that can provide a basis for decision-making under environmental uncertainties. Furthermore, the essential part of belief state is that it can be updated after each corresponding action in order to incorporate one additional step of information into the history. It is considered beneficial to capture the variations from dynamic environment and consequently obtain more accurate information of the environment. As shown in Fig. 1, the updated belief state is acquired as the outcome of state estimator, which is composed by the inputs of observation, action, and previous belief state. Therefore, the resulting belief state $b(s_{k+1})$ w.r.t. the state s_{k+1} can be obtained as

$$b(s_{k+1}) = P_r(s_{k+1}|b(\boldsymbol{S}_k), a_k, z_k) = \frac{o(s_{k+1}, a_k, z_k) \sum_{s_k \in \boldsymbol{S}_k} \Gamma(s_k, a_k, s_{k+1}) b(s_k)}{P_r(z_k|b(\boldsymbol{S}_k), a_k)} \tag{2}$$

where $b(s_k)$ indicates the former belief state of s_k. The parameter $\Gamma(s_k, a_k, s_{k+1})$ represents the state transition probability from s_k to s_{k+1} according to the action a_k, i.e. $\Gamma(s_k, a_k, s_{k+1}) = P_r(s_{k+1}|a_k, s_k)$. The denominator of (2) can be considered as a normalizing factor, which is obtained as

$$P_r(z_k|b(\boldsymbol{S}_k), a_k) = \sum_{s_k \in \boldsymbol{S}_k, s_{k+1} \in \mathbf{S}_{k+1}} \sum o(s_{k+1}, a_k, z_k) \cdot \Gamma(s_k, a_k, s_{k+1}) b(s_k) \tag{3}$$

C. Reward and Value Functions

In order to ensure optimal decision is made by adopting the POMDP-based approach, it is necessary to provide a measurement such as to evaluate the cost or to reward the update from each state. An immediate reward function $r(s_k, a_k, s_{k+1}, z_k)$ is defined to represent the reward by executing action a_k which turns from state s_k to s_{k+1} associated with the observation z_k. Since both the state transition and observation function are probabilistic, the expected immediate reward $R(s_k, a_k)$ can be obtained as

$$R(s_k, a_k) = \sum_{s_{k+1} \in \boldsymbol{S}_{k+1},} \sum_{z_k \in \boldsymbol{Z}_k} \Gamma(s_k, a_k, s_{k+1}) \cdot o(s_{k+1}, a_k, z_k) \cdot r(s_k, a_k, s_{k+1}, z_k) \tag{4}$$

It is noticed that the expected immediate reward function $R(s_k, a_k)$ is denoted as the one-step value function since only the present reward is the major concern. The optimal policy can be directly determined by adopting the reward function as in (4). However, certain period of time is always considered to evaluate the value of reward. Therefore, the decision policy by exploiting the POMDP is determined by optimizing the L-step value function with $L \geq 1$.

III. Proposed POMDP-based Spectrum Handoff (POSH) Scheme

In this section, the POMDP framework will be utilized to model the spectrum handoff problem in a slotted overlay CR network. The proposed POSH scheme is exploited under the single CR user scenario in Subsection A. The protocol implementation of proposed POSH scheme will be explained in Subsection B.

A. System Model for POSH Scheme

In the considered CR network, there are N channels that are available to be accessed by both the primary and the secondary users. Based on the secondary user's point of view, each channel is assumed to be either in the busy state, i.e. occupied by the primary user, or in the idle state, i.e. free to be accessed. Considering that $c_{i,k}$ denotes the state of the ith channel in time slot k, the state of the entire network in the kth time slot can be written as

$$s_k = [c_{1,k}, \dots c_{i,k}, \dots c_{N,k}],\ c_{i,k} \in \{0, 1\},\ \forall s_k \in \boldsymbol{S}_k \tag{5}$$

where $c_{i,k} = 0$ indicates the idle state and $c_{i,k} = 1$ represents the busy state. The most essential part in spectrum handoff is the target channel selection, which is defined as the action set within the POMDP framework. In other words, an action a_k at the time instant k is to appropriately choose the target handoff channel from the entire N channels within the CR network, i.e. $a_k = \{1, \dots, N\}$. After the execution of an action, the channel state can consequently be observed. The set of observations $z_k \in \{0, 1\}$ can be defined as the sensing outcome, where 0 represents the idle state and 1 stands for the busy state.

Furthermore, the transition probability can be determined by modeling a channel as an M/G/1 system with arrival rate λ and service rate μ. By assuming Poisson traffic for the arrival packets, the probability distribution of arriving packets can be represented as

$$P_r(n_{\lambda,k} = x) = \frac{e^{-\lambda}\lambda^x}{x!} \tag{6}$$

where $n_{\lambda,k}$ denotes the number of arriving packets in the kth time slot. With the execution of action a_k, the channel transition probability $\tau(c_{i,k}, a_k, c_{i,k+1})$ represents the transition from the present channel state $c_{i,k}$ to the channel state $c_{i,k+1}$ at the next time slot. By adopting the result from (6), the transition probability from idle to idle state for a channel $c_{i,k}$ after executing action

a_k can be acquired as

$$\tau(c_{i,k}=0,a_k,c_{i,k+1}=0)=\frac{P_r(n_{\lambda,k}=0,c_{i,k}=0)}{P_r(c_{i,k}=0)}=\frac{P_r(n_{\lambda,k}=0)\cdot P_r(c_{i,k}=0)}{P_r(c_{i,k}=0)}=e^{-\lambda} \tag{7}$$

for $i=\{1,\ldots,N\}$. It is noted that the second equality in (7) is attributed to the fact that the availability of a channel in any kth time slot is independent to the total number of arrival packets within the same slot. On the other hand, the transition probability for the channel $c_{i,k}$ coming from busy to idle state can be expressed as

$$\begin{aligned}\tau(c_{i,k}=1,a_k,c_{i,k+1}=0)&=\frac{P_r(n_{\lambda,k}=0,n_{\lambda,k-1}>0,T_{s,k}\leq 1)}{P_r(c_{i,k}=1)}\\&=\frac{P_r(n_{\lambda,k}=0)\cdot P_r(n_{\lambda,k-1}>0)\cdot P_r(T_{s,k}\leq 1)}{P_r(c_{i,k}=1)}\end{aligned} \tag{8}$$

where the second equality is also contributed to the independency of the three probabilities within the numerator of (8). The parameter $T_{s,k}$ is the total service time in time slot k which includes both the time durations for serving packets coming into this kth time slot and the remaining packets acquired from the previous $(k-1)$th slot. It is assumed that $\gamma_1,\gamma_2,\ldots\gamma_\alpha$ are the random variables of a packet service time with mean value of $1/\mu$, where α represents the number of packets arrived from the previous $(k-1)$th slot, i.e. $n_{\lambda,k-1}=\alpha$. The time server takes for serving these α packets within the kth slot is denoted as $T_{\alpha,k}=\sum_{j=0}^{\alpha}\gamma_j P_r(n_{\lambda,k-1}=\alpha)$. Therefore, the third term in the numerator of (8) can be rewritten as

$$P_r(T_{s,k}\leq 1)=P_r(T_{s,k-1}\leq 1)\cdot P_r(T_{\alpha,k}\leq 1)+P_r(T_{s,k-1}>1)\cdot P_r(T_{s,k-1}-1+T_{\alpha,k}\leq 1) \tag{9}$$

which is the combination of two cases as follows: (a) the packets can be served in both previous and this time slots; and (b) the packets have not been entirely served in the previous slot but are able to be served in this time slot. Furthermore, the denominator of (8) that represents the probability for a busy channel can be expressed as

$$P_r(c_{i,k}{=}1){=}P_r(n_{\lambda,k-1}{>}0){+}P_r(n_{\lambda,k-1}{=}0){\cdot}P_r(T_{s,k-1}{>}1) \tag{10}$$

Based on (7) and (8), the transition probabilities from idle to busy state and from busy to busy state can be respectively obtained as $\tau(c_{i,k}=0,a_k,c_{i,k+1}=1)=1-\tau(c_{i,k}=0,a_k,c_{i,k+1}=0)$ and $\tau(c_{i,k}=1,a_k,c_{i,k+1}=1)=1-\tau(c_{i,k}=1,a_k,c_{i,k+1}=0)$. As a result, by assuming that each channel $c_{i,k}$ is independent with each other for $i = 1$ to N, the transition probability for the entire network $\Gamma(s_k, a_k, s_{k+1})$ can be obtained as

$$\Gamma(s_k, a_k, s_{k+1}) = \prod_{i=1}^{N} \tau(c_{i,k} = \varsigma_1, a_k, c_{i,k+1} = \varsigma_2) \tag{11}$$

where $c_{i,k} \in s_k$, $c_{i,k+1} \in s_{k+1}$, and ς_1, $\varsigma_2 \in \{0, 1\}$, The main objective of proposed POSH scheme is to select a target channel that has the minimum waiting time, i.e. the smallest number of waiting slots required for the CR user if the target channel is still occupied by the primary user. Note that the time required for spectrum handoff of a CR user is defined as the time duration from the termination of packet transmission in one channel to the starting time of retransmission in another channel.

The waiting time, which is served as the cost function within the POMDP framework, will be minimized by the POSH scheme with the selection of an optimal channel in the spectrum handoff process. The immediate cost is considered as the total number of waiting slots n_w required by the secondary user while executing a specific action, i.e. $a^* = a_k$, for spectrum handoff. Consequently, we define the expected cost $C(s_k, a_k)$ as

$$\begin{aligned} C(s_k,a_k) &= \frac{1}{R(s_k,a_k)} = n_w^{a_k} \\ &= E[n_w=\ell|a^*=a_k] = \sum_{\ell=0}^{\infty} \ell \cdot P_r(n_w=\ell|a^*=a_k) = \sum_{\ell=1}^{\infty} \ell \cdot P_r\left(\bigcap_{p=1}^{\ell} c_{a_k,k+p-1}=1, c_{a_k,k+\ell}=0,\right) \\ &= \sum_{\ell=1}^{\infty} \ell \cdot \tau(c_{a_k,k+\ell-1}=1, a_k, c_{a_k,k+\ell}=0) \cdot P_r\left(\bigcap_{p=1}^{\ell} c_{a_k,k+p-1}=1\right) \\ &= \sum_{\ell=1}^{\infty} \ell \cdot\ \tau(c_{a_k,k+\ell-1}=1, a_k, c_{a_k,k+\ell}=0) \cdot P_r(c_{a_k,k}=1) \cdot \tau(c_{a_k,k}=1, a_k, c_{a_k,k+1}=1)^{\ell-1} \end{aligned} \tag{12}$$

where $c_{a_k,k}$ denotes the channel state after selecting channel a_k at the time instant k. Noted that the cost function $C(s_k, a_k)$ is defined as the inverse of the expected immediate reward $R(s_k, a_k)$ in (4) that will be utilized in the POMDP formulation.

B. Protocol Implementation of POSH Scheme

An overlay slotted CR network with partially observable information is considered for the POSH scheme, which indicates that the secondary user is not allowed to coexist with the primary user while the time duration for packet transmission is divided into time slots. As shown in Fig. 1, partial channel information $o(s_{k+1}, a_k, z_k)$ is assumed available to be observed by the secondary users, which will be exploited for the update of belief state $b(s_{k+1})$ as in (2). The secondary user utilizes the updated belief state in order to estimate the channel state of the CR network.

According to the POSH scheme, an L-step value function will be adopted to obtain the corresponding action that results in the minimal waiting time after the handoff process. In other words, based on the L-step value function $V_L^*[b(s_k)]$, which is mapped from the belief state space, the CR user will determine the feasible action to take in order to achieve the highest reward. The L-step value function for the CR user can be obtained as

$$V_L^*[b(s_k)] = \max_{a_k \in \boldsymbol{A}_k} \sum_{s_k \in \boldsymbol{S}_k} b(s_k) \cdot R(s_k, a_k) + \rho \sum_{z_k \in \mathbf{Z}_k} P_r(z_k | b(\mathbf{S}_k), a_k) \cdot V_{L+1}^*[b(s_{k+1})] \tag{13}$$

where ρ is denoted as a discount factor for convergence control of the value function. The probability $P_r(z_k|b(\mathbf{S}_k), a_k)$ is defined as in (3). At the beginning of the time slot where the spectrum handoff occurred, the CR user will choose a target channel that possesses the minimum waiting slots based on the results obtained from the L-step value function as in (13). After switching to the target channel, the CR user will conduct the sensing task for observing the newly updated channel state even though only partial state information is obtainable. After waiting for the required time slots that are determined by the POSH scheme, the secondary user can start to conduct its packet transmission within the target channel.

Moreover, it is noticed that the computation of L-step value function in (13) is considered complex and in general difficult to solve. The dimension of belief state grows exponentially as the number of channel is augmented, which makes it difficult to be adopted for practical implementation. A reduced state strategy has been proposed in [18] to establish an approximated linear state vector, which can effectively decrease the computation complexity of the value function. The complex optimization problem associated with (13) can therefore be resolved in an efficient manner.

IV. Performance Analysis of Proposed POSH Scheme

In this section, the analytical model for proposed POSH scheme is derived in Subsection A in order to analyze its performance. The models for both the non-spectrum handoff (NSH) scheme and the randomly choose strategy (RCS) will also be demonstrated. The effectiveness of the analytical models is to serve as validation purpose for these schemes, which will be compared with simulation results as in Section VI. Furthermore, the analytical models for these three handoff algorithms under practical considerations will also be derived and explained in Subsection B.

A. Analytical Modeling of Spectrum Handoff Schemes

The analytical models for the three spectrum handoff schemes, including NSH, RCS, and POSH mechanisms, will be derived and studied in this subsection. It is noted that the parameter a_k defined in Section II emphasizes the action executed at the time slot k, and consequently to acquire the reward function $R(s_k, a_k)$ at time k as in (12). However, it is not essential to point out a particular moment in analytical expressions, i.e. the subscript k for each action a_k will be neglected in the remaining discussion. Instead, the action a_s is defined as the selected target channel which can be either the current channel a_c or the destination channel a_d, where $a_d \in \{1, \ldots, N\}$ and $a_d \neq a_c$. The channel selected by the action a_s will be retained for a time period until another action is executed.

1) NSH Scheme: Let $n_{w,nsh}$ be the expected waiting time if the NSH scheme is performed, the CR user will not switch to other channels but stay at its current channel a_c to wait for the next spectrum hole. Similar to (12), the expected waiting time $n^{a_c}_{w,nsh}$ can be obtained as

$$\begin{aligned} n_{w,nsh} &= E[n_w = \ell | a^* = a_c] \\ &= \sum_{\ell=1}^{\infty} \ell \cdot P_r \left(\bigcap_{p=1}^{\ell} c_{a_c,k+p-1} = 1, c_{a_c,k+\ell} = 0 \right) \\ &= \sum_{\ell=1}^{\infty} \ell \cdot \ \tau(c_{a_c,k+\ell-1} = 1, a_c, c_{a_c,k+\ell} = 0) \cdot \tau(c_{a_c,k} = 1, a_c, c_{a_c,k+1} = 1)^{\ell-1} \end{aligned} \tag{14}$$

It is noted that the third equality in (14) indicates that the NSH method is adopted under the condition that no spectrum handoff is executed at the current time k even though the current channel state is busy, i.e. $c_{a_c,k} = 1$. Therefore, the expected waiting time by exploiting NSH scheme $n_{w,nsh}$ can be obtained by assigning $P_r(c_{a_c,k} = 1) = 1$ in (12).

2) RCS Scheme: Let $n_{w,rcs}$ be the expected waiting time as the RCS scheme is performed, the CR user will randomly switch to a target channel a_s from the network spectrums 1 to N to acquire channel access. Therefore, for the calculation of $n_{w,rcs}$, there exists probability

$P_r(a^* = a_s)$ for the action a_s to select one channel within all the N channels as below:

$$\begin{aligned} n_{w,rcs} &= \sum_{a_s=1}^{N} E[n_w = \ell | a^* = a_s] \cdot P_r(a^* = a_s) \\ &= \frac{1}{N} \cdot E[n_w = \ell | a^* = a_c] + \frac{1}{N} \cdot \sum_{a_d=1, a_d \neq a_c}^{N} E[n_w = \ell | a^* = a_d] \\ &= \frac{1}{N} \cdot n_{w,nsh} + \frac{1}{N} \cdot \sum_{a_d=1, a_d \neq a_c}^{N} n_w^{a_d} \end{aligned} \tag{15}$$

where $n_{w,nsh}$ is defined in (14). The parameter $n_w^{a_d}$ denotes the expected waiting time by selecting the channel a_d without staying at the current channel a_c, which can be computed from (12) by assigning $a_k = a_d$. In the case that the traffic pattern of all the N channels are identical, (15) can be reformulated by incorporating (14) as

$$\begin{aligned} n_{w,rcs} =& \frac{1}{N} \left[1 + \sum_{a_d=1, a_d \neq a_c}^{N} P_r(c_{a_d,k} = 1) \right] \cdot \\ & \sum_{\ell=1}^{\infty} \ell \cdot \tau(c_{a_s,k+\ell-1} = 1, a_s, c_{a_s,k+\ell} = 0) \cdot \tau(c_{a_s,k} = 1, a_s, c_{a_s,k+1} = 1)^{\ell-1} \end{aligned} \tag{16}$$

As illustrated in (16), the expected waiting time obtained from the RCS scheme should be less or at least equal to that acquired from NSH method, i.e. $n_{w,rcs} \leq n_{w,nsh}$, since the probability $P_r(c_{a_d,k} = 1) \leq 1 \ \forall a_d \neq a_c$. The benefit for using the random channel selection scheme over the case to remain at the current channel can therefore be analytically revealed.

3) POSH Scheme: The channel selection behavior of both the NSH and RCS schemes are straightforward such that their analytical models can be directly expressed by stationary probabilities and transition probabilities. The proposed POSH scheme, on the other hand, determines its target channel by the POMDP policy which is mapped by the belief state at each step as shown in Fig. 1. Since the value of belief state is obtained from the observation, action, and former belief state at each step, it is not possible to predict and obtain the target channel in advance. Nevertheless, the analytical model of POSH scheme can still be approximately estimated since the updated belief state will gradually approach to stationary probability considering that the network is not rapidly varying. Let $n_{w,posh}$ be the expected waiting time as the POSH scheme is adopted, the resulting formulation is similar to the RCS scheme except that the probabilistic distribution $\tilde{P}_r(a^* = a_s)$ of action a^* is considered non-uniform in this case, i.e.

$$n_{w,posh} = \sum_{a_s=1}^{N} E[n_w = \ell | a^* = a_s] \cdot \tilde{P}_r(a^* = a_s) \tag{17}$$

Let $n_w^{a_{d1}}$ and $n_w^{a_{d2}}$ be the first and second minimum expected waiting time resulted from action a_{d1} and a_{d2} by adopting the proposed POSH scheme, respectively. These two actions can be expressed as

$$\begin{aligned} a_{d1} &= \arg\min_{\forall a_s} n_w^{a_s} \\ a_{d2} &= \arg\min_{\forall a_s, a_s \neq a_{d1}} n_w^{a_s} \end{aligned} \tag{18}$$

where the expected waiting time by conducting spectrum handoff $n_w^{a_s}$ can be obtained from (12) by assigning $a_k = a_s$. The statistical distribution of the chosen action a^* in proposed POSH scheme can be acquired as

$$\tilde{P}_r(a^* = a_s) = \begin{cases} 1, & \text{for } a_s = a_{d1}, \text{ and } n_{w,nsh}^{a_{d1}} \leq n_w^{a_{d2}} \\ 0.5, & \text{for } a_s = a_{d1} \text{ or } a_{d2}, \text{ and } n_{w,nsh}^{a_{d1}} > n_w^{a_{d2}} \\ 0, & \text{otherwise} \end{cases} \tag{19}$$

where $n_{w,nsh}^{a_{d1}}$ denotes the expected waiting time by staying at the channel a_{d1} without spectrum handoff. It can be observed that the first case $\tilde{P}_r(a^* = a_s) = 1$ in (19) happens under the situation that a_s is selected as a_{d1} and $n_{w,nsh}^{a_{d1}} \leq n_w^{a_{d2}}$. This case indicates that the expected waiting time obtained by staying at the channel a_{d1} will be comparably smaller or equal to that from the POSH-based spectrum handoff scheme $n_w^{a_{d2}}$. It is suggested not to conduct spectrum handoff to another channel a_{d2}, which results in the probability of staying at the channel $a^* = a_{d1}$ to be equal to 1, i.e. $\tilde{P}_r(a^* = a_{d1}) = 1$. On the other hand, the other case with $n_{w,nsh}^{a_{d1}} > n_w^{a_{d2}}$ should also be taken into account. It is considered that the previous selected channel is a_{d1}. If the expected waiting time resulted from a_{d1} without spectrum handoff is larger than that from a_{d2} by conducting spectrum handoff, the corresponding CR user will decide to switch into channel a_{d2}. Nevertheless, instead of remaining at channel a_{d2}, CR user will choose a_{d1} again at the next spectrum handoff since the waiting time $n_w^{a_{d1}}$ is smaller than $n_{w,nsh}^{a_{d2}}$ as depicted in (18). As a result, the channels a_{d1} and a_{d2} will alternatively be chosen depending on the previous action of the CR user, which results in $\tilde{P}_r(a^* = a_s) = 0.5$ for either $a^* = a_{d1}$ or a_{d2} if $n_{w,nsh}^{a_{d1}} > n_w^{a_{d2}}$.

According to the probabilistic distribution of the action a^* as obtained in (19), the expected waiting time of proposed POSH scheme can be reformulated from (17) as

$$n_{w,posh} = \begin{cases} n_{w,nsh}^{a_{d1}}, & \text{if } n_{w,nsh}^{a_{d1}} \leq n_w^{a_{d2}} \\ \frac{1}{2}n_w^{a_{d1}} + \frac{1}{2}n_w^{a_{d2}}, & \text{if } n_{w,nsh}^{a_{d1}} > n_w^{a_{d2}} \end{cases} \tag{20}$$

The benefits of these analytical models can provide the flexibility to evaluate the performance of different spectrum handoff schemes in advance. A feasible mechanism can be selected by the CR user that will be most beneficial in specific circumstance. Performance validation and comparison between these schemes will be illustrated later in Section VI.

B. Practical Considerations for Spectrum Handoff Schemes

In the previous subsection, according to the POMDP-based channel selection policies, the analytical results show that the proposed POSH scheme should provide reduced expected waiting time than that from both the RCS and NSH algorithms at the occurrence of spectrum handoff. However, the ideal circumstance is assumed where only data transmission is considered in a specific time slot. In practice, it's inevitably to spend a period of time to detect the network condition and to make sure that spectrum handoff can be successfully executed. It is intuitive to recognize that additional periods of time can be required by the proposed POSH scheme for conducting the POMDP-based channel selection with partially observable channel information. Therefore, practical consideration for spectrum handoff that involves channel sensing and hand-shaking will be discussed in this subsection. The performance difference between these schemes under the practical circumstance can consequently be observed.

As mentioned in previous sections, the time slotted system is considered in this paper as shown in Fig. 2. It is required for the CR user to perform spectrum sensing on its current channel at the beginning of each time slot in order to assure the availability of the present channel. If the outcome of spectrum sensing is observed to be idle, the CR user can remain in the same slot to conduct packet transmissions. The receiver will consequently return an acknowledgement (ACK) frame at the end of this slot to acknowledge the reception of data packet. On the other hand, in the case that the sensing outcome is busy, additional messages will be delivered in order to perform different spectrum handoff schemes which are stated as follows.

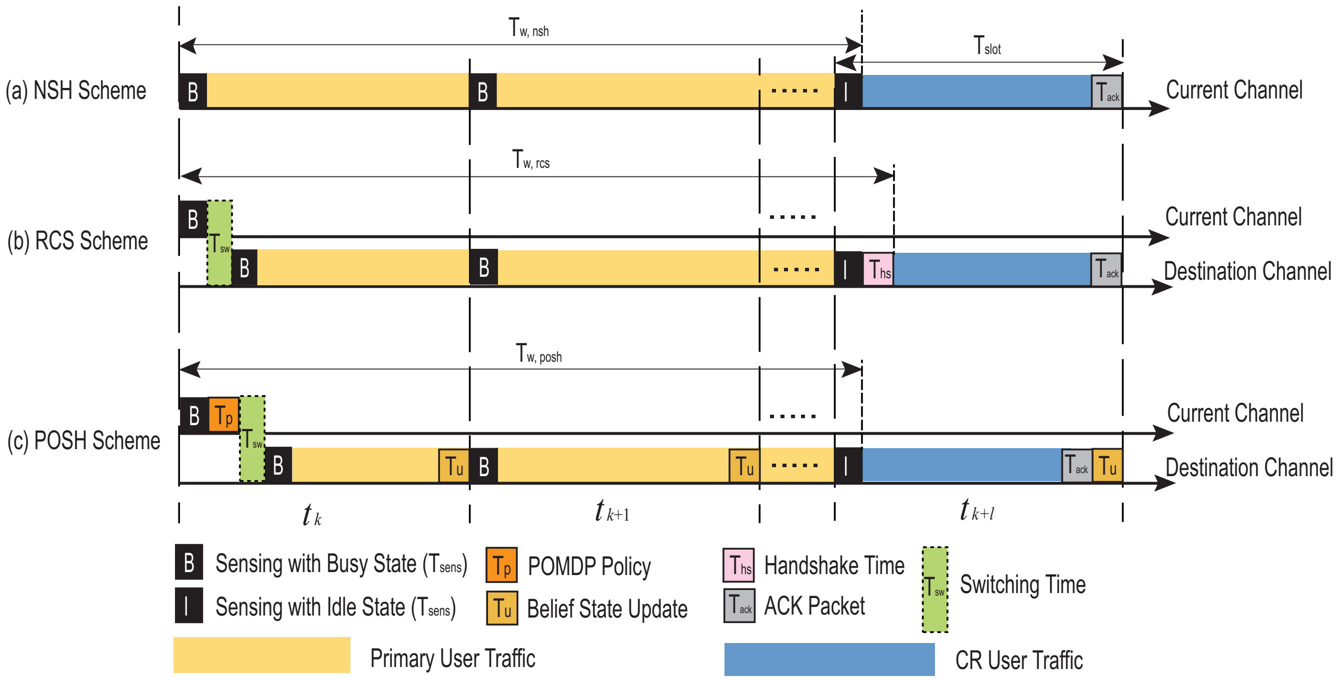

Fig. 2. Practical consideration for the time-slotted channels with different spectrum handoff protocols: (a) NSH scheme, (b) RCS scheme, and (c) POSH scheme.

1) NSH Scheme: As shown in Fig. 2.(a), the behavior for the time-slotted channel with the adoption of NSH scheme is depicted. The time slots t_k and $t_{k+\ell}$ (for $\ell \geq 0$) are utilized to represent the initial and final slots that are considered in the various handoff schemes. At the slot t_k, the intention from primary user to utilize this channel is observed during the spectrum sensing period. Based on the NSH scheme, the CR user will remain silent on the current channel and wait until the primary user to finish its transmissions. Considering that the traffic from primary user has not been observed during the sensing period of slot $t_{k+\ell}$, the CR user can consequently conduct its data transmission. Therefore, the total waiting time by adopting the NSH scheme (i.e. $T_{w,nsh}$) can be expressed as

$$T_{w,nsh} = n_{w,nsh} \cdot T_{slot} + T_{sens} \tag{21}$$

where the expected number of waiting time slots $n_{w,nsh}$ can be obtained from (14). The parameter T_{slot} represents the time duration of each slot and T_{sens} denotes the time interval of sensing period. Furthermore, the net transmission time within a time slot by adopting the NSH method (i.e. $T_{s,nsh}$) can be acquired as

$$T_{s,nsh} = \frac{T_{slot} - T_{sens} - T_{ack}}{n_{w,nsh} + 1} \tag{22}$$

where T_{ack} indicates the required time for returning the ACK packet to conduct handshake for data transmission. It can be observed that the net transmission time $T_{s,nsh}$ will be reduced with larger number of waiting slots $n_{w,nsh}$.

2) RCS Scheme: The practical consideration for the RCS scheme is illustrated in Fig. 2.(b). After the initial sensing, the CR transmitter will randomly select a target channel for spectrum handoff, where the determination process is assumed short and negligible. Consider the RCS scheme with N channels in the network, there are $1/N$ probability that the CR user will remain at its current channel; while there are $(N-1)/N$ possibility switching to another spectrum. The average waiting time of RCS scheme $T_{w,rcs}$ can be obtained as

$$\begin{aligned} T_{w,rcs} =& \frac{1}{N} \cdot T_{w,nsh} + \frac{1}{N} \sum_{a_d=1, a_d \neq a_c}^{N} [P_r(c_{a_d,k} = 1) \cdot n_w^{a_d} \cdot T_{slot} \\ &+ P_r(c_{a_d,k} = 0) \cdot (T_{sw} + T_{sens}) + T_{sens} + T_{hs}] \end{aligned} \tag{23}$$

where $T_{w,nsh}$ is obtained from (21) if the CR user is determined to stay at the existing channel. In the case that the CR user is suggested to switch to another channel, both the switching time T_{sw} and an additional sensing time T_{sens} will be required in order to observe if the destination channel is busy or not. If the target channel is occupied by the primary user with probability $P_r(c_{a_d,k} = 1)$, additional waiting time slots $n_w^{a_d}$ are required until the channel becomes idle to be utilized. On the other hand, if the randomly selected channel is found to be idle with probability $P_r(c_{a_d,k} = 0)$, both the CR transmitter and receiver will spend the time interval T_{hs} for exchanging handshake messages in order to confirm the utilization of target channel. Moreover, the resulting net transmission time in a slot $T_{s,rcs}$ can therefore be acquired as

$$\begin{aligned} T_{s,rcs} =& \frac{T_{slot} - T_{sens} - T_{hs} - T_{ack}}{N(n_{w,nsh} + 1)} + \frac{1}{N} \sum_{a_d=1, a_d \neq a_c}^{N} \frac{1}{n_w^{a_d} + 1} \cdot [P_r(c_{a_d,k} = 1) \cdot (T_{slot} - T_{sens} \\ &- T_{hs} - T_{ack}) + P_r(c_{a_d,k} = 0) \cdot (T_{slot} - T_{sens} - T_{sw} - T_{sens} - T_{hs} - T_{ack})] \end{aligned} \tag{24}$$

where the computation of (24) can be depicted from Fig. 2.(b).

3) POSH Scheme: The proposed POSH scheme with practical consideration is shown in Fig. 2.(c). It is assumed that all the CR users share identical network condition and observe the same sensing consequence. Since the POMDP policy is simultaneously performed by both CR transmitter and receiver, it is unnecessary to exchange handshake messages with required time duration T_{hs} in order to inform the receiver which spectrum is selected as the target channel. Nevertheless, it is considered that and additional time interval T_p is required by the CR user to implement the POMDP-based policy, and the time T_u to update the belief state at the end of each slot. Consequently, the overall waiting time $T_{w,posh}$ can be represented as

$$\begin{aligned} T_{w,posh} =& \frac{1}{N} \cdot T_{w,nsh} + \frac{N-1}{N}[P_r(c_{a_s,k}=1) \cdot n_{w,posh} \cdot T_{slot} \\ & + P_r(c_{a_s,k}=0) \cdot (T_{sens} + T_p + T_{sw}) + T_{sens}] \end{aligned} \tag{25}$$

where a_s will either be a_{d1} or a_{d2} according to the conditions as stated in (19). The net transmission time in a slot $T_{s,posh}$ becomes

$$\begin{aligned} T_{s,posh} = & \frac{1}{N(n_{w,posh}+1)}\{(T_{slot} - T_{sens} - T_{ack} - T_u) + (N-1)[P_r(c_{a_d,k}=1) \cdot (T_{slot} \\ & - T_{sens} - T_{ack} - T_u) + P_r(c_{a_d,k}=0) \cdot (T_{slot} - T_{sens} - T_p - T_{sw} - T_{sens} - T_{ack} - T_u)]\} \end{aligned} \tag{26}$$

By comparing (25) and (26) from the POSH scheme with (23) and (24) from the RCS scheme, it can be observed that the performance difference between these two protocols will be dominated by (a) the parameters $n_{w,posh}$ and $n_w^{a_d}$ $\forall a_d = 1, a_d \neq a_c$, and (b) the parameter set (T_p, T_u) and T_{hs}. It is apparently that $n_{w,posh}$ should be smaller than $n_w^{a_d}$ from the RCS algorithm since the POSH scheme is designed to select the minimal waiting time for spectrum handoff. On the other hand, the parameters (T_p, T_u) that are implemented in the POSH scheme should be feasibly chosen in order not to result in excessive computation overheads. Due to the large amount of system states and the complexity of witness algorithm [19–21], it is considered a complicate process to calculate a POMDP-based algorithm. It can be found in (5) that as the number of channel increases, the total number of system state will be augmented exponentially which makes the update process of belief state becomes complicate. A reduced form of system state was introduced in [3; 18] to be adapted in the problems with POMDP-based formulation. It has been proved to reduce the total number of states that becomes equivalent to the number of channels in the system, which can effectively decrease the computational complexity. Furthermore, an efficient approach for belief state update is also exploited as in [18] to simplify the updated procedure.

Since the number of reduced belief state is equal to the number of channels as N and each of the state is updated by a specific equation, it can be concluded that the time complexity of belief state update becomes $O(N)$. The computation cost for the parameter set (T_p, T_u) can therefore be effectively reduced.

V. Proposed POMDP-based Multi-user Spectrum Handoff (M-POSH) Protocol

In Section III, the POSH scheme is introduced to provide the POMDP-based policy for a single CR user in order to determine the target channel for spectrum handoff. In the case that the network exists more than one CR user whose transmissions are interrupted by the primary users at a specific time slot, it is possible that those CR users will select an identical frequency channel for spectrum handoff. Therefore, the consequence of performing the original POSH scheme in multi-user network will result in packet collisions among the CR users that intend to perform spectrum handoff. In this section, a multi-user POSH (M-POSH) protocol is proposed to distribute the CR users to different opportunistic spectrums rather than contending the access right in the same channel. The main purpose of proposed scheme is to reduce the waiting time of entire network by ensuring that every possible spectrum hole can be fully exploited, whereas the fairness for channel access among all CR users can still be maintained. In the following two subsections, the system model and implementation of the proposed M-POSH scheme will be described.

A. System Model of M-POSH Protocol

The system model of proposed M-POSH protocol is described as follows. It is assumed that the number of CR users n is smaller than the number of total licensed spectrums in a slotted CR network, i.e. $n < N$. Unlike the POSH scheme, the M-POSH protocol not only needs to consider the traffic of primary user but also requires to coordinate the channel access among the secondary users. Moreover, instead of exchanging messages among the CR users in distributed manner, a common control channel is utilized to exchange required information between the CR users. There has been arguments regarding whether to utilize a dedicate channel for delivering control messages. The investigation in [22] provides analytical results in order to illustrate the benefits for adopting an dedicated control channel in the network.

The belief state for multi-user can be extended from that for single user as defined in Subsection II.B and (5). The belief state of the rth CR user is represented as $b_r(c_{i,k})$, where $c_{i,k} \in \{0,1\}$ denotes the state of the ith channel in time slot k. Let $\tilde{\mathcal{A}}_k$ denotes the action set representing the channels that are utilized by the CR users at time slot k, i.e. $\tilde{\mathcal{A}}_k \in \boldsymbol{A}_k$ where $\boldsymbol{A}_k$ represents the entire action set which corresponds to all the channels in the network as defined in Subsection II-A. The update for belief state in multi-user scenario can be obtained as

$$b_r(c_{i,k+1}) = \begin{cases} 0, & \text{if } (z_{r,k}=0,\ a_{r,k}=i) \text{ and } a_{r,k} \notin \tilde{\mathcal{A}}_k \\ 1, & \text{if } (z_{r,k}=1 \text{ and } a_{r,k}=i) \text{ or } a_{r,k} \in \tilde{\mathcal{A}}_k \\ b_r(c_{i,k}) \cdot \tau(c_{i,k}=0, a_{r,k}, c_{i,k+1}=0) & \\ +[1-b_r(c_{i,k})] \cdot \tau(c_{i,k}=1, a_{r,k}, c_{i,k+1}=0), & \text{if } a_{r,k} \neq i \end{cases} \tag{27}$$

where $a_{r,k}$ represents the action of the rth user in time slot k, and $z_{r,k}$ denotes the observation of the rth user in slot k. The update process of belief state in (27) is derived via the reduced strategy as in [3] for POMDP-based formulation. For the rth user that decides to take action $a_{r,k}$ to access the ith channel, i.e. $a_{r,k} = i$, the update of the rth user's belief state $b_r(c_{i,k+1})$ at time $(k+1)$ will be determined by its corresponding observation $z_{r,k}$ on the same ith channel at time k. In other words, the update of belief state $b_r(c_{i,k+1}) = 0$ if the ith channel is observed to be in the idle state at time k, i.e. $z_{r,k} = 0$; while $b_r(c_{i,k+1}) = 1$ in the case that $z_{r,k} = 1$. Another condition for the belief state at the $(k+1)$th time slot to be in the busy state is that the action taken at time slot k belongs to the busy channel set, i.e. $a_{r,k} \in \tilde{\mathcal{A}}_k$. Furthermore, if the rth user is using a channel other than the ith channel at current time k, i.e. $a_{r,k} \neq i$, the update process of belief state for the ith channel to remain in the idle state at time $(k+1)$ will be determined as shown in the third term of (27). The idle probability for the belief state at the $(k+1)$th time slot is equal to the idle transition probability $\tau(c_{i,k}=0, a_{r,k}, c_{i,k+1}=0)$ times the idle probability at time k plus the busy to idle probability $\tau(c_{i,k}=1, a_{r,k}, c_{i,k+1}=0)$ times the busy probability at the same kth time slot.

B. Implementation of M-POSH Protocol

Without loss of generality, it is assumed that all the existing CR users are initially located and operated on different frequency spectrums. After the channel sensing period, a handshaking time interval is designed in the proposed M-POSH protocol that all the CR users will listen to a common control channel for potential handoff messages. In the case that a CR user intends to conduct spectrum handoff, it will broadcast a handoff message on the control channel in order to announce all the other CR users regarding the change of network condition. Since there may exist more than one CR users that need to broadcast their handoff messages simultaneously in the same time slot, it is possible that these messages from different CR users will collide with each other. A random backoff contention window [23] is therefore utilized in the proposed M-POSH scheme in order to resolve the potential packet collision problem. Each CR user that intends to deliver the handoff message on the control channel will wait for a random number in a pre-specified interval such as to ensure the success of message transmission. It is noted that prioritized channel access between the CR users can also be implemented by assigning different ranges of contention windows among the CR users, e.g. CR users with higher priority channel access should be designed with a smaller range of contention window in order to possess high opportunity to obtain channel access.

The handoff message delivered from each CR user mainly includes the prioritized destination channel list, i.e. $\boldsymbol{D}_{r,k} = [d_{r,1,k}, \ldots, d_{r,i,k}, \ldots, d_{r,N,k}]$ where $d_{r,i,k}$ represents the channel with ith priority for user r to select at time slot k. The determination of channel priorities within the $\boldsymbol{D}_{r,k}$ set is based on the required waiting time for user r to handoff to that specific spectrum, which can be individually computed from (12) as

$$d_{r,i,k} = \arg \min_{\forall a_{r,k} \in \boldsymbol{A}_k,\, a_{r,k} \neq d_{r,j,k} \forall j < i} n_w^{a_{r,k}} \tag{28}$$

for $i = 1$ to N. Note that the channel with smaller waiting time will be assigned with higher priority in the prioritized destination channel list $\boldsymbol{D}_{r,k}$, i.e. with smaller value of index i. After the handoff messages are broadcast in the control channel during the handshaking time interval, all the CR users that intend to conduct spectrum handoff will determine their destination channel based on the prioritized destination channel lists $\boldsymbol{D}_{r,k}$ from the received handoff messages. The CR user that possesses smaller backoff counter will have higher priority to select the channel with comparably smaller waiting time slots.

The following example is utilized to explain the mechanism of proposed M-POSH protocol. It is considered that there are total of five channels in the network, i.e. $N = 5$. There exists a primary user resides in channel 4 and three CR users r_1, r_2, and r_3 initially locate in channel 1, 2, and 3, respectively. Each user conducts data transmission with its distinct packet arrival rate. In the case that two primary users intend to utilize their original channels 1 and 2 at time slot k, the secondary users r_1 and r_2 will yield from their corresponding channels 1 and 2 after conducting channel sensing. Handoff messages will be broadcast to the control channel by r_1 and r_2 during the handshaking time interval based on the random backoff mechanism. It is assumed that the backoff counter for r_1 and r_2 is equal to 4 and 7 respectively, which indicates that handoff message from r_1 will be delivered at the 4th minislot and that from r_2 will be broadcast at the 7th minislot. The prioritized destination channel lists within the handoff messages for r_1 and r_2 can be obtained based on the required waiting time slots in that channel, which are assumed as $\boldsymbol{D}_{r_1,k} = \{5,1,2,3,4\}$ and $\boldsymbol{D}_{r_2,k} = \{5,3,1,2,4\}$ in this example. Channel 5 is selected as the first entry in both of the lists since it is not occupied by any user at the time slot k. Noted that the different channel priorities between $\boldsymbol{D}_{r_1,k}$ and $\boldsymbol{D}_{r_2,k}$ can happen due to their difference in channel observation and update based on the POMDP-based policy. According to the value of backoff counter, user r_1 will have higher priority than r_2 in choosing the destination channel for spectrum handoff, i.e. channel 5 will be selected since it is in the first entry of its channel list $\boldsymbol{D}_{r_1,k}$. On the other hand, user r_2 will notice that r_1 has higher priority in selecting the destination channel and both users possess the same channel 5 as the first entry in the prioritized destination channel list. The second entry, i.e. channel 3, in $\boldsymbol{D}_{r_2,k}$ will be selected by r_2 for spectrum handoff. Therefore, user r_1 will utilize the empty channel number 5 and r_2 will handoff to channel 3 waiting the required time slots for r_3 before conducting packet transmission. The performance of proposed M-POSH protocol for multiple CR user scenarios will be evaluated via simulations in next section.

C. Analytical models

1) Control Channel: In order to broadcast handoff messages during the interval T_{hs}, all CR users have to contend for access to the control channel. And the contention behavior is analyzed based on [23], which studied the process of the backoff operations with a Markov chain model. Let τ be the probability that the user transmits packet, and p be the probability that each packet collides. Then we can obtain the equation of τ and p as:

$$\tau(p) = \frac{2(1-2p)}{(1-2p)(W+1) + p \cdot W(1-(2p)^m)} \tag{29}$$

$$p(\tau) = 1 - (1-\tau)^{n-1} \tag{30}$$

TABLE 1 : PARAMETERS

Parameter	Value
PHY header	192 bits
MAC header	224 bits
T_{RTS}	(160 bits+PHY header)/R
T_{CTS}	(112 bits+PHY header)/R
T_{ACK}	(112 bits+PHY header)/R
σ	20 μs
δ	1 μs
SIFS	16 μs
DIFS	56 μs
CW_{min}	32
Maximum backoff stage	5
channel bit rate (R)	1 Mbps

where $W = CW_{min}$ is the minimum contention window, m is the maximum backoff stage, and n is the number of secondary users who are contending. By iteratively solving these two equations we can obtain the value of τ and p. Let P_{tr} be the probability that there is at least one transmission in a slot time, and P_s be the probability that a transmission is successful, conditioned on the fact that at least one user transmits. Then we have $P_{tr} = 1 - (1-\tau)^{n-1}$ and $P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}$. The average time spent on the control channel for a successful handshakes, denoted as E[$T_{average}$], can be obtained as:

$$E[T_{average}] = T_s + \sigma\frac{1-P_{tr}}{P_{tr}P_s} + T_c(\frac{1}{P_s} - 1) \tag{31}$$

where σ is the slot time size, T_s and T_c are the time spent for a successful transmission and the time used when a collision happened, respectively. T_s and T_c is given as:

$$\begin{cases} T_s = T_{RTS} + SIFS + \delta + T_{CTS} + SIFS + \delta + E[P] + SIFS + \delta + T_{ACK} + DIFS + \delta \\ T_c = T_{RTS} + DIFS + \delta \end{cases} \tag{32}$$

where δ is the propagation delay, and T_{RTS}, T_{CTS} and T_{ACK} represent the duration of the RTS, CTS and ACK frames, respectively, and the E[P] is the average packet payload size.

Let N_{max} be the maximum number of users that can complete the handshaking in the duration of T_{hs}, then we can obtain $N_{max} = T_{hs}/E[T_{average}]$ on average. Because we assumed that the number of CR users n is smaller than the number of total licensed spectrums N, if $N < N_{max}$, so does $n < N_{max}$, we assume that all the user who need to utilize the control channel can successfully exchange the handshaking packets in the duration of T_{hs}.

2) Performance Analysis: The channel selection behavior of each user in M-POSH is based on the proposed POSH scheme. And the characteristic of the throughput of the M-POSH scheme is something to do with the POSH scheme. We start the analysis with a special case that the number of CR users equals to the number of total licensed spectrums, i.e. n = N. If all the network channels can be occupied by the CR users, the users will decide to stay at the original channel to reduce the collision due to the spectrum handoff. And that's the first case in (19), i.e. $n_{w,nsh}^{a_{d1}} \leq n_w^{a_{d2}}$, the expected waiting time by staying at the current channel will be comparably smaller or equal to that from the spectrum handoff scheme. So we can derive $n_{w,mposh}$, the expected waiting time if the M-POSH scheme is performed, is approach the expected waiting time as the NSH scheme is adopted. From (14), we can derive

$$n_{w,mposh} = n_{w,nsh} = \sum_{\ell=1}^{\infty} \ell \cdot \ \tau(c_{a_c,k+\ell-1} = 1, a_c, c_{a_c,k+\ell} = 0) \cdot \tau(c_{a_c,k} = 1, a_c, c_{a_c,k+1} = 1)^{\ell-1} \tag{33}$$

when n = N.

Next let us consider the case of $n < N$. The advantage of the M-POSH protocol is that distribute the CR users to exploit the available channels, when the $n = N - 1$, means there is one more available channel can be utilized by the $N - 1$ CR users. Because one more available channel means there is one more chance for the CR user switching to other channel if $n_{w,nsh}^{a_{d1}} > n_w^{a_{d2}}$, we can derive from (20) that $n_{w,mposh}$ is equal to $\frac{1}{2}n_{w,nsh} + \frac{1}{2}n_{w,posh}$ when $n = N - 1$. And also we can derive $n_{w,mposh}$ when $n = N - 2, N - 3, ..., 1$. With one lesser CR users, means there is one more available channel every time the CR users executing spectrum handoff. And the expected waiting time becomes $\frac{1}{2}n_{w,mposh} + \frac{1}{2}n_{w,posh}$ every time the number of CR users is decreased in one. Finally, $n_{w,mposh}$ can be represented as:

$$n_{w,mposh} = n_{w,nsh}\frac{1}{2^{N-n}} + n_{w,posh}\sum_{\ell=1}^{N-n}\frac{1}{2^{\ell}}, \forall n \leq N \tag{34}$$

VI. Performance Evaluation

In this section, simulations are presented to demonstrate the performance of proposed POSH and M-POSH protocols. The major focus in the simulations is to obtain the required waiting time

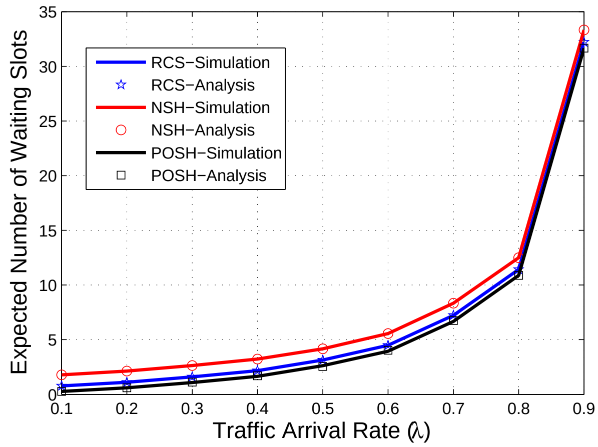

Fig. 3. Performance validation: the expected number of waiting time slots for a single spectrum handoff versus traffic arrival rate of primary user.

and the net transmission time for the secondary user under the occurrence of spectrum handoff. Since full channel state information is required by all of the existing spectrum handoff algorithms, it is considered unfair to compare the existing schemes within the environment adopted by the proposed POSH and M-POSH algorithms, where only partial channel information is observable. Therefore, the proposed scheme will be compared with two different cases as mentioned in Section IV, including both the NSH scheme and the RCS mechanism. The traffic of the primary user follows the Poisson distribution, and the service time is assumed to be a uniform distribution with mean $1/\mu = 1$. Three channels with channel states $s_k = [c_{1,k}, c_{2,k}, c_{3,k}]$ are considered in the simulations; while the discount factor in (13) is selected as $\rho = 1$. The reduced state strategy is utilized in the simulations to obtain the numerical results of the POMDP-based optimization problem.

A. Model Validation

The analytical models for required waiting time slots of the three schemes, including NSH, RCS, and POSH algorithms, as presented in (14), (16), and (20) are validated via simulations as shown in Fig. 3. It can be observed that the expected number of waiting time slots for a single spectrum handoff from all these three schemes increase as the traffic arrival rate (λ) of the primary user is augmented. Under different arrival rates, the proposed POSH algorithm can

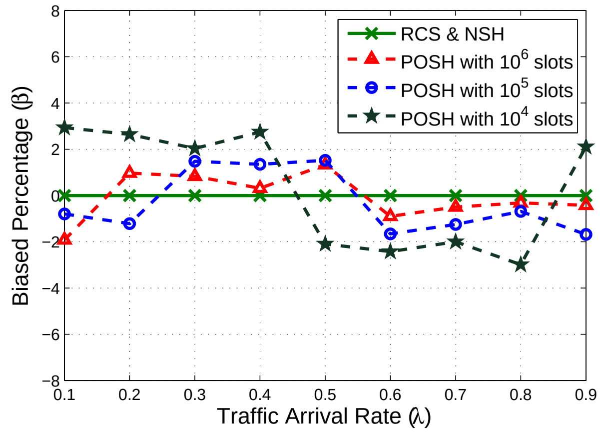

Fig. 4. Performance validation: biased percentage β versus traffic arrival rate of primary user.

provide the smallest waiting time slots comparing with the other two schemes. Furthermore, it can also be seen that the simulation results of both NSH and RCS schemes match with their corresponding analytical results. On the other hand, there exists slight difference between the analytical and simulation results of the proposed POSH scheme. The major reason for this deviation can be contributed to the definition of non-uniform probability $\tilde{P}_r(a^* = a_s)$ in (19) as described in its analytical model, which is designed to be a stationary probability. However, the POSH scheme involves non-stationary updating process of the belief state for the estimation of channel state. The deviation resulting from the stationary model of POSH scheme will further be studied as illustrated in Fig. 4.

In order to clearly illustrate the difference between the analytical and simulation results, the biased percentage β is introduced and is defined as $\beta = \frac{n^a_{w,\zeta} - n^s_{w,\zeta}}{n^s_{w,\zeta}} \times 100$ where $n^a_{w,\zeta}$ and $n^s_{w,\zeta}$ correspond to the expected waiting time slots obtained from analysis and simulation respectively. The parameter ζ indicates either one of the three spectrum handoff schemes is adopted. Fig. 4 illustrates the biased percentage β for the three schemes under different traffic arrival rates of the primary user. It is noted that the proposed POSH method is implemented under the simulation runs with different numbers of transmission time slots, i.e. $T = 10^4$, 10^5, and 10^6. It can be observed that even the non-stationary behavior of belief state can not be exactly modeled and analyzed, the analytical results derived by stationary probability can still approach to the simulation values within 3% of estimation difference. It can also be seen from Fig. 4 that the

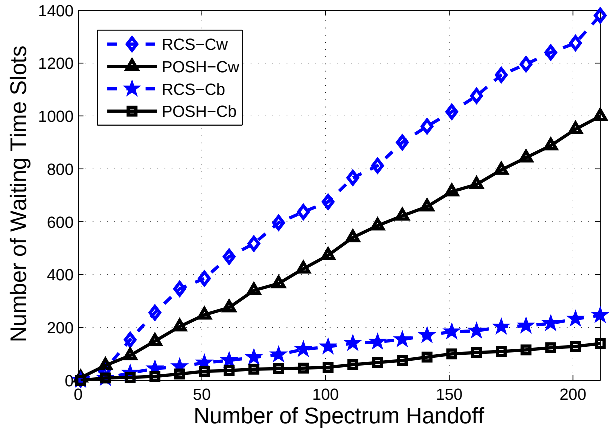

Fig. 5. Performance comparison: number of waiting time slots versus number of spectrum handoff.

bias will be diminished as the number of transmission time slots is increased for the simulations. This results reveal the case that with longer transmission time slots, the incomplete and non-stationary network information can be updated more accurately. The simulation results will tend to possess stationary behaviors as is presented by the analytical model in (20).

B. Performance Comparison

Fig. 5 shows the performance comparison of the number of waiting time slots versus the total number of spectrum handoff for both the proposed POSH scheme and the RCS method. Two different channel conditions are considered for comparison purpose as follows. A better channel condition C_b is chosen with the transition probability from idle to idle state for each channel as $\tau(c_{i,k} = 0, a_k, c_{i,k+1} = 0) = 0.8, 0.7, 0.65$ for $i = 1, 2, 3$; while that from busy to idle state is selected as $\tau(c_{i,k} = 1, a_k, c_{i,k+1} = 0) = 0.4, 0.5, 0.55$ for $i = 1, 2, 3$. On the other hand, a worse channel condition C_w is determined with the transition probability from idle to idle state as $\tau(c_{i,k} = 0, a_k, c_{i,k+1} = 0) = 0.4, 0.3, 0.35$, and that from busy to idle state is set as $\tau(c_{i,k} = 1, a_k, c_{i,k+1} = 0) = 0.1, 0.2, 0.15$. For fair comparison, the NSH scheme is not implemented in this case since the CR user can always stay at the channel with better condition. It is intuitive to observe from Fig. 5 that the total number of waiting time slots is increased as the number of spectrum handoff is augmented. Furthermore, the secondary user has to wait for comparably more time slots in the worse channel case by adopting both schemes. Nevertheless,

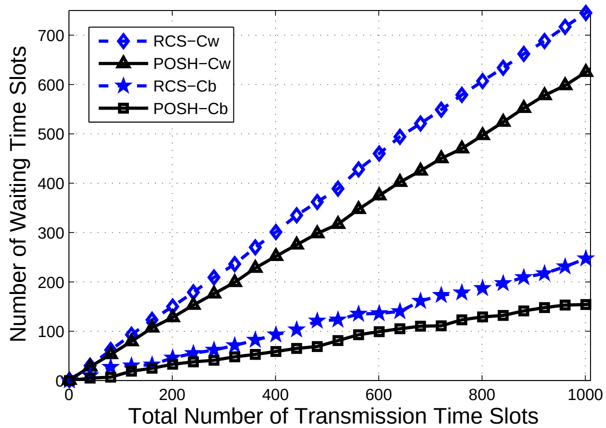

Fig. 6. Performance comparison: number of waiting time slots versus total number of transmission time slots.

the total waiting time slots acquired from the proposed POSH protocol is smaller than that from the RCS scheme under both channel conditions. It is also observed that the POSH protocol can provide better performance as the number of spectrum handoff is increased. The reason can be contributed to the situation that more updated belief states are acquired by the POSH scheme as the number of handoff is augmented.

Fig. 6 illustrates the performance comparison between the number of waiting time slots and the total number of transmission time slots. It is noticed that different numbers of waiting time slots and handoff numbers will be resulted by each scheme at every specific number of transmission time slots. In other words, the combining effects from both the waiting time slots and the handoff numbers will be revealed in Fig. 6 at each horizontal data point. It can be observed that the proposed POSH algorithm still outperforms the RCS scheme under both the C_b and C_w channel conditions. Even though the effect from the total number of spectrum handoff has not been considered in the value function as in (13), the POSH scheme can still provide smaller waiting time comparing with the RCS method.

Figs. 7 and 8 illustrate the performance comparison among the POSH, the RCS, and the NSH schemes under different values of packet arrival rate λ of the primary user. Comparing the case in Fig. 3 with a single spectrum handoff, Fig. 7 shows the averaged performance comparison under a larger fixed number of spectrum handoff equal to 250. On the other hand, Fig. 8 illustrates the comparison between these three protocols under the number of transmission time slots equal

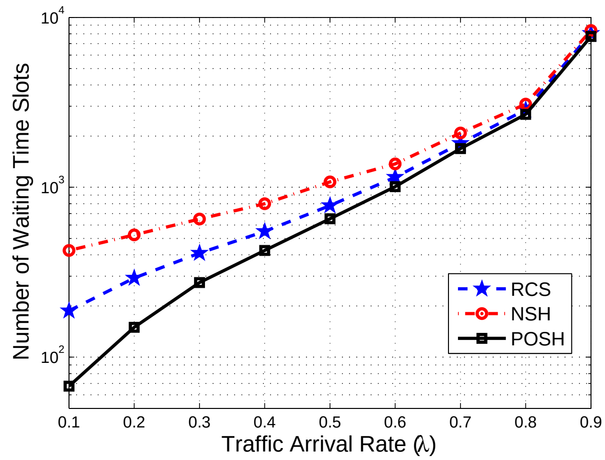

Fig. 7. Performance comparison: number of waiting time slots versus traffic arrival rate of primary user under numbers of spectrum handoff $= 250$.

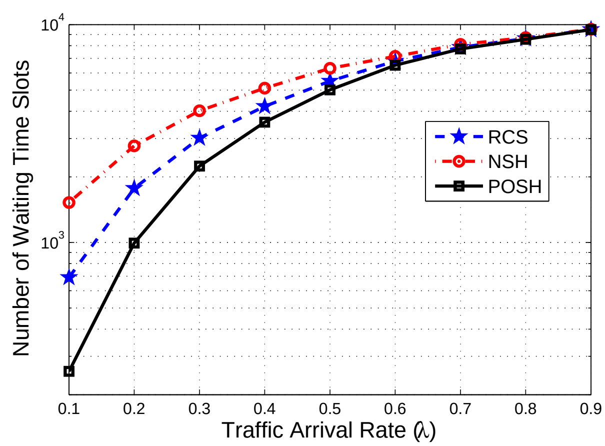

Fig. 8. Performance comparison: number of waiting time slots versus traffic arrival rate of primary user under number of transmission time slots $= 1200$.

to 1200. It can be observed from both figures that the proposed POSH scheme can outperform the other two methods under different packet arrival rates. The benefits from the adoption of proposed POSH algorithm is especially revealed at smaller packet arrival rates since there can be more opportunity for the POSH scheme to select a feasible target channel to conduct spectrum handoff.

Practical consideration for the three handoff schemes are presented as shown in Figs. 9 and 10.

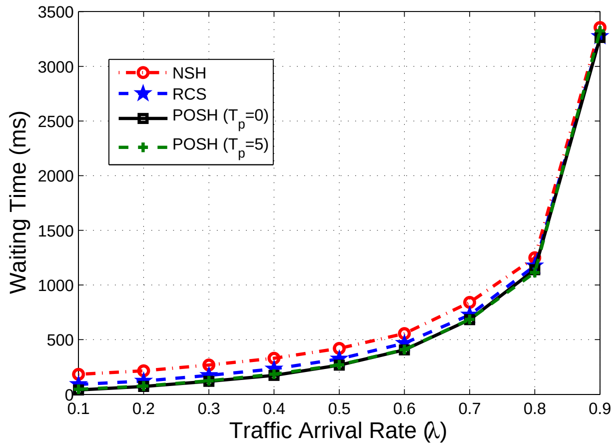

Fig. 9. Performance comparison with practical consideration: waiting time versus traffic arrival rate of primary user.

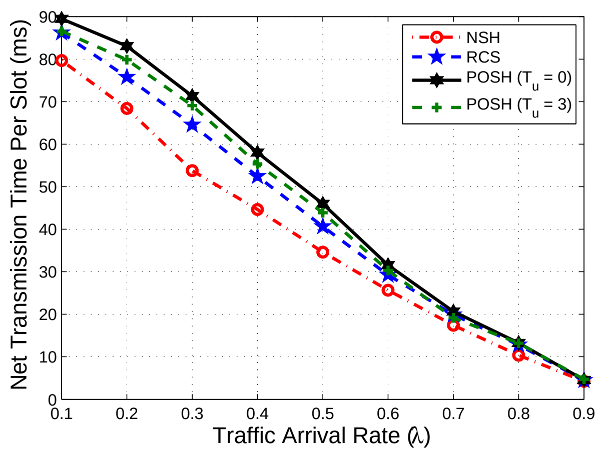

Fig. 10. Performance comparison with practical consideration: net transmission time per slot versus traffic arrival rate of primary user.

The corresponding parameters are listed as follows: $T_{slot} = 100$ ms, $T_{sens} = 5$ ms, $T_{sw} = 10$ ms, $T_{hs} = 1$ ms, and $T_{ack} = 1$ ms. Fig. 9 illustrates the waiting time obtained from (21), (23), and (25) for the NSH, RCS, and POSH scheme respectively. Two cases with required computation time $T_p = 0$ and 5 ms for implementing the POMDP-based policy are considered; while the update time for belief state $T_u = 3$ ms. With practical consideration, the POSH algorithm is demonstrated to result in the smallest waiting time under different packet arrival rate of primary user. Even though the calculation of POMDP-based policy requires additional computation time, the overall performance is still better in comparison with the NSH and RCS methods. Furthermore, it is observed in Fig. 9 that the waiting time $T_{w,posh}$ will only be affected by the computation time T_p if the destination channel of spectrum handoff has high probability to be in the idle state. In other words, T_p will only degrade the performance of proposed POSH scheme at lower packet arrival rate of primary user, and will become uninfluential under higher primary traffic rate. Nevertheless, since the POSH scheme can provide better performance among the three handoff schemes at lower primary traffic (as shown in Figs. 7 and 8), it can be concluded that the degraded effect from T_p will not be significant by adopting the POSH scheme.

In order to better present the utilization of licensed spectrum, Fig. 10 is exploited to illustrate the net transmission time per time slot as was computed from (22), (24), and (26) for the NSH, RCS, and POSH scheme respectively. Two cases with the update time of belief state $T_p = 0$ and 3 ms for the proposed POSH scheme are considered; while the required time for POMDP-based policy $T_p = 5$ ms. It is noticed that the update time T_u is required for the proposed POSH scheme at the end of each time slot; while the computation time for POMDP-based policy T_p will only be utilized as spectrum handoff occurs. It is intuitive to observe that the net transmission time resulted from all the three schemes decreases as the packet arrival rate λ of primary traffic is increased. Furthermore, as λ is incremented, the net transmission time of proposed POSH protocol can become similar to or even worse than that obtained from the RCS and NSH schemes, e.g. the net transmission time acquired from the POSH scheme with $T_u = 3$ ms is worse than that from the RCS protocol as $\lambda > 0.65$. Therefore, practical consideration for these handoff schemes can provide a channel selection criterion for the CR users to determine the feasible handoff scheme to be applied in order to obtain their destination channel for spectrum handoff.

Figs. 11 illustrates the analysis and simulation results of the M-POSH scheme. And the analysis model for expected waiting time slots of M-POSH scheme as presented in (34) is effectual. Figs. 11 shows the performance for the expected waiting time slots versus the traffic arrival rate of primary user under the situation of different number of CR users, i.e. n. It can be observed that the expected number of waiting time slots increases more significantly when the number of CR users is increasing gradually. More CR users means lesser available channels can be utilized while executing spectrum handoff, and more the required waiting time slots.

Figs. 12 and 13 compare the performance of NSH, RCS, and M-POSH protocols under the

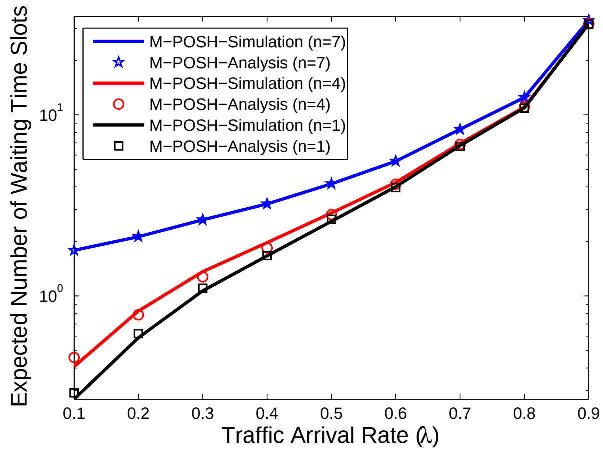

Fig. 11. Performance validation: the expected number of waiting time slots versus traffic arrival rate of primary user.

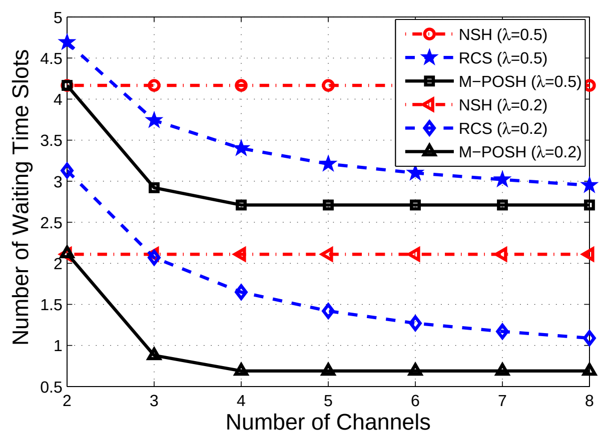

Fig. 12. Performance comparison: number of waiting time slots versus number of channels (with 2 CR users).

circumstance of multiple CR users within multi-channels network. Fig. 12 shows the performance comparison with two CR users under different numbers of available channels; while Fig. 13 illustrates the comparison with 7 channels under different numbers of CR users. The analytical expected waiting time slots of the M-POSH scheme as in (34) is also shown in this figure. Two different arrival rates of primary traffic are considered for all the three schemes, i.e. $\lambda = 0.2$ and 0.5. It is apparently to observe that the NSH scheme results in the same performance under different numbers of channels and CR users since it does not perform any spectrum handoff activity. In other words, the NSH scheme in multi-user scenario can be regarded as the

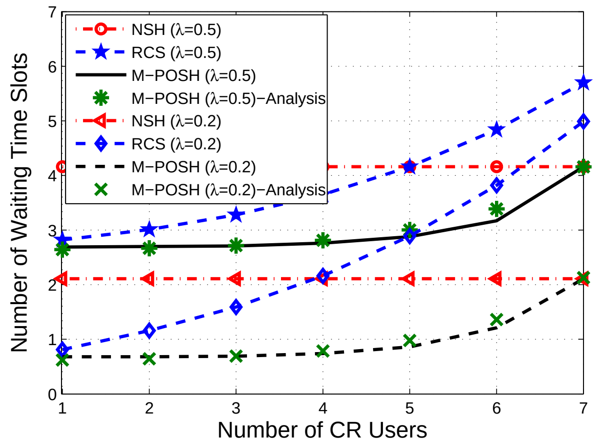

Fig. 13. Performance comparison: number of waiting time slots versus number of CR users (with 7 channels).

combination of single users without mutual interactions. On the other hand, regarding the RCS and M-POSH schemes, the expected number of waiting time slots is decreased as the number of available channels is augmented; while it is increased with the augmentation of total number of CR users due to potential packet collisions happened in the network. The performance of RCS scheme can becomes worse than that from the NSH method under certain circumstances since the NSH scheme at least guarantees that packet collisions will not happen in the network. From example as in Fig. 13, the RCS scheme with $\lambda = 5$ results in higher number of waiting time slots comparing with the NSH method if the number of CR users is greater than 5.

Nevertheless, with the consideration of potential packet collisions between the CR users, the proposed M-POSH protocol can adaptively select the destination channel based on the availability of network channels. As shown in both Figs. 12 and 13, the M-POSH scheme outperforms both the RCS and NSH algorithms under different numbers of channels and CR users. It is also observed from certain end data points of both figures that the M-POSH and the NSH schemes will result in the same number of waiting time slots, i.e. the most left data points in Fig. 12 under number of channels $= 2$ with two CR users, and the most right data points in Fig. 13 under number of CR users $= 7$ with 7 channels. This indicates that if all the network channels are occupied, the CR users will decide to stay at the current channel by adopting the proposed M-POSH protocol in order to reduce the probability of packet collision between the CR users. On the other hand, as long as the network contains more available channels that can be utilized, the M-POSH protocol will distribute the CR users that intend to conduct handoff to exploit those available channels. Consequently, the performance of M-POSH scheme can achieve the optimal performance as that obtained from the POSH scheme for single user case. The merits of the proposed POSH and M-POSH protocols can therefore be observed.

VII. Conclusion

This paper proposes a spectrum handoff strategy based on partially observable Markov decision process (POMDP) in the overlay cognitive radio (CR) networks. With only partially observable state information, the proposed POMDP-based spectrum handoff (POSH) scheme selects the optimal destination channel in order to achieve the minimal waiting time for packet transmission. Furthermore, in order to consider the network with multiple CR users, the multi-user POSH (M-POSH) protocol is proposed to resolve the packet collision problem among multiple CR users that intend to conduct spectrum handoff. It is observed from both the simulation and analytical results that both the proposed POSH and M-POSH protocols can effectively reduce the waiting time of spectrum handoff for a partially observable CR network.

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Analysis and Determination of Cooperative MAC Strategies from Throughput Perspectives

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Abstract

In recent years, cooperative communication has been developed as a new communication strategy that incorporates a relay node to assist direct point-to-point transmission. By exploiting cooperative diversity, different types of techniques have been proposed to improve transmission reliability from the physical layer perspective. However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance network throughput in view of the medium access control (MAC) performance. In this paper, system throughput of combined direct/cooperative communication is evaluated by exploiting the proposed analytical model based on the IEEE 802.11 MAC protocol. The feasibility of adopting either cooperative or direct communication is also studied in the analytical model. In terms of network throughput, whether to adopt cooperative schemes depends on the tradeoff between cooperative transmission delay and channel condition of direct communication. Moreover, two cooperative MAC protocols are proposed to determine the circumstances to activate cooperative communication according to the channel conditions. The full-CSI based cooperative (FCC) MAC protocol is introduced to choose both the transmission scheme and the relay node according to the full channel information. However, the overhead caused by the FCC scheme can degrade the throughput performance as the number of available relays is significantly increased. Therefore, the bitwise competition based cooperative (BCC) MAC protocol is utilized to efficiently determine a feasible relay node for data transmission. Simulations are performed to validate the effectiveness of proposed analytical models and cooperative MAC protocols. It is observed that the proposed BCC scheme can outperform both the FCC protocol and conventional direct transmission with enhanced system throughput.

Keywords: Cooperative communication, performance analysis, IEEE 802.11 standard, medium access control, relay selection.

I. Introduction

Due to the unreliable environment for wireless communication, different types of transmission schemes have been developed to maintain the quality of communication. Multi-input multi-output (MIMO) systems are introduced to achieve high capacity by taking advantages of multipath channels and spatial diversity. However, multi-antenna system equipped within mobile devices may not be easily deployed due to the limitation of its physical size. Recently, techniques for cooperative communications are proposed to effectively enhance the diversity gain and robustness based on the broadcast nature of wireless communication. Through the help of relays in the network, the virtual antenna array can be formed in order to increase the transmission reliability. In other words, data communication between the source and the destination is captured by the relay, which duplicates the frame and consequently delivers it to the destination. In order to acquire diversity gain, the duplicated frames are received and combined at the destination by exploiting different methods, e.g. the maximum ratio combining (MRC) algorithm. Moreover, the amplify-and-forward (AF) and decode-and-forward (DF) proposed in [1] are the two commonly used schemes in cooperative communications. In the AF scheme, the relay simply amplifies and forwards the frames that are acquired from the source; while the relay forwards the received frames to the destination after decoding them correctly in the DF scheme.

Research work have been conducted to explore the cooperative communications from various aspects. The analysis of cooperative diversity by adopting different cooperative schemes has been investigated in [2]–[4]; while [5] develops several cooperative strategies and calculates the resulting capacity. The work presented in [6]–[8] also delivers the cooperative schemes from the physical (PHY) layer perspectives. The symbol-error-rate performance analysis and optimum power allocation are provided in [6] and [7] with different modulation types. Variable-rate two-phase collaborative communication scheme is proposed in [8] which also provides performance analysis of outage probability. Moreover, the performance of cooperative communication can further be improved with the utilization of coding strategy as shown in [9], [10]. With the consideration of fading channels, distributed space-time coding schemes and their associated performance analysis are introduced in [11]–[13]. Furthermore, cooperative automatic repeat request (ARQ) techniques in [14]–[16] exploit the cooperative diversity to achieve efficient retransmission; while [17] provides the analysis of frame error rate (FER) under various cooperative ARQ protocols.

However, it is noticeable that most of the research work focuses on cooperative communications from the viewpoint of information theory and PHY layer design. Although the FER can be ameliorated by means of the cooperative diversity, there is no assurance to result in enhanced network throughput due to the tradeoff between the FER and the longer frame transmission time. In general, the cooperative schemes will lead to prolonged frame transmission time no matter the AF-based or the DF-based protocols are applied. With the adoption of half-duplex antennas, two phases are required for relay-based communication in order to complete the data transmission. In other words, data frame must be delivered from the source to both the destination and the relay with duplicated frame transmitted from the relay to the destination.

In order to evaluate the combined system including the conventional direct transmission and the cooperative communication in terms of network throughput, a suitable analytical model from the medium access control (MAC) perspective should be exploited. The IEEE 802.11 [18] has been considered a well-adopted standard for wireless local area networks (LANs). In the IEEE 802.11 MAC protocol, the distributed coordination function (DCF) is utilized as the basic mechanism for channel access. The DCF ensures that each node can acquire a fair opportunity to access the wireless medium according to the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme. A random backoff process is executed in each node for the purpose of decreasing the probability of data collision. Moreover, the request-to-send (RTS)/ clear-to-send (CTS) exchange before the data transmission is employed in order to resolve the potential hidden terminal problem. A great amount of existing research [19]–[21] contributes to the establishment of analytical models for the IEEE 802.11 MAC protocol. The saturation throughput of IEEE 802.11 DCF is obtained via a two-dimensional Markov chain model as proposed in [19]. Work presented in [20], [21] further considers channel error conditions into the design of analytical models.

In this paper, the backoff model of IEEE 802.11 MAC extended from [19], [20] is adopted to analyze the saturation throughput of cooperative techniques. Both cooperative and direct communications are considered in the design of the proposed analytical model. Simulations are also exploited for validating the effectiveness of proposed model. It can be observed from the analytical results that the performance of cooperative communication is affected by various factors, especially the FER and the frame transmission delay. Cooperative schemes in general result in decreased FER; while the rerouting delay incurred by the cooperative process can considerably degrade the network throughput. The feasible circumstances to adopt the cooperative algorithms is suggested in this paper by considering the tradeoff between the FER and the transmission delay for the enhancement of network throughput.

Furthermore, it is important to provide feasible determination mechanisms to choose an appropriate relay for cooperative communication while there are more than one available relay in the network. The CoopMAC protocol proposed in [22] provides cooperation from mobile stations with higher data rate to assist the other stations with lower data rate during data transmission. The relay selection scheme in CoopMAC protocol is merely based on the observations from previous data transmissions. Moreover, the CD-MAC [23] and CMAC [24] protocols are developed to proactively and randomly select the feasible relays respectively. However, the determination schemes within these cooperative MAC protocols can result in degraded performance under fast-changing channel conditions. There are research works such as [25]–[27] that focused on the topic of relay selection according to the network channel conditions. Energy issue is further considered in [28] in order to balance the power consumption of mobile users. Game theory is also exploited in [29] to provide a theoretical infrastructure for relay selection. However, most of these existing techniques for relay selection only considers the channel conditions instead of throughput performance, which will result in decreased throughput performance in spite of possible improvement of FER. In other words, a suitable design of MAC protocol by considering both the FER and the transmission time is necessitate for increasing the network throughput in cooperative communication.

Therefore, based on all the issues mentioned above, two MAC protocols are proposed in this paper to provide the determination mechanisms to activate the cooperative communication after acquiring the instantaneous channel state information (CSI). In the full CSI based cooperative (FCC) MAC protocol, the destination node will select a feasible relay based on the acquisition of all the channel information. On the other hand, in order to decrease the excessive exchanges of control frames, the bitwise competition based cooperative (BCC) MAC protocol is proposed to choose an appropriate relay after acquiring the channel information between the source and relay nodes. The channel states between the potential relay nodes are contended based on bit-by-bit manner in order to select the feasible node to conduct packet forwarding to the destination. Even though only partial CSI information is obtained by the proposed BCC protocol, the resulting throughput performance can still be increased with reduced control overhead. Based on the

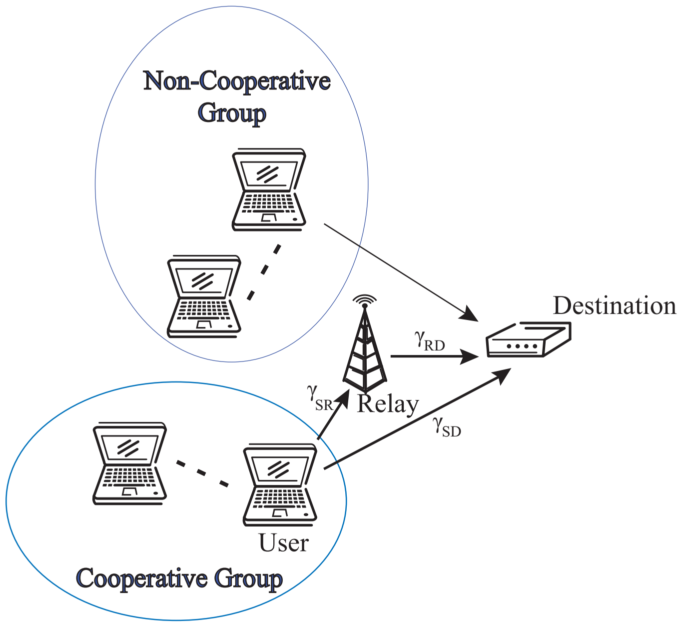

Fig. 1. Network scenario with the combined direct/cooperative transmission scheme.

simulation results, it is discovered that both proposed FCC and BCC protocols can significantly enhance the network throughput, especially in the case that the direct communicating channel is under deep fading environments.

The rest of this paper is organized as follows. The modeling of backoff operations with combined direct/cooperative strategy is presented in Section II. Section III describes the analytical modeling and validation for the saturation throughput based on the combined strategy. Section IV explains the proposed FCC and BCC MAC protocols for relay selection; while numerical evaluation is performed in Section V. Section VI draws the conclusions.

II. Markovian Model with Combined Direct/Cooperative Strategy

As shown in Fig. 1, the network scenario considered in the performance analysis consists of one destination, one fixed relay, and N user nodes. In general, the destination node can be regarded as an access point for uplink data transmission. In this paper, instead of assigning mobile devices to serve as the relays for frame transmission, one fixed relay node is considered and exploited. The major reason is primarily owing to the excessive power consumption that will be incurred within the mobile devices while relaying data frames for other network nodes. Furthermore, security issues and potential unknown movements are also concerned to adopt mobile devices for data forwarding. In addition, the users in the network can be adaptively categorized into

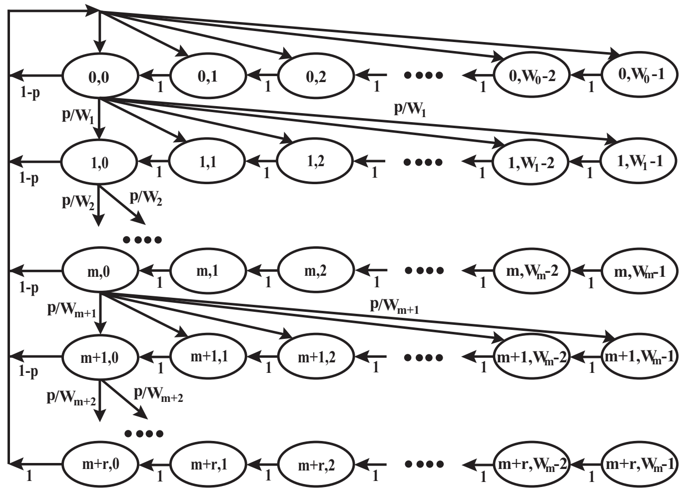

Fig. 2. Markov chain model for the backoff mechanism with the combined direct/cooperative strategy.

non-cooperative and cooperative groups depending on the transmission requirements. The users in non-cooperative group transmit data frames based on conventional direct transmissions; while those in cooperative group transmit their data frames via the assistance of relay node. The total number of nodes in the non-cooperative and cooperative groups are denoted as N_{dir} and N_{coop}, respectively. It is noted that DF cooperative communication is adopted in the analysis. That is, the source transmits the data frame to both the relay and destination in phase I. In phase II, the relay forwards the received data frame to the destination if the data is correctly decoded by the relay. Finally, the MRC method is utilized by the destination to combine the data frames from both the source and relay. Moreover, the channels between these network nodes are modeled as independent, flat Rayleigh fading, and zero-mean additive white Gaussian noise with unit variance. Each node is equipped with a single antenna where half-duplex transmission is assumed, i.e. simultaneously transmitting and receiving data frames is not considered. The parameters γ_{SD}, γ_{SR}, and γ_{RD} as illustrated in Fig. 1 denote the instantaneous received signal-to-noise ratio (SNR) of the source-destination link, the source-relay link, and the relay-destination link respectively. Their corresponding average received SNR values are represented as σ_{SD}, σ_{SR}, and σ_{RD}.

In order to evaluate the throughput performance of the system which adopts both the direct and cooperative strategies, the conventional model for backoff mechanism is adjusted to incorporate both the direct and cooperative schemes. The Markov chain model of the backoff mechanism is shown in Fig. 2. The backoff operation $(s(t), b(t))$ consists of two stochastic processes, where

$s(t) \in [0, m+r]$ indicates the backoff stage with the maximum $m+r$ times of retransmission opportunities, and $b(t) \in [0, W_i]$ denotes the backoff timer whose maximum value at the ith stage can be represented as

$$W_i = \begin{cases} 2^i \cdot W & 0 \leq i \leq m \\ 2^m \cdot W & m < i \leq m+r \end{cases} \tag{1}$$

where W denotes the minimum contention window size. The parameter p as shown in Fig. 2 represents the probability of receiving an inaccurate frame at the destination. The unsuccessful reception of data frames at the destination is resulted from either the frame collision or transmission error. It is noticed that the meaning of parameter p within the Markov chain model can be different in each node depending on which group it belongs to. The parameters p_{dir} and p_{coop} are introduced as the probabilities of receiving an inaccurate frame at the destination via the direct and cooperative transmission, respectively. Specifically, owing to different FER values caused by different transmission schemes, the parameter p will be replaced by p_{dir} in the Markov chain model for nodes in the non-cooperative group. On the other hand, p_{coop} will substitute the parameter p with nodes in the cooperative group. For simplicity, the parameter p will still be utilized in some of the following derivations in the case that both groups share the same equations.

Furthermore, the transition probabilities, which are defined as $P_t(i_1, k_1 \mid i_0, k_0) \triangleq P_t(s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0)$, can be obtained as

$$\begin{cases} P_t(i, k \mid i, k+1) = 1 & k \in [0, W_i - 2], i \in [0, m+r] \\ P_t(i, k \mid i-1, 0) = \frac{p}{W_i} & k \in [0, W_i - 1], i \in [1, m+r] \\ P_t(0, k \mid i, 0) = \frac{1-p}{W_0} & k \in [0, W_0 - 1], i \in [0, m+r-1] \\ P_t(0, k \mid m+r, 0) = \frac{1}{W_0} & k \in [0, W_0 - 1] \end{cases} \tag{2}$$

Let $\pi_{i,k} \triangleq \lim_{t \to \infty} P_t(s(t) = i, b(t) = k)$ be defined as the stationary probability with $i \in [0, m+r]$ and $k \in [0, W_i - 1]$, the stationary probabilities can be correlated to $\pi_{0,0}$ as follows:

$$\begin{cases} \pi_{i,k} = \frac{W_i - k}{W_i} \cdot \pi_{i,0} & k \in [0, W_i - 1], i \in [0, m+r] \\ \pi_{i,0} = p^i \cdot \pi_{0,0} & i \in [0, m+r] \end{cases} \tag{3}$$

Consequently, based on $\sum_{i=0}^{m+r} \sum_{k=0}^{W_i - 1} \pi_{i,k} = 1$, the stationary probability $\pi_{0,0}$ can be obtained as

$$\pi_{0,0} = \left[\sum_{i=0}^{m} p^i w_i + \sum_{i=m+1}^{m+r} p^i w_m \right]^{-1} \tag{4}$$

where $w_i = (W_i + 1)/2$ and $w_m = (W_m + 1)/2$. The characteristics of proposed Markov chain model with combined strategy can be illustrated via (2)-(4) after p, i.e. p_{dir} and p_{coop}, can be obtained. The determination of these two probabilities is explained as follows.

The probabilities that a node in the non-cooperative and cooperative group transmit within a randomly selected time slot, i.e. the conditional transmission probabilities τ_{dir} and τ_{coop}, can be respectively expressed as

$$\tau_{dir} = \sum_{i=0}^{m+r} \pi_{i,0} = \pi_{0,0} \left(\frac{1 - p_{dir}^{m+r+1}}{1 - p_{dir}} \right) \tag{5}$$

$$\tau_{coop} = \sum_{i=0}^{m+r} \pi_{i,0} = \pi_{0,0} \left(\frac{1 - p_{coop}^{m+r+1}}{1 - p_{coop}} \right) \tag{6}$$

Let $\overline{P}_{f(dir)}$ and $\overline{P}_{f(coop)}$ denote the average FER resulted from transmission error through the direct and the cooperative transmission respectively. The following relationships can be obtained:

$$p_{dir} = 1 - (1 - \overline{P}_{f(dir)})(1 - p_c) \tag{7}$$

$$p_{coop} = 1 - (1 - \overline{P}_{f(coop)})(1 - p_c) \tag{8}$$

where the collision probability p_c in (7) and (8) is acquired as

$$p_c = 1 - [\mathcal{R}_{cg}(1 - \tau_{coop})^{N_{coop}-1}(1 - \tau_{dir})^{N_{dir}} + (1 - \mathcal{R}_{cg})(1 - \tau_{coop})^{N_{coop}}(1 - \tau_{dir})^{N_{dir}-1}] \tag{9}$$

with $\mathcal{R}_{cg}$ denoting the ratio of the node number in cooperative group to the total number of interfering neighbors, i.e. $\mathcal{R}_{cg} = N_{coop}/N$. Therefore, it can be observed that both p_{dir} and p_{coop} are functions of the conditional transmission probabilities τ_{dir} and τ_{coop}. On the other hand, by substituting (4) into (5) and (6), the probabilities τ_{dir} and τ_{coop} can be represented as a function of p_{dir} and p_{coop} respectively. As a result, the values of p_{dir}, p_{coop}, τ_{dir}, and τ_{coop} can be acquired through numerically solving the nonlinear equations from (5) to (8).

III. Throughput Analysis for Direct/Cooperative Schemes

The saturation throughput based on the Markovian model as proposed in Section II will be analyzed and compared. The feasible occasion to adopt either the direct or the cooperative scheme will be explored under different channel conditions. In the first subsection, the FER values are calculated for both direct and cooperative strategies. The saturation throughput analysis is described in the second subsection; while the performance comparisons are conducted in the third subsection. In order to effectively enhance the system performance, the results obtained from throughput analysis will be utilized in the design of feasible cooperative MAC protocols, which will be described in Section IV.

A. FER Calculation for Direct/Cooperative Transmissions

In this subsection, the average FER values through both the direct and cooperative links, i.e. $\overline{P}_{f(dir)}$ and $\overline{P}_{f(coop)}$, will be obtained from the average SNR values via their corresponding channel conditions. The derivations from instantaneous SNR to its resulting FER value has been studied in [6], [30], [31]. Several influential factors are considered within their formulation, including the modulation type, coding strategy, channel condition, and frame sizes. In order to facilitate the derivation of throughput performance in the next subsection, an efficient model as proposed in [31] is utilized by adopting an exponential relationship between the instantaneous FER $P_{f,ij}$ and SNR value γ_{ij} as

$$P_{f,ij} = \begin{cases} \alpha \cdot e^{-g\gamma_{ij}}, & \gamma_{ij} > \gamma_t \\ 1, & \gamma_{ij} \leq \gamma_t \end{cases} \tag{10}$$

where the subscript ij within the parameters represents the channel from node i to node j. For example, as shown in Fig. 1, γ_{SD} indicates the instantaneous received SNR of the source-destination link associated with its corresponding instantaneous FER value $P_{f,SD}$. Depending on different modulation and coding schemes, the parameters α, g, and the threshold γ_t within (10) can be obtained from the least-square fitting method as shown in [31]. Simply stated, the instantaneous FER $P_{f,ij}$ can be derived from the exponential function if the received SNR γ_{ij} exceeds the threshold γ_t; otherwise, $P_{f,ij}$ is set to be 1. Moreover, due to the exponential distribution of received SNR for Rayleigh fading channel, the probability distribution function (pdf) of received SNR γ_{ij} can be acquired as

$$f_{\Gamma_{ij}}(\gamma_{ij}) = \frac{1}{\sigma_{ij}} e^{-\gamma_{ij}/\sigma_{ij}} \tag{11}$$

where σ_{ij} corresponds to the average received SNR of the channel from node i to node j, i.e. $\sigma_{ij} \triangleq E[\gamma_{ij}]$.

The average FER via conventional direct transmission, i.e. $\overline{P}_{f(dir)}$, can be derived by calculating the average FER of the source-destination channel $\overline{P}_{f,SD}$. By considering the relationship between instantaneous and average FER values over the channel realizations, the average FER $\overline{P}_{f(dir)}$ from direct link can be obtained as

$$\begin{aligned} \overline{P}_{f(dir)} = \overline{P}_{f,SD} &= \int_0^\infty P_{f,SD} \cdot f_{\Gamma_{SD}}(\gamma_{SD}) d\gamma_{SD} \\ &= \int_0^{\gamma_t} 1 \cdot \frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}} d\gamma_{SD} + \int_{\gamma_t}^\infty \alpha e^{-g\gamma_{SD}} \cdot \frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}} d\gamma_{SD} \\ &= 1 - \frac{g\sigma_{SD}}{1 + g\sigma_{SD}} e^{-\gamma_t/\sigma_{SD}} \end{aligned} \tag{12}$$

where $f_{\Gamma_{SD}}(\gamma_{SD})$ and σ_{SD} are obtained as defined in (11). On the other hand, due to the utilization of DF scheme in cooperative communication, whether the relay can correctly decode the received data frame or not is required to be considered in the derivation of $\overline{P}_{f(coop)}$. In other words, if the relay correctly decodes the received data frame, the destination can combine two copies of data frame from both the source and relay nodes. Otherwise, only one copy of the data frame will be received at the destination. Therefore, the FER value $\overline{P}_{f(coop)}$ by adopting the cooperative scheme is obtained as

$$\overline{P}_{f(coop)} = (1 - \overline{P}_{f,SR}) \cdot \overline{P}_{f,(SR)D} + \overline{P}_{f,SR} \cdot \overline{P}_{f,SD} \tag{13}$$

where $\overline{P}_{f,SD}$ can be acquired from (12). $\overline{P}_{f,SR}$ represents the average FER from the source to the relay and is obtained similar to $\overline{P}_{f,SD}$ as

$$\overline{P}_{f,SR} = 1 - \frac{g\sigma_{SR}}{1 + g\sigma_{SR}} e^{-\gamma_t/\sigma_{SR}} \tag{14}$$

Furthermore, $\overline{P}_{f,(SR)D}$ in (13) represents the average FER at the destination after combining data frames from both the source and relay. The calculation of $\overline{P}_{f,(SR)D}$ can be acquired with the consideration of both source-destination and relay-destination channels as

$$\begin{aligned}
\overline{P}_{f,(SR)D} &= \int_0^\infty \int_0^\infty P_{f,(SR)D} \cdot f_{\Gamma_{SD}}(\gamma_{SD}) f_{\Gamma_{RD}}(\gamma_{RD}) d\gamma_{SD} d\gamma_{RD} \\
&= \int_0^{\gamma_t} \int_0^{\gamma_t - \gamma_{RD}} 1 \cdot (\frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}})(\frac{1}{\sigma_{RD}} e^{-\gamma_{RD}/\sigma_{RD}}) d\gamma_{SD} d\gamma_{RD} \\
&+ \int_0^{\gamma_t} \int_{\gamma_t - \gamma_{RD}}^\infty \alpha e^{-g(\gamma_{SD}+\gamma_{RD})} \cdot (\frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}})(\frac{1}{\sigma_{RD}} e^{-\gamma_{RD}/\sigma_{RD}}) d\gamma_{SD} d\gamma_{RD} \\
&+ \int_{\gamma_t}^\infty \int_0^\infty \alpha e^{-g(\gamma_{SD}+\gamma_{RD})} \cdot (\frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}})(\frac{1}{\sigma_{RD}} e^{-\gamma_{RD}/\sigma_{RD}}) d\gamma_{SD} d\gamma_{RD} \\
&= 1 - \left[\frac{\sigma_{RD}}{\sigma_{RD} - \sigma_{SD}} \frac{g\sigma_{RD}}{1 + g\sigma_{RD}} e^{-\gamma_t/\sigma_{RD}} - \frac{\sigma_{SD}}{\sigma_{RD} - \sigma_{SD}} \frac{g\sigma_{SD}}{1 + g\sigma_{SD}} e^{-\gamma_t/\sigma_{SD}} \right]
\end{aligned} \tag{15}$$

where $P_{f,(SR)D}$ is the instantaneous FER at the destination after DF combination. It is noted that the benefit of adopting exponential relationship between the FER and its corresponding SNR as in [31] can be observed. With the knowledge of both channel conditions and estimated parameters α, g, and γ_t, the average FER $\overline{P}_{f(coop)}$ through cooperative communication can therefore be derived as in (13). The results obtained above will be utilized to measure the suitability of cooperative communication compared to the direct transmission under different channel conditions.

B. Saturation Throughput Analysis

The purpose of this subsection is to obtain the relationship between the SNR values and the corresponding network throughput based on the results obtained from the previous subsection.

For the derivation of throughput performance, a contention-based MAC protocol with cooperative communications is adopted. It is designed based on the IEEE 802.11 CSMA/CA scheme [19] associated with the usage of RTS/CTS exchanges. For the purpose of informing network nodes regarding the activation of cooperative communication, two new control frames named cooperative ready-to-send (cRTS) and cooperative clear-to-send (cCTS) are created. It is noted that the cRTS and cCTS fames have the same structures as the RTS and CTS frames respectively except for the subtype field of MAC header. In other words, several reserved values of the subtype field in IEEE 802.11 standard can be utilized to create these new control frames for representing different control messages. Moreover, the channel will be secured to be collision-free after the exchanges of either the RTS/CTS frames or the cRTS/cCTS frames. Specifically, nodes in the cooperative group first initiate the cRTS frame in order to notify the other nodes for data delivery via cooperative communication. The cooperative communication will therefore be activated if the cCTS frame is issued by the corresponding destination. Subsequently, the source will transmit the data frame in the first phase to both the relay and the destination. The relay will forward the received data frame to the destination after a short inter-frame space (SIFS) duration, which completes the second phase of the cooperative scheme. On the other hand, nodes in the non-cooperative group will transmit their data frame based on the conventional RTS/CTS exchange for channel reservation. Due to the comparably smaller size to the data frames, the frame error of non-data frames is considered neglected. It is noticed that the scheme mentioned above will be utilized as a preliminary evaluation of saturated network throughput in the next subsection. Other contention-based MAC protocol with cooperative diversity can also be designed and analyzed in similar manner.

The saturation throughput is defined as the fraction of time utilized to successfully transmit the payloads. In order to facilitate the computation of network throughput, two associated probabilities p_{tr} and p_{wc} are introduced as follows. The parameter p_{tr} denotes the probability that at least one transmission occurs in the considered time slot, i.e.

$$p_{tr} = 1 - (1 - \tau_{coop})^{N_{coop}} (1 - \tau_{dir})^{N_{dir}} \tag{16}$$

Moreover, p_{wc} indicates the probability of a non-collided transmission on the condition that at least one node is transmitting. It is composed by two probabilities $p_{wc(cg)}$ and $p_{wc(ncg)}$, i.e. $p_{wc} = p_{wc(cg)} + p_{wc(ncg)}$. The parameter $p_{wc(cg)}$ represents one node in the cooperative group reserves the channel while the other nodes remain silent during the time slot, i.e. no collision occurs. On the other hand, $p_{wc(ncg)}$ represents that one node in the non-cooperative group successfully reserves the channel and transmits its data frames. These two probabilities can be obtained as

$$p_{wc(cg)} = \frac{N}{p_{tr}}[\mathcal{R}_{cg}\tau_{coop}(1-\tau_{coop})^{N_{coop}-1}(1-\tau_{dir})^{N_{dir}}] \quad (17)$$

$$p_{wc(ncg)} = \frac{N}{p_{tr}}[(1-\mathcal{R}_{cg})\tau_{dir}(1-\tau_{dir})^{N_{dir}-1}(1-\tau_{coop})^{N_{coop}}] \quad (18)$$

Furthermore, the saturation throughput S, which is defined as a function of $\mathcal{R}_{cg}$, $\overline{P}_{f(dir)}$, and $\overline{P}_{f(coop)}$, can be expressed as

$$S(\mathcal{R}_{cg}, \overline{P}_{f(dir)}, \overline{P}_{f(coop)}) = \frac{E[L_P]}{E[T_B]+E[T_S]+E[T_C]+E[T_E]} \quad (19)$$

The expected values within (19) are obtained as follows. $E[T_B] = (1-p_{tr})\delta$ indicates the average duration of non-frozen backoff time in a virtual time slot. It is noted that the virtual time slot represents the time duration between two consecutive backoff timers. The parameter δ is defined as the size of one slot time specified in the physical layer of IEEE 802.11 standard. The average duration of successful transmission in a virtual time slot is acquired as

$$E[T_S] = p_{tr}[p_{wc(cg)}(1-\overline{P}_{f(coop)})T_{s(coop)} + p_{wc(ncg)}(1-\overline{P}_{f(dir)})T_{s(dir)}] \quad (20)$$

where $T_{s(dir)}$ and $T_{s(coop)}$ are the required time intervals for a successful transmission via the direct and the cooperative communications respectively. These two parameters are obtained as

$$T_{s(dir)} = T_{RTS}+T_{CTS}+T_{Header}+T_{Payload}+T_{ACK}+3T_{SIFS}+4\rho+T_{DIFS} \quad (21)$$

$$T_{s(coop)} = T_{cRTS}+T_{cCTS}+2T_{Header}+2T_{Payload}+T_{ACK}+4T_{SIFS}+5\rho+T_{DIFS} \quad (22)$$

where ρ is denoted as the propagation delay. It is noted that the meanings of the other parameters are revealed by their corresponding subscripts, e.g. T_{Header} indicates the time interval for transmitting the header in a frame, and T_{DIFS} corresponds to the time duration of a distributed inter-frame space (DIFS). Moreover, $E[T_C]$ represents the average time duration for transmissions with collisions in a virtual time slot. The mean duration of a failure transmission caused by the channel fading and noises is denoted as $E[T_E]$. Both $E[T_C]$ and $E[T_E]$ are obtained as

$$E[T_C] = p_{tr}(1-p_{wc})T_c \quad (23)$$

$$E[T_E] = p_{tr}[p_{wc(cg)}\overline{P}_{f(coop)}T_{e(coop)} + p_{wc(ncg)}\overline{P}_{f(dir)}T_{e(dir)}] \quad (24)$$

where T_c denotes the time interval for the transmissions with the occurrence of frame collisions, i.e. $T_c = T_{RTS}+\rho+T_{DIFS}$. On the other hand, the parameters $T_{e(dir)}$ and $T_{e(coop)}$ are the required time durations to receive and detect the error frame caused from the channel fading and noises. Both values are considered the same as that for successful transmissions, i.e. $T_{e(dir)} = T_{s(dir)}$

and $T_{e(coop)} = T_{s(coop)}$. Finally, the parameter $E[L_P]$ represents the average payload bits that are successfully transmitted in a virtual time slot, which can be acquired as

$$E[L_P] = p_{tr}\{p_{wc(cg)}(1-\overline{P}_{f(coop)})E[L_{Payload}] + p_{wc(ncg)}(1-\overline{P}_{f(dir)})E[L_{Payload}]\} \tag{25}$$

where $E[L_{Payload}]$ indicates the average number of payload bits in a data frame. The saturation throughput S as defined in (19) can therefore be obtained. Moreover, two special cases for the saturation throughput S are considered as follows. S_{dir} represents the saturation throughput if all the nodes are in the non-cooperative group; while S_{coop} indicates that with the exploitation of cooperative schemes for the entire system, i.e. all the nodes are in the cooperative group. These two special cases can be defined as

$$S_{dir} \triangleq S(\mathcal{R}_{cg} = 0, \overline{P}_{f(dir)}, \overline{P}_{f(coop)} = 0) \tag{26}$$

$$S_{coop} \triangleq S(\mathcal{R}_{cg} = 1, \overline{P}_{f(dir)} = 0, \overline{P}_{f(coop)}) \tag{27}$$

Whether it is suitable to adopt the cooperative schemes can be intuitively observed from the two extreme cases as described in (26) and (27). In general, cooperative protocols can improve the FER with the cooperation of the relay node, i.e. $\overline{P}_{f(coop)} < \overline{P}_{f(dir)}$. However, successful transmission time via the cooperative link is inherently longer than that from the original direct communication, i.e. $T_{s(coop)} > T_{s(dir)}$. Due to the tradeoff between the FER and the required transmission time, there is no guarantee that the saturation throughput from the cooperative communication (S_{coop}) will be higher than that from the direct link (S_{dir}). The analytical models derived in this subsection will be utilized to determine the suitable occasions to exploit the cooperative communication, as will be presented in the next subsection.

C. Throughput Comparison between Direct and Cooperative Communications

Before describing the details of proposed cooperative MAC protocols in Section IV, preliminary analytical results will be observed and validated via simulations in this subsection. From the throughput perspective, the feasible situations to adopt either the cooperative or the conventional direct communication will be discussed. The saturation throughput $S(\mathcal{R}_{cg}, \overline{P}_{f(dir)}, \overline{P}_{f(coop)})$ as defined in (19) can be obtained according to the average FER values computed via respective direct (i.e. from (12)) and cooperative links (i.e. from (13)). In order to validate the analytical model, the network scenario adopted in the simulations includes 30 user nodes with a fixed relay and a destination node. Table I illustrates the relevant parameters that are utilized in the analysis and simulations. Notice that the parameters α, g, and γ_t in Table I can be obtained

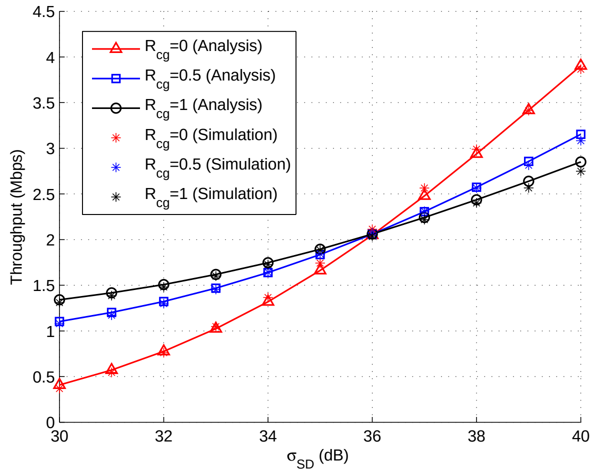

Fig. 3. Throughput Performance versus the channel quality of direct link σ_{SD} under various values of $\mathcal{R}_{cg}$.

based on the least-squire fitting method from [31] while the QPSK modulation is adopted. The other parameters are acquired from the IEEE 802.11a standard.

Table I : System Parameters

Approximation Parameter (α)	1.07439
Approximation Parameter (g)	0.000112484
SNR Threshold (γ_t)	28.0477 dB
Number of Nodes (N)	30
Minimum Window Size (W)	32
Maximum Backoff Stage (m)	5
Maximum Retry Limit (r)	2
MAC Header	224 bits
PHY Header	192 bits
cRTS/RTS	(160+PHY Header) bits
cCTS/CTS	(112+PHY Header) bits
ACK	(112+PHY Header) bits
Payload	8184 bits
Basic Rate	6 Mbps
Data Rate	12 Mbps
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs
Propagation Delay	1 μs

Fig. 3 shows the throughput performance and validation under different values of average SNR σ_{SD} from the source-destination link and the ratio $\mathcal{R}_{cg}$. It is noted that the saturation throughput S is obtained from (19) under pre-defined channel conditions of the source-relay and relay-destination links, i.e. $\sigma_{SD} = \sigma_{RD} = 40$ dB. Within the total of 30 network nodes, the numbers of nodes in the cooperative group are selected as 0, 15, and 30 which result in $\mathcal{R}_{cg} = 0$, 0.5, and 1. In other words, there are $\mathcal{R}_{cg}$ ratio of nodes in the network conducting their packet transmission based on cooperative manner. As shown in Fig. 3. there exists a crossing point around 36 dB of σ_{SD} that illustrates the decision point regarding the feasible situation to activate the cooperative communication. With a larger number of nodes in the cooperative group, e.g. the curve with $\mathcal{R}_{cg} = 1$, degraded throughput performance is observed as the average SNR of source-destination link σ_{SD} is larger than 36 dB. Therefore, direct transmission should be adopted under comparably better channel conditions between the source and destination since the exploration of cooperative communication will result in prolonged transmission time, which causes degraded effect on the throughput performance. Nevertheless, under a worse channel condition for direct link, i.e. below 36 dB in this case, the usage of cooperative communication will significantly improve the resulting throughput performance.

In addition, since coding schemes are not exploited in the derived analytical model, the average SNR σ_{SD} shown in Fig. 3 will be in general overestimated. In other words, the required SNR σ_{SD} for achieving the same throughput will be reduced while a specific coding strategy is adopted. Therefore, similar trend as in Fig. 3 can also be derived with the exploitation of a specific coding scheme. Furthermore, it can be observed from Fig. 3 that the results obtained from both simulations and analytical model coincide with each other under different SNR values of σ_{SD}. Noted that the slight discrepancies at higher σ_{SD} values are mainly contributed to the usage of approximated FER calculation presented in Subsection III-A. Since the exponential function as in (10) results in faster decay in FER than that in realistic cases as the SNR values are increased, the throughput acquired from analytical model will possess slightly larger value than that from simulations under higher values of σ_{SD} as shown in Fig. 3. However, this negligible modeling difference does not deteriorate the advantage of exploiting the exponential FER approximation due to its simplicity and efficiency.

A closer examination on the dependency between the ratio $\mathcal{R}_{cg}$ and the throughput performance is provided in Fig. 4. It illustrates the saturation throughput achieved by the combined direct/cooperative communication system, which includes several nodes conducting direct transmission while others transmit their packets via cooperative communication. The left plot shows the case with worse direct channel quality, i.e. $\sigma_{SD} = 35$ dB; while better channel condition is

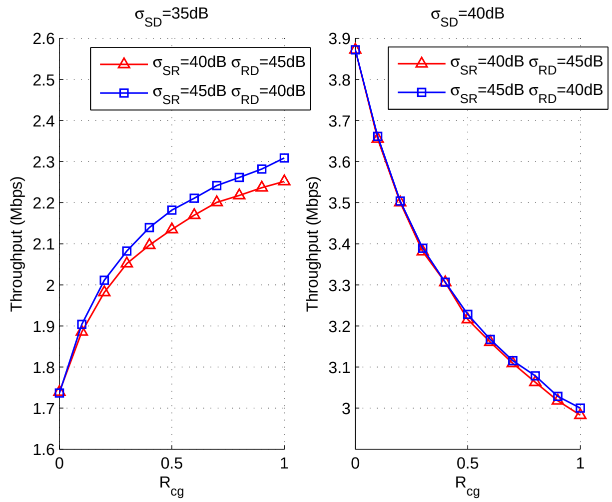

Fig. 4. Throughput performance versus different values of the ratio $\mathcal{R}_{cg}$ (left plot: worse direct channel quality $\sigma_{SD} = 35$ dB; right plot: better direct channel quality $\sigma_{SD} = 40$ dB).

illustrated in the right plot, i.e. $\sigma_{SD} = 40$ dB. As shown in the left plot of Fig. 4, it can be observed that more nodes in the cooperative group, i.e. with larger $\mathcal{R}_{cg}$ value, will increase the throughput performance under worse direct channel conditions. Conversely, the throughput performance will be significantly degraded as the ratio $\mathcal{R}_{cg}$ is increased when the quality of source-destination channel improves as can be seen from the right plot of Fig. 4. Specifically, as the channel quality of direct link is good enough, transmissions from the source directly to the destination is considered a better choice since the decreased FER resulted from cooperative communication may not be significant. On the other hand, the prolonged transmission time induced by the cooperative communication can cause negative effect on the throughput performance. Therefore, whether a node should join the cooperative group depends on the channel qualities of both the direct and cooperative links.

It is also noted that more throughput improvement can be achieved with better source-relay link compared to the relay-destination link. As shown in the left plot in Fig. 4, the combination of $\sigma_{SR} = 45$ and $\sigma_{RD} = 40$ dB results in higher throughput performance comparing with the case with $\sigma_{SR} = 40$ and $\sigma_{RD} = 45$ dB. This results can be explained by the adoption of DF scheme within cooperative communication. The source-relay link should provide good enough channel quality such that the relay can correctly decode the corresponding frame. Otherwise, full diversity gain will not be achieved with the exploration of cooperative communication. Therefore, the source-relay channel plays a more important role than the relay-destination channel

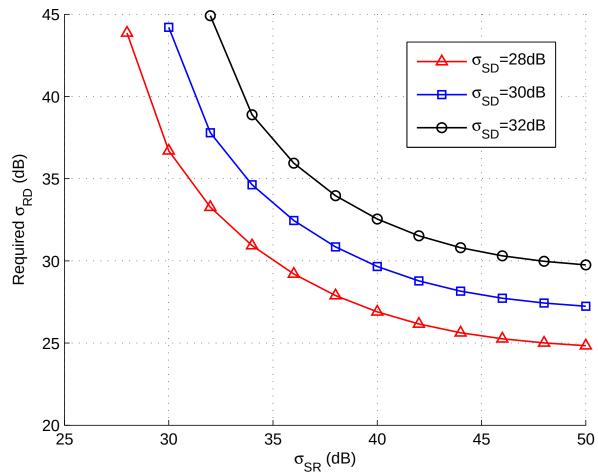

Fig. 5. Required average SNR σ_{RD} via cooperative communication for achieving the same throughput as that with direct transmission under specific σ_{SD} and σ_{SR} values.

for throughput enhancement, especially under poor channel quality of the direct link. In other words, as the source is suffering from severe fading channel and noises to the destination, a better source-relay channel is considered more important compared to the relay-destination channel in order to allow the destination to acquire another copy of data frames. This results will further be explored in the design of proposed cooperative MAC protocol to provide efficient channel acquisition process, which will be explained in Section IV.

Fig. 5 shows the occasions for cooperative mechanism to have a better performance than the direct communication under different SNR values. With pre-defined average SNR values of the source-destination and the source-relay channels, the theoretically required average SNR of the relay-destination channel is obtained through the cooperative communication in order to have the same throughput as that via the direct transmission, i.e. $S_{dir} = S_{coop}$ where S_{dir} and S_{coop} are acquired from (26) and (27) respectively. For every specific σ_{SD} and σ_{SR}, each point on the curves represents the value of σ_{RD} that satisfies the following condition:

$$\sup\left\{\sigma_{RD} : S_{coop}(\sigma_{SD}, \sigma_{SR}, \sigma_{RD}) \geq S_{dir}(\sigma_{SD})\right\} \tag{28}$$

For example, as $\sigma_{SD} = 30$ dB and $\sigma_{SR} = 40$ dB, the cooperative scheme with $\sigma_{RD} > 30$ dB can outperform the conventional direct communication in network throughput. Each curve in Fig. 5 can also be explained as the case while $S_{coop} = S_{dir}$ for a specific average SNR of the direct link. The region above the curve represents the situations of $S_{coop} > S_{dir}$. Moreover, it is especially noticed that Fig. 5 can be utilized as a reference plot to determine the suitability for adopting the cooperative schemes as opposed to the direct communication, which will further be explored in the design of cooperative MAC protocols in next section.

IV. Proposed Cooperative MAC Protocols

According to analytical study as described in the previous section, whether to adopt either the direct transmission or cooperative communication depends on the variations of channel conditions. In order to improve the throughput performance, cooperative communication should be activated when the channel quality of direct link is comparably worse than that of the cooperative links, i.e. based on the criterion as illustrated in Fig. 5. Furthermore, a pre-specified single relay node is assumed to be available in the previous analysis. In realistic situation, how to select an appropriate relay node among the available network nodes is considered crucial for the improvement of network throughput. Based on the reasons mentioned in the previous section, fixed relays are also exploited in the design of proposed cooperative MAC protocols. For instance, several relay nodes can be pre-assigned and placed within the transmission range of an access point in order to assist for data transmission. The total number of required fixed relays can be determined based on the total numbers of users, the transmission range of access point, and the required system performance. The feasible locations and numbers of relays within the network is considered pre-determined information, which is not within the scope of this paper. Therefore, for the enhancement of throughput performance, the objectives for the design of proposed cooperative MAC protocols consist of the following: (a) to determine if cooperative communication should be employed, and (b) to select a feasible relay node based on available relays within the network.

The schematic diagrams for the design of proposed MAC protocols are depicted in Fig. 6. It shows the transmission sequences including both the handshake and data transmission processes based on the combined direct/cooperative strategy. Noted that frames transmitted by either the source, relay, or destination are denoted with different colors, e.g. frames with blue color are transmitted from the source. Moreover, the channel access method adopted in the proposed protocols is modified from the distributed coordination function (DCF) in IEEE 802.11 standard, which requires the source to contend for the channel usage before transmitting data frames to the destination. As shown in Fig. 6, the three different types of transmission processes in the proposed protocols are explained as follows.

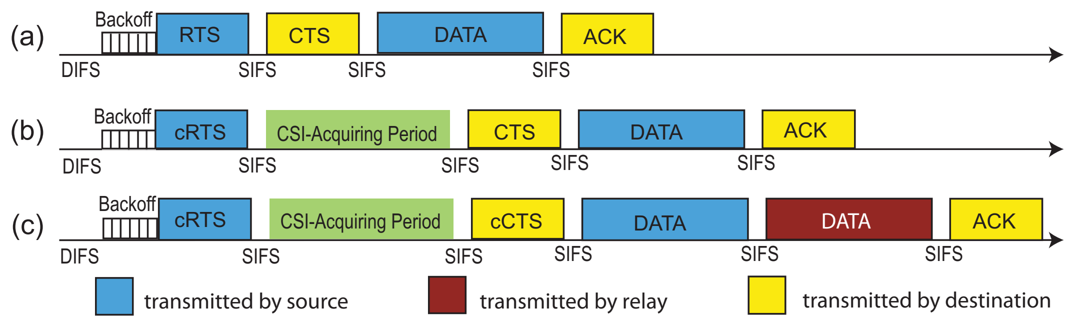

Fig. 6. The schematic diagrams of both the handshake process and data transmission for (a) direct transmission in non-cooperative group, (b) direct transmission in cooperative group, and (c) cooperative transmission in cooperative group.

(a) *Direct transmission in non-cooperative group:* Conventional DCF mechanism is exploited for the nodes in non-cooperative group. The source will initiate the transmission of RTS frame after the channel has been sensed in the idle state for the time durations of both a DIFS and the backoff timer. After receiving the RTS frame, the other nodes within the network will set their corresponding network allocation vectors (NAVs) in order not to interfere with the on-going transmission between the source and destination. Data transmission will be started by the source after receiving the CTS frame delivered by the destination. Successful reception of the acknowledgement (ACK) frame by the source will complete the data transmission process.

(b) *Direct transmission in cooperative group:* Instead of initiating conventional RTS frame, the source within the cooperative group will issue the cRTS frame in order to notify the request of cooperative communication. However, the source does not possess enough information to determine whether to activate the cooperative communication or not. The decision to transmit via either the direct or cooperative communication is made by the destination after considering the instantaneous channel conditions. In order to conduct appropriate decision, it is required for the destination to acquire the channel state information (CSI) from the relays, which is implemented within the CSI-acquiring period as shown in Fig. 6. In other words, the relays will utilize this time period to transmit the channel information between the source and relays by adopting a specific mechanism, i.e. either the proposed FCC or BCC protocol, which will be described later in this section. It is noted that the destination can also obtain the channel conditions of source-destination and relay-destination links by measuring the received control frames from the source and relays respectively. After obtaining the required channel information, the destination will make the decision to transmit data frames either through the direct transmission or via the help from relay. In the case that direct transmission scheme is notified by the decision metrics, the conventional CTS control frame will be forwarded from the destination to both the source and relays. It indicates that only direct communication between the source and destination should be utilized for data transmission.

(c) *Cooperative transmission in cooperative group:* Similar to the process as described in (b), this case also happens as the network nodes belong to the cooperative group. If the direct link suffers from deep fading channel condition, cooperative communication will be chosen by the destination via either the FCC or BCC scheme after the CSI-acquiring period. The cCTS frame which will fill in the identifier of a relay that should participate in this cooperative communication will be transmitted by the destination in order to inform both the source and the chosen relay. Sequentially, cooperative communication for the two-phase data transmission will be activated, i.e. the source first transmits the data frame to both the destination and selected relay, and followed by the data forwarding process from the relay to destination. It is noted that the time gap between two frame transmissions is designed as an SIFS as shown in Fig. 6. After the cooperative combining process is conducted by the destination, an ACK frame will be delivered to the source to complete the entire transmission procedure.

As described in both processes (b) and (c), it is required for the destination to determine whether the cooperative communication should be adopted. Based on the saturation throughput as derived in Section III, the instantaneous throughput $S_{I(\zeta)}$ is utilized as the decision metrics for the destination node, where the subscript ζ in $S_{I(\zeta)}$ denotes the different transmission schemes, i.e. $S_{I(\zeta)} = \{S_{I(coop)}, S_{I(dir)}\}$. Since the decision metrics adopted at the destination should be implemented based on realtime manner, the instantaneous throughput for the direct and cooperative communication is simplified from the average throughput as derived in (26) and (27) respectively. The average successfully transmitted payload bits $E[L_P]$ in (25) will become $(1 - P_{f(\zeta)})E[L_{Payload}]$, where the average length of payload bits in a data frame $E[L_{Payload}]$ is defined as in (25). The instantaneous FER $P_{f(\zeta)}$ can be obtained from each instantaneous FER of communication link $P_{f,SD}$, $P_{f,SR}$, and $P_{f,(SR)D}$, i.e. $P_{f(dir)} = P_{f,SD}$ and $P_{f(coop)} = (1 - P_{f,SR})P_{f,(SR)D} + P_{f,SR}P_{f,SD}$. Noted that the probability for at least one transmission occurs in a time slot p_{tr} and the probability of a non-collided transmission $p_{wc(cg)}$ and $p_{wc(ncg)}$ in (25) are equal to 1 since the throughput $S_{I(\zeta)}$ is considered at each instantaneous time slot after one node has already reserved the channel. Moreover, instead of obtaining the

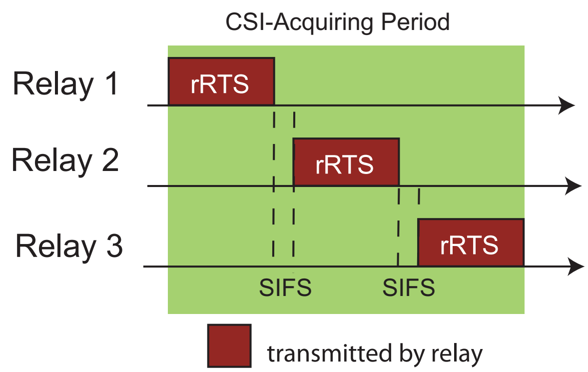

Fig. 7. The schematic diagram of process in CSI-acquiring period with FCC protocol.

average time durations $E[T_B]$, $E[T_S]$, $E[T_C]$, and $E[T_E]$ in (19), the required instantaneous transmission time $T_{I(\zeta)}$ is obtained for the considered communication scheme. The parameter $T_{I(\zeta)}$, which includes the handshake and data transmission processes, can be estimated according to the ratio of the frame length to the data rate for the corresponding scheme. Therefore, the instantaneous throughput $S_{I(\zeta)}$ can be obtained as

$$S_{I(\zeta)} = \frac{E[L_{Payload}]}{T_{I(\zeta)}}(1 - P_{f(\zeta)}) \tag{29}$$

It is noted that the instantaneous throughput $S_{I(dir)}$ and $S_{I(coop)}$ will be computed directly within the destination by gathering the channel information during the CSI-acquiring period. After acquiring the instantaneous throughput $S_{I(dir)}$ and $S_{I(coop)}$ with different relays, the destination will determine if cooperative communication should be adopted. In the case that cooperative scheme is exploited, the destination will further select the most feasible relay for data forwarding based on either the proposed FCC or BCC MAC protocol, which are described as follows.

A. Full CSI based Cooperative (FCC) MAC Protocol

The design concept of the proposed FCC protocol is to provide full channel information of the potential relays such that the destination node can obtain sufficient information to select a feasible relay node for data forwarding. As shown in Fig. 7, a control frame named relay ready-to-send (rRTS) is created to carry the channel information of source-relay link from the relays to destination. It is designed to have the same structure as the CTS frame except that additional one-byte is added to store the channel information between source and relay. Moreover, since the relays are assumed to be deployed in advance, each relay can be assigned with a specific number representing its sequence to transmit the corresponding rRTS frame. According to the design of FCC scheme, the relays will transmit their rRTS frames sequentially within the CSI-acquiring period as depicted in Fig. 7. The channel quality between the source and the corresponding relay can consequently be delivered from the relay to destination. The SIFS durations are assigned between the rRTS frames from different relays. On the reception of rRTS frames, the destination will also measure the channel information of relay-destination links from the corresponding relays. After receiving all the channel information through the rRTS frames sending from the neighboring relays, the destination can therefore select a feasible relay node if cooperative communication is to be exploited.

B. Bitwise Competition based Cooperative (BCC) MAC Protocol

Based on the design of FCC scheme as mentioned above, it is beneficial to provide available channel information via all different relays for the destination to conduct relay selection scheme. However, due to the elongated CSI-acquiring period, the throughput performance can be severely degraded if the total number of relay nodes are increased, i.e. excessive rRTS frames are to be sequentially delivered to the destination node. On the other hand, small CSI-acquiring period can result in the incompleteness of delivering channel condition from the relays to destination. Therefore, the design concept of proposed BCC scheme is to compromise between the overhead caused by the exchange of channel information and sufficient information for the destination to conduct suitable decisions. A pre-specified length of CSI-acquiring period is provided for all the relays in the network to conduct *relay contention process*. The winner after the contention period will be the only relay to transmit its rRTS frame to the destination for reporting the channel condition of source-relay link.

As was discovered in the left plot of Fig. 4 that the channel quality of source-relay link is more important than the link between the relay and destination by adopting the DF scheme. Noted that similar results and observations can also be obtained in [6]. Therefore, without considering the relay-destination link, only the channel quality of source-relay link is considered for the selection of a feasible relay. As shown in Fig. 8, the bitwise competition in the CSI-acquiring period is designed to choose the appropriate relay, including 8 bits of channel information sequence and 2 bits of relay identifier. It is noted that every bit occupies one time slot which is defined in the IEEE 802.11 PHY layer standard. After receiving the cRTS frame transmitted from the source, the relays estimate their corresponding channel conditions for source-relay links. The relays will transform the channel quality into an 8-bit channel information sequence, where better channel

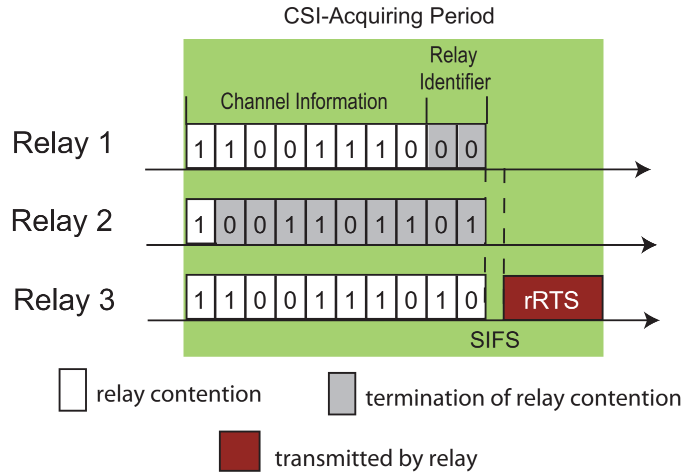

Fig. 8. The schematic diagram of process in CSI-acquiring period with BCC protocol.

condition will be represented by a larger value of channel information sequence. For example, an all ones 8-bit sequence indicates the best channel condition for the source-relay link. In addition to the sequence obtained from channel quality, the relays also transform their specific identification number into the 2-bit relay identifier in order to avoid potential collision under the situations that two relays may have the same channel information sequence. Therefore, based on the channel condition and identification number, all the neighboring relays will initiate the relay contention process within the CSI-acquiring period. Noted that each bit value with one denotes that the corresponding relay will issue an active signal; while the zero value in a bit represents that the relay will remain silent and continue listening to the channel status during that slot.

For example, a three-relay scenario is considered to explain the relay contention process of proposed BCC protocol. Both channel information and identification number are available for each relay as depicted in Fig. 8. All the three relays will transmit signals during the first slot; while only Relay 2 will become silent in the second slot. Relay 2 keeps monitoring the channel state in the second slot and detects that it is in the busy state. Consequently, Relay 2 will quit from the relay contention process since it realizes that there is at least one relay that has better channel quality of source-relay link. The remaining two relays will continue the relay contention process in order to become the winner in the following slots. However, both relays possess the same channel condition which result in the same channel information sequence as indicated in Fig. 8. The purpose of the last two bits, i.e. the relay identifier, come into play for resolving the contention between Relays 1 and 3. According to the identification numbers, Relay 3 will become the final winner within the relay contention process. An rRTS frame will be transmitted from Relay 3 to the destination in order to deliver the channel information of source-relay link. Based on the decision metrics within the destination, either a CTS or cCTS frame will be transmitted by the destination in order to notify if either the direct or the cooperative transmission should be activated. The performance evaluation and comparison between the proposed FCC and BCC protocols will be conducted in the next section.

V. Performance Evaluation

Numerical results are performed to evaluate the throughput performance of conventional direct transmission and proposed FCC and BCC protocols. The network scenario for performance evaluation and comparison is described as follows. Similar to Fig. 1, a single destination is assumed to locate at the center of the considered network, which confines a circular region with radius equal to 50 meters. The source nodes, which denotes the users, are randomly located within the area between 30 and 50 meters from the destination. Based on the observation from [32], suitable relay deployment is to place the relays around the intermediate location between the users and destination in order to appropriately enhance the network throughput. Therefore, stationary relays are uniformly distributed around the circle which is 20 meters from the destination. Various numbers of sources and relays will be considered under different simulation cases. In the case that either the FCC or BCC scheme is adopted, the destination is the node to determine whether the direct or cooperative communication should be adopted for each data transmission. It is also noted that the pathloss exponent is set to 4 in the following simulations. The other parameters utilized in the simulations is selected the same as in Table I.

Figs. 9 and 10 illustrate the throughput performance for proposed FCC and BCC protocols respectively under different SNR values σ_{DB}. The parameter σ_{DB} is defined as the average received SNR between the destination and a source located at the boundary of destination's transmission range. Noted that the average received SNRs of other links can also be computed according to the distances of the links compared to that located at the boundary with σ_{DB}. The total number of relays are selected as 4, 6, and 8 in both cases; while that for the sources is chosen as 30. It is intuitive to observe in both figures that the throughput performance is increased under both schemes as the value of σ_{DB} is augmented. However, in the proposed FCC protocol, the increased number of relays will degrade the throughput performance as shown in Fig. 9. The main reason is due to the requirement to transmit additional rRTS frames by adopting the

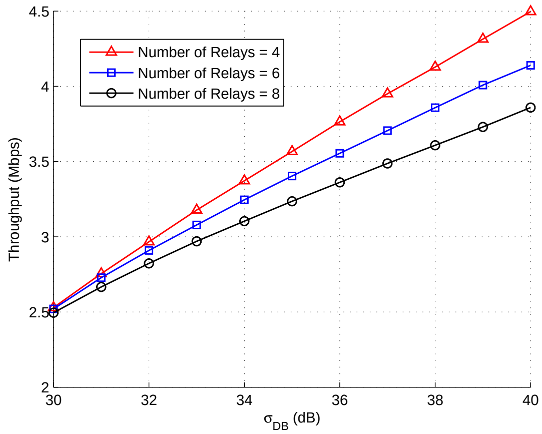

Fig. 9. Throughput performance versus average SNR value of boundary node σ_{DB} using FCC protocol (number of sources $= 30$).

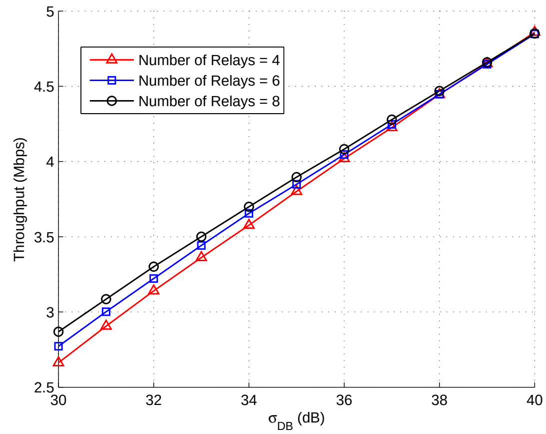

Fig. 10. Throughput performance versus average SNR value of boundary node σ_{DB} using BCC protocol (number of sources $= 30$).

FCC scheme as the number of relays is increased. Throughput performance will consequently be decreased since excessive overheads are introduced by the elongated CSI-acquiring period. On the other hand, the throughput performance is enhanced as the number of relays is increased by applying the proposed BCC protocol. The reason is that additional relays can provide data forwarding services for more users within the fixed CSI-acquiring period. Even though only partial channel information is available by adopting the BCC scheme's relay contention process, the resulting throughput performance can still be improved with augmented number of relays. Furthermore, as shown in Fig. 10, the throughput enhancement due to the increased number of relays becomes insignificant as σ_{DB} is augmented, i.e. all three lines converge as σ_{DB} is around 40 dB. This is attributed to the situation with sufficiently good channel quality, i.e. with larger σ_{DB} values, where direct transmission will mostly be activated by the destination. Consequently, the number of relays will result in less impact on the throughput performance.

Figs. 11 and 12 are illustrated to compare the throughput performance of proposed protocols with various number of relays. The total numbers of sources are selected as 20, 30, and 40 for both cases. It is noted that the SNR value σ_{DB} is chosen as 30 dB for observing the effectiveness of proposed schemes under relatively poor channel quality. It can be discovered that throughput performance can be enhanced as the number of relays is smaller than 4 in both proposed protocols. However, as the number of relays is larger than 4, the throughput obtained

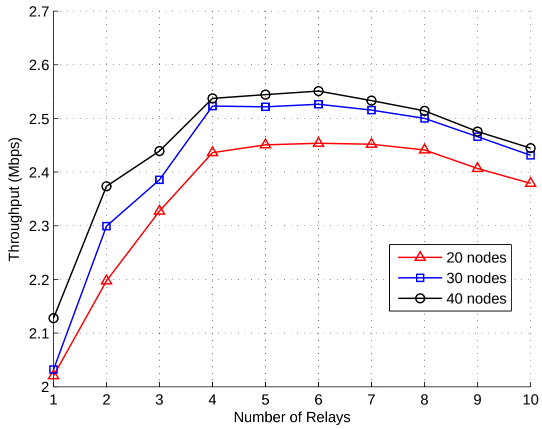

Fig. 11. Throughput performance versus number of relays using FCC protocol with different number of sources (σ_{DB} = 30 dB).

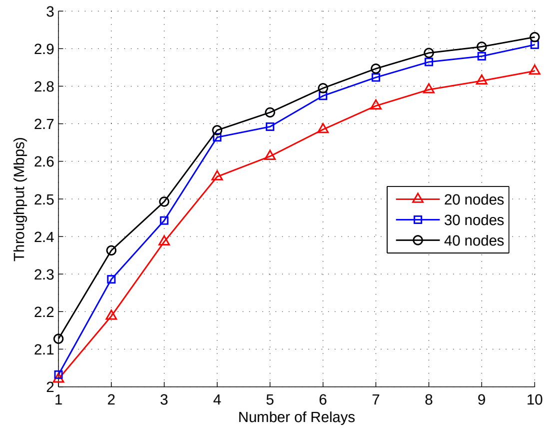

Fig. 12. Throughput performance versus number of relays using BCC protocol with different number of sources (σ_{DB} = 30 dB).

from the FCC scheme decreases as the number of relay is augmented. The BCC protocol, on the other hand, can still result in enhanced throughput performance as the number of relays is increased as in Fig. 12. Similar to the reasons as mentioned in the previous paragraph, the FCC protocol introduces additional overheads by sending excessive rRTS frames as the number of relays is increased. A harmful effect will occur when the control overheads can not be compensated by the enhancement of throughput resulted from the cooperative communication. In contrary, the BCC protocol will still be beneficial from the additional relays due to the limited CSI-acquiring period. Furthermore, similar trend can be obtained in both figures as the number of users is increased. The network throughput will be enhanced with increasing number of sources, however, the amount of improvement becomes smaller as the number of sources continues to grow.

Figs. 13 and 14 show the throughput improvement of proposed protocols compared to direct transmission under different numbers of relays and numbers of users, respectively. The SNR value σ_{DB} is also chosen as 30 dB in both figures. The total number of users is set to be 30 in Fig. 13; while the number of relays is selected as 5 in Fig. 14. As shown in Fig. 13, it can be seen that the FCC scheme can provide slightly better performance than BCC protocol as the number of relays is equal to either 1 or 2. The reason is that the FCC protocol collects full channel information and makes the best decision on relay selection. However, the BCC scheme chooses the feasible relay only based on the channel quality of source-relay links, which may not result

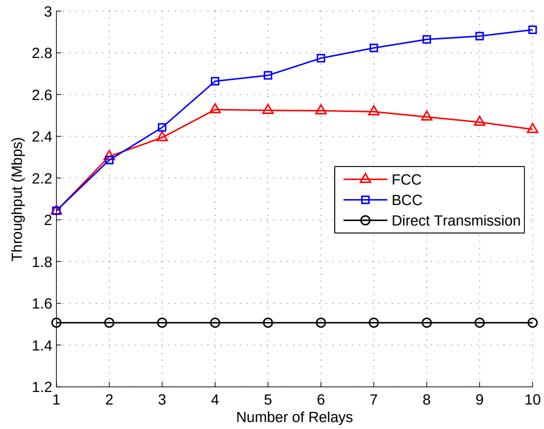

Fig. 13. Throughput comparison versus number of relays with direct transmission and proposed protocols ($\sigma_{DB} = 30$ dB).

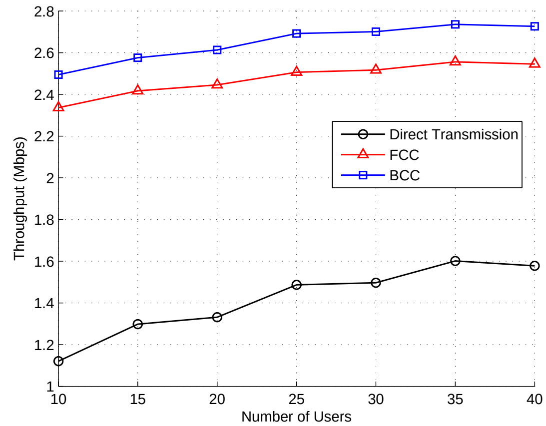

Fig. 14. Throughput comparison versus number of users with direct transmission and proposed protocols ($\sigma_{DB} = 30$ dB).

in the best relay considering both source-relay and relay-destination channels in the cooperative communication. Nevertheless, as the number of relays is increased, the performance from FCC protocol degrades due to excessive overhead caused by transmitting channel information via the rRTS frames. The BCC protocol can outperform the FCC scheme in throughput performance owing to its efficient design of relay contention process. Furthermore, both proposed protocols can still provide better performance than that from direct transmission under different numbers of relays. Noticed that this figure can also be utilized as a reference plot to determine the number of relays to be deployed in order to achieve the required throughput performance. The impact from the number of users on throughput performance is illustrated in Fig. 14. It is intuitive that total network throughput will be increased with augmented number of users. However, owing to potential frame collision, the resulting throughput performance may reach its saturation point or even decreases as the number of users is increased. Nevertheless, the proposed BCC scheme can provide much better throughput performance compared to both the FCC protocol and conventional direct communication.

Fig. 15 shows the average number of retransmissions by adopting direct transmission and proposed protocols under different channel conditions. Noted that the number of relays is selected as 5 in both FCC and BCC schemes. It can be discovered that both proposed protocols can effectively reduce the number of retransmissions especially under relatively poor channel condition, e.g. around 1.3 less retransmissions under $\sigma_{DB} = 30$ dB. Both FCC and BCC

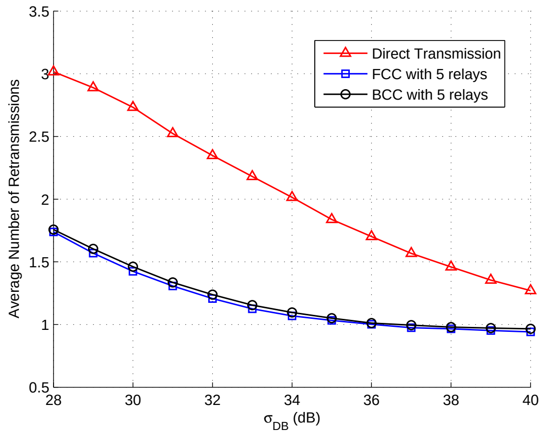

Fig. 15. Average number of retransmissions versus average SNR value of boundary node σ_{DB} via direct transmission and proposed protocols.

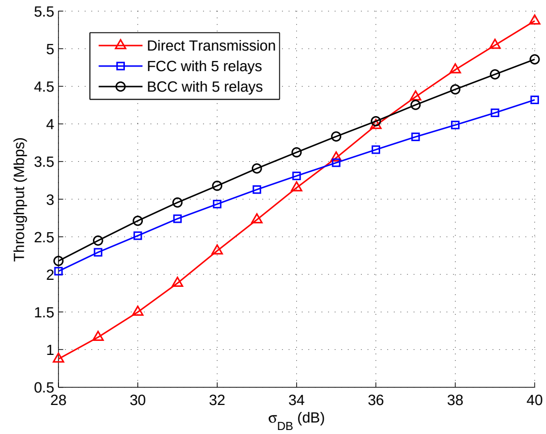

Fig. 16. Throughput performance versus average SNR value of boundary node σ_{DB} via direct transmission and proposed protocols.

algorithms result in similar number of retransmissions under different SNR values. On the other hand, although the acquisition of full channel information can be beneficial to reduce the number of retransmissions, the prolonged transmission time resulting from the FCC protocol will degrade the throughput performance as shown in Fig. 16. This figure illustrates the dependency of throughput performance with the conventional direct transmission and the proposed protocols under different channel conditions. Both the FCC and BCC protocols can provide better performance than direct transmission under poor channel conditions. It is also noted that the BCC protocol can further improve the throughput performance compared to the FCC scheme due to its limited transmission time for relay contention. As the channel condition improves, the transmission overhead introduced by proposed protocols will result in relatively lower throughput performance comparing with direct transmission. Nevertheless, the proposed cooperative MAC protocols will still be advantageous especially under the environments with comparably poor channel conditions.

VI. Conclusion

This paper presents performance analysis and protocol designs of cooperative communication from the medium access control (MAC) perspectives. An analytical model which consists of both the conventional direct communication and the cooperative mechanism is proposed to evaluate the suitability for adopting the cooperative scheme. In order to enhance the network throughput, it is suggested in this paper that not only the cooperative diversity but also the transmission delay should be considered in the design of cooperative communications. Moreover, both the full-CSI based cooperative (FCC) MAC protocol and bitwise competition based cooperative (BCC) MAC protocol are proposed to adaptively choose the appropriate relay for data forwarding against the variation of channel conditions. Although the FCC protocol is designed based on full channel information, the overhead introduced by the exchange of control frames can result in degraded throughput performance. On the other hand, the BCC protocol adopts the relay contention process to limit the time period for acquiring channel information, which effectively reduces the communication overhead. Simulation results show that both the proposed MAC protocols can provide enhanced throughput performance compared to direct communication, especially under poor channel conditions.

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