Spectrum-Aware Opportunistic Routing in Multi-Hop Cognitive Radio Networks

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***Abstract*—In this paper, cognitive routing coupled with spectrum sensing and sharing in a multi-channel multi-hop cognitive radio network (CRN) is investigated. Recognizing the spectrum dynamics in CRN, we propose an opportunistic cognitive routing (OCR) protocol that allows users to exploit the geographic location information and discover the local spectrum access opportunities to improve the transmission performance over each hop. Specifically, based on location information and channel usage statistics, a secondary user (SU) distributedly selects the next hop relay and adapts its transmission to the dynamic spectrum access opportunities in its neighborhood. In addition, we introduce a novel metric, namely, cognitive transport throughput (CTT), to capture the unique properties of CRN and evaluate the potential relay gain of each relay candidate. A heuristic algorithm is proposed to reduce the searching complexity of the optimal selection of channel and relay. Simulation results are given to demonstrate that our proposed OCR well adapts to the spectrum dynamics and outperforms existing routing protocols in CRN.**

***Index Terms*—Cognitive radio, multi-hop transmission, opportunistic routing, dynamic spectrum access.**

I. Introduction

COGNITIVE radio network (CRN) has been emerging as a prominent solution to improve the efficiency of spectrum usage to meet the increasing user demand on broadband wireless communications. In CRN, secondary users (SUs) can utilize spectrum access opportunities for unlicensed transmissions when primary users (PUs) do not occupy the licensed spectrum. Therefore, the most critical issue in CRN is the exploration and exploitation of the spectrum access opportunities for SUs' transmissions and in the meantime preventing harmful interference to PUs' transmissions [1], [2]. While most research in CRN has focused on a single-hop wireless access network, the research community has recently realized that cognitive paradigm can be applied in multi-hop networks to provide great potential for unexplored services and enable a wide range of multimedia applications with the extended network coverage.

To fully explore the potentials of the multi-hop CRN in support of multimedia applications, it is crucial to study routing in dynamic spectrum access system, taking into account the unique properties of the cognitive environment. Existing research efforts mainly focus on effective spectrum sensing and sharing schemes in the physical and MAC layers. Some recent studies indicate that the next major breakthrough in CRN lies in utilizing the diversity gain of spare spectrum in the time, frequency, and space domains to enhance transmissions among SUs [3]. However, in multi-hop CRN, SUs distributed at different locations may have different views of the usage patterns of PUs over multiple frequency channels, which makes it extremely challenging for SUs to coordinate with each other and to exploit the multi-channel and multi-user diversity gain. Some preliminary works on spectrum-aware routing have been proposed for joint channel assignment and route establishment [4], [5], [6]. However, these routing algorithms are based on a pre-determined end-to-end routing table, which is more suitable for static spectrum access system where the channel conditions do not change frequently, e.g., in a CRN operating in TV bands [7]. In dynamic spectrum access system, spectrum access opportunities of mobile SUs may change over hops from time to time, which makes it very difficult and costly to maintain a routing table. Some recent research extends the work in a wide spectral band under highly dynamic channel conditions other than TV bands [8], [9]. A QoS differentiation scheme and an opportunistic relay forwarding scheme are proposed in our previous works [9], [10], respectively, considering heterogeneous channel usage patterns. These works either mainly focus on the QoS provisioning in a multi-channel scenario or only exploit the diversity of channel propagation characteristics in multi-hop transmissions, which do not specify the impact of the channel usage statistics on SUs' transmissions, especially in a multi-hop CRN.

In this paper, we study cognitive routing in a multi-channel multi-hop CRN, by utilizing channel usage statistics in the discovery of spectrum access opportunities to improve transmission performance of SUs. The main contributions of this paper are four-fold: (i) we propose an opportunistic cognitive routing (OCR) protocol in which forwarding links are selected based on the locally identified spectrum access opportunities. Specifically, the intermediate SU independently selects the next hop relay based on the local channel usage statistics so that the relay can quickly adapt to the link variations; (ii) the multi-user diversity is exploited in the relay process by allowing the sender to coordinate with multiple neighboring SUs and to select the best relay node with the highest forwarding gain; (iii) We design a novel routing metric to capture the unique properties of CRN, referred to as cognitive transport throughput (CTT). Based on the novel metric, we propose a heuristic algorithm that achieves superior performance with reduced computation complexity. Specifically, CTT represents the potential relay gain over the next hop, which is used in

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the channel sensing and relay selection to enhance the OCR performance; and (iv) we evaluate the performance of the proposed OCR in a multi-hop CRN. Simulation results show that the proposed OCR protocol adapts well to the dynamic channel/link environment in CRN.

The remainder of the paper is organized as follows. The related work is presented in Section II. The system model is introduced in Section III. A multi-channel opportunistic cognitive routing protocol is proposed in Section IV. To maximize the relay performance of the OCR, a novel routing metric is designed and the practical implementation issues are discussed in Section V, followed by performance evaluation in Section VI. Concluding remarks are given in Section VII.

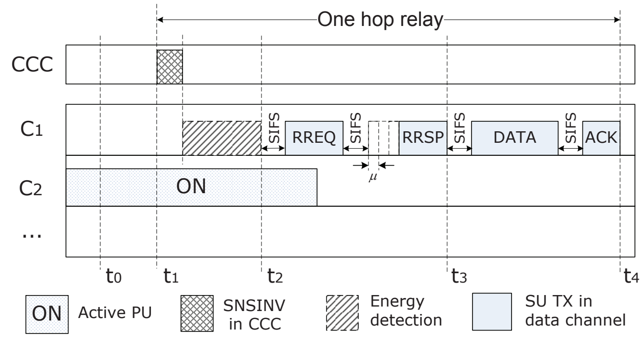


Fig. 1. The opportunistic cognitive routing timeline

II. Related Work

Routing in CRN can be formulated as a global optimization problem with the channel-link allocation for data flows in the network [11]. Xin et al. [4] propose a layered graph to depict the topology of CRN in a snapshot and allocate multiple links over orthogonal channels to enhance the traffic throughput by establishing a near-optimal topology. Pan et al. [5] propose a joint scheduling and routing scheme according to the long term statistics of the link transmission quality for SUs. Gao et al. [12] develop a flow routing scheme which mitigates the network-wide resource for multicast sessions in multi-hop CRN. These works on cognitive routing predetermine an end-to-end relay path in CRN based on the global network information. However, the channel conditions of secondary links are highly dependent on PUs' activities in CRN. SUs usually need to track the channel status by periodic sensing [13] or field measurements [3]. When the channel status changes, source nodes need to re-calculate a path. Khalif et al. [8] show that the involved computation and communication overhead for re-building routing tables for all flows is nontrivial, especially when the channel status changes frequently.

Compared with centralized scheduling, distributed opportunistic routing is more suitable for a dynamic CRN since SUs can select the next hop relay to adapt to the variations of local channel/link conditions [14], [15]. Instead of using a fixed relay path, a source node broadcasts its data to neighboring nodes, and selects a relay based on the received responses under current link conditions [14]. Liu et al. [16] propose to apply an opportunistic routing algorithm in CRN where the forwarding decision is made under the locally identified spectrum access opportunities. So far, most opportunistic routing protocols have been studied in a single channel scenario. In a multi-channel system, the channel selection and relay link negotiation may introduce extra delay, which degrades the performance of the network. How to extend opportunistic routing in a multi-channel CRN is still an open research issue.

It is also recognized that with available localization services, geographic routing can achieve low complexity and high scalability under dynamic link conditions in various wireless networks, such as wireless mesh networks [17], ad hoc networks [18] and vehicle communication networks [19]. With geographic routing, a node selects a relay node that is closer to the destination for achieving distance advances in each hop. Chowdhury and Felice [6] introduce geographic routing into CRN to calculate a path with the minimal latency. However, their work still focuses on building routing tables and thus is not suitable for dynamic CRN. Considering the unique features of CRN, it is essential to design a distributed opportunistic routing algorithm by tightly coupling with physical layer spectrum sensing and MAC layer spectrum sharing to adapt to the network dynamics in CRN.

III. System Description

We consider a multi-hop CRN where multiple PUs and SUs share a set of orthogonal channels, $C = \{c_1, c_2, ..., c_m\}$. SUs can exchange messages over a common control channel (CCC)[1]. Each SU is equipped with two radios: one half-duplex cognitive radio that can switch among C for data transmissions and the other half-duplex normal radio in CCC for signaling exchange.

When a source SU communicates with a destination node outside its transmission range, multi-hop relaying is required. As shown in Fig. 1, at each hop, the sender first senses for a spectrum access opportunity and selects a relay node in the detected idle channel[2]. We model the occupation time of PUs in each data channel as an independent and identically distributed alternating ON (PU is active) and OFF (PU is inactive) process. SUs track the channel usage pattern, i.e., ON or OFF, and obtain the channel usage statistics through periodic sensing operations. Generally, the statistics of channel usage time change slowly. The parameter estimation is beyond the scope of this paper and the details can be found in [3], [13]. With GPS or other available localization services, SUs can acquire their own location information, and the source nodes have the corresponding destinations' location information, e.g., an edge router or a gateway in the network. A summary of main notations used in the paper is given in Table I for easy reference.

IV. Opportunistic Cognitive Routing (OCR) Protocol

In this section, an opportunistic cognitive routing (OCR) protocol is proposed where SUs forward the packets in the

[1]The CCC can be implemented by bidding on a narrow spectrum band [20] or accessing the temporarily spare spectrum bands in a predefined frequency hopping sequence [21].

[2]In some extreme case when geographic routing fails to reach the destination, we can apply the right-hand rule for route recovery as proposed in GPSR [17].

TABLE I
SUMMARY OF NOTATIONS

Symbol	Definition
$C = \{c_j\}$	Channel set, $j = \{1, 2, ..., m\}$
$\mathbf{N}_S$	The SU set of the sender S's neighbors
$\mathbf{R}_D$	The set of relay candidates for the destination D
$\mathbf{R}_D^{c_j}$	The set of relay candidates for the destination D in the channel c_j
$A_D(S, R)$	Relay advancement of the link SR for D
$(c^*, \mathbf{R}_D^{c^*})$	The transmission channel and the ordered relay set selected by MAXCTT
$CTT(c_j, \mathbf{R}_D^{c_j})$	The cognitive transport throughput (CTT)
$d(S, D)$	Euclidian distance between S and D
$E[T_{ON}^{c_j}](E[T_{OFF}^{c_j}])$	Mean duration of a busy(idle) c_j
$\mathcal{F}_{OFF}^{c_j}(t)$	CDF of the OFF duration of c_j
$I_R^{c_j}$ $(\overline{I_R^{c_j}})$	SU R detects c_j to be idle (busy)
T_{detc}	Per channel energy detection delay
T_{DTX}	Per hop data packet transmission delay
T_{init}	Sensing initialization delay
T_{relay}	Per hop transmission delay in OCR
$T_{RREQ}(T_{RRSP})$	RREQ (RRSP) message transmission delay
T_{RS}	Per hop relay selection delay
T_{SNS}	Per hop sensing delay
T_{switch}	Transceiver switching time
t_0	The latest channel status observation time
$P_i^{c_j}$	The probability that R_i is selected as the relay in c_j
$P_{OFF,R}^{c_j}(t_0, t_1)$	The probability that c_j is idle at t_1, $t_1 > t_0$.
$P_R^{c_j}(t_1, t_2)$	The probability that c_j is idle during $[t_1, t_2]$ at R
$P_{relay,R_i}^{c_j}$	The probability that the relay via R_i succeeds in c_j
$P_{RSfail}^{c_j}$	The probability that relay selection fails in c_j
V_{R_i}	The priority of R_i in the relay selection.
$X_{R_t R_r}^{c_j} = 1(0)$	SUR_t and SU R_r are (not) affected by the same PU in c_j
ρ_{c_j}	The chance for an idle state in c_j
μ	Backoff mini-slot
γ	The maximum channel propagation delay

locally identified spectrum access opportunities. To adapt to the channel dynamics, SUs opportunistically select the relay nodes from multiple candidates according to the distance gain and the channel usage statistics.

A. Protocol Overview

As shown in Fig. 1, the per hop relay in OCR includes three steps, i.e., channel sensing, relay selection, and data transmission.

In the channel sensing step, the sender searches for a temporarily unoccupied channel in collaboration with its neighbors using energy detection technique. Before sensing the data channel, the sender broadcasts a short message, i.e., *sensing invitation* (SNSINV), in the CCC to inform neighboring nodes of the selected data channel, and the location information of the sender and the destination. The transmission of SNSINV message in the CCC follows the CSMA/CA mechanism as specified in IEEE 802.11 MAC. Upon receiving the SNSINV, the neighboring SUs set the selected data channel as non-accessible so that no SU will transmit in the selected data channel during the sensing period of the sender. In this way, the co-channel interference from concurrent secondary transmissions can be mitigated. Using the location information in SNSINV, the neighboring SUs evaluate whether they are eligible relay candidates, e.g., whether a relay node is closer to the destination than the sender and thus can provide a relay distance gain. Eligible relay candidates will collaborate with the sender in channel sensing and relay selection. Other SUs cannot transmit in the selected data channel during the reserved time period specified in SNSINV. When the channel is sensed idle, i.e., no PU activity is detected, the sender will initiate a handshake with relay candidates in the relay selection step. Otherwise, the sender selects another channel and repeats the channel sensing process.

In the relay selection step, the sender selects the next hop relay from the relay candidate SUs. Specifically, when the channel is sensed idle, the sender first broadcasts a routing request (RREQ) message to the relay candidates. Eligible candidates reply routing response (RRSP) messages in a sequence specified by the sender. A relay candidate is assigned a higher priority to transmit RRSP after a shorter backoff window if it has a larger link throughput [14], a greater relay distance advancement [17], or a higher link reliability [22]. A candidate SU keeps listening to the data channel until it overhears an RRSP or it transmits an RRSP when its backoff timer reaches zero. The sender selects the first replying relay candidate as the next hop relay. If the sender receives no RRSP message, which implies no relay candidate is available in the selected channel, it will repeat the channel sensing and relay selection steps. After a successful RREQ-RRSP handshake, the sender transmits data to the selected relay node in the data transmission step.

B. Analysis of the OCR Protocol

We study the impacts of PUs' activities on the performance of the proposed OCR protocol. In CRN, when PUs appear in a channel, an SU needs to stop its current transmission, update its record of the channel status, and reselect a data channel. Thus, PUs' appearance will result in a larger transmission delay, and involve extra overhead for channel sensing and relay selection. To evaluate the impacts of PUs' activities on the protocol performance, we first introduce the main performance metrics, namely, relay distance advancement and per hop transmission delay. Based on the introduced metrics, we then analyze the success probability in each step, i.e., channel sensing, relay selection, and data transmission.

1) Performance Metrics

We first introduce the relay distance advancement and the per hop delay for performance evaluation. The relay advancement is measured by the geographic distance gain. For a sender S in CRN, $\mathbf{N}_S$ is the set of SUs within its transmission range. The neighboring relay candidate set for the relay to the destination D is denoted by $\mathbf{R}_D \subseteq \mathbf{N}_S$. If an SU $R \in \mathbf{N}_S$ is selected as the relay, the relay advancement $A_D(S, R)$ in terms of the difference in the distance between the SU pairs, (S, D) and (R, D) can be expressed by

$$A_D(S, R) = d(S, D) - d(R, D), \tag{1}$$

where $d(S, D)$ and $d(R, D)$ are the Euclidian distances between (S, D) and (R, D), respectively.

The per hop transmission delay T_{relay} is comprised of three parts: sensing delay (T_{SNS}), relay selection delay (T_{RS}), and packet transmission delay (T_{DTX}).

The sensing delay T_{SNS} includes the transmission time of an SNSINV message, T_{init}, and the energy detection time, T_{detc},

$$T_{SNS} = T_{init} + T_{detc}. \tag{2}$$

Based on the relay capability, candidate SUs are sorted in a given prioritized order. In the relay selection, the i-th relay candidate R_i sends an RRSP message only when the first $i-1$ higher-priority candidates are not available. Therefore, the relay selection delay $T_{RS}(i)$ is given by

$$T_{RS}(i) = T_{RREQ} + (i-1)\mu + T_{RRSP} + 2\ SIFS, \tag{3}$$

where T_{RREQ} and T_{RRSP} are the transmission time of an RREQ message and an RRSP message, respectively, and μ is the duration of one mini-slot in the backoff period. According to [23], the length of a mini-slot can be calculated as $\mu = 2 \cdot \gamma + t_{switch}$, where γ is the maximum channel-propagation delay within the transmission range, and t_{switch} is the time duration that the radio switches between the receiving mode and the transmitting mode.

Once R_i is selected, the packet transmission delay T_{DTX} is

$$T_{DTX} = T_{DATA} + T_{ACK} + 2\ SIFS, \tag{4}$$

which includes the packet transmission delay (T_{DATA}) and the ACK transmission time (T_{ACK}).

The transmission delay $T_{relay}(R_i)$ via the relay at R_i is the delay sum

$$T_{relay}(R_i) = T_{SNS} + T_{RS}(i) + T_{DTX}. \tag{5}$$

2) Channel Sensing

Denote $I_R^{c_j}$ ($\overline{I_R^{c_j}}$) as the event that c_j is sensed to be idle (busy) by an SU R in the channel c_j. A channel is determined to be idle given that it is sensed idle at the starting time of t_1 and remains idle until sensing completes at t_2, as shown in Fig.1. According to the renewal theory, the channel status can be estimated by the distribution of the channel state duration and the sensing history [24]. Specifically, given the channel status (idle or busy) observed at an earlier time, e.g., t_0, we have $P_{OFF,R}^{c_j}(t_0, t_1)$, the probability that c_j is idle (OFF) at t_1, $t_1 > t_0$. Assume ON and OFF durations follow exponential distributions with mean $1/E[T_{ON}^{c_j}]$ and $1/E[T_{OFF}^{c_j}]$[3],

$$\begin{aligned} & P_{OFF,R}^{c_j}(t_0, t_1) \\ = & \begin{cases} \rho_{c_j} + (1-\rho_{c_j})e^{-\Delta_{c_j}(t_1-t_0)}, & \text{if } c_j \text{ is OFF at } t_0, \\ \rho_{c_j} - \rho_{c_j}\ e^{-\Delta_{c_j}(t_1-t_0)}, & \text{if } c_j \text{ is ON at } t_0, \end{cases} \\ & \text{where} \begin{cases} \rho_{c_j} = \frac{E[T_{OFF}^{c_j}]}{E[T_{ON}^{c_j}]+E[T_{OFF}^{c_j}]}, \\ \Delta_{c_j} = \frac{1}{E[T_{ON}^{c_j}]} + \frac{1}{E[T_{OFF}^{c_j}]}. \end{cases} \end{aligned} \tag{6}$$

Note that ρ_{c_j} indicates the chance for an idle state in c_j.

We then calculate the likelihood of the channel staying idle during the sensing period. According to the renewal theory, the residual time of a state in an alternating process truncated since the time origin can be expressed by the equilibrium distribution of the state duration [24]. Thus, the probability that the channel at R stays in the idle state during the sensing period $[t_1, t_2]$ can be calculated as

$$P_R^{c_j}(t_1, t_2) = \int_{t_2-t_1}^{\infty} \frac{\mathcal{F}_{OFF}^{c_j}(u)}{E[T_{OFF}^{c_j}]} du, \tag{7}$$

where $\frac{\mathcal{F}_{OFF}^{c_j}(t)}{E[T_{OFF}^{c_j}]}$ is the probability density function (PDF) of the residual time of an idle channel since the time origin when it is observed as idle. $\mathcal{F}_{OFF}^{c_j}(t)$ is the cumulative distribution function (CDF) of the duration of the OFF state in c_j with the mean $E[T_{OFF}^{c_j}]$. Then, the probability that R detects a spectrum access opportunity in c_j is given by

$$Pr\{I_R^{c_j}\} \;=\; P_{OFF,R}^{c_j}(t_0, t_1) \cdot P_R^{c_j}(t_1, t_2). \tag{8}$$

For the OCR protocol, $Pr\{I_S^{c_j}\}$ denotes the probability of sensing success when the sender S detects c_j as an idle channel. Once the sender finds an idle channel, it will move to the relay selection step. Otherwise, the sender will switch to another channel and initiate the channel sensing process.

3) Relay Selection

After detecting an idle channel, the sender needs to select a relay for data forwarding. In OCR, the prioritized RRSP transmission enables the relay candidate of the highest relay priority to notify the sender its availability for data forwarding. However, active PUs may interrupt the handshaking process and cause the failures in the relay selection when an SU candidate cannot reply due to the detection of active PUs. Such case is very rare, and it happens only when a nearby PU turns on during the selection period. Since the relay selection is very short in time, usually less than 1 millisecond, we mainly consider the case when a candidate SU detects the selected channel which is occupied by an active PU in the sensing. In this case, the candidate will not respond to the RREQ. If no relay candidate responds to the RREQ message at the moment, the relay selection fails. Therefore, we have

$$P_{RSfail}^{c_j} \;=\; Pr\{I_S^{c_j}\} \cdot Pr\Big\{ \bigcap_{R_i \in \mathbf{R}_D^{c_j}} \overline{I_{R_i}^{c_j}} \;\Big|\, I_S^{c_j} \Big\}, \tag{9}$$

where $Pr\{I_S^{c_j}\}$ indicates the probability that the sender initiates the relay selection when it detects an idle channel as defined in Eq. (8). In c_j, one feasible relay selection $\mathbf{R}_D^{c_j} = \{R_1, R_2, \ldots, R_n\}$ contains a set of SUs in $\mathbf{R}_D$ with the size of $n = |\mathbf{R}_D^{c_j}|$. Denote V_{R_i} as the priority of R_i in the RRSP transmission. $\mathbf{R}_D^{c_j}$ is sorted in the descending order of V_{R_i}, i.e., $V_{R_1} > V_{R_2} > \ldots > V_{R_n}$. The event that no relay candidate replies in the relay selection step, is equivalent to the event that all SUs in $\mathbf{R}_D^{c_j}$ sense the channel busy in the previous sensing with the probability $Pr\Big\{ \bigcap_{R_i \in \mathbf{R}_D^{c_j}} \overline{I_{R_i}^{c_j}} \;\Big|\, I_S^{c_j} \Big\}$.

In the CRN, we assume that an SU is affected by at most one active PU in one frequency band. Such assumption holds in the frequency bands such as the downstream bands in cellular network where the adjacent cells/sectors are usually assigned with different working frequencies to

[3]which are commonly used in other works [3], [13]

avoid the co-channel interference [25]. Thus, the channel usage pattern is mainly determined by the PU activity at the spot of the individual SU. Let $X^{c_j}_{R_tR_r} = 1$ if a pair of SUs, R_t and R_r, are affected by the same PU in c_j, and $X^{c_j}_{R_tR_r} = 0$ otherwise. $X^{c_j}_{R_tR_r}$ can be acquired and maintained by the periodic exchange of the channel status in the SU's neighborhood. A cognitive transmission is successful only if both ends of the link are not influenced by active PUs. For example, if the channel utilities of c_j at R_t and R_r are $\rho^{c_j}_{R_t}$ and $\rho^{c_j}_{R_r}$, respectively, the link quality of the link l_{tr} can be expressed by $P^{c_j}_{l_{tr}} = \rho^{c_j}_{R_t} \cdot \rho^{c_j}_{R_r}{}^{(1-X^{c_j}_{R_tR_r})}$. Therefore, $Pr\Big\{\bigcap_{R_i\in\mathbf{R}^{c_j}_D} \overline{I^{c_j}_{R_i}} \,\Big|I^{c_j}_S\Big\}$ in Eq. (9) is given by

$$\begin{aligned} &Pr\Big\{\bigcap_{R_i\in\mathbf{R}^{c_j}_D} \overline{I^{c_j}_{R_i}} \,\Big|I^{c_j}_S\Big\} \\ =\ & Pr\Big\{\overline{I^{c_j}_{R_1}}\,\Big|I^{c_j}_S\Big\}\cdot\prod_{i=2}^{n} Pr\Big\{\overline{I^{c_j}_{R_i}}\,\Big|\Big\{\bigcap_{k=1}^{i-1}\overline{I^{c_j}_{R_k}}\Big\}\cap I^{c_j}_S\Big\} \\ =\ & (1-X^{c_j}_{SR_1})Pr\Big\{\overline{I^{c_j}_{R_1}}\Big\} \\ & \cdot\prod_{i=2}^{n}\Big[(1-X^{c_j}_{SR_i})Pr\Big\{\overline{I^{c_j}_{R_i}}\Big\}^{\prod_{k=1}^{i-1}(1-X^{c_j}_{R_kR_i})}\Big]. \end{aligned} \tag{10}$$

Suppose that the i-th relay candidate R_i in the selected relay selection order $\mathbf{R}^{c_j}_D$ is available, R_i will be selected as the next hop relay with the probability $P^{c_j}_i$, given that previous $i-1$ candidates are not available,

$$P^{c_j}_i = \begin{cases} Pr\{I^{c_j}_S\}\cdot Pr\{I^{c_j}_{R_1}\,|I^{c_j}_S\}, & \text{for } i=1, \\ Pr\{I^{c_j}_S\}\cdot Pr\Big\{\Big\{\bigcap_{k=1}^{i-1}\overline{I^{c_j}_{R_k}}\Big\}\cap\{I^{c_j}_{R_i}\}\Big|I^{c_j}_S\Big\}, & \\ & \text{for } 2\le i\le n, \end{cases} \tag{11}$$

where $Pr\Big\{\Big\{\bigcap_{k=1}^{i-1}\overline{I^{c_j}_{R_k}}\Big\}\cap\{I^{c_j}_{R_i}\}\Big|I^{c_j}_S\Big\}$ can be expressed as

$$\begin{aligned} &Pr\Big\{\Big\{\bigcap_{k=1}^{i-1}\overline{I^{c_j}_{R_k}}\Big\}\cap\{I^{c_j}_{R_i}\}\Big|I^{c_j}_S\Big\} \\ =\ & Pr\Big\{\overline{I^{c_j}_{R_1}}\Big|I^{c_j}_S\Big\}\cdot\prod_{u=2}^{i-1} Pr\Big\{\overline{I^{c_j}_{R_u}}\Big|\Big\{\bigcap_{r=1}^{u-1}\overline{I^{c_j}_{R_k}}\Big\}\cap I^{c_j}_S\Big\} \\ & \cdot Pr\Big\{I^{c_j}_{R_i}\Big|\Big\{\bigcap_{k=1}^{i-1}\overline{I^{c_j}_{R_k}}\Big\}\cap I^{c_j}_S\Big\} \\ =\ & (1-X^{c_j}_{SR_1})Pr\Big\{\overline{I^{c_j}_{R_1}}\Big\} \\ & \cdot\prod_{u=2}^{i-1}\Big[(1-X^{c_j}_{SR_l})Pr\Big\{\overline{I^{c_j}_{R_u}}\Big\}^{\prod_{r=1}^{u-1}(1-X^{c_j}_{R_rR_u})}\Big] \\ & \cdot\Big[\prod_{k=1}^{i-1}(1-X^{c_j}_{R_kR_i})\Big]Pr\{I^{c_j}_{R_i}\}^{(1-X^{c_j}_{SR_i})}. \end{aligned} \tag{12}$$

4) Data Transmission

Once R_i is selected, the data transmission in the link l_{SR_i} succeeds when no active PU appears during the transmission period $[t_3, t_4]$ in c_j. Thus, the successful relay probability at current hop via R_i can be expressed by

$$\begin{aligned} P^{c_j}_{relay,R_i} &= P^{c_j}_i\cdot P^{c_j}_{l_{SR_i}}(t_3,t_4) \\ &= P^{c_j}_i\cdot P^{c_j}_S(t_3,t_4)\cdot P^{c_j}_{R_i}(t_3,t_4)^{(1-X^{c_j}_{SR_i})}. \end{aligned} \tag{13}$$

V. Joint Channel and Relay Selection

We then jointly consider the selection of the sensing channel and relay node to improve the performance of the proposed OCR. As many factors, including channel usage statistics, the relay distance advances, and transmission priority of relay candidates, may affect the relay performance, we introduce a new metric to capture these factors and apply it in a heuristic algorithm to select the best relay in one data channel at a reduced computation complexity.

A. Novel OCR Metric

We design a new metric, the cognitive transport throughput (CTT), $CTT(c_j, \mathbf{R}^{c_j}_D)$, to characterize the one hop relay performance of OCR in the selected channel c_j with the selected relay candidate set $\mathbf{R}^{c_j}_D$, in unit of bit·meter/second.

$$\begin{aligned} CTT(c_j,\mathbf{R}^{c_j}_D) &= E\big[L\cdot\frac{A^{c_j}_D}{T^{c_j}_{relay}}\big] \\ &= \sum_{R_i\in\mathbf{R}^{c_j}_D} P^{c_j}_{relay,R_i}\frac{L\cdot A_D(S,R_i)}{T_{relay}(R_i)} \end{aligned} \tag{14}$$

The physical meaning of the CTT defined in Eq. (14) is the expected bit advancement per second for one hop relay of a packet with the payload L in the channel c_j. To improve the OCR performance, we should maximize the one hop relay performance along the path as one hop performance improvement contributes to the end-to-end performance. In addition, as the multi-user diversity is implicitly incorporated in the relay selection process, we can also achieve a high multi-user diversity gain by maximizing CTT. From Eq. (14), we can jointly decide channel c_j and the corresponding relay selection order $\mathbf{R}^{c_j}_D$ to maximize CTT.

B. Heuristic Algorithm

To obtain c^* and $\mathbf{R}^{c^*}_D$ for the largest CTT, we can exhaustively search for all possible combinations of the sensing channel and the subset of the relay candidate set. Given m channels and up to n relay candidates, an exhaustive search needs to find the locally optimal one in each channel by comparing the value of CTT under all possible permutations of the set of relay candidates. Since the CTT value is sensitive to the set size as well as the permutation, given that k candidate nodes are incorporated in the relay selection, $1\le k\le n$, there are $P(n,k)$ types of opportunistic forwarding patterns. Therefore, over m channels, the exhaustive search should take $m\cdot\sum_{k=1}^{n}P(n,k)$ times of the CTT calculation to return the global optimum. If n goes to infinity, we can get $\lim_{n\to\infty} m\cdot\sum_{k=1}^{n}P(n,k) = \lim_{n\to\infty} m\cdot\sum_{k=0}^{n}\frac{n!}{(n-k)!} = \lim_{n\to\infty} m\cdot n!\cdot\big[\sum_{k=0}^{n}\frac{1}{k!}-1\big]$. Thus the exhaustive search running time is $O(m\cdot n!\cdot e)$, where e is the base for natural logarithms. We can see that once n becomes very large, the exhaustive search becomes infeasible in real implementations.

To reduce the complexity, we propose an efficient heuristic algorithm to reduce the searching space yet achieve similar performance of the optimal solution. The performance comparison will be given in the following section.

Given independent channel usage statistics in different channels, we can decompose the optimization problem into two phases. First, we compare all possible relay selection orders in each channel and find the optimal one which maximizes the CTT. Then, we choose the relay selection order with the largest CTT value over all channels and select the corresponding channel as the sensing channel. Since the number of channels is usually limited, it is more important to reduce the searching complexity for the best relay selection order in a single channel.

To find the optimal relay selection order, the sender should decide both the number of the relay candidates and the relay priority of each candidate. According to Eq. (14), a neighboring SU, R_i, is an eligible relay candidate if it contributes to a positive relay distance advancement, $A_D(S, R_i)$. One feasible relay selection order $\mathbf{R}_D^{c_j}$ in c_j is an ordered subset of $\mathbf{R}_D$ in the descending order of relay priority V_{R_i}. A larger size of $\mathbf{R}_D^{c_j}$ includes more relay candidates and achieves a higher diversity gain, which improves the per hop throughput at the cost of the increased searching complexity.

To reduce the searching space and improve the algorithm efficiency, we have the following Lemma.

Lemma 5.1: Given a feasible relay selection set $\mathbf{R}_D^{c_j}$, $\exists R_{i_1}, R_{i_2} \in \mathbf{R}_D^{c_j}$, if $V_{R_{i_1}} > V_{R_{i_2}}$, $X^{c_j}_{R_{i_1}R_{i_2}} = 1$, then $CTT(c_j, \mathbf{R}_D^{c_j} \setminus \{R_{i_2}\}) \geq CTT(c_j, \mathbf{R}_D^{c_j})$.

Proof: Suppose $\mathbf{R}_D^{c_j} = \{R_1, \ldots, R_{i_1}, \ldots, R_{i_2}, \ldots\}$. According to Eq. (11), if $V_{R_{i_1}} > V_{R_{i_2}}$, $X^{c_j}_{R_{i_1}R_{i_2}} = 1$ and $X^{c_j}_{R_{i_1}R_{i_2}} = 1$, $P^{c_j}_{i_2} = 0$. Thus, $P^{c_j}_{relay,R_{i_2}} = 0$. From Eq. (14),

$$
\begin{aligned}
CTT(c_j, \mathbf{R}_D^{c_j}) &= \sum_{r=1}^{i_2-1} P^{c_j}_{relay,R_r} \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r)} \\
&\quad + \sum_{r=i_2+1}^{|\mathbf{R}_D^{c_j}|} P^{c_j}_{relay,R_r} \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r)} \\
&\leq \sum_{r=1}^{i_2-1} P^{c_j}_{relay,R_r} \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r)} \\
&\quad + \sum_{r=i_2+1}^{|\mathbf{R}_D^{c_j}|} P^{c_j}_{relay,R_r} \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r) - \mu} \\
&= CTT(c_j, \mathbf{R}_D^{c_j} \setminus \{R_{i_2}\}),
\end{aligned}
$$

which shows that the CTT performance does not drop when R_{i_2} is deleted from $\mathbf{R}_D^{c_j}$. ■

Lemma 5.1 indicates that we can reduce the size of the relay selection by excluding the relay candidates that are affected by the same PU. The reduced set of relay candidates will not degrade CTT. Specifically, for a given set of relay candidates, the sender groups the SUs that are affected by the same PU, selects the SU with the highest relay priority, and deletes other SUs in a group from the set.

We observe the following property which can be used to further reduce the searching space.

Property 5.2: **(Tail Truncation Rule)** Given a feasible relay selection $\mathbf{R}_D^{c_j}$, $\exists R_i \in \mathbf{R}_D^{c_j}$, $X^{c_j}_{SR_i} = 1$, then $CTT(c_j, \mathbf{R}_D^{c_j}) = CTT(c_j, \mathbf{R}_D^{c_j} \setminus \{R_k | R_k \in \mathbf{R}_D^{c_j}, V_{R_k} < V_{R_i}\})$.

Proof: If S and R_i are affected by the same PU, $Pr\left\{\overline{I^{c_j}_{R_i}} \middle| I^{c_j}_S\right\} = 0$. According to Eq. (11), $P^{c_j}_k = 0, \forall R_k \in \mathbf{R}_D^{c_j}, V_{R_k} < V_{R_i}$. Thus,

$$
\begin{aligned}
CTT(c_j, \mathbf{R}_D^{c_j}) &= \sum_{r=1}^{i} P^{c_j}_{relay,R_r} \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r)} \\
&\quad + \sum_{r=i+1}^{|\mathbf{R}_D^{c_j}|} 0 \cdot \frac{L \cdot A_D(S, R_r)}{T_{relay}(R_r)} \\
&= CTT(c_j, \mathbf{R}_D^{c_j} \setminus \{R_k | R_k \in \mathbf{R}_D^{c_j}, \\
&\qquad V_{R_k} < V_{R_i}\}),
\end{aligned}
$$

which shows that the CTT performance does not change when the relay candidates are removed from $\mathbf{R}_D^{c_j}$ with lower priority than R_i. ■

Property 5.2 indicates that the size of the relay candidate set can be further reduced by deleting SUs whose relay priorities are lower than the SU that is affected by the same PU as the sender. In other words, we can reduce the searching set without degrading the performance of the current flow while the deleted candidates can also participate in other transmissions, which further improve the network performance.

As discussed above, the relay priority plays a critical role in relay selection. It is well known that in geographic routing, the node closest to the destination is the best next hop relay as it provides the greatest distance gain. It is also proved that the geographic routing approaches the shortest path routing with the distance advance metric [26]. Therefore, we also apply the distance advance and verify its efficiency in the proposed OCR.

Thus, the CTT metric can be approximated as

$$
\begin{aligned}
CTT(c_j, \mathbf{R}_D^{c_j}) &\simeq \frac{L}{T_{relay}} \cdot \sum_{i=1}^{|\mathbf{R}_D^{c_j}|} P_{relay,R_i} A_D(S, R_i) \\
&= \frac{L}{T_{relay}} \cdot E[A_D^{c_j}],
\end{aligned} \tag{15}
$$

where $E[A_D^{c_j}]$ is the estimated relay advancement in c_j, and T_{relay} is the estimated one hop transmission delay in Eq. (5). To maximize the CTT in each channel, we need to find an optimal relay selection to maximize $E[A_D^{c_j}]$. When opportunistic routing over independent links uses $E[A_D^{c_j}]$ as a routing metric, [26] has proved that the optimal relay priority should be set according to the distance of the relay candidate to the destination. In addition, the maximum $E[A_D^{c_j}]$ increases with the number of relay candidates. Therefore, we can assign the relay priority in the descending order of $A_D(S, R)$.

We then propose a heuristic algorithm, MAXCTT, as shown in Algorithm 1. The inputs are the channel set C, the set of relay candidates $\mathbf{R}_D$, and the maximum number of relay candidates in relay selection r_{max}. MAXCTT selects the SUs from $\mathbf{R}_D$ to form the relay selection order $\mathbf{R}_D^{c_j}$ and

Algorithm 1 MAXCTT(C, $\mathbf{R}_D$, r_{max})

1: $c^* \leftarrow 0$; $\mathbf{R}_D^{c^*} \leftarrow \emptyset$; $CTT_{max} \leftarrow 0$;
2: **for** each c_j **do**
3: $\quad \mathbf{N} \leftarrow \mathbf{R}_D$; $\mathbf{R}_E \leftarrow \emptyset$; $\mathbf{R}_D^{c_j} \leftarrow \emptyset$; $R_p \leftarrow \emptyset$; $CTT_{c_j} \leftarrow 0$;
4: $\quad$ **while** ($\mathbf{N} \neq \emptyset$) **do**
5: $\qquad \mathbf{R}_E \leftarrow$ insert an SU $R_i \in \mathbf{N}$ that has max $A_D(S, R_i)$; Remove $R_j \in \mathbf{N}$ with $X_{R_i R_j} = 1$ from $\mathbf{N}$;
6: $\quad$ **end while**
7: $\quad$ **while** ($\mathbf{R}_E \neq \emptyset$ && $|\mathbf{R}_D^{c_j}| < r_{max}$ && $X_{SR_p} \neq 1$) **do**
8: $\qquad$ **for** each SU $R_i \in \mathbf{R}_E$ **do**
9: $\qquad\quad \mathbf{R}_T \leftarrow \mathbf{R}_D^{c_j} + R_i$; Sort $\mathbf{R}_T$ in the descending order of $A_D(S, R)$; Get CTT on $\mathbf{R}_T$ according to Eq. (14);
10: $\qquad\quad$ **if** ($CTT > CTT_{c_j}$) **then**
11: $\qquad\qquad CTT_{c_j} \leftarrow CTT$; $R_p \leftarrow R_i$;
12: $\qquad\quad$ **end if**
13: $\qquad$ **end for**
14: $\qquad \mathbf{R}_D^{c_j} \leftarrow$ insert R_p in the descending order of $A_D(S, R)$; $\mathbf{R}_E \leftarrow \mathbf{R}_E - R_p$;
15: $\quad$ **end while**
16: $\quad$ **if** ($CTT_{c_j} > CTT_{max}$) **then**
17: $\qquad c^* \leftarrow c_j$; $\mathbf{R}_D^{c^*} \leftarrow \mathbf{R}_D^{c_j}$; $CTT_{max} \leftarrow CTT_{c_j}$;
18: $\quad$ **end if**
19: **end for**
20: **return** $(c^*, \mathbf{R}_D^{c^*})$;

calculates the achieved CTT_{c_j} in each c_j. By comparing CTT_{c_j} over the channels, MAXCTT returns the channel c^* that has CTT_{max} and the corresponding relay selection order $\mathbf{R}_D^{c^*}$ as the algorithm output.

Specifically, an eligible relay candidate set $\mathbf{R}_E$ is formed by excluding the SUs affected by the same PU in c_j according to Lemma 5.1, which is a subset of $\mathbf{R}_D$ (line 4–line 6). A recursive searching [14] is then applied to obtain $\mathbf{R}_D^{c_j}$. At the beginning of the searching step, $\mathbf{R}_D^{c_j}$ contains no SU. Each time, $\mathbf{R}_D^{c_j}$ includes one more relay candidate out of the remaining SUs in $\mathbf{R}_E$ which provides the best CTT improvement (line 8–line 14). The selected relay candidates are sorted in the descending order of $A_D(S, R)$ in $\mathbf{R}_D^{c_j}$. The formed $\mathbf{R}_D^{c_j}$ contains all relay candidates from $\mathbf{R}_E$, and it satisfies the requirements of r_{max} and Property 5.2 (line 8). The recursive searching obtains the optimal $\mathbf{R}_D^{c_j}$ in c_j when the size of the selection order is at most 2, and it achieves almost the same performance as the optimal solution when the final order contains more than 2 candidates according to Lemma 5.1 in [14]. Suppose that the largest size of $\mathbf{R}_E$ over the channels is n, at most $m \cdot \sum_{k=1}^{n} k$ times of the CTT calculations are required to find CTT_{max}. Thus, the time complexity of MAXCTT is $O(m \cdot n^2)$, which is much lower than exhaustive search.

VI. Performance Evaluation

In this section, we evaluate the performance of the OCR protocol by simulation under different network settings, e.g., channel conditions, number of SUs, and traffic loads, using an event-driven simulator coded in C/C++ [10], [27]. The network parameter settings are shown in Table II if no other specification is made in the individual study.

TABLE II
Simulation Parameters

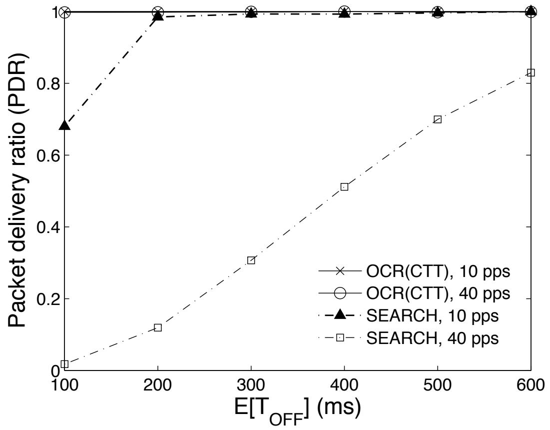
Number of channels	6
$\{\rho_{c_1}, \rho_{c_2}, \rho_{c_3}, \rho_{c_4}, \rho_{c_5}, \rho_{c_6}\}$	{0.3, 0.3, 0.5, 0.5, 0.7, 0.7}
Number of PUs per channel	11
PU coverage	250 m
$E[T_{OFF}]$	[100 ms, 600 ms]
Number of SUs	[100, 200]
SU transmission range	120 m
Source-destination distance	700 m
SU CCC rate	512 kbps
SU data channel rate	2 Mbps
CBR delay threshold	2 s
Mini-slot time, μ	4 μs
Per channel sensing time	5 ms
Channel switching time	80 μs
PHY header	192 μs
r_{max}	2

A. Simulation Settings

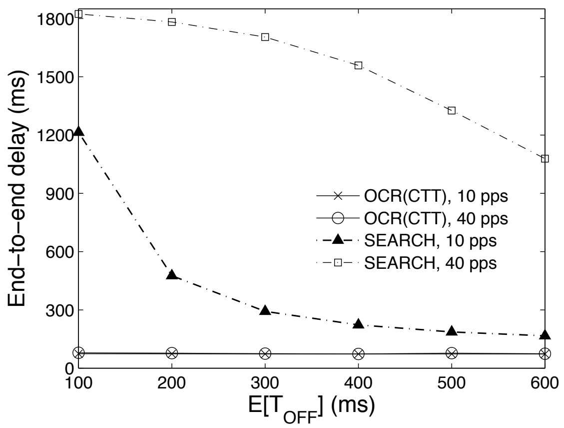
The PU activity in each channel is modeled as an exponential ON-OFF process with parameters $1/E[T_{ON}]$ and $1/E[T_{OFF}]$, and the idle rate $\rho = E[T_{OFF}]/(E[T_{ON}] + E[T_{OFF}])$ is selected accordingly. The channel status is updated by periodic sensing and on-demand sensing before data transmissions. We set up a CRN with multiple PUs and SUs randomly distributed in an 800×800 m^2 area. We set a pair of SUs as source and destination with a distance of 700 m, and a constant bit rate (CBR) flow is associated with the SU pair with packet size 512 bytes and flow rate of 10 packets per second (pps). The unit disc model is applied for the data transmission. The channel switch time is 80 μs [28], the minimum sensing duration with energy detection is 5 ms, and a mini-slot is 4 μs [23]. We evaluate the performance of the proposed OCR protocol in terms of the end-to-end delay, the packet delivery ratio (PDR) and the hop count, i.e., the total number of transmission hops between the source and destination SUs. We run each experiment for 40 s and repeat it 500 times to calculate the average value.

We then compare the performance of the OCR protocol with that of SEARCH [6], based on different metrics for the channel and relay selection, which are listed as follows.

1) SEARCH: SEARCH [6] is a representative geographic routing protocol in CRN. It sets up a route with the minimal latency before data transmissions. If an active PU is detected which blocks the route, SEARCH pauses the transmissions and recalculates the route. We modify SEARCH by updating route periodically to adapt to the dynamic changing spectrum access opportunities along the route.
2) OCR (CTT): For OCR (CTT), the channel and the relay candidate set are jointly selected by using the proposed CTT metric and heuristic algorithm proposed in Section V.
3) OCR (OPT): For OCR (OPT), the channel and the relay candidate set are determined by exhaustively searching



(a) Packet delivery ratio (PDR)



(b) End-to-end delay

Fig. 2. Performance comparison between OCR and SEARCH under different channel conditions (Number of SUs: 200, flow rate: 10/40 pps)

for the biggest CTT over all possible channel-relay sets.

4) GOR: For geographic opportunistic routing (GOR) algorithm, the SU first selects the channel with the greatest success probability of packet transmissions; if the channel is sensed idle, the SU then select a relay SU over the channel. The relay selection order is based on the location information and the relay capability of SUs [16].
5) GR: For geographic routing (GR), an SU first selects the channel for sensing as in GOR. If the selected channel is sensed idle, the SU then selects the SU closest to the destination as the next hop relay.

B. PU Activities

We first evaluate the performance of OCR under different PU activity patterns. The average PU OFF duration $E[T_{OFF}]$ varies from 100 ms (high channel dynamics) to 600 ms (low channel dynamics). The PDR performance of OCR and SEARCH are compared under different traffic loads in Fig. 2(a). A smaller $E[T_{OFF}]$, e.g., 100 ms, indicates the available time window is shorter and thus SUs' transmissions are more likely to be interrupted by PUs. We can see a marked PDR improvement under dynamic channel conditions for the

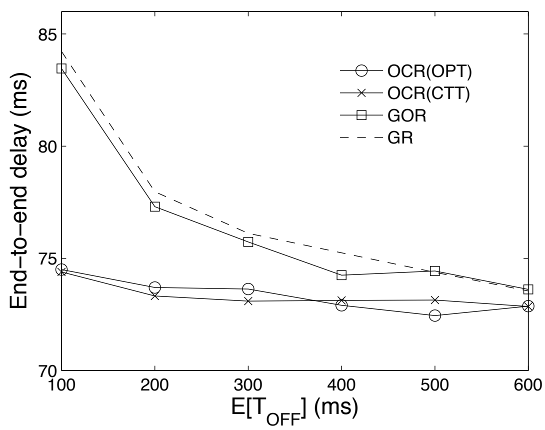


Fig. 3. Performance comparison under different traffic loads and PU activities (Number of SUs: 200, flow rate: 10 pps)

TABLE III
AVERAGE NEIGHBOR DENSITY UNDER DIFFERENT SU DENSITIES

Number of SUs	100	120	140
Average number of neighbors	7.0686	8.4823	9.8960
Number of SUs	160	180	200
Average number of neighbors	11.3097	12.7235	14.1372

per hop relay schemes, e.g., OCR (CTT), compared with SEARCH which is based on the global route establishment. In OCR (CTT), SUs are allowed to locally search and exploit spare spectrum and select the available links for data forwarding. Thus, OCR (CTT) can adapts well in the dynamic data channels. On the contrary, SEARCH uses a pre-determined routing table. Once an active PU is detected along the relay path, intermediate SUs should defer the packet relay until they update their routing tables according to the current channel availabilities in CRN. Since more SUs are involved in the route establishment, the handshakes between SUs in the network to establish the relay path introduce a large overhead and results in a longer delay.

Fig. 2(b) and Fig. 3 compare the end-to-end delay performance. All routing protocols achieve a better delay performance when the idle channel state becomes longer, e.g., from 100 ms to 600 ms, as more packets can be transmitted during the idle state. When the channel state change frequently, SEARCH needs to update routing tables accordingly which involves a long delay for route recovery. Our proposed OCR protocols are opportunistic routing algorithms that quickly adapt to the dynamic channel environment and achieve better delay performance compared with SEARCH. OCR (CTT) also outperforms GR and GOR since the latter two protocols perform the channel and relay selection separately while OCR (CTT) jointly considers the channel selection and relay selection.

C. Multi-user Diversity

We investigate the impacts of node density on the relay performance. The number of SUs in CRN varies from 100 to 200. When the number of SUs is large, the sender has more neighbors as shown in Table III. With more SUs in the neighborhood, the relay is more likely to find a feasible

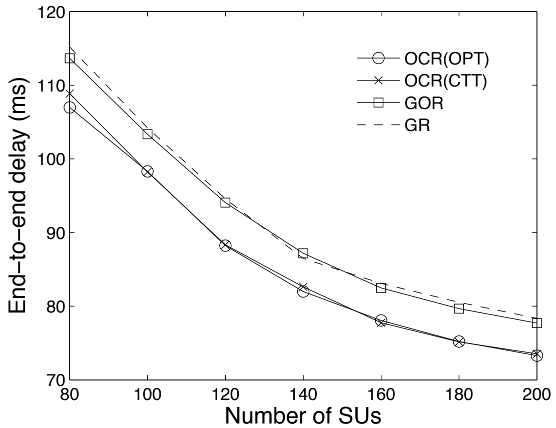
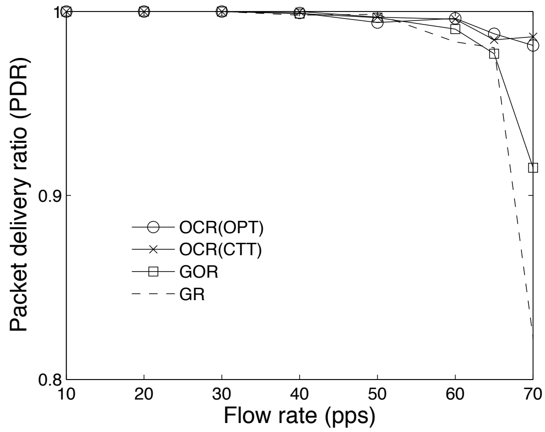
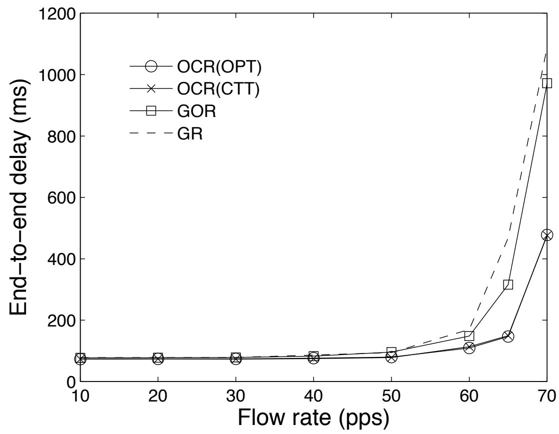


Fig. 4. Performance comparison of end-to-end delay under different SU densities (flow rate: 10 pps, $E[T_{OFF}] = 200\ ms$)



(a) Packet delivery ratio (PDR)



(b) End-to-end delay

Fig. 5. Performance comparison under different traffic loads (Number of SUs: 200, $E[T_{OFF}] = 200\ ms$)

relay link with better relay distance advance, which reduces the hop count number. The relay performance increases with the number of SUs due to the larger diversity gain. As a result, for all protocols, the hop count of the end-to-end relay decreases and the PDR increases with SU density by exploiting the multi-user diversity in CRN. The end-to-end delay performance under different SU densities is compared in Fig. 4. For GR and GOR, a channel is selected first, and then SUs coordinates to serve as relay. The coordination overheads increase with the number of SUs, which also degrades the PDR performance. The proposed OCR (CTT) jointly considers the channel and relay selection, and SU coordination overhead is minimized as sender determines the relay selection order based on the relay priority.

We also compare the performance of the heuristic algorithm for the channel-relay selection in OCR (CTT) with the optimal one in OCR (OPT) where the selection is based on exhaustive search. Fig. 4 shows that OCR (CTT) achieves almost the same performance as OCR (OPT), even when the returned number of the selected relay candidates is only 2, according to the value of r_{max} in Table II. Table III indicates that as the SU density increases in the network, the number of neighbors along the forwarding direction of the sender will increase accordingly. For example, given 160 SUs over 6 channels, the average number of neighbors of an SU is around 11. OCR (OPT) takes over 6.5×10^8 times of the CTT calculation to find the globally optimal solution which is infeasible for real time implementation. In the simulated scenario, although at most 4 neighbors are under independent PU coverage which significantly reduces the searching space, OCR (OPT) still takes 384 runs while OCR (CTT) only needs 60 runs, which achieves the marked reduction at the computational expense.

D. Effectiveness of Routing Metric

We further compare the performance of OCR (CTT) with that of GR and GOR to evaluate the effectiveness of routing metrics used in the channel and relay selection. We first compare the performance under different traffic loads. We change the traffic load by varying the flow rate from 10 pps (light load) to 70 pps (heavy load). As shown in Fig. 5(a) and Fig. 5(b), when the traffic load increases, the PDR and delay performance degrade. However, the decreasing rate of OCR (CTT) is much lower than that of GR and GOR. This is because OCR (CTT) jointly considers the optimal channel and link selection, while the other two OCR protocols select the channel and relay separately.

We define P_{ef} to be the ratio of the number of successful relay transmissions to the number of the sensing operations performed in the data channels. P_{ef} indicates the effectiveness of the routing metrics since the transmission relies on detection of an idle channel and an available relay node. If P_{ef} approaches to 1, the selected channel for each hop relay almost surely is available for data transmission. Fig. 6 shows the performance of P_{ef} under different node densities. In all network scenarios, OCR (CTT) outperforms GR and GOR, because CTT metric jointly considers the channel access and relay selection.

VII. Conclusions

In this paper, we have proposed an opportunistic cognitive routing (OCR) protocol to improve the multi-hop transmission performance in CRN. We have studied the impact of PU activities on the operation of OCR in channel sensing, relay selection and data transmission. Furthermore, we have pro-

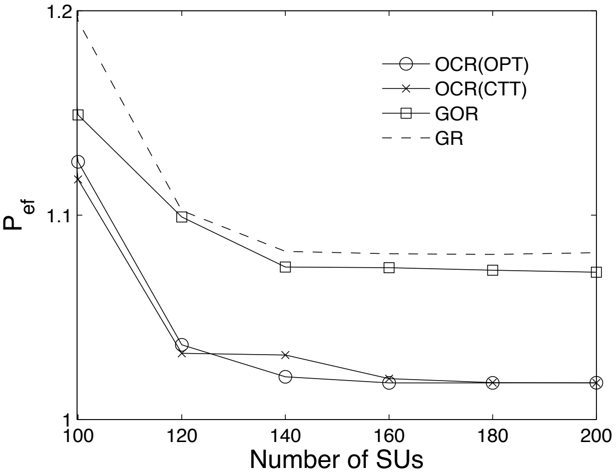


Fig. 6. Performance comparison under different SU densities (flow rate: 10 pps, $E[T_{OFF}] = 200\ ms$)

posed a novel metric, CTT, for the channel and relay selection. Based on the metric, we have proposed a heuristic channel and relay selection algorithm which approaches optimal solution. We have compared the performance of OCR (CTT) with that of the existing routing approaches, e.g., SEARCH, GR and GOR and shown that the proposed OCR achieves the highest PDR and the lowest delay. In our future work, we will study protocol design with uncertain channel usage statistics and the impacts of the measurement errors on the protocol performance.

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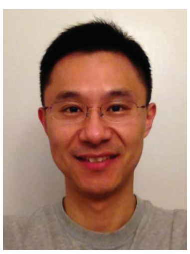

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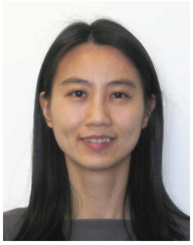

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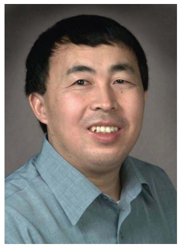

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