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Delay efficient opportunistic routing in asynchronous multi-channel cognitive radio networks

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Abstract In this paper, we are interested in designing efficient distributed opportunistic routing protocols for multi-hop multi-channel cognitive radio networks (CRNs). In CRNs, secondary users (SUs) access unused primary channels opportunistically, which induces considerable end-to-end delays for multi-hop routing. The primary cause of the delay overhead is that the set of available channels change dynamically over time due to the activities of primary users, making it challenging to effectively explore the spectrum diversity. Our approach towards working with such a dynamic network is to construct a cross-layer distributed opportunistic routing protocol. Our protocol jointly considers the channel sensing strategy, the forwarder selection for each SU, and the package division scheme on each link. We mathematically model the expected delay of each hop along the routing path. This delay model sheds lights on our expected end-to-end delay analysis, from which we develop a distributed algorithm to derive the system parameters for the opportunistic routing protocol. Extensive simulation results indicate the improved performance of our opportunistic routing protocol in terms of end-to-end delay, especially for CRNs with highly dynamic channel conditions.

Keywords Cross-layer routing · Forwarding set · Cognitive radio network · Opportunistic routing

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1 Introduction

The spectrum is one of the most valuable resources available for wireless communication. However, numerous experimental studies show that the licensed spectrum is not efficiently used in both the time and space dimension, leading to a phenomenon referred to as spectrum holes (Akyildiz et al. 2006). On the contrary, communications over unlicensed spectrum become more and more overcrowded due to the tremendous growth of wireless applications. The inefficient utilization of licensed spectrum and crowded unlicensed spectrum necessitate a new communication paradigm, Cognitive Radio Networks (CRNs), in order to counteract this issue. The idea of CRNs is to equip Secondary Users (SUs) with Cognitive Radios (CRs) that are able to sense and hop to different channels opportunistically and dynamically. Exploiting the flexibility of the CRs to enable wireless nodes to dynamically access the spectrum and utilize the spectrum holes has proven to be a promising paradigm (Akyildiz et al. 2006).

In CRNs, one important constraint is that the data transmitted on any channel by SUs should not affect the communications of primary users (PUs), or such interference should be limited and constrained by some predefined thresholds. These constraints introduce a myriad of challenges to the protocol design for CRNs. One of the most significant challenges is to minimize the end-to-end delay in multi-hop CRNs. In this framework, the set of available channels is dynamically changing over time and varies from node to node. To further complicate matters, such heterogeneity is usually difficult, if not impossible, to predict accurately in real time. Since each SU must find an idle channel prior to forwarding the packet to its neighbors in large scale multi-hop CRNs, additional delays are incurred at each relay node along the path from the source to the destination. Unfortunately, most existing research for delay analysis focuses on single hop CRNs (Wang et al. 2010). This type of analysis cannot be easily extended to multi-hop scenarios. The works in Ren et al. (2010, 2012) theoretically analyze multi-hop delay in CRNs from the perspective of connectivity. Most recently, Liu et al. (2011) provides an opportunistic routing protocol for multi-hop CRNs that jointly considers channel selection and sensing. However, their designs only consider local information, which do not work well for heterogenous CRNs (i.e., the spectrum holes are not uniform). Our design in this paper studies the end-to-end delay from a global perspective, which can adapt robustly to various CRNs with non-uniform spectrum holes.

When considering a multi-hop multi-channel CRN, the logical topology of the whole network is highly dynamic and often disconnected at a given time instance. Moreover, the available time for a secondary link over a primary channel changes dynamically and may be shorter than the time needed to finish a complete packet transmission, i.e., the transmission of SUs can be interrupted by PUs at any time. For these reasons, computing a fixed routing path for a session is clearly not a good choice. The variable nature of CRNs motivates the use of opportunistic routing since it can potentially adapt well to the real-time channel availabilities. With opportunistic routing, packets may transverse the network over different paths and even possibly over different channels for the same link. This leads to two problems to solve in order to design an opportunistic routing protocol for multi-hop multi-channel CRNs. The first is how to detect and choose a “good” channel in real time. Often, the quality of channels differs even for the same SU, and the same channel may have different idle distribution for different SUs. Moreover, the length of idle periods may be different for the same SU on the same channel. Adaptively choosing an idle channel under such high channel diversity is challenging. The second problem is how to detect and select a “good” forwarder in real time. While the sender and forwarder should have a common idle channel, the forwarder should have a relatively low expected delay to the sink. Identifying a forwarder that meets these conditions is not trivial, especially in a CRN.

In this paper, we develop a cross-layer routing method for a multi-channel multi-hop CRN, and aim to minimize the delay from the source to a common destination, or sink. For practical consideration, our design does not assume the network is synchronized. We employ the idea of opportunistic forwarding to reduce single hop delays, thus reducing the overall end-to-end delay significantly. Specifically, each SU jointly selects the channel and next hop for packet forwarding. We divide the joint selection process into three stages, with an accurate model for the delay of each stage. Based on this fine-grained design and systematic delay analysis, the delay to the sink is significantly reduced through dynamic programming technology. Our contributions in this paper are as follows. First, we design a routing protocol for asynchronous multi-channel multi-hop CRNs that is easy to implement and delay efficient. Second, the delay to the sink for each packet from different SUs is explicitly and accurately modeled, and we present a low complexity heuristic algorithm with the objective of minimizing the delay, which obtains a solution close to optimal one. Finally, we evaluate the performance of our protocol via both theoretical analysis and extensive simulations.

The remainder of the paper is organized as follows. In Sect. 2, we provide a comprehensive literature review related to the delay problem in CRNs. In Sect. 3, we describe the system model and introduce the opportunistic forwarding protocol. In Sect. 4, we divide the forwarding protocol into three stages and analyze each one mathematically. In Sect. 5, we illustrate the performance of our algorithm and compare it against other algorithms through simulation results. We conclude the paper in Sect. 6.

2 Related work

Spectrum availability in CRNs is frequently changing, resulting in extensive delays, as SUs along the routing path must wait for the channel to be idle. To address this challenge, many researchers have looked towards both theoretical and practical solutions. With the objective of supporting delay sensitive communications of unlicensed users, Wang et al. (2012) studies the optimal admission control and channel allocation decisions in cognitive overlay networks. The authors formulate it into a Markov decision process problem and solve it by transforming the original formulation into a stochastic shortest path problem. Wang et al. (2010) considers a CRN where multiple SUs contend for spectrum usage with random access over available primary channels. In Chen et al. (2011), the authors explore the problem of minimizing queueing delays for opportunistic access of multiple continuous time Markov channels. Each of these efforts focuses on delay performance in single-hop CRNs.

For multi-hop CRNs, Ren et al. (2010) analyzes the multi-hop delay of ad hoc CRNs, where the transmission delay of each hop consists of the waiting time for the availability of the communication channel and propagation delay. With the help of the techniques from continuum percolation and ergodicity, the authors in Ren et al. (2010) establish the scaling law of the minimum multi-hop delay with respect to the source destination distance. Han and Yang (2010) derives an information propagation speed upper bound in CRNs. The derived upper bound is tight when the number of primary channels is large. Most recently, Liu et al. (2012) uses continuum percolation theory to investigate the scaling behavior of transmission delay in large scale ad hoc CRNs. They consider different scenarios of CRNs to obtain a wide range of theoretical results. For single channel multi-hop CRNs, Ji et al. (in press) proposed a three-step unicast scheme based on a carefully constructed cell-based virtual backbone. The induced delay from their unicast scheduling algorithm scales linearly with the transmission distance between the source and the destination.

Recently, the approach of opportunistic routing has also been widely employed. Opportunistic routing (Biswas and Morris 2004) is a routing mechanism that takes advantages of the broadcast characteristic of wireless transmission, and is often used to compensate for unreliable links due to the dynamic wireless environment. In Kim et al. (2008), the authors employ opportunistic routing to minimize end-to-end delay and maximize the lifetime of wireless sensor networks. Opportunistic routing is also employed to minimize energy consumption by routing a single packet in Mao et al. (2011). Since opportunistic routing does not need prior setup of the route, it is more suitable for CRNs with frequent changes of spectrum availability. The authors in Khalife et al. (2008) are among the first to use opportunistic routing for CRNs. They proposed a novel probabilistic metric towards selecting the best path to the destination in terms of the spectrum/channel availability capacity. Their approach, however, does not account for spectrum availability time. In a CRN, both spectrum handoff and required transmission time can significantly impact network connectivity and routing. Hence, in Badarneh and Salameh (2011), the authors introduce a novel routing metric that jointly considers the spectrum availability of idle channels and the required CR transmission times over those channels. This metric aims at maximizing the probability of success (PoS) for a given CR transmission, which consequently improves network throughput. In the analysis, they analytically derive a closed-form expression for the PoS based method on a stochastic model of PUs activities under the Rayleigh fading channel model. In Shiang and Schaar (2008), the authors propose an algorithm to determine the channel decision strategies of the neighboring CR users over time in order to identify the channels that are likely to be used by them. However, their algorithm requires extensive information exchange between neighbors and it is not clear how long the network would take to converge to the optimal solution. In Lin and Chen (2010), the authors proposed SAOR (spectrum aware opportunistic routing) for a single-channel CRN. SAOR considers the opportunistic link characterized by successful transmission rate and channel availability. In practice, there is usually more than one channel available in a CRN, and it is important for the routing protocol to make full utilization of all the channels in order to achieve lower end-to-end delay and higher throughput. In Khalife et al. (2011), the authors propose MSAOR (multi-channel spectrum aware opportunistic routing) based on link delay analysis. The MSAOR algorithm attempts to broadcast packets on every channel of the CR link to exploit the benefits of multiple channels, thus reducing the link delay and further reducing the end-to-end delay. Their analysis shows that MSAOR achieves a lower link delay than SAOR. Liu et al. (2011) considers heterogeneous channel occupancy patterns, and introduces opportunistic routing into the CRN where the statistical channel usage and the physical capacity in the wireless channels are exploited in the routing decision. To support opportunistic transmissions in CRNs, Liu et al. (2011) further discusses how to predict and evaluate the channel utility when the SUs need to explore multiple channels and the sensing delay is significant in the relay operation. However, none of the above works (Liu et al. 2011; Khalife et al. 2008; Badarneh and Salameh 2011; Lin and Chen 2010; Khalife et al. 2011; Liu et al. 2011; Cai et al. 2013, 2012; Ji et al. 2013) systematically and accurately model the expected end-to-end delay. In this paper, we aim to develop a distributed algorithm to derive the configuration for opportunistic routing with the objective of minimizing the expected end-to-end delay.

3 System model

3.1 Network elements and channel model

We consider a static multi-hop multi-channel cognitive radio network (CRN) with N secondary users (SUs). Denote $\mathcal{S} = \{s_1, s_2, \ldots, s_N\}$ as the set of all SUs in the CRN, where s_N is the destination of all the data packets, referred to as the sink. Assume there are K orthogonal channels that are licensed to the primary users in the CRN deployment area. Denote the set of channels as $\mathcal{K} = \{c_1, c_2, \ldots, c_K\}$, further denote the bandwidth of c_k as w_k. Each SU s_i is equipped with a half-duplex cognitive radio (CR) that can access any of these K primary channels on the condition that the channel is available (e.g., idle) to the associated node (SU). All of the CRs can only stay on one channel at any time. During the idle state, (i.e., there is no data transmission), the CRs of all SUs periodically hop on K channels in a round-robin manner to ensure fair channel utilization consideration. Once a SU has data packet to transmit, the corresponding CR senses the K channels to detect an idle channel to access. In order to achieve a desirable level for detection quality by PHY-layer sensing (i.e., sensing accuracy) (Kim and Shin 2008), assume a predefined amount of time t_S is needed to accurately sense the channel and the CRs or SUs can only sense one channel at one time.

In this paper, we assume the SUs employ uniform transmission power and the corresponding transmission range is R. Based on this assumption, the PU occupation of c_k for s_i is modeled as an independent and identically distributed alternation 0 (idle) and 1 (busy) process, and the holding time for the states of idle and busy is exponentially distributed with mean λ_{ik} (s) and μ_{ik} (s), respectively. When c_k is idle for s_i during time interval $[t, t + \tau]$, we say c_k is available to s_i, which essentially means that s_i is able to access c_k to transmit data under any primary constraints, and the data transmitted by any SU within the receiving range of s_i during this time interval can be received and decoded successfully by s_i. For the convenience of analysis, we assume the above mentioned exponential distributions for all the SUs on different channels are independent. Note that the values of parameters μ_{ik} and λ_{ik} depend not only on the traffic loads and the physical locations of primary users (PUs) around s_i, but also on the transmission power of s_i. The methodology of parameters estimation is beyond the scope of this paper, please reference Kim and Shin (2008), Wellens et al. (2010) and Ren et al. (2009) for the detailed analysis about channel accessibility for SUs in CRNs.

3.2 Topology link and opportunistic forwarding link

For a pair of SUs s_i and s_j, a topology link Ren et al. (2010) exists between them if and only if $d(i, j) \leq R$, where $d(i, j)$ denotes the euclidian distance between s_i and s_j. Denote $\mathcal{E}$ as the set of these topology links, i.e., $\mathcal{E} = \Big\{e_{ij} \mid i, j \in \{1, 2, \ldots, N\},\ d(i, j) \leq R\Big\}$. Assume in the considered CRN, all SUs are topologically connected to the sink s_N, i.e., for any s_i, there exists at least one node sequence $s_{i_0}, s_{i_1}, \ldots, s_{i_h}, s_{i_{h+1}}$, such that $d(i_l, i_{l+1}) \leq R$ for any $0 \leq l \leq h$, where $i_0 = i$, and $i_{h+1} = N$.

Unlike traditional ad-hoc wireless networks, whether two SUs can communicate with each other in a CRN depends not only on the physical distance between them, but also on the transmission activity of PUs, i.e., the availability of the channels. Thus, the ability of SUs to employ links in $\mathcal{E}$ for data transmission varies over time due to the activities of PUs. There are cases where some topology links present extremely low opportunity to SUs and should be judiciously employed. Let $\mathcal{N}_i$ denote the set of SUs in the transmission range of s_i, i.e., $\mathcal{N}_i = \{s_j \mid d(s_i, s_j) \leq R\}$. Each SU s_i selects a subset of $\mathcal{N}_i$ as its forwarding set on channel k, which is denoted as F_{ik}. We say e_{ij}^k is an opportunistic forwarding link from s_i to s_j on channel k if $e_{ij} \in \mathcal{E}$ and $s_j \in F_{ik}$. Let $F_i = (F_{i1}, F_{i2}, \ldots, F_{iK})$, and $F = (F_1, F_2, \ldots, F_N)$, then the space of F_i is $\mathcal{F}_i = \mathcal{P}(\mathcal{N}_i)^K$, and the space of $\mathcal{F} = \mathcal{F}_1 \times \mathcal{F}_2 \times \cdots \times \mathcal{F}_N$, where $\mathcal{P}(\mathcal{N}_i)$ is the power set of $\mathcal{N}_i$.

3.3 Opportunistic forwarding

To reduce the relaying delay of each hop, we utilize the idea of opportunistic forwarding from Biswas and Morris (2004) for multi-hop routing. Due to the broadcast nature of the wireless channel, signals transmitted by a source node can potentially be overheard by all the neighboring nodes. Thus opportunistic forwarding has the potential to reduce the data forwarding delay under a dynamic (opportunistic) spectrum environment in CRNs. Without loss of generality, let us assume s_i has a data packet to transmit to the sink s_N at time t. In general, this packet should be transmitted to the sink through multi-hop routing, especially in large scale CRNs. For ease of description and analysis, we divide the single hop packet forwarding process into three stages, i.e., idle channel detection stage, forwarder detection stage and packet transmission stage.

In the idle channel detection stage, s_i continuously senses one of K channels in each time duration of t_S (e.g., a sensing period). If s_i senses any channel c_k to be idle, then the CR of s_i hops to c_k and the channel detection stage is finished, otherwise, s_i continues to sense for another duration of t_S on another of the K channels. During each sensing period, the decision of which channel to sense has to be carefully chosen to reduce the overall delay. Denote u_i as the sensing scheme of s_i, and let $U = \{u_1, u_2, \ldots, u_N\}$, where the space of U is denoted as $\mathcal{U}$. We will discuss how a node decides which channel to sense in Sect. 4.1.3.

In the forwarder detection stage, s_i uses channel c_k (for s_i) that was detected to be idle during the previous stage. At the beginning of this stage, s_i starts broadcasting a probing message that includes its id. The time needed to transmit the probing message is denoted as t_P. All nodes in $\mathcal{N}_i$ sojourning on channel k can potentially hear the probing message. Assume that $s_j \in \mathcal{N}_i$, and the CR of s_j remains on channel k, which is idle for s_j during the broadcast of the probing message, then s_j can receive the probing message by s_i successfully. Afterwards, s_j checks whether it is in the forwarding set of s_i on c_k. (We simply assume all nodes stores a list of nodes which indicate whether it is in their forwarding set, this can be implemented with local information exchange.)

If it is, s_j immediately replies with an ack on c_k. Denote the time needed for an ack transmission as t_A. At the same time, the CR of s_j stops hopping and remains on c_k for any following potential data transmission task. In the case that multiple CRs are tuned on c_k and reply with acks simultaneously, we use a backoff scheme to avoid the ack-collision. The explicit back-off strategy will be discussed in Sect. 4.1.2. We assume the extra time needed for ack replying is t_E. After each probing message, s_i checks whether there is any ack from the nodes in F_{ik}. Once an ack is received, the forwarder detection stage is finished. If no ack is received, s_i repeatedly broadcasts probing messages and listens until an ack is successfully received. As we will show later, the choice of F_{ik} significantly affects the overall expected delay to the sink, while the optimal choice of the forwarding set is not necessarily equal to $\mathcal{N}_i$. In Sect. 4.1.2, we analyze how to choose the optimal forwarding set on each channel c_k for all the SUs.

During the last stage, s_i transmits the data to s_j on c_k, which were determined in the second and first stages, respectively. To provide reliability, once s_j receives the whole packet, it replies with an ack message. Forwarding is completed only if s_i receives the ack message successfully. If the channel is sensed busy for either s_i or s_j, the transmission will be suspended. If the packet transmission on the opportunistic forwarding link e_{ij}^k is interrupted by the activities of PUs, s_i must retransmit the entire message again. Intuitively, the larger the size of the packet, the higher the probability that the transmission is interrupted, since longer continuous idle time on e_{ij}^k is needed for successful transmission. Without loss of generality, let us assume the size of all packets is σ. To solve the above problem, we divide the packet into equal-size frames if σ is "too big" for the opportunistic forwarding link e_{ij}^k. For each frame, an additional message size of ν is needed for practical consideration, i.e., protocol overheads for each packet. Let b_{ij}^k denote the number frames the packet is divided into on the opportunistic forwarding link e_{ij}^k. Then the space of b_{ij}^k

is $\mathbf{N}^{+}$. Let $B_k = \left[b_{ij}^k, i = 1, 2, \ldots, N, j = 1, 2, \ldots, N\right]$, then the space of B_k is denoted as $\mathcal{B}_k = \mathbf{N}_{+}^{N\times N}$. Further let $B = (B_1, B_2, \ldots, B_K)$, then the space of B is denoted as $\mathcal{B} = \mathcal{B}_1 \times \mathcal{B}_2 \times \cdots \times \mathcal{B}_K$. We discuss the packet division in detail in Sect. 4.1.1.

3.4 Problem

In this paper, we consider that a SU s_i has a packet with size σ to deliver to the sink through multi-hop relaying in a K-channel CRN. According to the description in the previous subsection, the stochastic process with which the packet traverses the CRN from s_i to the sink s_N is jointly determined by the channel sensing scheme (the first stage), opportunistic forwarding sets (the second stage) of each SU and packet division strategies (the third stage) over each opportunistic forwarding link. Our first objective is to minimize the expected delay of forwarding a packet of size σ from a source s_i to the sink, which is denoted as $D_i(U, F, B)$. Formally, given the topology of a static CRN, the number of channels K, the bandwidth w_k of each channel c_k and the opportunistic channel environments, i.e., λ_{ik} and μ_{ik}, we aim to solve the delay optimization problem, $\min_{U,\ F,\ B} D_i(U, F, B)$.

4 Joint channel sensing and opportunistic forwarding

4.1 Local expected delay analysis

In this subsection, we will first establish a recursive relationship for the expected delay from s_i to the sink, i.e., the expression of $D_i(U, F, B)$. According to the description of opportunistic forwarding in Sect. 3.3, we can naturally divide the analysis into three stages: idle channel detection, forwarder detection and packet transmission. For ease of analysis, we will discuss and analyze the time needed for each stage in a reverse order.

4.1.1 Packet transmission

Assume s_i has already chosen the forwarder node s_j on channel c_k in the second and first stages of opportunistic forwarding, respectively. As mentioned in Sect. 3.3, the size of frame on each opportunistic forwarding link should be carefully decided due to the dynamic nature of the links in CRN. If the frame size is chosen to be either too large or too small, then this will result in larger overall transmission delays. To avoid this overhead, we explicitly quantify the transmission delay as a function of the number of frames.

Let us first analyze the probability $\theta_{ik}(t)$ that c_k is idle for s_i during any time duration t. As mentioned before, the states of idle and busy are exponentially distributed with mean λ_{ik} (s) and μ_{ik} (s), respectively, and these distributions are independent. Let $\alpha_{ik} = \frac{\lambda_{ik}}{\lambda_{ik}+\mu_{ik}}$, then the probability that channel k is idle for any time instance is α_{ik}. If c_k is idle for s_i for a given time instance, then due to the memoryless nature of the exponential distribution, the probability that the idle state can continue another duration of t is $e^{-\frac{1}{\lambda_{ik}}t}$, thus,

$$\theta_{ik}(t) = \alpha_{ik} e^{-\frac{1}{\lambda_{ik}}t}. \tag{1}$$

Assume a packet of size σ is divided into b_{ij}^k equal-size frames for transmission on opportunistic forwarding link e_{ij}^k. For each frame, an idle duration of $t = (\sigma/b_{ij}^k + \nu)/w_k + t_A$ is needed. Considering idle periods of s_i on c_k, for any duration of t, the probability that channel k is idle for s_j is $\theta_{jk}(t)$. Channel k must be idle for both s_i and s_j in order for s_i to transmit packets successfully to s_j. Thus, the expected number of frames that can be forwarded to s_j in an idle period on channel k from s_i is

$$\delta_{ij}^k = \frac{\lambda_{ik}}{t}\theta_{jk}(t) = \frac{\lambda_{ik}\lambda_{jk}}{t(\lambda_{jk} + \mu_{jk})} e^{-\frac{1}{\lambda_{jk}}t}. \tag{2}$$

Finally, the expected time for forwarding b_{ij}^k frames on the opportunistic forwarding link e_{ij}^k is (Here we consider the complicated case $\frac{b_{ij}^k}{\delta_{ij}^k} \geq 1$. For the one $\frac{b_{ij}^k}{\delta_{ij}^k} < 1$, similar results can be easily obtained)

$$\begin{aligned} T_{ij}^k(b_{ij}^k) &= \frac{b_{ij}^k}{\delta_{ij}^k}\lambda_{ik} + \left(\frac{b_{ij}^k}{\delta_{ij}^k} - 1\right)\mu_{ik} \\ &= \frac{b_{ij}^k}{\delta_{ij}^k}(\lambda_{ik} + \mu_{ik}) - \mu_{ik} \\ &= \frac{(\lambda_{ik} + \mu_{ik})(\lambda_{jk} + \mu_{jk})te^{\frac{1}{\lambda_{jk}}t} b_{ij}^k}{\lambda_{ik}\lambda_{jk}} - \mu_{ik}, \end{aligned} \tag{3}$$

where $t = (\sigma/b_{ij}^k + \nu)/w_k + t_A$. The first line of (3) indicates that if b_{ij}^k frames need to be forwarded, the expected number of times of idle states is $\frac{b_{ij}^k}{\delta_{ij}^k}$ since δ_{ij}^k frames can be forwarded in each idle period. The total expect time for forwarding should include $\frac{b_{ij}^k}{\delta_{ij}^k}$ idle states and $\frac{b_{ij}^k}{\delta_{ij}^k} - 1$ busy states.

Let $\frac{dT_{ij}^k}{db_{ij}^k} = 0$,
we have

$$z = \frac{\sigma}{2\lambda_{jk} w_k}\left(1 + \sqrt{1 + \frac{4\lambda_{jk}}{\nu/w_k + t_A}}\right) \tag{4}$$

since $b_{ij}^k \in \mathbf{N}^+$, the optimal value of b_{ij}^k minimizing T_{ij}^k is,

$$b_{ij}^{k*} = \underset{x \in \left\{\lfloor z \rfloor, \lceil z \rceil\right\}}{\operatorname{argmin}} T_{ij}^k(x). \tag{5}$$

The above analysis uniquely defines the optimal packet division scheme B^* over all the opportunistic forwarding links. The minimum expected time needed for transmiting a packet of size σ on the opportunistic forwarding link e_{ij}^k is determined as well. According to (4) and (5), B^* depends only on the channel bandwidth of each channel and the mean time of idle periods on each channel for different SUs, which are all given parameters in this paper.

4.1.2 Forwarder detection

Now assume s_i has already detected an idle channel c_k for itself in the first stage. Next it hops to c_k and starts the forwarder detection on this channel. Thus, the following discussion is based on the assumption that s_i hops onto c_k, which is idle for s_i at this moment. Before the analysis, assume that the forwarding set F_{ik} of s_i on c_k is already given, where $F_{ik} \subseteq \mathcal{N}_i$. Moreover, as mentioned in Sect. 3.3, a back-off scheme has to be provided for the SUs in F_{ik} to avoid possible ack-collision. Without loss of generality, assume the SUs in F_{ik} are prioritized and sorted as $s_{i1}, s_{i2}, \ldots, s_{i|F_{ik}|}$. From the viewpoint of s_i, s_{ij} has higher priority than $s_{ij'}$ and thus has a shorter back-off time than $s_{j'}$ if $1 \leq j < j' \leq |F_{ik}|$. We will next focus on how to select the forwarding set F_{ik} and how to prioritize the SUs in F_{ik}.

Let $t_I = t_P + t_E + t_A$. In any duration of t_I, s_i broadcasts a probing message and it can receive an ack message successfully, if and only if in this time duration, c_k is idle for s_i and at least one SU in F_{ik}. Now assume in time interval $[t, t + t_I]$, c_k is idle for s_i and it broadcasts a probing message at time t. The probability ϕ_{ik} that s_i does not receive any ack message in time interval $[t + t_P, t + t_I]$ is equal to the probability that during any period of t_I, c_k is not idle for any SU in F_{ik}. Notice that during the idle state, the CRs of all SUs periodically hop on K channels in a round-robin manner. Thus,

$$\phi_{ik} = \prod_{j=1}^{|F_{ik}|} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right) = \prod_{j=1}^{|F_{ik}|} \left(1 - \frac{1}{K}\alpha_{jk} e^{-\frac{1}{\lambda_{jk}} t_I}\right), \tag{6}$$

where α_{jk} is defined in previous subsection.

For ease of analysis, we first assume c_k is always idle for s_i during the probing-ack process. When s_i starts to broadcast probing messages on channel k, the probability $\Phi_{ik}^{l,h}$ that the l-th node s_l in F_{ik} becomes the forwarder right after the h-th probing period is equal to the probability that c_k is not idle for any SU in F_{ik} during the past $h-1$ probing periods, and during the h-th one, c_k is idle for s_l while busy for any SU $s_j \in F_{ik}$, where $j < l$, i.e.,

$$\Phi_{ik}^{l,h} = \phi_{ik}^{h-1} \frac{1}{K}\theta_{lk}(t_I) \prod_{j=1}^{l-1} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right). \tag{7}$$

The probability $\psi_{i,k,l}$ that s_i forwards packets to the l-th node in F_{ik} (i.e., s_{il}) on channel c_k is

$$\psi_{i,k,l} = \sum_{h=1}^{\infty} \Phi_{ik}^{l,h} = \frac{\theta_{lk}(t_I) \prod_{j=1}^{l-1} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)}{K\left(1 - \prod_{j=1}^{|F_{ik}|}\left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)\right)} = \frac{\theta_{lk}(t_I) \prod_{j=1}^{l-1} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)}{K(1-\phi_{ik})}. \tag{8}$$

Finally, under the assumption that c_k is always idle for s_i, the expected time needed for s_i to find a forwarder on c_k is,

$$\sum_{h=1}^{\infty} \sum_{l=1}^{|F_{ik}|} h t_I \Phi_{ik}^{l,h} = \frac{t_I}{K\left(1 - \prod_{j=1}^{|F_{ik}|}\left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)\right)} = \frac{t_I}{K(1-\phi_{ik})}. \tag{9}$$

Note that above analysis is under the assumption that c_k is always idle for s_i during the probing-ack process. In fact, the channel c_k is alternatively idle and busy for s_i with exponential distributions with mean λ_{ik} and μ_{ik}, respectively. Thus, for each expected idle period of λ_{ik}, s_i has to suspend probing for an expected duration of μ_{ik} before the next opportunity of accessing a channel arises. Equivalently, for each $\frac{\lambda_{ik}}{t_I}$ iterations of probing-ack, s_i has to wait for an expected time of μ_{ik} for the next probing-ack. More specifically, let $[x]^+ = 1$ if $0 < x < 1$, else $[x]^+ = \lfloor x \rfloor$ and further let $z = \left[\frac{\lambda_{ik}}{t_I}\right]^+$. Now considering the h in (9), when $h \in [\delta z + 1, (\delta+1)z]$, expected additional time of $\delta\mu_{ik}$ has to be accounted for, where $\delta \in \mathbf{N}^*$. Thus, the overall additional time for s_i to finish probing on c_k is

$$\sum_{\delta=1}^{\infty} \sum_{j=\delta z+1}^{(\delta+1)z} \phi_{ik}^{j-1} \delta\mu_{ik} = \mu_{ik} \sum_{\delta=1}^{\infty} \delta\phi_{ik}^{\delta z} \sum_{j=0}^{z-1} \phi_{ik}^{j} = \mu_{ik} \frac{1-\phi_{ik}^z}{1-\phi_{ik}} \sum_{\delta=1}^{\infty} \delta\phi_{ik}^{\delta z} = \mu_{ik} \frac{1-\phi_{ik}^z}{1-\phi_{ik}} \frac{\phi_{ik}^z}{(1-\phi_{ik}^z)^2} = \frac{\phi_{ik}^z}{(1-\phi_{ik})(1-\phi_{ik}^z)} \mu_{ik}. \tag{10}$$

According to above analysis, the actual expected time needed at s_i for forwarder detection on the channel c_k is

$$d_{ik} = \frac{t_I}{K(1-\phi_{ik})} + \frac{\phi_{ik}^z}{(1-\phi_{ik})(1-\phi_{ik}^z)}\mu_{ik}. \tag{11}$$

Now assume the expected delay (to the sink) of D_j is given for any $s_{ij} \in F_{ik}$. Then, from the beginning of the second stage (forwarder detection) at s_i, the expected delay to forward the data packet to the sink is

$$\begin{aligned} D_{ik}(F_{ik}) &= d_{ik} + \sum_{j=1}^{|F_{ik}|} \psi_{i,k,j}(T_{ij}^k + D_j) \\ &= \frac{t_I + \sum_{l=1}^{|F_{ik}|} \theta_{lk}(t_I) \prod_{j=1}^{l-1} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)(T_{il}^k + D_l)}{K(1-\phi_{ik})} \\ &\quad + \frac{\phi_{ik}^z}{(1-\phi_{ik})(1-\phi_{ik}^z)}\mu_{ik}, \end{aligned} \tag{12}$$

where T_{ij}^k is determined in previous subsection. Now our objective is to minimize D_{ik}, which not only depends on how to choose F_{ik} from $\mathcal{N}_i$, but also on how to prioritize the SUs in F_{ik}. For the prioritizing strategy, we have following theoretical result.

Theorem 1 *For any $F_{ik} \subseteq \mathcal{N}_i$, $D_{ik}(F_{ik})$ is minimized when s_{ij} has higher priority than $s_{ij'}$ if and only if $T_{ij}^k + D_j \leq T_{ij'}^k + D_{j'}$, where $s_{ij}, s_{ij'} \in F_{ik}$.*

Proof Considering (12), both $\frac{\phi_{ik}^z}{(1-\phi_{ik})(1-\phi_{ik}^z)}\mu_{ik}$ and $K(1-\phi_{ik})$ are independent from the order of the SUs in F_{ik}. The argument we need to prove is that $g(F_{ik}) = \sum_{l=1}^{|F_{ik}|} \theta_{lk}(t_I) \prod_{j=1}^{l-1} \left(1 - \frac{1}{K}\theta_{jk}(t_I)\right)(T_{il}^k + D_l)$ is minimized when s_{ij} has higher priority than $s_{ij'}$ if and only if $T_{ij}^k + D_j \leq T_{ij'}^k + D_{j'}$. We prove this argument by contradiction.

If the argument is not true, their must exist a pair of SUs s_{im} and s_{in}, where $n = m+1$, in F_{ik} that violates the argument above. Without loss of generality, assume $T_{im}^k + D_m > T_{in}^k + D_n$, and L is any prioritized list of SUs from F_{ik} such that s_{im} has higher priority than s_{in} from the viewpoint of s_i. Further, denote L' as another prioritized list of SUs that is the same to L except that s_{im} and s_{in} are switched. Following we prove $g(L) - g(L') \geq 0$.

$$\begin{aligned} g(L) - g(L') = (T_{im}^k + D_m)\theta_{mk}(t_I) \prod_{l=1}^{m-1} \left(1 - \frac{1}{K}\theta_{lk}(t_I)\right) \\ + (T_{in}^k + D_n)\theta_{nk}(t_I) \prod_{l=1}^{m} \left(1 - \frac{1}{K}\theta_{lk}(t_I)\right) \end{aligned}$$

$$
\begin{aligned}
&-(T_{in}^k + D_n)\theta_{nk}(t_I)\prod_{l=1}^{m-1}\left(1-\frac{1}{K}\theta_{lk}(t_I)\right)\\
&-(T_{im}^k + D_m)\theta_{mk}(t_I)\left(1-\frac{1}{K}\theta_{nk}(t_I)\right)\prod_{l=1}^{m-1}\left(1-\frac{1}{K}\theta_{lk}(t_I)\right)\\
&= \theta_{mk}(t_I)\theta_{nk}(t_I)\prod_{l=1}^{m-1}\left(1-\frac{1}{K}\theta_{lk}(t_I)\right)(T_{im}^k + D_m - T_{in}^k - D_n)\\
&\geq 0 \qquad (13)
\end{aligned}
$$

□

According to above theorem, the back-off strategies of SUs in F_{ik} can be easily determined according to their priorities from the viewpoint of s_i. Considering the expression of $D_{ik}(F_{ik})$ in (12), the second term of (12) is minimized when $F_{ik} = \mathcal{N}_i$. Due to the theoretic results of Kim et al. (2008), the first term of $D_{ik}(F_{ik})$ can be minimized in time complexity of $\mathcal{O}(|\mathcal{N}_i|log|\mathcal{N}_i|)$. However, the complexity of minimizing $D_{ik}(F_{ik})$ is $\mathcal{O}(2^{|\mathcal{N}_i|})$. Based on the algorithm from Kim et al. (2008), we propose an algorithm with time complexity of $\mathcal{O}(|\mathcal{N}_i|log|\mathcal{N}_i|)$, which provides an efficient solution.

Algorithm 1: Candidate-Forwarding-Set-Searching

input : Sender index i, channel index k,
sorted $\mathcal{N}_i$ in increasing order of $T_{ij}^k + D_j$,
$w_k, \mu_{ik}, \lambda_{ik}, D_j$ for $\forall s_j \in \mathcal{N}_i$

output: F_{ik}

```
1 T_min ← +∞;
2 r ← −1;
3 S ← ∅;
4 for l ← 1 to |N_i| do
5     S ← S + {s_l};
6     if D_ik(S) < T_min then
7         T_min ← D_ik(S);
8         r ← l;
9 return F_ik = {s_i1, s_i2, ..., s_i|F_ik|};
```

4.1.3 Idle channel detection

To finish the analysis of the three-stage opportunistic forwarding, we now discuss the idle channel detection stage with channel sensing. For each channel sensing, a duration of t_S is needed. After each sensing, if c_k is sensed busy for s_i, it has to sense for another time period of t_S, and make a decision of which channel to sense; otherwise, s_i can finish the channel detection stage and hops to c_k for forwarder detection. In this section, we answer the question on how to select a channel to sense at each sensing period. Formally, assume the expected time for idle channel detection is $T_i^s(u_i)$ under sensing scheme u_i. The objective is to find the optimal sensing scheme u_i^* to minimize

D_i, i.e. solve following optimization problem,

$$u_i = \underset{u_i \in \mathcal{U}}{\operatorname{argmin}} D_i(u_i) = \underset{u_i \in \mathcal{U}}{\operatorname{argmin}} \left\{ T_i^s(u_i) + \sum_{l=1}^{K} g_l(u_i) D_{il}^* \right\} \tag{14}$$

where $g_l(u_i)$ is the probability that s_i hops to c_l after the idle channel detection stage under sensing scheme u_i, and the optimal value of D_{il}^* has been derived in the previous subsection.

Denote x_{ik}^h as the probability that c_k will be sensed to be idle by s_i after h times of channel sensing, if c_k will be sensed at the $h+1$th sensing period. Let $x_h = (x_{i1}^h, x_{i2}^h, \ldots, x_{iK}^h)$, then u_i is a mapping from x_h to $\mathcal{K}$. At the beginning of the first sensing period, s_i has no sensing result, or the latest sensing result is from a "long time before", which means it is meaningless in practice (Kim and Shin 2008), thus, in this paper we can safely assume $x_{ik}^0 = \frac{\lambda_{ik}}{\lambda_{ik}+\mu_{ik}}$. Define $P_{X,Y}^{i,k}(\Delta_t)$ as the probability that the state of c_k for s_i is Y at time $t + \Delta_t$ under the condition that the state of c_k for s_i is X at time t, where $X, Y \in \left\{\text{busy(1), idle(0)}\right\}$, further let $\beta_{ik} = \frac{\lambda_{ik}}{\lambda_{ik}+\mu_{ik}}$, then due to the analysis in Kim and Shin (2008),

$$P_{X,Y}^{i,k}(\Delta_t) = \beta_{ik}(1 - e^{-(\lambda_{ik}+\mu_{ik})\Delta_t}) \qquad X = 1, Y = 0, \tag{15}$$

where α_{ik} is defined in Sect. 4.1.1, and we further have

$$x_{ik}^h = \begin{cases} \alpha_{ik} & h = 1 \text{ or } u_i(x_l) \neq k \;,\, 1 \leq l < h, \\ P_{1,0}^{i,k}\Big((h-\zeta)t_S\Big) & c_k \text{ is busy at } \zeta\text{th sensing}, \end{cases} \tag{16}$$

where $\zeta = \operatorname{argmax}_l \left\{u_i(x_l) = k\right\}$.

According to (15) and (16), the space of x_h is infinite, and the state of x_h not only depends on x_{h-1}, but also on the previous states and sensing decisions. Instead of providing an optimal solution for (14), we propose an adaptive greedy sensing scheme as follows,

$$u_i(x_h) = \underset{k}{\operatorname{argmin}} \left\{ t_S + D_{ik} + (1 - x_{ik}^h)\mu_{ik} \right\}. \tag{17}$$

Once a channel is sensed idle for s_i, the idle channel detection stage is finished, otherwise, it updates x_h according to (16) and continues to sense based on the above sensing scheme. We provide the following algorithm to evaluate the expected value of $D_i(u_i)$ given u_i in (17), in which ϵ is a threshold for accuracy control of the estimation of expected delay D_i.

Theorem 2 *The upper bound of the expected value of $D_i(u_i)$ is* $\min_{k\in\{1,2,\ldots,K\}} \left\{\alpha_{ik} t_S + \beta_{ik}\mu_{ik} + D_{ik}\right\}$.

Algorithm 2: Expected-Delay-Evaluation

input : Sender index i, $\mu_{ik}, k = 1, 2, \ldots, K$, $\left\{D_{i1}, D_{i2}, \ldots, D_{iK}\right\}$

output: Expected delay from s_i to the sink, i.e., D_i

$D = 0$;
$P = 1$;
$h = 1$;
$D_m = \max\left\{D_{i1}, D_{i2}, \ldots, D_{iK}\right\}$;
while $PD_m \geq \epsilon$ **do**
  for $k \leftarrow 1$ ***to*** K **do**
    update x_{ik}^{h} *according to* (16);
  $k = \text{argmin}_k\left\{t_S + D_{ik} + (1 - x_{ik}^{h})\mu_{ik}\right\}$;
  $D = D + P(t_S + x_{ik}^{h} D_{ik})$;
  $P = P(1 - x_{ik}^{h})$;
  record that c_k *is busy at hth sensing*;
  $h \leftarrow h + 1$;
return $D + \epsilon$;

Proof Consider (17), once s_i received a packet, it will sense channel c_k, where $k = \text{argmin}_k\left\{t_S + D_{ik} + (1 - x_{ik}^{h-1})\mu_{ik}\right\}$, and the expected time to wait for c_k to be idle is $\alpha_{ik}t_S + \beta_{ik}\mu_{ik}$. If c_k is sensed busy and s_i switches to a different channel $c_{k'}$ in the following sensing period, the expected time to wait must be smaller compared to staying on c_k. Thus, the upper bound of the expected value of $D_i(u_i)$ is the expected time wait to c_k to be idle together with D_{ik}. □

4.2 Global opportunistic routing tree construction

In the previous subsection, we established a recursive relationship between a sender and its neighbors with respect to their expected delays to the sink. We also constructed the candidate channel set and the forwarding sets on different channels for the sender to reduce the expected delay, based on the delays of its neighbors to the sink. In this subsection, we present a distributed iterative based algorithm to reduce the expected delay to the sink for each SU as shown in Algorithm 3.

As we can see, Algorithm 3 is distributed and each SU runs this algorithm until the candidate forwarder sets for each SU are stable. Initially, only the sink broadcast its expected delay (i.e., 0) to its neighbors. Other SUs calculate their packet division scheme on different channels from line 8 to line 11. After that, once a SU in the CRN receives any expected delay value (to the sink), it updates its forwarding sets on each channel and estimates the expected delay to the sink with Algorithm 1 and Algorithm 2, respectively. If the delay is reduced, then this information should be broadcast to its neighbors. Notice that this algorithm is a pre-configuration algorithm. We do not discuss how to schedule this information exchange (e.g., broadcast) process. Assume each iteration (h) is perfectly scheduled in Algorithm 3, then clearly the algorithm will convergence within a finite iterations since the opportunistic routing tree defined by the forwarding sets derived from Algorithm 3 is loop-free.

Algorithm 3: Opportunistic-Routing-Tree-Construction

input : Second user index i, $\mathcal{K}$, $\mathcal{N}_i$, w_k, $\mu_{ik}, \lambda_{ik}, k = 1, 2, \ldots, K$
output: $F_{i1}, F_{i2}, \ldots, F_{iK}$

$h \leftarrow 0$;
if $i = N$ **then**
  $D_i^{(h)} \leftarrow 0$;
  broadcast $D_i^{(h)}$;
  return $\emptyset$;
else
  $D_i^{(h)} \leftarrow \infty$;
for $k \leftarrow 1$ ***to*** K **do**
  for $j \in \mathcal{N}_i$ **do**
    $z = \frac{\sigma}{2\lambda_{jk} w_k}\left(1 + \sqrt{1 + \frac{4\lambda_{jk}}{v/w_k + t_A}}\right)$;
    $b_{ij}^k = \text{argmin}_{x \in \{\lfloor z \rfloor, \lceil z \rceil\}} T_{ij}^k(x)$;
if *receive expected delays from* $\mathcal{N}_i$ **then**
  $h \leftarrow h + 1$;
  update forwarding sets on each channels with algorithm 1;
  update expected delay $D_i^{(h)}$ with algorithm 2;
  if $D_i^{(h)} < D_i^{(h-1)}$ **then**
    broadcast $D_i^{(h)}$;
return $F_{i1}, F_{i2}, \ldots, F_{iK}$;

Remarks Notice it is possible that after running Algorithm 3, no nodes will use s_i as a forwarder on channel k. Then s_i does not need to hop to channel k when it is on the idle state, which means the "K" in (6) should be further reduced. Then, the idle probability ϕ_{ik} will also be increased. Thus, we can run Algorithm 3 again to prune the solution. We will demonstrate the benefit of this tuning in simulation section.

5 Simulation results

In this section, we provide simulation results to illustrate the performance of our distributed routing protocol in terms of the delay to the sink. Since in our protocol, each hop forwarding is divided into three stages, we name this protocol three stage opportunistic routing (TS-Opp-R). For the pruned version, we prevent SUs from hopping to the channels that their neighbors will not employ after running TS-Opp-R. We name this enhanced protocol as TS-Opp-R-Pruned. In the simulation, we compare our TS-Opp-R and TS-Opp-R-Pruned protocols with the following two algorithms:

- **Deterministic Shortest Path Routing (D-SP-R):** In this routing protocol, each SU has only one fixed forwarding node. The shortest path was determined from using the well-known Bellman-Ford algorithm. The link length is derived from the expected single hop delay on each channel, and the SUs in the CRN always choose the best forwarder on some channel in terms of expected cumulated delay. We have the advantage of exploiting channel diversity and path diversity with opportunistic routing as compared to D-SP-R.

– **Aggressive Opportunistic Routing (A-Opp-R):** This algorithm is also an opportunistic routing, which is modified from Liu et al. (2011). In the protocol design of Liu et al. (2011), any one hop neighbor of a SU can potentially receive and forward the packet, i.e., they do not specify designated forwarders, which means their protocol does not guarantee loop-free routing. For this consideration, we modify their algorithm such that only the neighbors with smaller expected delay (derived from our iterative Algorithm 3 and analysis in Sect. 4) can be employed as next hop forwarders. This modification essentially improved the delay performance compared to the original one. As the name implies, the SU selects all the neighbors with smaller expected delay as a forwarder. Through comparison to this protocol, we show the importance of carefully selecting the forwarders on different channels for different nodes, as analysed in Sect. 4.1.2.

In our simulation, a static CRN with 400 SUs are randomly deployed over a $1{,}000 \times 1{,}000$ m area, where the sink is located at the bottom-left corner. The transmission range of SUs is set to $100m$. The parameters t_S, t_P, t_A and t_C are set to 1, 2, 1, 0.5 and 1 ms, respectively. The bandwidth of each channel is randomly set within the interval [10, 55 Mbps]. The parameter ν is set to 2 bytes. Without specification, in the following simulation we set the number of channels to 5, the parameters λ_{ik} and μ_{ik} are set as a random number in the interval [30, 40 ms], and the packet size is set to 500 bytes.

We first compare our algorithms with the other two for above mentioned default parameters settings as shown in Fig. 1. For ease of illustration, we permute the nodes according to the ascending order of the delay corresponding to the delay results of protocol TS-Opp-R-Pruned. As we can see, the performance of our protocols are better than that of both D-SP-R and A-Opp-R. Interestingly, the delay performance of A-Opp-R is even worse than D-SP-R, which further indicates the importance of carefully choosing forwarding sets during opportunistic routing. Also, the benefit of preventing the CRs of SUs from hopping to “unnecessary” channels in terms of reducing delay is significant.

We next compare the average delay performance of these four algorithms for different number of channels, i.e., the number of channels vary from 2 to 10. Fig. 2a provides the overall comparison. A-Opp-R performs much worse than other three protocols. For clear comparison of the other three protocols, we narrow the delay window as shown in Fig. 2b. As we can see, with an increase in the number of channels, the average delay will first decrease, and after a unstable window, the average delay will continue increasing. The reason is that by increasing the number of channels, the nodes have more choice for forwarding, and they can employ a “best” channel for forwarding considering the overall delay performance. Additionally, the single hop delay will increase at the same time since the SUs hop on different channels during idle status. The issue of how to reduce the size of the unstable channel size window and find the optimal channel size and optimal channel hopping scheme for opportunistic forwarding will be considered in our future work.

The average delay performance comparison results of these four algorithms with different channel availability are shown in Fig. 3. In this simulation, we adjust the

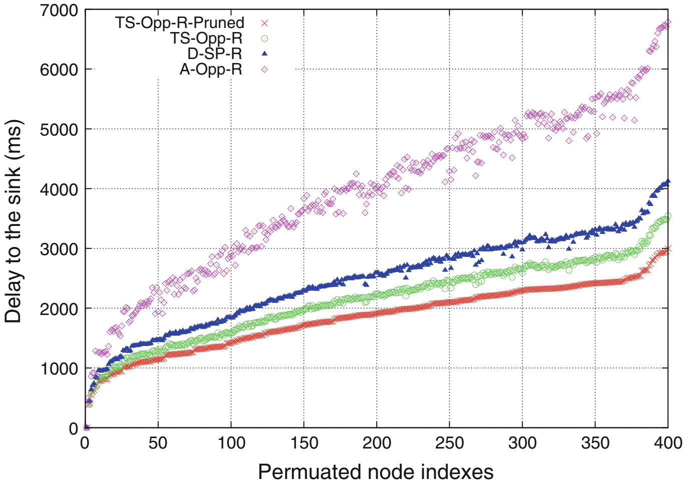


Fig. 1 Expected delay to the sink for all SUs

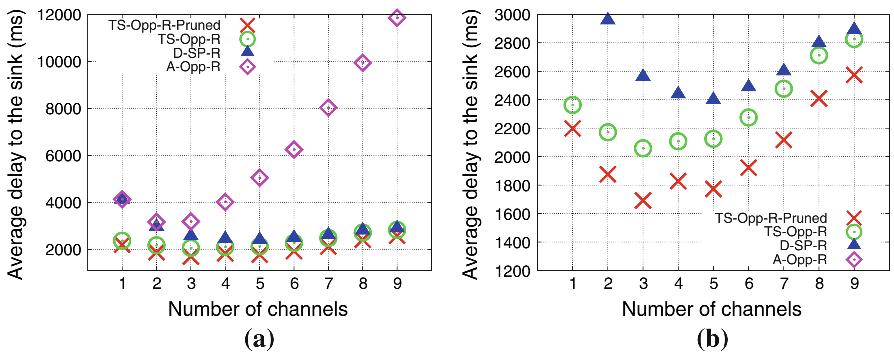
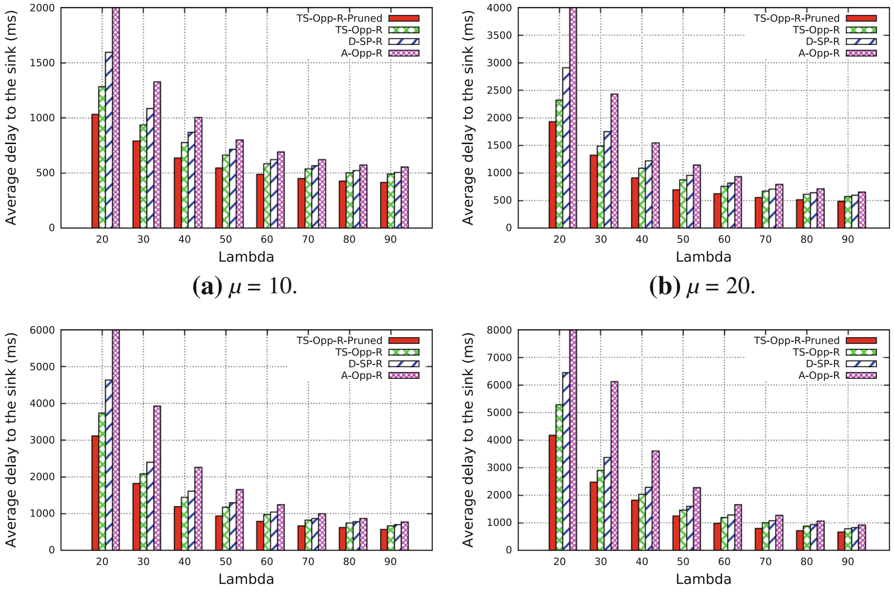


Fig. 2 Average delay with different number of channels

channel availability by changing the parameters λ_{ik} and μ_{ik}, e.g., for $\mu = 10$ and $\lambda = 30$, we set λ_{ik} and μ_{ik} as a random value in the interval $[10ms, 20ms]$ and $[30ms, 40ms]$, respectively. In Fig. 3a, we set $\mu = 10$ and measure the average delay with the increase of λ from 20 to 90.μ is set to 20, 30 and 40 for Fig. 3b, c, d, respectively. The larger the λ and the smaller the μ, the more degree of channel availability for SUs. As we can see, these protocols are all sensitive to λ and μ. Our protocols show significant improvement over the other two, especially under a highly dynamic channel environment. Moreover, the average delays of our protocols increases slower than other two protocols, with the reduction of channel availability.

We lastly compare the average delay performance of these algorithms for different packet sizes. We vary the size of the packets from 200–1,000 bytes. As shown in Fig. 4, our protocols both outperform the other two algorithms in terms of average delays when considering the packet size. In fact, as the packet size increases, the



(a) $\mu = 10$. **(b)** $\mu = 20$. **(c)** $\mu = 30$. **(d)** $\mu = 40$.

Fig. 3 Average delay with different channel availability (Lambda = λ)

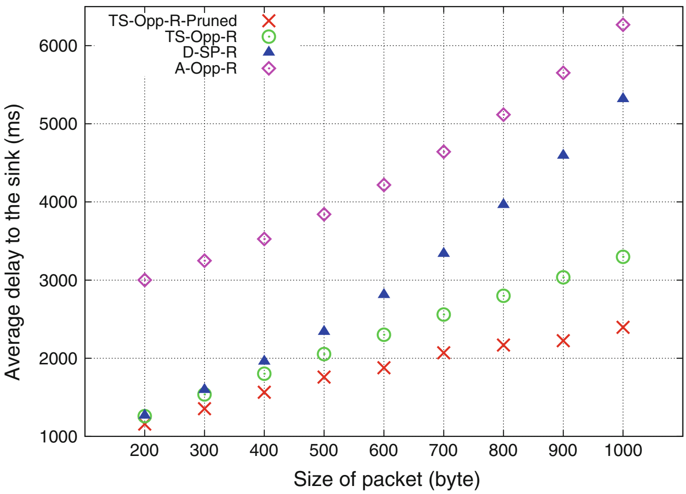


Fig. 4 Average delay with different packet size

rate of increase of average delay is much lower for our protocols as compared to the other two algorithms. This leads to an even greater improvement as the packet size increases.

6 Conclusion

In this paper, we proposed a cross-layer distributed opportunistic routing protocol for multi-hop multi-channel CRNs. Specifically, our routing protocol works towards minimizing the overall expected end-to-end delay by jointly considering the channel sensing strategy, forwarder selection for each SU and packet division scheme on each link. We also provided a mathematical expected delay model, based on which we designed a distributed algorithm to determine system parameters for each SU during opportunistic routing. Note that, the overall framework can be extended to multiple end-to-end flows, however,multiple end-to-end flows will cause fewer spectrum opportunities since SUs will compete idle channel themselves. The most challenging part for the framework is how to decide the candidate forwarding set. In order to capture the forwarding set, more factors need to be taken into account. For example, load balance for each SU needs to be considered since we do not want an SU to be included in too many forwarding sets We also performed extensive simulations to evaluate the performance of our opportunistic routing protocol in terms of end-to-end delay, especially for CRNs with highly dynamic channel conditions. Results show that our routing protocols have lower delay, regardless of the number of channels, channel availability, or packet size, thus improving the overall performance.

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