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Routing for cognitive radio networks consisting of opportunistic links

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Summary

Cognitive radio (CR) has been considered a key technology to enhance overall spectrum utilization by opportunistic transmissions in CR transmitter–receiver link(s). However, CRs must form a cognitive radio network (CRN) so that the messages can be forwarded from source to destination, on top of a number of opportunistic links from co-existing multi-radio systems. Unfortunately, appropriate routing in CRN of coexisting multi-radio systems remains an open problem. We explore the fundamental behaviors of CR links to conclude three major challenges, and thus decompose general CRN into cognitive radio relay network (CRRN), CR uplink relay network, CR downlink relay network, and tunneling (or core) network. Due to extremely dynamic nature of CR links, traditional routing to maintain end-to-end routing table for *ad hoc* networks is not feasible. We locally build up one-step forward table at each CR to proceed based on spectrum sensing to determine trend of paths from source to destination, while primary systems (PSs) follow original ways to forward packets like tunneling. From simulations over *ad hoc* with infrastructure network topology and random network topology, we demonstrate such simple routing concept known as CRN local on-demand (CLOD) routing to be realistic at reasonable routing delay to route packets through. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: cognitive radio; cognitive radio networks; routing; unidirectional link; cooperative relay networks; opportunistic links

1. Introduction

Cognitive radio (CR) establishing opportunistic CR-link transmission from a CR-transmitter (CR-Tx) to CR-receiver (CR-Rx) during the spectrum hole of primary system (PS) [1], has been considered as a key technology toward future wireless communications to enhance spectrum utilization efficiency. The CR concept can be generalized to cooperative co-existing multi-radio systems if the terminal devices are

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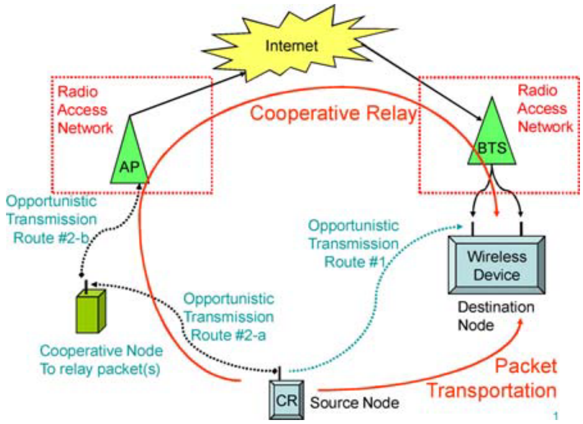

Fig. 1. Cooperative relay from CR source to CR destination in CRN.

equipped with software defined radio (SDR) capability, so that CRs and nodes in co-existing multi-radio systems can form a general cognitive radio network (CRN) *via* cooperative relay [2]. Figure 1 depicts an example of such a cooperative relay scenario. The network coding study of cognitive radio relay networks (CRRNs) has shown that networking CRs with the help of cooperative relay by PS nodes can significantly improve network level throughput (than just link level efficiency) by 130% under the constraint of no interference to PS traffic [3], in average for randomly generated network topology.

However, by networking CRs with nodes in co-existing multi-radio systems, network layer functions of CRN emerge as open problems due to their nature of heterogeneous wireless networks, although they have been heavily investigated in wireless network research. One core feature in network layer functions is routing, as the focus in this paper. Close explorations of CRN routing include routing algorithms in *ad hoc* networks, in sensor networks, and in heterogeneous (most likely wired) networks. However, routing in *ad hoc* networks and routing in sensor networking differ from routing in CRN because heterogeneous nature and temporarily available link nature of CRN [4]. Most heterogeneous network routing algorithms are applied in wired networks and could not support wireless.

Let us consider mobile *ad hoc* networks (MANETs) as a sort of homogeneous multi-hop packet radio networks (mh-PRN). Routing of mh-PRN and therefore MANETs has been studied for years. MANET is considered as a collection of mobile nodes communicating over wireless links without infrastructure and MANET relies on multi-hop concepts to transport the packets and each node acts like a router by itself, with common assumption of limited resource for routing. Conventional routing protocols are based on either link-state or distance vector algorithms aiming at identifying optimal routes to every node in the MANET. Topological changes often encountered in MANET are reflected through propagation of periodic updates. To update and to maintain the routing consumes tremendous bandwidth and is not practical. For IP-based MANET, routing protocols can be generally categorized as *proactive* and *reactive*, depending on whether the protocol continuously updates the routes or reacts on-demand. Proactive protocols, also known as *table-driven* protocols, continuously determine the network connectivity and already available routes to forward a packet. Such kind of routing protocols is obviously infeasible to frequently re-configurable mobile networks like CRN, due to extreme dynamics of links. Reactive protocols, also known as *on-demand* protocols, invoke determination of routes only when it is needed (i.e., on-demand). There are two well known reactive protocols, *dynamic source routing* (DSR) [5] and *ad hoc on-demand distance vector* (AODV) [6]. When a route is needed, reactive protocols conduct some sort of global search such as flooding, at the price of delay to determine a route, but reflecting the most update network topology (i.e., availability of links). Although routing algorithms in MANET has been widely studied such as Reference [7], they are hard to be applied in CRN routing due to difficulty in heterogeneous topology and opportunistic links in CRN, due to route discovery delay and loss, inevitable delay of packets forwarding into node-disjoint route(s), large delay on link status confirmation, and not feasible to maintain end-to-end information.

The rest of this paper is organized as follows. Section 2 summarizes mathematical characterization of CRN routing and the fundamental challenges. Section 3 introduces trusted CRN to alleviate part of these challenges. Section 4 proposes a localized version of on-demand routing for opportunistic links. Simulations results of static topology and random network topology to verify effectiveness of the proposed routing are presented in Section 5. As conclusion in Section 6, routing over opportunistic links to network CRs is indeed feasible.

2. Mathematical Characterization of Routing in Cognitive Radio Networks

Prior to routing of any CRN packets/traffic, the very first function of CRN network layer is *association*,

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which means a CRN to successfully access the general CRN (including PS). In principle, after sensing possible transmission opportunities (i.e., spectrum holes), a CR must complete association then execute dynamic spectrum access (DSA) through physical layer transmission and medium access control, to send packet(s) from CR transmitter to CR receiver. Here, the CR receiver can be a CR or a node in PS. In addition to regular association (or registration) to a network/system (typically PS), the challenge would be quick association for a CR to another node in CRN (either another CR or a node in PS or multi-radio system) under very short available time window, which would be realized *via* trusted mechanism as another part of the paper.

The primary difference and thus challenges between routing of CRN and routing of wireless *ad hoc* (or sensor) networks would be summarized as follows:

(a) *Link Availability*: CRN links are available under idle duration of primary system(s) that DSA can effectively fetch such opportunities, after successful spectrum sensing. Consequently, links in CRN, especially those involving CRs as transmitters and/or receivers, are stochastically available in general, which gives CRN topology to be random even under all nodes being static, not to mention mobile nature of CRN. Although wireless *ad hoc* networks and sensor networks have similar phenomenon, links in CRN can vary much more rapidly as link available duration is only fraction of inter-arrival time for traffic and control signaling packets. That is, link available period in CRN is in the range of milliseconds, instead of seconds, minutes, hours, and even days, like its wireless networking counterparts.

(b) *Unidirectional Links*: Typical wireless networks have bi-directional links, as radio communication is half-duplex. In typical wireless *ad hoc* and sensor networks, unidirectional links might be possible due to the asymmetric transmission power and/or different interference levels at receivers. We may treat unidirectional links to be rare in wireless networking. However, in CRN, unidirectional links are more likely due to the fact that a CR node may just have an opportunity to transmit in one time duration and there is no warrantee to allow the opportunity for transmission from the other direction. Another possible situation is that a CR node wants to leverage an existing PS to (cooperatively) relay packets, however, the other direction might not be permitted, and *vice versa*. Generally speaking, a link involving a CR node is likely uni-directional. It distinguishes CRN from other wireless networks, especially for network layer functions.

(c) *Heterogeneous Wireless Networks*: Different from typical wireless *ad hoc* or sensor networks, CRN is generally formed by heterogeneous wireless networks (co-existing PSs and CR nodes to form *ad hoc* networks). Inter-system handover is usually required for routing in such heterogeneous wireless networks. However, CR links might be available for just an extremely short duration and its successful networking lies in cooperative relaying among such heterogeneous wireless networks. If we further consider network security, to enable CRN for spectrum efficiency of wireless networks at the price of losing security might be questionable, as there is not enough time for a CR node to get secure certificate within the short opportunistic window. A compromise to operate among heterogeneous wireless networks and CR nodes for CRN routing is obviously needed.

To ensure a CRN link to be available for network layer functioning, we may go back to hardware operation. Assuming that a genie observes CRN operation for both PS and CR, CR must utilize the spectrum hole window to complete transmission of packet(s). Suppose such a spectrum window period is denoted by T_{window}. It is clear that

$$T_{\text{window}} \geq T_{\text{sense}} + T_{\text{CR}-\text{Transmission}} + T_{\text{ramp}-\text{up}} + T_{\text{ramp}-\text{down}} \quad (1)$$

where T_{sense} stands for minimum sensing duration to ensure CR transmission opportunity and acquisition of related communication parameters; $T_{\text{CR}-\text{Transmission}}$ is the transmission period for CR packets; $T_{\text{ramp}-\text{up/down}}$ means the ramping (up or down) period for transmission. Equation (1) ignores propagation delay and processing delay at the transmitter–receiver pair, which can be considered as a portion of ramp-up/down duration. The maximum duration of spectrum hole (availability) can be considered as the time duration for beacon signals.

It is obvious that we have to mathematically model the link availability in CRN. Since the link is either available for opportunistic transmission(s) or not available, considering the timings for the change of link availability, we can adopt an embedded continuous-time Markov chain and the rates specifying this continuous-time Markov chain can be obtained from

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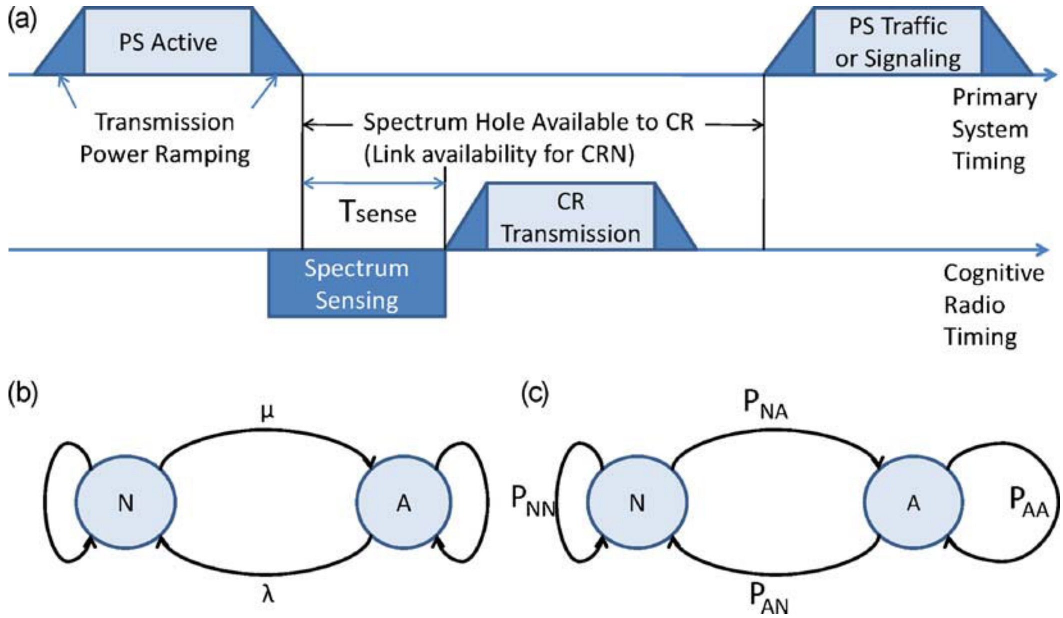

Fig. 2. Link availability of CRN: (a) CR transmission opportunity window, (b) continuous-time Markov chain model for link availability, and (c) embedded discrete-time Markov chain.

the statistics of spectrum measurement [4]. Figure 2(b) depicts continuous-time Markov chain or general cases, while Figure 2(c) illustrates such 2-state Markov chain with fixed timing (say, PS's beacon signal time separation), where state 'A' stands for 'link available' and state 'N' stands for 'link not available'. A link between node X and node Y in CRN can define two unidirectional links $X \rightarrow Y$ and $Y \rightarrow X$. *Via* simple 2-state embedded Markov chain model, it allows general study on natures of network layer functions for CRN, and thus effective design, under challenges (A) and (B). Routing of MANET with uni-directional links was explored [8], however, it is still open for routing with opportunistic links as Figure 2. Recent research considering homogeneous *ad hoc* networks, start-networks, or mesh networks, has modeled spectrum utilization of CRN to help routing in CRN [9–13]. However, they usually do not treat the stochastic and dynamic nature of CR links into routing or spectrum utilization/sharing.

One of the recent major efforts to deal with stochastic nature in wireless *ad hoc* networks is opportunistic routing [14]. Its subsequent research [15–17] dealt with opportunistic routing in multi-hop *ad hoc* networks through negotiation with distributed slotted MAC to ensure highest priority receiver for higher throughput in lossy wireless environments pretty much like cooperative communication to create diversity order to against severe fading. The source node determines the prioritized candidate list prior to broadcasting packets. The nodes relaying a packet are determined after the packet being transmitted, which allows source node to opportunistically take advantage of inherently random outcomes. The destination nodes send the ACK back to the source node after successfully received the packet. The well known ExOR algorithm has been presented in References [14,18]. The key feature of opportunistic routing is to take advantage of numerous but unreliable wireless links into a probabilistic manner with two key issues in design: to generate the prioritized candidate list and to avoid duplicated packets at the destination. Opportunistic routing cannot be directly applied in CRN under obvious reasons, no warrantee of feedback due to asymmetric nature of links in CRN, and 'opportunistic' nature (link availability) in links of CRN. Consequently, routing in CRN, especially with opportunistic links, is still open to research and different from opportunistic routing, while Reference [18] presents a good approach to combine on-demand and opportunistic routing and thus to initiate idea in Section 4.

3. Trusted Cognitive Radio Networking (TCRN)

To mathematically tackle challenge (C), we may introduce a trust mechanism in addition to typical network security schemes. Please note an interesting observation that the security in CRN shall lie on the ground

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of end-to-end nodes, and intermediate nodes in CRN (either CRs and/or nodes in PSs) can simply forward the CR traffic packets (i.e., cooperative relay inside CRN). Such cooperative relay of packets can be facilitated as amplify-and-forward (AF) and decode-and-forward (DF), while intermediate nodes in CRN have almost limited security treats by relaying packets. Compress-and-forward (CF) cooperative networking might jeopardize the security of intermediate nodes due to mixing relay packets and own traffic together. In the following, the cooperative relay suggests either AF or DF, but not CF.

We can now classify a node in CRN and thus traffic/control packets from such node into three categories during the operation of CRN:

(i) *Secure*: The node has executed security check that is good throughout entire heterogeneous wireless networks, such as through public key infrastructure (PKI) check. The packets and messages from this node can go all the way in CRN as secure clearance. A node classified as 'secure' can be a CR and a node in a co-existing PS.

(ii) *Trusted*: This level of security for 'trusted' is not as effective as 'secure'. As CR is generally not possible to complete security check of several rounds handshaking protocol within the timing window of an available link (i.e., CR to CR or CR to PS node), we create a security level of *trusted* that enables packet transmission over available opportunistic unidirectional links. In case a CR source node that generates packet(s) for opportunistic transmission, the CR receiver node (either a CR or a node in PS) recognizing such CR source node as 'trusted' can relay packets toward CR sink node *via* appropriate routing mechanism. Please note that CR source node and CR sink node shall complete their end-to-end security check in advance by all means. A CR receiving node should always maintain a table of trusted/secure nodes around, based on security check and historical update. In other words, any node in CR only allows reception of packets from its secure and trusted neighboring node. Such a table is localized and is not large in number of neighboring nodes. The methodology of update trusted-node table is described in Reference [19].

(iii) *Lure*: A CR node is neither secure nor trusted by its target-receiving node, and it is classified as 'lure'. The major reason to be rated as lure shall be from bad historical actions, such as spreading virus, wasting bandwidth in a wireless network, attacking wireless network, selfish behaviors, etc. Such a lure node actually loses its CR capability in practice of CRN operation.

The purpose of introduction of trust mechanism is clear, that is, to create a homogeneous networking functioning environment for heterogeneous wireless networks, and thus to allow cooperative relay of packets in spite of opportunistic and extremely dynamic link availability of CRN. In other words, we shall encourage nodes from all kinds of wireless networks to act as nodes in CRN by providing some incentive programs, so that these nodes can effective relay packets from trusted CR source nodes, to form a large scale of *homogeneous multi-hop ad hoc network* under the same *trust* level across different wireless networks.

Let us summarize some critical issues of CRN network layer operation in the following:

- CRN consists of CRs and nodes from various co-existing PSs, which may operate using different communication parameters, in different frequency bands, and in different geographical locations. SDR inside a CR is capable of reconfigurable realization for multiple systems operating at multiple frequency bands.
- CR source node (initiation point of traffic) and CR destination (termination point of traffic) node should conduct their own end-to-end security beyond trust level by employing CRN nodes to complete bidirectional verification.
- CRN nodes are assumed to conduct only AF or DF cooperative relaying, under trust domain of CRN.
- Nodes in secure domain may reject relays from trusted nodes, which suggests that such links are not available in trusted multi-hop packet radio network routing. Similarly, nodes in trusted domain (i.e., typical nodes in CRN) may reject connection requests from lure nodes.
- Any packet from CR source node, once getting into a PS or infrastructure, the packet follows operation of the PS or infrastructure, to enjoy the benefits from existing systems and networks. For example, a CR source node wishes to relay its packets through *near-by* WiFi to access a web site of Internet, where near-by means radio accessibility as a kind of localization. As long as the packets from CR source node are allowed to access point of WiFi, these packets transport as WiFi packets. A CR terminal device is therefore capable of conversion/re-configurability among multiple physical layer transmissions and multiple medium access control scheme.

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The general CRN operation can therefore be summarized as the following figure. We have an infrastructure network as the core that might be just Internet, and several radio access networks (RAN) that provides various ways to access core infrastructure network. Mobile stations (MS) are associated with certain RAN technology. Each CR is capable of configuring itself into appropriate radio system to transport packets for communication/networking purpose. RAN, MS, and infrastructure can be just any specific PS, and there are a few possible PSs co-exist in the figure. A CR may also be a MS of a PS. Bidirectional links have double arrows, and all links in PSs shall be bidirectional. Opportunistic links owing to CR's DSA and certain *ad hoc* links have single arrow in the figure. From CR source node, there are three different cooperative paths to transport the packets. There are also three cooperative paths to CR sink as the final destination. Please note that outgoing path 3 and incoming path 3 generally represent CRRN described earlier.

As we can clearly observe from the figure, CRN consists of CRs and PSs. CR dynamic spectrum access (DSA) at physical layer transmission and medium access control works between CR transmission and CR receiver in a CR (or DSA) link. CRN routing establishes on top of these CR links and bidirectional links in PSs. Let us summary again:

- *CR transmitter* and *CR receiver* form a *CR link*, typically using DSA. CR receiver may be a CR or a node in PS.
- *CR source node* and *CR destination node* form a virtual link like a session in CRN. CR destination node can be a CR or any node in PS. In case CR destination node is a CR, we call as *CR sink*.

4. Routing of Dynamic and Unidirectional CR Links in CRN

To conduct CRN routing over unidirectional CR links and usually bidirectional links in PS (mobile stations in PS can form *ad hoc* with possible unidirectional links) as earlier description, we can extend on-demand routing protocols of MANET for CRN routing by

(i) Each CR link is modeled by a 2-state Markov chain, independent with other CR links.
(ii) Without knowing specific PS, all links in PS are assumed to be bidirectional and can support our routing protocol. As a matter of fact, the entire behavior inside a PS can be treated as a 'link' by queuing model of this PS if we just follow the PS operation.
(iii) Typical MANET routing algorithms are trying to isolate unidirectional links [8], as they are likely to be very localized. However, unidirectional links are inevitable in CRN. Fortunately, we may assume the depth (i.e., number of hops) from CR to PS to be within hops, due to their roles in wireless access to infrastructure or purely *ad hoc*.
(iv) The fact of CR links to be unidirectional is usually true at one instant. At next instant, this CR link might be still unidirectional but reverse its direction depending on network situations. By introducing trust mechanism, CRN would pretty much like an *ad hoc* network with 'temporarily' unidirectional links.

For routing in CRN, we care one major purpose of CRN, to reduce latency of traffic due to more cooperative paths, especially for CR source not possible to transport packets to CR destination node without CRN technology. In the mean time, there are a few issues that we want to make sure in CRN routing.

- Since CR shall not interfere with PS(s), we should avoid the global or periodic advertisement of any CR node, though such advertisement is common in *ad hoc* network routing.
- For a CR link that is the link with CR as transmitter, we shall avoid acknowledgement over the link, as there might not be enough opportunistic time window to execute this acknowledgement.
- For the same reasons as above two points, we shall not use *hello* packet in common *ad hoc* network routing.
- CRN routing must be able to detect and to minimize possibility of any *loop* or any *dead-end*, where dead-end means 'no way to forward the packet further within a reasonable amount of time duration'; loop means 'the packet that was forwarded to another route will come back in a repeated way'.

We assume localized connectivity to be concerned in CRN routing, which is pretty much true for CRN operation and routing as the CR links are only opportunistic. Under highly dynamic nature, it is likely in vain by trying large-scale or global optimization. Our strategy is to forward the packet over an effective opportunistic CR link, toward appropriate direction/trend. It exactly matches the philosophy of reactive (or on-demand) routing in *ad hoc* networks [20].

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Consequently, taken the spirit of AODV routing, we create CRN local on-demand (CLOD) routing as follows. Each CR node executes routing only when there is a need (on-demand). The routing message include the following routing overhead information:

- CR destination node IP.
- CR source node IP.
- Message ID (i.e., msg_id).
- CR relay node IP (cr_relay_ip).
- CR transmitter IP (cr_tx_ip) and its radio-type (cr_tx_type) for the received packet/frame.
- CR receiver IP (cr_rx_ip) and its radio-type (cr_rx_type) for the forwarding packet/frame.
- Sequence number seq_count associated with the path (cr_tx_ip, cr_relay_ip, cr_rx_ip), starting from 0, and add 1 for each same path.
- Time counter at CR relay node, time_counter, starting from 0 and adding 1 for a new time slot duration.

In case a new CR node or a new mobile station of PS gets into scenario, we may not immediately be able to acquire its IP address, and we then can use an ID to serve the purpose of table. Each node maintains localized table(s) to connect possible neighboring nodes, rather than global or end-to-end tables. The table at each node is used when there is a demand for routing. CLOD routing consists of three phases in operation: sensing phase, path discovery phase, and table update phase.

4.1. Sensing Phase

The CR node listens to the radio environments, that is, spectrum sensing of multiple co-existing systems (and even possible different frequency bands), to update its *forward-path table*. The forward-path table records information regarding each potential CR receiver, history, the estimate of its trust on the CR node, and communication parameters to adjust SDR. Each potential CR receiver is identified by IP address that could be acquired from its past transmission, or by ID designated by the CR node. History can be a simple flag to indicate the potential CR receiver to be trustworthy or not, based on history and learning process. Finally, communication system parameters can be obtained from spectrum sensing to adjust SDR.

4.2. Path Discovery Phase

Once the CR node originates a packet/frame to destination or receives a packet/frame for relay, it checks backward-path table for any violation. In case no violation from the checking, the CR node selects another CR node from forward-path table to relay the packet/frame. The selection is based on availability of CR links and forward-path table. Of course, those links to PS have the highest priority. On the other hand, in case violation happens, the CR relay node seeks opportunity to 'negative-acknowledge' CR transmitter based on backward-path table. CR transmitter node shall try to re-route the packet to another CR relay node if possible, or further back if no route available.

4.3. Table Update Phase

In addition to link selection to complete routing, a *backward-path route* associated with this relay has to update as a part of *backward-path table*. Each backward-path route consists of parameters msg_id, cr_rx_ip, cr_rx_type, cr_tx_ip, cr_tx_type, and seq_count.

Both cr_rx_type and cr_tx_type are to specify the operation of co-existing multi-radio systems (or overlay wireless systems/networks) in CRN (Figure 4).

It is obvious that the parameter *history* in forward-path table plays a key role in routing. Backward-path table is useful to prohibit routing disasters from loops and dead-ends. The violation is defined as detection of either loop existence or dead-end existence. Seq_count plays its role to determine the existence of a loop. Timeout for not possible to relay a packet is issued to avoid dead-end, which is a useful information to update the backward-path table.

For the case that negative-acknowledgement (nor the positive-acknowledgement from destination) cannot trace back all the way to CR source node, likely due to some permanent unidirectional links, end-to-end timeout can terminate the routing and re-start a new round of routing.

5. Control of CRN

5.1. Flow Control of CRN

Flow control can happen in two types in CRN: First of all, end-to-end flow control between CR source node and CR destination node, while a typical credit-based flow control such as leaky-bucket can does the work. However, for completely successful operation of CRN on-demand routing protocols, such as CRN-ODV or CRN-DSR, we need another function, flow control in CRN network layer. Different from conventional first-type flow control in computer networks, flow control

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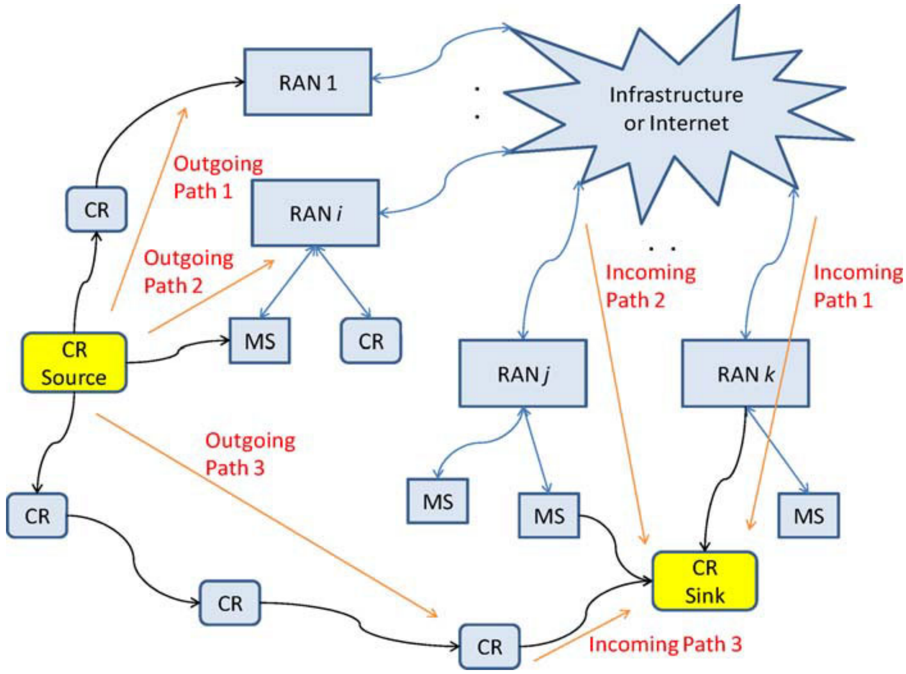

Fig. 3. Routing packets in cognitive radio network.

in CRN is primarily for damage control purpose. Since it is not possible for us to ensure neither dead-end nor loop not happening in AODV, we have to detect these two cases and to stop CR link relaying packets under these scenarios, such that network bandwidth would not waste. To achieve such a goal, loop detection by checking sequence number and dead-end detection by 'maximum resend attempt' parameter would be needed and associated with routing.

Furthermore, we may observe that the entire CRN of CRs and PSs as Figure 3 is actually formed by several segments as Figure 5, while the packets are routed from CR source node to CR destination node (or CR sink), through these segments:

- Uplink CRN.
- Co-existing Multi-Radio PSs usually with infrastructure or core network (such as Internet), functioning like a CRN tunneling in backbone by inspiration from Reference [21].
- Downlink CRN.
- CRRN (described in Reference [3]).

CRRN can be considered as a special kind of CRN consisting of pure CRs, with the only purpose to relay packets.

The traffic flow can be categorized as

- CR source node → Uplink CRN → PS and infrastructure → downlink CRN → CR destination node.
- CR source node → CRRN → CR destination node.

Routing in CRN thus has another hidden agenda based on above segmentation or decomposition. For uplink CRN, the routing shall try to reach the PS *via* opportunistic CR links. For example, in Figure 5, when CR relay node is in the process to select forwarding path, it has tendency to select the node 'closer' to PS, which is the node in RAN 1. On the contrary, the routing shall try to leave the PS *via* opportunistic CR links for downlink CRN. When a CR node in path discovery phase based on forward-path table, parameter (or field more precisely) *history* thus plays a key role to provide such information in node selection. In other words, routing in uplink CRN and downlink CRN is not totally stochastic, and there shall be a drift along the direction inside a dynamic topology CRN. It reminds us the movement of ants, and literatures about ant routing provide more opportunities to develop effective update of parameter/field history in the Table [22,23].

We also note that CRN routing shall favor a way to forward packets in an effective way for overlay/co-existing multi-radio systems, which suggests longer

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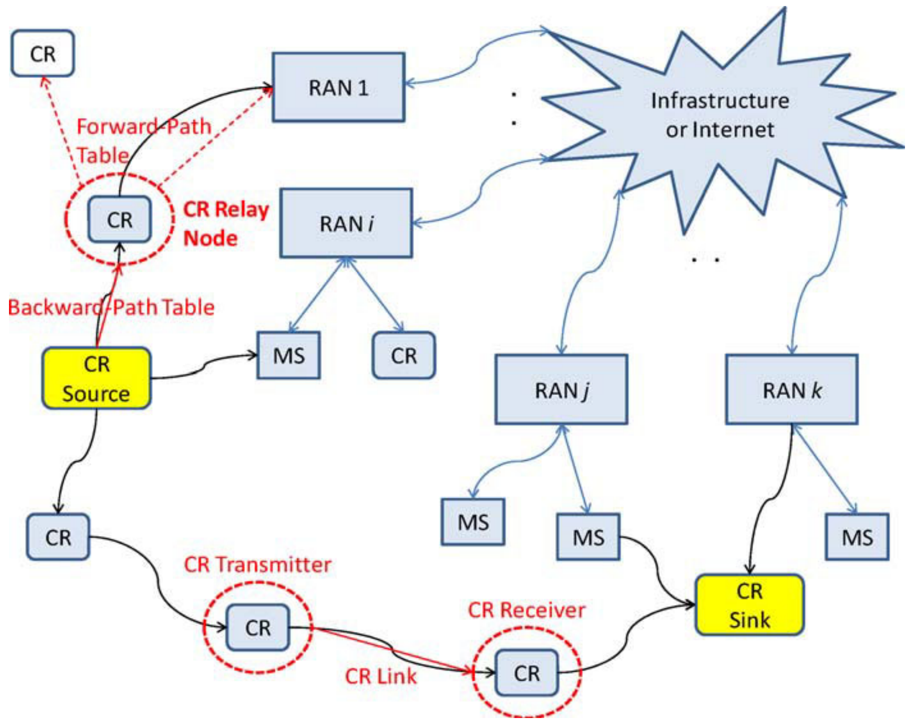

Fig. 4. CLOD routing.

range PS to be favored in relaying packets for a CR relay node as long as among possible choices, and thus another potential enhancement of CRN routing efficiency.

5.2. End-to-End Error Control in CRN

Conventional concept of packet error control lies in physical layer and data link layer. However, error

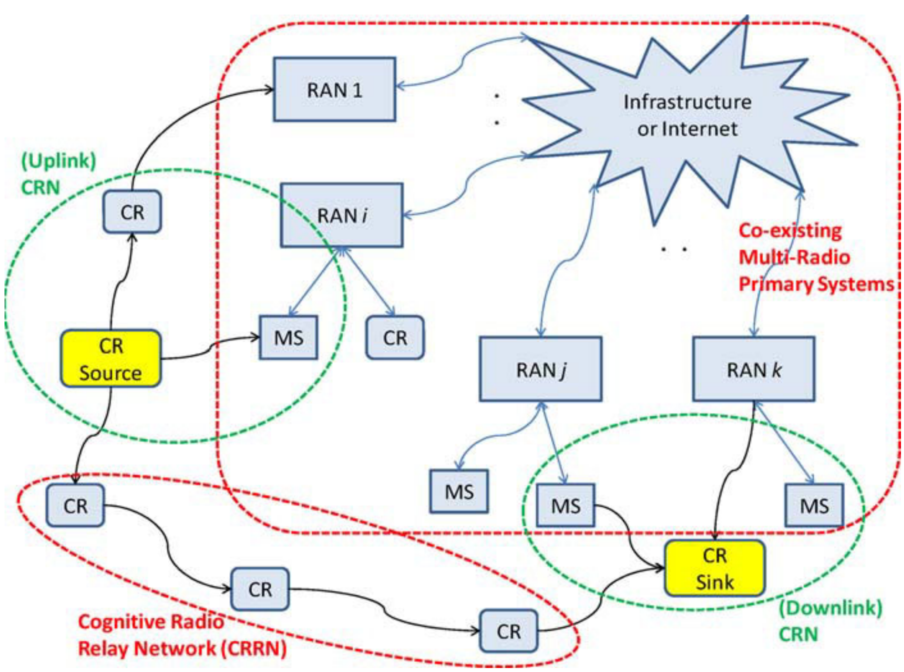

Fig. 5. Segmentation or decomposition of CRN.

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control shall be useful to support CRN functions. Please recall that links in CRN are dynamically available and it might not be feasible to conduct ARQ between CR transmitter and CR receiver in a CRN link. Furthermore, CRN routing just try the best to forward the packets and the CR sink might receive multiple copies of one transmitted packet, while these copies of one packet might not be correct as no error protection other than forward error control (FEC) available. Conventional network layer requires extremely low packet error rate, which is warranted by physical layer FEC, CRC check, and data link control. For CRN, data link control may or may not exist, and error control between CR source node and sink node is needed, while re-transmissions shall be minimized due to much higher price than common (wireless) networks. We can immediately borrow the idea from *hybrid automatic request* (HARQ) to conduct CRN network layer error control, to significantly reduce the error control traffic between CR source node and CR destination node [24]. As Figure 3, for the purpose of reliable packet transportation in wireless networks, CR destination node may receive three (or more) copies of a packet from CR source node, which suggests application of HARQ to create more path diversity and to enhance error control capability. The challenge for HARQ in CRN lies in the uncertain number of copies for a packet to be received at CR destination node and in the uncertain arrival times of these copies. Last but not the least, such end-to-end control shall be conducted based on CR 'session', rather than CR 'link'.

6. Numerical Results

General CRN routing is an extremely complicated mechanism. However, we can design experiments to verify our proposed routing under the opportunistic links, which would be the first closer-to-realistic exploration in literatures for CRN routing.

6.1. Independent Opportunistic Links

We start explorations by assuming each opportunistic link in CRN is independently available under a given link-availability probability. The first experiment is to demonstrate feasibility of CRN, as the generalization of cooperative relay among CRs and nodes in PS, capable of forwarding packets from CR-source node to CR-destination node.

The objective of this simulation is to compute routing delay, when routing path is establishing based on available channel. The routing delay is defined as delay caused by routing through these dynamically opportunistic links, without considering other factors such as transmission delay, processing delay, etc. Our simulation follows the topology as Figure 6, with the following assumptions:

- There is one CR source and one CR destination. Link direction is like shown in the figure above. Arrows shows the direction of the link. Although there are unidirectional link in the scenario, in this stage of

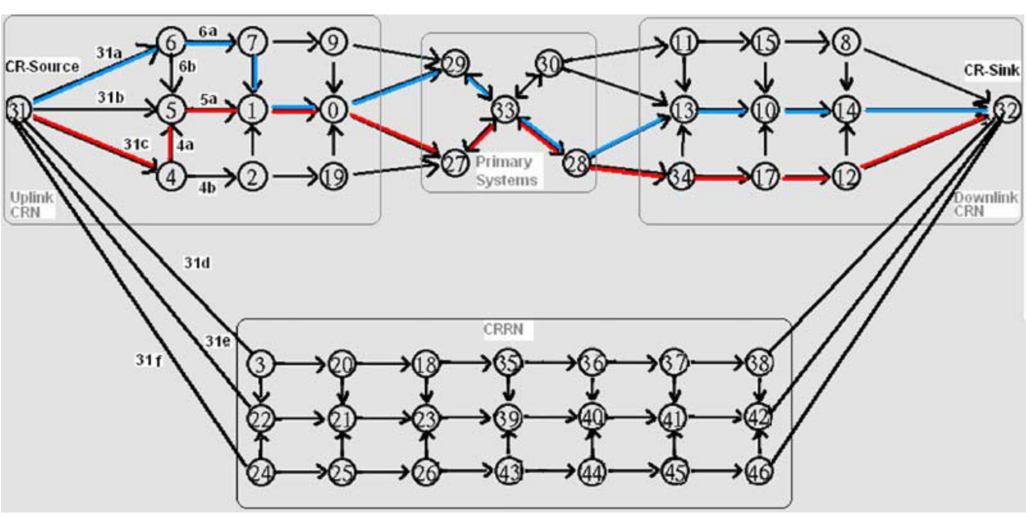

Fig. 6. Topology of CRN in simulations.

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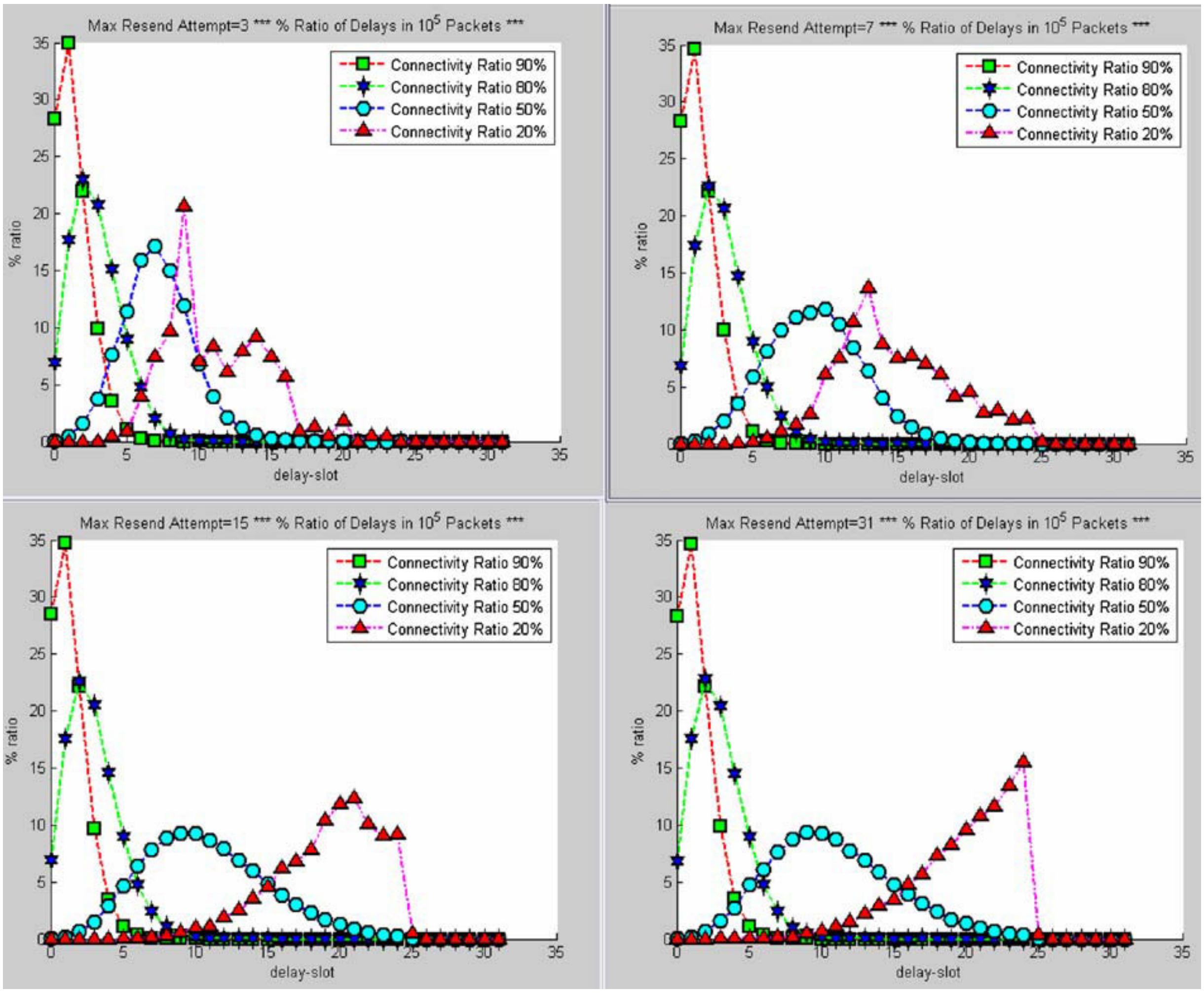

Fig. 7. Distribution of routing delay caused by channel connectivity (available to CR opportunistic transmission in terms of probability), while x-axis: routing delay and y-axis: percentage of packets.

the simulation, they do not have special effect or function.

- Every node has a routing table (forward path table) to summarize potentially available links with receiving nodes. We assume spectrum sensing capability.
- So far there is no backward path table, because no acknowledgement is sending by receiver.
- When data start to transmitting, node checks the available channel in order. At this stage of the work, none of the channels has priorities. For example, in Figure 5, source node 31 has six channels and in every iteration it always starting to scan with 31a and next 31b, 31c, ..., and so on.
- Every channel has Markov based availability function. We properly select the seed to generate random numbers to ensure statistical meaning.
- Channel propagation delay, or delay in the PSs is neglected, computing delay is the delay only caused by routing. In one slot a node can scan only one channel if it is available, delay counter will not be increased otherwise it will be increased.
- During the packet transmission, zero delay means all channels which is checked first were available, so nodes do not have to check the second channel to forward the packet.
- Simulations repeat 10^5 times, that is, 10^5 packets are sent.

Figures 7–10 summarizes the simulation of CRN example shown in Figure 6. Connectivity means the probability of a link available to CR transmission. According to wide range of study, the spectrum of

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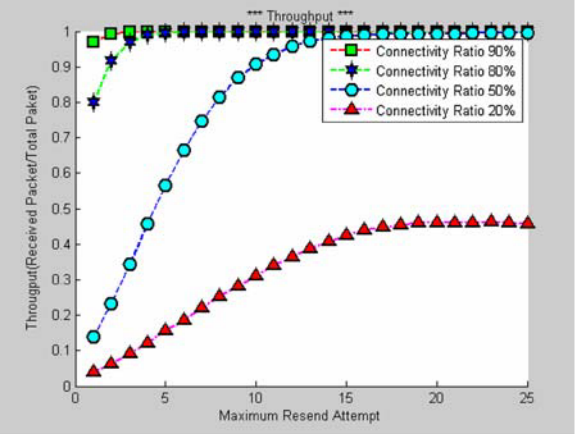

Fig. 8. Throughput *versus* maximum resend attempt.

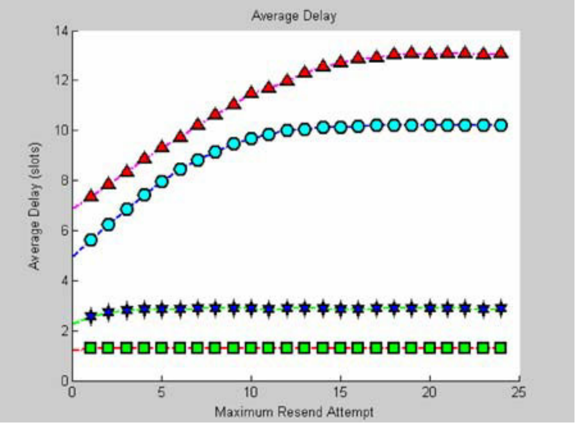

Fig. 9. Average delay *versus* maximum resend attempt.

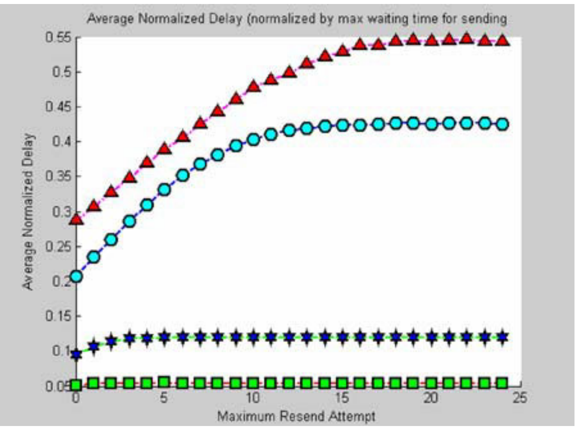

Fig. 10. Average normalized delay *versus* maximum resend attempt (normalization with respect to the maximum waiting time for sending (24 slot—round trip slot).

PSs may be used with 10–20% duty cycle, and thus 90 and 80% connectivity may have more reference value. As we can clearly see that our proposed routing can work under the dynamically available uni-directional links, with tolerable routing delay, in a well-behaved but general network topology case. Since we define maximum resent attempt as the life time (or duration) for a node to hold the packet without successful relaying out. Under four different pre-selected values for maximum resent attempt, the distribution (percentage of packets in simulations) of routing delay is illustrated in Figure 7.

From above simulations, we may have some interesting and valuable observations, where throughput means network routing throughput (may not be 1 due to opportunistic nature) and delay means routing delay excluding transmission delay:

- Under relatively light traffic load that is suggested by the high availability (or probability) of link connection, the routing delay (i.e., delay caused by routing in opportunistic link availability) has smooth distribution as expected to demonstrate the effective routing capability, as Reference [3] implies CRN supporting significant network level throughput gain at lighter traffic load in PS. However, for low link availability, routing in CRN would be in troubles.
- At reasonable link availability, throughput can approach 1 to warrantee successful delivery of packets over opportunistic links as Figure 8.
- High link availability (i.e., connectivity ratio) indeed suggests good routing performance, as long as better than 50% or so. When the PS is heavily loaded to result in low link availability, CR packets cannot be stochastically delivered even increasing MRA as Figure 8.
- Maximum resend-attempt (MRA) can also help networking throughput at the price of routing delay (i.e., delay caused by routing), with saturation phenomenon suggesting that holding longer at a node cannot help network efficiency. It also implies that end-to-end control at CR-session level makes sense by certain time-out mechanism.

6.2. Random Network Topology

In the following, we will consider a more dynamic network topology to verify our idea in the proposed CRN routing. Recall decomposition of CRN in Figure 5, the most general path can be treated as CR-Source to CR(s) to PS-tunnel to CR(s) to CR-Destination. PS trunk here plays a role like tunnelling with just

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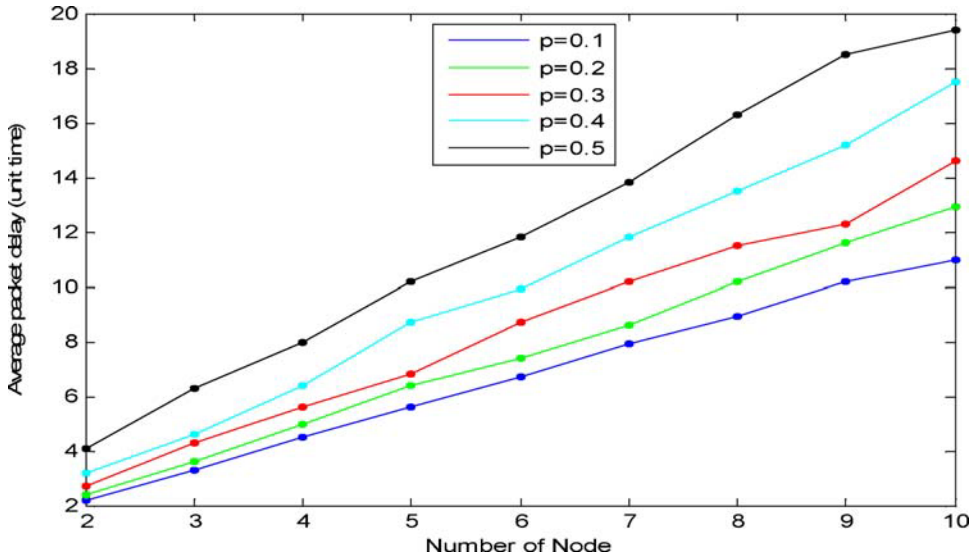

Fig. 11. Delay performance of linear topology ($P = P_{AN} = P_{NN}$).

propagation delay (assuming a unit-time slot for the time being). For cognitive radio relay networking (CRRN), we can simply take out the PS-tunnelling. For each hop, we also assume the packet transmission delay to be a unit-time slot. Now, the problem is to calculate the accumulated delay (latency) from CR source to CR destination under unidirectional link (the link might be unavailable and the latency increases).

First of all, we will study the one-dimensional case (linear case) where the state transition of CR node can be modeled as Markov Chain as Figure 2, with $P_{AA} + P_{AN} = 1$ and $P_{NA} + P_{NN} = 1$. Since there is not guaranteed end-to-end route between CR source and CR destination under unidirectional link, where the network topology might change very quickly, each packet will be sent directly from one node to another.

Each node has two states, namely available (state A) and unavailable (State N). If a packet arrives at certain node, it will wait for one or more time slot until the node state value turns to be 1. For example, if the previous state value is 0 which means the current link is not available, the packet will wait for one more time slot. After that, if the state value is changed to 1 with probability P_{NA}, the packet will be transmitted to the next hop according to the current node's route table. If the state value is still 0 with probability P_{NN}, the packet has to wait for the next time slot. Finally, the packet will be discarded if the maximum resend-attempt (MRA) exceeds.

Now, let us suppose there are N hops on a route path from source to destination. Each of the nodes is unidirectional with the Markov chain state transmission. If the link is available, each hop is equivalent to 1 time slot, or else the one hop latency will be larger than 1, which depends on Markov chain probability. Intuitively, we can see that the latency from source to destination is determined by the number of nodes on the route, the Markov chain probability as well as the MRA. Let the initial states of N hops on the route be $\{1\ 0\ 0\ 0\ 1 \ldots 0\}$ and $P_{AA} = P_{NA} \in [0, 1]$. Taking $N = 4$, the initial state is $\{0\ 1\ 0\ 1\}$, $P_{AA} = P_{NA} = 0.1$ as an example shown below: CR-Source to CR to CR to CR to CR-Destination. The end-to-end source to destination packet delay is 4.5, according to the simulation. From Figure 11 we can observe as follows:

- the average packet delay increase with P_{AN} (and/or P_{NN});
- the growth of delay is faster than the growth of number of node (or P_{AN}/P_{NN});
- for a given N and P_{AN}/P_{NN} as well as MRA, we can estimate the average packet delay (whether the packet can arrive or it will be discarded).

Next, we shall look into the general network topology in two-dimension scenario as Figure 12. Our simulations assume 50 randomly deployed CR nodes in 200 (unit length) by 200 (unit length) rectangular. Each CR has communication range of 50 m. That is, $N = 50$, $[X, Y] = 200 \times 200$ (unit length)^2, $R = 50$ (unit length). Each of the 50 CRs wishes to transmit data packet to CR Destination (CR Sink) which is located at

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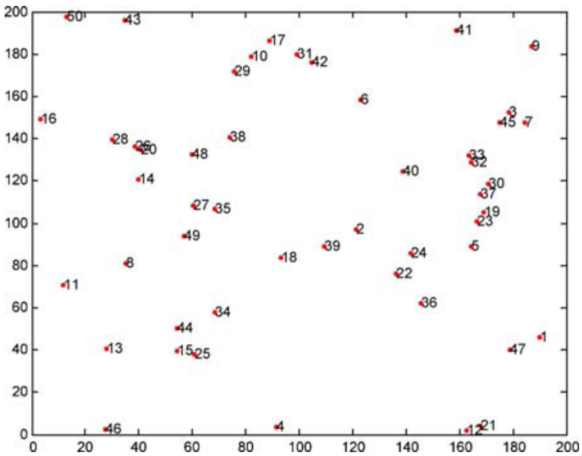

Fig. 12. Random network topology in 2D.

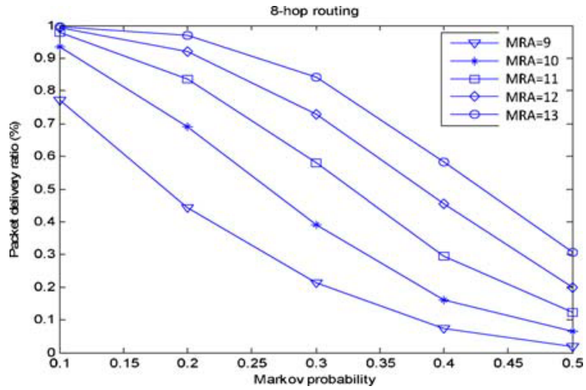

Fig. 13. Success rate of packet delivery *vs.* p given 8-hops routing.

Table I. End-to-end latency of N-hop when $P=P_{AN}=P_{NN}=0.1$

N	2	3	4	5	6	7	8	9	10
Latency (unit time)	2.2	3.3	4.5	5.6	6.7	7.9	8.9	10.2	11

(100, 225) outside. We temporarily do not consider MS/PS tunneling and it is a pure CRN. Later on, the network performance can be improved with the introduction of MS/PS tunneling.

Based on our routing algorithm, we can build the corresponding route table finally to CR Destination *via* greedy algorithm. Suppose there is a source CR node 4 having data to send to CR destination node. It takes the route $\{4 \rightarrow 25 \rightarrow 8 \rightarrow 14 \rightarrow 38 \rightarrow 17\}$. Considering the unidirectional link with Markov chain property, we calculate the accumulated end-to-end packet delay based on the one-dimensional experience we studied above. If we let $p=0.1$ and MRA $=10$, we can get an averaged packet delay of 6.7 according to Table I. If $p=0.4$, the final end-to-end delay is 9.9 which is less than MRA. If $p=0.5$ the packet from node 4 will be discarded since the final delay is larger than MRA. In this case, the packet cannot be successfully transmitted to CR sink.

It is interesting to observe that the network topology (density) plays a very important role on the packet transmission delay. When the CR increases its transmission radius, the network density gets higher and it takes less latency to reach CR sink (or destination). On the other hand, the interference as well as energy consumption would also increase. It is a kind of tradeoff between latency and energy consumption. For the same network topology, if $R=80$ (unit-length), the corresponding route of node 4 is $\{4 \rightarrow 18 \rightarrow 6\}$ and the corresponding end-to-end packet delay becomes smaller. Finally, if we replace some of the CR nodes with MS/PS, the end-to-end packet delay will be much shortened since there is a backbone (trunk or tunneling) network between CR source and CR destination (or sink). Taking the same network topology as an example when $R=50$ (unit-length), if we replace the route from node 8 to node 38 with a trunk network, the route from node 4 to CR sink is as follows, with final average end-to-end packet delay $3.3+1=4.3$ when $p=0.1$. Figure 13 presents a non-surprising numerical result, being consistent with observations of fixed topology.

7. Conclusions

With CR's advantages in spectrum utilization, networking CRs is critical to practical applications. While little attention has been paid to CRN routing up to this moment, we summarized key features of CR links, developed decomposition methodology for CRN, and then proposed CLOD routing protocol for CRN with on-demand local table at each CRN node. Our simulations verify our proposed CRN routing concepts indeed working and reasonably effective in well-structured cooperative relay network topology with and without infrastructure. Proper routing of CRN can significantly improve network level efficiency given fixed spectrum, as long as PS traffic load is not high, which proves networking CR nodes to be a useful concept. Of course, there requires more efforts to facilitate details of CRN routing such as learning routing parameters [25], while this paper lights initially successful effort toward the final realization of CRN.

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Kwang-Cheng Chen received B.S. from the National Taiwan University in 1983, M.S. and Ph.D from the University of Maryland, College Park, United States, in 1987 and 1989, all in electrical engineering. From 1987 to 1998, he worked with SSE, COMSAT, IBM Thomas J. Watson Research Center, and National Tsing Hua University, in mobile communications and networks. Since 1998, he has been with the Graduate Institute of Communication Engineering and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, ROC, and is the Distinguished Professor and Irving T. Ho Chair. He actively involves the technical organization of numerous leading IEEE conferences, including as the Technical Program Committee Chair of *1996 IEEE International Symposium on Personal Indoor Mobile Radio Communications*, TPC co-chair for IEEE Globecom 2002, General Co-Chair for 2007 IEEE Mobile WiMAX Symposium in Orlando, 2009 IEEE Mobile WiMAX Symposium in Napa Valley, and IEEE 2010 Spring Vehicular Technology Conference. He has served editorship with a few IEEE journals and many international journals, and served various positions in IEEE. He also actively participate various wireless international standards. He has authored and co-authored over 200 technical papers and 18 granted US patents. He co-edits (with R. DeMarca) the book *Mobile WiMAX* published by Wiley 2008, and authors a book *Principles of Communications* published by River 2009, and co-author (with R.Prasad) another book *Cognitive Radio Networks* published by Wiley 2009. He was elected as an *IEEE Fellow* in 2006 and received numerous awards and honors. His research interests include wireless communications and networks, nano-computation/communication, and cognitive science.

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