Semi-Structure Routing and Performance Analysis for Cognitive Radio Networks

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***Abstract*—Routing is one of the most important and fundamental issues in Cognitive Radio Networks (CRNs). In this paper, we propose an effective routing scheme. Our main contributions are threefold. First, we propose a spectrum-aware Semi-Structure Routing (SSR) framework which incorporates power control. By employing *forwarding zones* and *routing zones*, SSR can effectively utilize the local real-time spectrum dynamics and meanwhile guarantee the global routing performance. Second, considering the lack of analytical models for routing protocol performance [1] in CRNs, we analyze the upper bound of the induced latency and scalability of SSR. Finally, extensive simulation results are presented to validate the performance of SSR.**

I. Introduction

Recently, to alleviate the unbalanced and inefficient spectrum utilization on licensed spectrum bands, a new communication paradigm, Cognitive Radio Networks (CRNs), is proposed [7]-[9]. In the CRN paradigm, routing is one of the most fundamental operations. The existing routing protocols for CRNs can be categorized into three classes, named *metric/rule based routing protocols* (e.g. [2], etc), *resource aided routing protocols* (e.g. [3], etc), and *optimization based routing protocols* (e.g. [5], etc).

Most of the existing metric/rule based routing protocols employ either some *global/network-wide measurements*, e.g. accumulated spectrum opportunity, or some *local measurements* to obtain routes from sources to destinations. However, for global/network-wide measurements, they usually cannot fully take account in the local real-time spectrum dynamics of CRNs. On the other hand, local measurements usually cannot provide any overall performance guarantee to the induced routes. For the resource aided routing protocols, they require some extra resources, e.g. Common Control Channel (CCC), common link control radio, etc, to accomplish route selection. Therefore, they may not be suitable for some cases due to the unavailability of these resources. In addition, most of the existing optimization based routing protocols formulate the routing problem as various optimization problems, which are computationally difficult (NP-hard) and thus not applicable in practice. For the provided corresponding heuristic solutions, as some metric based routing algorithms, they either cannot fully take account in the spectrum dynamics or have no performance guarantee. More importantly, as indicated in [1], deriving analytical models for routing protocol behaviors is still an open problem. This motivates us to develop a routing framework which considers both the local real-time spectrum dynamics and the global routing efficiency followed by deriving a mathematical analytical framework for the routing protocol.

The contributions of this paper are summarized as follows. First, we propose a Semi-Structure Routing (SSR) framework for CRNs, which is a joint spectrum-aware routing and energy-efficient power control strategy. On the one hand, by introducing the *forwarding zone* concept and the *single node to a set* communication model, an intermediate node may choose its next hop from a set of possible relays, which enables SSR to effectively take into account the local real-time spectrum dynamics and to improve spectrum utilization efficiency. On the other hand, by introducing the *routing zone* concept, the overall performance of SSR can also be guaranteed by avoiding high-cost tortuous routes from sources to destinations. In addition, without sacrificing local spectrum opportunities or increasing global routing cost, we incorporate power control to SSR which attempts to carry out each data transmission with the lowest allowed working power and finally improves SSR's energy efficiency. Second, considering the lack of analytical models for routing protocol performance [1], we demonstrate the upper bound of the induced latency and the scalability performance of SSR. The result is consistent with the scaling law [10] of CRNs, which implies that SSR is scalable in large-scale CRNs. Finally, extensive simulation results are presented to validate the performance of SSR with respect to both latency and energy consumption.

II. System Model

In this paper, we consider a dense secondary network coexisted with a primary network. Both the networks are assumed to deploy in a square region of size A.

Primary Network: The primary network consists of m Poisson distributed PUs denoted by set $V_p = \{S_1, S_2, \cdots, S_m\}$. The network time is supposed to be slotted with each time slot of length τ during which a primary/secondary data packet transmission can be carried out. At the very beginning of each time slot, each PU determines to initiate a data transmission, i.e. to be a primary transmitter, or keeps silent (a PU receiver can be regarded as silent since it does not cause interference to other transmissions).

We assume that there are κ available licensed spectrum bands, denoted by $\mathcal{B} = \{B_1, B_2, \cdots, B_\kappa\}$. All the spectrum bands are supposed to be independent. During each time slot, the primary transmitters working on spectrum band B_i $(1 \leq i \leq \kappa)$ are assumed to be distributed according to a two-dimensional Poisson point process X_T^i with density λ_i. Based on the Displacement Theorem, it can be concluded that the distribution of primary receivers is correlated to the process X_T^i during a time slot, which is actually another two-dimensional Poisson point process X_R^i also with density λ_i.

Secondary Network: We consider a dense secondary network consisting of n SUs, denoted by $s_1, s_2, \cdots, s_n$. All the SUs are independently and identically distributed (i.i.d.) over the square area. Formally, the dense secondary network distribution model can be defined as follows.

Definition 2.1: Given a secondary network consisting of n SUs and deployed in a square area of size A, it is dense scaling if $\sqrt{A} \cdot \sqrt{\frac{\log n}{n}} = O(1)$ with high probability (almost sure), i.e. $A = O(\frac{n}{\log n})$; otherwise, this network is extended scaling.

Therefore, without loss of generality, we assume $A = \frac{c_0 n}{\log n}$, where c_0 is a changeable constant value. Next, we present the *power model* and *communication model* of the secondary network as follows.

Power Model: Power control has significant impacts on the performance of CRNs [6]. To benefit from power control, we assume each SU can work with l levels of power, denoted by $\mathcal{P} = \{P_1, P_2, \cdots, P_l\}$ where $P_i < P_j$ for $1 \leq i < j \leq l$. According to the *free space propagation model*, the transmission range of a SU working with power P_i $(1 \leq i \leq l)$ is defined as $r_i = \sqrt[\alpha]{\frac{c_1 \cdot P_i + c_2}{c_3}}$, where α is the *path loss exponent* and c_1, c_2, and c_3 are constant values. Then, for a pair of SUs s_u and s_v, if the Euclidian distance between them $D(s_u, s_v)$ satisfies $D(s_u, s_v) \leq r_i$, we say there is a bidirectional link/edge, denoted by $\iota_{u,v}^i$ or $\iota_{v,u}^i$, between s_u and s_v. In addition, to guarantee power variety (transmission distance variety), we assume $r_l \geq 2r_1 + s/r_1$, where s is a constant value defined in Section III-B.

Let $E^i = \{\iota_{u,v}^i | s_u$ and s_v are any two SUs and $\max\{0, r_{i-1}\} < D(s_u, s_v) \leq r_i\}$, i.e. E^i is the set of all the possible links in the secondary network when all the SUs work with power P_i (except for the links formed by working with power P_j $(j < i)$). Consequently, to make the routing problem meaningful, we assume a network topology graph $G = (V, E)$ is connected, where V is the set of all the SUs and $E = \bigcup_{i=1}^{l} E^i$ is the set of all the possible links.

Since each SU can work with multiple levels of power, we define the neighborhood of a SU s_u as follows. For s_u, the set of its r_1 neighbors is defined as $N_u^1 = \{s_v | s_v \in V, s_v \neq s_u,$ and $D(s_u, s_v) \leq r_1\}$; similarly, for $2 \leq i \leq l$, the set of its r_i neighbors is defined as $N_u^i = \{s_v | s_v \in V, s_v \neq s_u, D(s_u, s_v) \leq r_i,$ and $s_v \notin \cup_{j=1}^{i-1} N_u^j\}$.

Communication Model: *Spectrum dynamics* is one of the main differences that distinguishes CRNs from traditional wireless networks. Since we assume that there are κ available licensed spectrum bands, for simplicity, suppose all the spectrum bands have the same capacity. At any time slot t, the available spectrum bands for a SU s_u working with power P_i is a subset of $\mathcal{B}$ denoted by $\mathcal{B}_u^{i,t}$, which can be obtained by spectrum sensing. Then, at a particular time slot t, s_u can transmit a data packet to s_v with power P_i on spectrum band B_k if (i) $D(s_u, s_v) \leq r_i$; (ii) $B_k \in \mathcal{B}_u^{i,t} \cap \mathcal{B}_v^{i,t}$; and (iii) this data transmission is interference-free with other ongoing secondary communications.

III. Semi-Structure Routing Framework

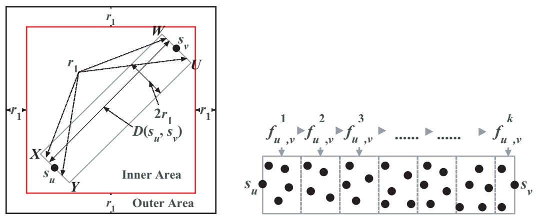
A. Network Partition

Since a CRN is assumed to be deployed in a square area (as shown in Fig.1(a)), we partition the network into *inner area* and *outer area* as follows. For any point in the network, if its Euclidean distance to any boundary of the network is no less than r_1, then this point is in the inner area of the network; otherwise, this point is in the outer area of the network. As shown in Fig.1(a), the area within the inner square is the inner area while the area between the inner square and the outer square is the outer area. For the SUs located in the inner area (respectively, outer area), we denote them by set V_I (respectively, V_O), i.e. $V_I = \{s_u | s_u$ is located in the inner area$\}$ (respectively, $V_O = \{s_u | s_u$ is located in the outer area$\}$).

B. Routing Framework in the Inner Area

1) Routing Zone and Forwarding Zone: Based on the network partition, we introduce our routing framework in a hierarchical manner. For convenience, we start from designing the routing strategy for the SUs located in the inner area of the network. Then, we extend this strategy to the case of routing from any SU to any other SU in the network.

For two SUs $s_u, s_v \in V_I$, suppose s_u is the data source which transmits some data to the destination s_v. To deliver the data from s_u to s_v, we have two objectives on selecting the route. The first one is to exploit the spectrum dynamics in the CRN, which implies that to select the next hop for an intermediate forwarding node, instead of defining a fixed routing metric, we consider the real-time spectrum dynamics at the current intermediate node and find the proper next hop from a specific set of possible next-hop nodes. During the next hop selection process, we tend to make the forwarding SU to work with a low level of power, which can reduce energy consumption and increase network concurrency. The second objective is to guarantee the overall routing performance. This implies that as long as the connectivity from the source to the destination and the spectrum availability can be guaranteed, we try to avoid circuitous data transmission paths which may cause unnecessary latency and cost during a data routing process.



(a) (b)

Figure 1. Routing zone and forwarding zone.

Considering the two objectives, we propose a spectrum-aware and overall performance-guaranteed *Semi-Structure Routing* (SSR) framework with power control. For a data transmission task from source s_u to destination s_v, we first construct a rectangular *routing zone*, denoted by $\mathcal{Z}_{u,v}$, connecting s_u and s_v, which is formally defined as follows. The routing zone $\mathcal{Z}_{u,v}$ of communication pair (s_u, s_v) is a rectangle Rct($XYUW$), where X, Y, U, and W are the four vertices of the rectangle, the length of edges XY and UW is $|XY| = |UW| = 2r_1$, the length of edges YU and WX is $|YU| = |WX| = D(s_u, s_v)$, and s_u and s_v are located at the midpoints of edges XY and UW, respectively. As shown in Fig.1(a), the routing zone of (s_u, s_v) is Rct($XYUW$).

Next, we further partition the routing zone into smaller rectangular zones starting from the s_u side, named the *forwarding zones*, with each of the forwarding zone having area size of $s = \min\limits_{\xi<0} \frac{c_0(2-c_4\xi)}{1-e^{\xi}}$, where ξ is any negative value, and c_0 and c_4 are some positive constant values. As shown in Fig.1(b), we partition $\mathcal{Z}_{u,v}$ into k forwarding zones starting from the s_u side denoted by $f_{u,v}^i$ $(1 \leq i \leq k)$. Note that, all the forwarding zones have an area size of s except for the last one $f_{u,v}^k$ which may have a smaller area size.

From the definition of forwarding zones, we know that s_u is in the first forwarding zone $f_{u,v}^1$ which is the starting point for routing, while s_v is in the last forwarding zone $f_{u,v}^k$ which is the ending point for routing. For convenience, the nodes in forwarding zone $f_{u,v}^i$ $(1 \leq i \leq k)$ is denoted by set $F_{u,v}^i$. Actually, except for the last forwarding zone $f_{u,v}^k$, we can mathematically prove that each $f_{u,v}^i$ $(1 \leq i \leq k-1)$ contains $\Omega(\log n)$ possible intermediate forwarding nodes, i.e. the cardinality of $F_{u,v}^i$ $(1 \leq i \leq k-1)$ satisfies $|F_{u,v}^i| \geq c_4 \log n$, where c_4 is a constant positive value (the proof is shown in the journal version due to space limitation). Furthermore, based on our network model, it can be straightforwardly proven that for $\forall s_w \in F_{u,v}^i$ and $\forall s_z \in F_{u,v}^{i+1}$, $s_z \in \cup_{j=1}^{l} N_w^j$, i.e. s_z is directly reachable from s_w by working with some level of power.

2) Spectrum-Aware SSR Framework: Now, we are ready to present our spectrum-aware SSR framework, which is shown in Algorithm 1. In Algorithm 1, we demonstrate the routing framework by routing one data packet from source s_u to destination s_v.

From Algorithm 1, we can see that Lines 1-12 are to deliver a data packet from source s_u to some node in the forwarding zone $f_{u,v}^{k-1}$ hop by hop (from the macroscopic view, forwarding zone by forwarding zone). At each hop, assuming that $s_w \in F_{u,v}^i$ is the current intermediate node which holds the data packet, s_w chooses its next hop s_z from a potential forwarding set $F_{u,v}^{i+1}$ according to the following rule: there exists a spectrum opportunity from s_w to s_z and s_w can obtain this spectrum opportunity with the minimum possible power level. Power level has a close relation to the spectrum opportunity. On the one hand, from a local view, a small power level implies less interference and shorter transmission distance, which can bring a specific link more spectrum opportunities. However, from a global view, a small power level also implies shorter transmission distance and potentially more transmission attempts and hops from the source to the destination. On the other hand, a large power level implies more interference, which reduces the number of spectrum opportunities for a specific link. Nevertheless, a large power level also implies more reachable neighbors which expands the selection space for the next hop and thus increases spectrum opportunity to a certain extent. Furthermore, a large power level can potentially decrease the number of transmission times and hops from the source to the destination. Lines 13-16 specify the last step of a routing process. Unlike previous steps where the next hop is chosen from a forwarding set, the next hop in this step is the final destination of this routing task. As long as there is a spectrum opportunity, the data will be routed to destination s_v from some intermediate node in $F_{u,v}^{k-1}$.

SSR takes into account both the local real-time spectrum dynamics and the global routing efficiency. The reasons are as follows: first, by introducing *forwarding zones*, each intermediate forwarding node can choose its next hop from a set of nodes (the size of this set is $\Omega(\log n)$) based on the real-time spectrum dynamics. From the microscopic view, it significantly increases the choices of an intermediate node as well as the spectrum opportunities, especially in CRNs with heavy-loaded primary activities. Therefore, SSR can effectively make use of the local real-time spectrum dynamics; second, by introducing a *routing zone*, the actual identified route from the source to the destination is restricted to the routing zone and has a bounded number of hops. From the microscopic view and with respect to transmission times and energy consumption, it avoids finding a high-cost tortuous path from the source to the destination, and thus it guarantees the global and overall efficiency of SSR. In addition, since $|F_{u,v}^i| = \Omega(\log n)$ for $1 \leq i \leq k-1$ and meanwhile the number of neighbors of any SU $s_w \in V$ also satisfies $\cup_{j=1}^{l} N_w^i = O(\log n)$, we do not sacrifice the potential available spectrum opportunities for a node in order to guarantee the overall efficiency of SSR; finally, without reducing local spectrum opportunities or increasing global routing cost, we incorporate power control with SSR. By the joint route selection and power control strategy, SSR attempts to carry out each data transmission task with the

Algorithm 1: The spectrum-aware SSR framework.

input : a CRN, a routing task from s_u to s_v
output: a route from s_u to s_v

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s_w ← s_u;
for i = 1; i < k − 1; i++ do
    flag = 0;
    for j = 1; j ≤ l; j++ do
        for ∀s_z ∈ N_w^j ∩ F_{u,v}^{i+1} do
            if B_w^{j,t} ∩ B_z^{j,t} ≠ ∅ then
                s_w transmits the data to s_z by working
                with power P_j on a randomly selected
                spectrum band from B_w^{j,t} ∩ B_z^{j,t};
                flag = 1;
                Break;
        if flag = 1 then
            Break;
        s_w ← s_z;
for j = 1; j ≤ l; j++ do
    if B_w^{j,t} ∩ B_v^{j,t} ≠ ∅ then
        s_w transmits the data to s_v by working with
        power P_j on a randomly selected spectrum
        band from B_w^{j,t} ∩ B_v^{j,t};
        Break;
```

lowest power level while not introducing extra data relays. This can reduce the overall energy consumption and increase the global network concurrency.

C. Extension: SSR in a CRN

In the previous subsection, we discuss the SSR framework in the inner area of a CRN, i.e. both source s_u and destination s_v satisfy $s_u \in V_I$ and $s_v \in V_I$. In this subsection, we extend SSR to the general case which is routing in a CRN. Specifically, we consider the routing problem from source s_u to destination s_v, where $s_u \in V$ and $s_v \in V$. Again, we assume a routing task is to deliver a data packet from s_u to s_v. For the multiple data packets routing tasks, they can be accomplished by applying this framework for each of the data packets.

For the routing problem from $s_u \in V$ to $s_v \in V$, we basically have four cases with respect to whether s_u (respectively, s_v) is located in the inner area (respectively, outer area). Correspondingly, we address the routing of each case as follows. For convenience, we refer to the SSR framework proposed in the previous subsection (Section III-B) as SSR-I in the following discussion.

Case 1: $s_u \in V_I$ and $s_v \in V_I$. We can apply SSR-I directly to carry ou the routing task.

Case 2: $s_u \in V_O$ and $s_v \in V_I$. If $s_v \in \cup_{i=1}^{l} N_u^i$, i.e. s_v is in the neighborhood of s_u, then s_u transmits the data directly to s_v when there is a spectrum opportunity. Otherwise, since s_u is located in the outer area, we select s_u's nearest neighbor s_w located in the inner area as its next hop, i.e. s_w satisfies (i) $s_w \in V_I \cap (\cup_{i=1}^{l} N_u^i)$; and (ii) $\nexists s_j$ such that $s_j \in V_I \cap (\cup_{i=1}^{l} N_u^i)$ and $D(s_u, s_j) < D(s_u, s_w)$. After selecting s_w, s_u transmits the data to s_w when there is a spectrum opportunity. Then, apply SSR-I to accomplish the routing from s_w to s_v.

Case 3: $s_u \in V_I$ and $s_v \in V_O$. If $s_v \in \cup_{i=1}^{l} N_u^i$, s_u transmits data directly to s_v when there is a spectrum opportunity. Otherwise, since s_v is located in the outer area, we first select s_v's nearest neighbor located in the inner area, denoted by s_z, as the last forwarding node. Then, apply SSR-I to accomplish the routing from s_u to s_z. Finally, s_z forwards the data to s_v when there is a spectrum opportunity.

Case 4: $s_u \in V_O$ and $s_v \in V_O$. If $s_v \in \cup_{i=1}^{l} N_u^i$, s_u transmits data directly to s_v when there is a spectrum opportunity. Otherwise, since both s_u and s_v are located in the outer area, we first find the nearest neighbors of s_u and s_v located in the inner area, denoted by s_w and s_z, respectively. Then, s_u transmits the data to s_w when there is a spectrum opportunity. Subsequently, apply SSR-I to transmit the data from s_w to s_z. Finally, s_z forwards the data to s_v when there is a spectrum opportunity.

D. Performance Analysis

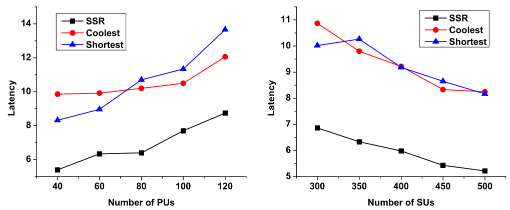
Now, we analyze the latency performance of SSR. Let $\Gamma_{u,v}$ and $D_{u,v} = D(s_u, s_v)$ be the expected routing latency and the physical distance from source s_u to destination s_v, respectively. The result is shown in Theorem 1.

Theorem 1: (i) $\Gamma_{u,v} \leq \frac{\max\{0, k-2\}}{p'_{\min}} + \frac{3}{p_{\min}}$, where $p_{\min} = \min\{1 - \prod_{j=1}^{\kappa}(1 - p_j) | p_j = f(\lambda_j, r_{i,I}^2 + R_I^2), 1 \leq i \leq l\} \geq 1 - \prod_{j=1}^{\kappa}(1 - f(\lambda_j, r_{l,I}^2 + R_I^2))$ is the lower bound of the *single node to single node* spectrum opportunity and $p'_{\min} = \min\{\Pr(s_z \to F_{u,v}^{\hbar}) | 1 \leq \hbar \leq k-1\}$ is the lower bound on the *single node to a set* (the set of nodes in a forwarding zone) spectrum opportunity, and k $(0 \leq k \leq \lceil \frac{2r_1}{s}(\sqrt{\frac{2c_0 n}{\log n}} - 2\sqrt{2}r_1)\rceil)$ is the number of forwarding zones on the route from s_u to s_v; (ii) $\lim_{n \to +\infty} \frac{\Gamma_{u,v}}{D_{u,v}} = \Theta(1)$, which is consistent with the scaling law on the connectivity-scalability of CRNs [10]. This implies SSR is scalable in large-scale CRNs.

Due to the space limitation, detailed theoretical analysis on the spectrum opportunities for SUs, the latency performance of SSR, and the energy consumption performance of SSR can be found in our journal version.

IV. Simulation and Analysis

In all the simulations, we consider a CRN deployed in a square region of size 100×100. The primary network is Poisson distributed and consists of m PUs. The secondary



(a) (b)

Figure 2. Latency performance of SSR vs. the number of PUs/SUs.

network consists of n randomly distributed SUs. The network time is slotted with each time slot of length one. To avoid collision and interference, we employ the typical TDMA protocol for the MAC layer and a "*first come first serve*" strategy as the transmission scheduling policy. For simplicity, we assume that all the PUs work with a fixed power level with transmission range R normalized to 15, while all the SUs can work with three levels ($l = 3$) of power P_1, P_2, and P_3 with transmission ranges r_1, r_2, and r_3 normalized to 10, 20, and 30 respectively. We also assume the interference ranges (R_I and $r_{1,I}, r_{2,I}, r_{3,I}$) of PUs and SUs are the same as their transmission ranges.We assume there are κ equal-capacity licensed spectrum bands available in the network. During each time slot, every PU equi-probably chooses one spectrum band to conduct activity with probability p_c, which is defined as the *PU activity*. For the other system parameters, the default settings are as follows: $A = 100 \times 100$, t$m = 80$, $n = 400$, $R = R_I = 15$, $r_1 = r_{1,I} = 10, r_2 = r_{2,I} = 20$, $r_3 = r_{3,I} = 30$, $\kappa = 2$, $p_c = 0.3$. Due to space limitation, more simulation results can be found in the journal version of this paper.

In the simulations, we compare SSR with Coolest [4] and Shortest. Coolest is a recently published routing algorithm for CRNs. In Coolest, the path with the most balanced and/or the lowest spectrum utilization by PUsis preferred for selecting a route. Shortest refers to the shortest path algorithm with respect to the Euclidian distance between the source and destination, which is a very basic and typical routing idea in both traditional wireless networks and CRNs. In the simulations, all the source-destination pairs are randomly generated.

When the number of PUs/SUs (i.e. m/n) is changed, the induced latency of SSR, Coolest, and Shortest is shown in Fig.2(a) and (b). From Fig.2(a), we can see that when the number of PUs increases, the induced latency of all the three algorithms increases. The reason is that if the PU activity p_c is fixed, more PUs imply more activities in the primary network. It follows that fewer spectrum opportunities are available for SUs and thus the latency of the all the algorithms increases. From Fig.2(a), we can also see that SSR has less latency than Coolest and Shortest. This is mainly because (i) by introducing forwarding zone, SSR can take into account the local real-time spectrum dynamics, which leads to high spectrum utilization efficiency; and (ii) by introducing routing zone, the identified route in SSR has a similar length as that in Shortest, which implies the overall performance of SSR can also be guaranteed. From Fig.2(b), the latency of all the algorithms decreases when the number of SUs increases. This is because that more SUs imply more spectrum opportunities and choices of pathes, which potentially reduces routing latency. Again, SSR is better since it considers both the local real-time spectrum dynamics and the global routing efficiency.

V. Conclusion

Considering the limitations of existing routing algorithms in CRNs, we propose a joint spectrum-aware semi-structure routing and power control framework, named SSR. SSR improves existing routing algorithms by taking into account both the local real-time spectrum dynamics and the global routing performance. Subsequently, we analyze the latency performance of SSR, which is scalable. The extensive simulation results validate the performance of SSR.

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