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Multi-layer based multi-path routing algorithm for maximizing spectrum availability

Duzhong Zhang[1,2] · Quan Liu[1,2] · Lin Chen[3] · Wenjun Xu[1,2] · Kehao Wang[1,2]

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Abstract Last 2 decades have witnessed the spectrum resources scarcity which is caused by wireless networks' ubiquitous applications. To utilize the rare spectrum resources more efficiently, Cognitive Radio (CR) technology has been developed as a promising scheme. However, in CR networks, a novel NP-Hard disjoint multi-path routing problem has been encountered due to the Primary Users' (PUs') random movements. To settle this problem, we present a *Spectrum History Matrix* mechanism to define long-term spectrum sensing information on time-spectrum level such that spectrum availability and *communication efficiency* can be quantized in CR networks. To lessen the possibility for an active PU to interrupt all paths simultaneously, a sub-optimal *Multi-layer based Multi-path Routing Algorithm* (*MMRA*) is provided to determine how to route multiple paths which are not under the same PUs' interference ranges. Through theoretical and simulation analyses, *MMRA* can not only settle the disjoint multi-path routing problem in polynomial time complexity, but also maximize *communication efficiency*.

✉ Duzhong Zhang
zhangduzhong@whut.edu.cn

Quan Liu
quanliu@whut.edu.cn

Lin Chen
chen@lri.fr

Wenjun Xu
xuwenjun@whut.edu.cn

Kehao Wang
kehao.wang@whut.edu.cn

1 School of Information Engineering, Wuhan University of Technology, Wuhan, China

2 Key Laboratory of Fiber Optic Sensing Technology and Information Processing, Ministry of Education, Wuhan, China

3 Laboratoire de Recherche Informatique (LRI-CNRS UMR 8623), University of Paris-Sud, 91405 Orsay, France

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1 Introduction

Unprecedented success of wireless networks in last 2 decades has caused the densification of wireless network application, since most available spectrum bands have been allocated by governments [1–3]. However, in [4], *Federal Communications Commission* (FCC) has reported that most of these allocated spectrum bands were only used in some limited geographical areas or periods of time, and the average utilizations of these bands vary from 15 to 85 %.

Apparently, these underused spectrum 'holes' are still available for novel wireless communications. As a promising technology to reuse these spare spectrum resources, *Cognitive Radio* (CR) has shown great potential on improving spectrum efficiency [5, 6]. The ordinary users in CR networks which are called *Secondary Users* (SUs) could intelligently percept spectrum conditions and self-adaptively access and reutilize the spectrum 'holes' unused by licensed users [*Primary Users* (PUs)] [7, 8].

Unfortunately, novel technology is always accompanied with novel problems. For fair communications between PUs and SUs in CR networks, SUs should not have impacts on PUs' normal data transmissions, so the problem of coordinating their communication relationships has attracted ubiquitous attentions from worldwide researchers [9, 10].

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However, most solutions on this problem simply cease SUs' signals when PUs are arriving, which would cause a lot of dropped data [11]. Although some reliable PUs avoidance mechanisms have been developed, there exist some key questions unsolved for this important CR networks' issue, especially in multi-path routing field. But few researchers focus on the multi-path routing in CR networks since most problems in this field could be transferred to simple versions in traditional ad hoc networks environment with mature solutions [12, 13].

Whereas, a novel *'Route Closeness'* problem which defined by Beltagy et al. in [14] has proposed a fresh CR networks multi-path routing research direction. As shown in Fig. 1, 2 paths should be selected from 3 candidates for data transmission, solid lines represent paths which are utilized, while dashed lines denote paths which are waiting. Suppose 1 PU could appear randomly to interfere any SUs' data transmissions in this network. Then, hard is how to route 2 paths for guaranteing an unstoppable communication when PU is arriving. This problem could be depicted simply in Fig. 1, if we choose close routes pattern shown in Fig. 1(a), 2 close nodes in the selected paths are under the same PU's interference range, so their data transmission may be broken simultaneously by PU's movement. Conversely, if Fig. 1(b)'s scenario is employed, communication of the 2 selected paths could not be stopped completely by PU.

Definitely, plenty of solutions could solve the problem in Fig. 1(a), e.g. hopping spectrum channels when data transmission is interfered. However, most solutions prefer to take reactive mode for mitigating interferences when

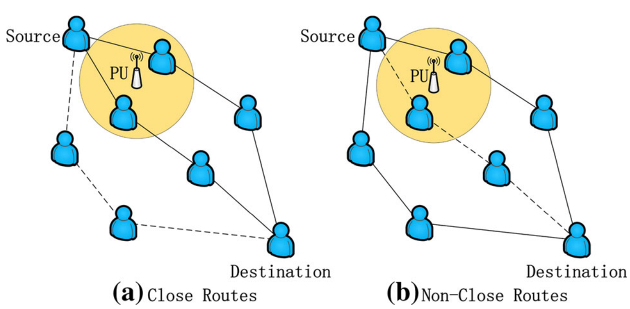

Fig. 1 Difference between close routes and non-close routes

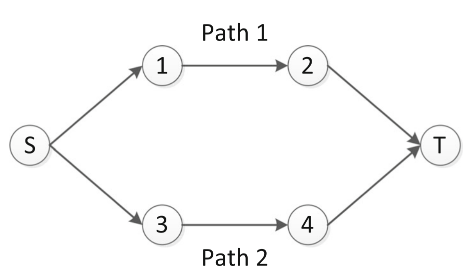

Fig. 2 Topology of network route

PUs are sensed. But in some specific scenarios, these type solutions would not be suitable (e.g. in real-time communication scenario, if PUs occupied most channels, hopping spectrum bands would take too much time to maintain data's time-sensitive). Thus, a proactive non-close multi-path routing mechanism is required. While, finding the non-close paths is proved to be *NP-Hard* in [14].

From another angle, the main target of finding non-close paths is to route multiple paths which are not covered by same PUs. Considering the irrelevance of selected paths in the sense of PUs' interference ranges, it is similar to the '*disjoint*' feature of traditional routing problem to some extent. Therefore, we would like to call the non-close paths routing problem as '*disjoint multi-path routing problem in CR networks*' in this paper.

In this case, we would like to provide a sub-optimal '*Multi-layer based Multi-path Routing Algorithm*' (*MMRA*) in this paper to settle the *disjoint multi-path routing problem in CR networks* for maximizing *communication efficiency*. In particular, a *Spectrum History Matrix* (*SHM*) mechanism is proposed to define spectrum historical sensing information in CR networks on time and spectrum levels. While a *Multi-layer Dividing Algorithm* is presented for reconfiguring multiple layer graphs according to *SHM* distribution, and a *Paths Selection* mechanism is utilized to select paths in these layers. So that, multiple paths could be selected to be '*disjoint*' in spectrum and time dimension. And through theoretical and simulation analyses, *MMRA* could solve *disjoint multi-path routing problem* in polynomial time complexity and maximize *communication efficiency*.

The rest of this paper is organized as follows: the related works about disjoint multi-path route in CR networks would be stated in Sect. 2. In Sect. 3, the problem definition and a comprehensive introduction of *Spectrum History Matrix* mechanism would be presented. While a detailed introduction of *Multi-layer based Multi-path Routing Algorithm* would be stated in Sect. 4. And Sect. 5 proposes the simulation performance, Sect. 6 is conclusion.

2 Related works

In this section, we would introduce some related works about the disjoint multi-path routing mechanisms in CR networks. Although few works have been done on this problem, three directions are discussed based on different focuses of these works specifically.

2.1 Geographic oriented

Firstly, some geographic oriented routing mechanisms are reviewed in this part. This type of solutions makes use of networks' nodes geographical information to route disjoint paths in which the nodes' locations have least probability under the same PU's interference range.

The route mechanism in [14] is a typically geographic oriented solution. Each network node's location has been fixed before routing, while all route paths are also the priority knowledge. Then, through calculating overlap areas between paths, a *Route Closeness Metric* could be constructed, and by comparing the *Route Closeness Metric*, multiple paths which have least overlap areas from other paths could be computed. So that, these paths could have least probabilities to be interfered with all other paths at the same time. However, it is hard to guarantee that the selected paths with least overlap areas are not under the same PUs. On the other hand, as the all routing information is needed, the collection of routing information would cost exponential level time. While although the all paths' amount may be fewer than nodes, the calculation and comparison of non-close paths' collection is still an exponential level operation. Consequently, this approach is hard to address problem in this paper.

In [15], a geographic oriented solution *Dead Zone Protocol* has been presented. By using cooperative links between CR nodes, a *Dead Zone* could be defined for nodes under the same PUs interference range. Therefore, disjoint paths could be selected through avoiding *Dead Zone* in geographical dimension, and the disjoint routing problem could be address. However, cooperative links should be established in advance, and PUs' interference ranges are always much larger than SUs in practical environment which would leads omissive SUs exist in *Dead Zone* establishment.

2.2 Spectrum oriented

In this part, a spectrum oriented type of approach would be presented. This type of solutions expects to find paths in CR networks which is disjoint on spectrum dimension.

Ju and Evans proposed a spectrum oriented solution in [16]. A *Spectrum Discovery Protocol* and a *Space Discovery Protocol* are presented to consist of the spectrum oriented approach. The *Spectrum Discovery Protocol* is responsible for isolating spectrum of nodes in one paths from neighbor paths' nodes, and the *Space Discovery Protocol* makes sure that the selected paths are disjoint in space dimension. Hence, multiple paths chosen by this mechanism would be disjoint in both spectrum and space dimensions from their neighbor CR nodes. But this approach could only select some neighbor disjoint paths which could not guarantee nodes in paths would be disjoint under PUs' interference. Thus, the steady multi-path communication in CR networks could not be realized.

2.3 Jammer oriented

In the anti-jamming communication field, there are a lot of mutual disjoint multi-path routing solutions. As some Jammer's natures are similar to PU's (larger transmission power, random appearance, non-priori-detection etc.), the anti-jamming routing approaches could provide some heuristic ideas for the problem in this paper.

In [17, 18], Zhang et al. stated a novel mechanism *Availability History Vector* (*AHV*) to define long-term spectrum statements under jammers' interference, and selected multiple paths which have least possibility for communication termination when jammers send interference signals by using greedy algorithm. Therefore, a steady communication could be assured in the anti-jamming communication environment. This approach has solved the anti-jamming problem well, and inspired us in this paper greatly. Whereas, anti-jamming environment is based on single spectrum channel, which is not the same as multi-channel PUs environment in CR networks, this type of solution is not suitable for disjoint routing problem in CR networks.

Similar to the work made by Zhang et al., a shortest multi-path routing and cooperative packet cashing mechanisms are designed for packets loss decreasing leaded by route faults in [19]. And Wu et al. introduced an IP-layer multi-path selection mechanism to collect 'least connectivity' paths through IP-layer topological disjointness utilization in [20].

3 Overview

Through introduction of related works on this field, few achievements could be selected out to address the *disjoint multi-path routing problem in CR networks*. As a novel solution on this problem, '*Multi-layer based Multi-path Routing Algorithm*' (*MMRA*) would be introduced comprehensively in this section, 2 main parts would be included, a detailed problem definition on disjoint route in CR networks and the *Spectrum History Matrix* (*SHM*) mechanism introduction.

3.1 Problem definition

As introduced in Sect. 1, the main purpose of this paper is to settle the *disjoint multi-path routing problem in CR networks*. So, we would like to analyse this problem precisely in this part.

In general, routing multiple '*disjoint*' paths in CR networks is a *NP-Hard* problem. Therefore, we turn to a sub-optimal modified problem, based on which a reliable mechanism is proposed to address the original problem in polynomial time complexity.

In CR network, *disjoint* paths mean that they do not locate under the same PUs' interference ranges rather than physically disjoint with other paths. Generally, PUs' movements and appearance locations are random, which is hard to be measured and predicted under multi-channel scenario. So, a novel measurable criterion, '*Communication Efficiency*', characterizing paths' *disjointness* is presented.

Specifically, *communication efficiency* is proposed to indicate transmission efficiency under PUs' interferences with full networks' load. Therefore, if multiple selected paths are *disjoint*, the data communication would not be completely interrupted by PUs. Then in infinite time, *communication efficiency* would become maximum definitely. On the contrary, for a long-term sensing period T, if R selected paths have maximum *communication efficiency*, they should have the most possibilities to be the *disjoint* paths in T and have a higher possibility to achieve maximum *communication efficiency* in future than other paths. So, the *disjoint multi-path routing problem* could be solved to some extent. Considering the feasibility to realize this assumption, 2 questions should be addressed, *communication efficiency* quantization and paths selection.

Consequently, *communication efficiency* quantization mechanism would be introduced following. For a CR network, suppose *communication efficiency* of selected paths in period T is δ_T, the value range of δ_T is from 0 to 1. If there are no PU at all spectrum bands in T period, all spectrum channels could be used for data transmission, and δ_T could be defined as 1. Conversely, if all spectrum bands are occupied by PUs, there would be no channel for communication, and δ_T must be 0. Obviously, it is easy to quantize δ in these extreme scenario, but for ordinary CR networks scenario, this question would be more difficult since it is hard to determine how much δ_T is when PUs appear randomly on spectrum bands in T period.

Hence, a *Spectrum History Matrix* (*SHM*) mechanism is introduced to quantize δ. Suppose that parameter S could be collected by *SHM* mechanism to quantize the discrete spectrum information in different channels and moments, which is indicated as '*spectrum availability*' of CR network in this paper. And function X could calculate and maximize them. Then, for N spectrum channels and T time period, δ could be depicted as

$$\delta_{T,N} = \frac{X(\{S_{t_i,n_j} | t_i \in [0,T], n_j \in [0,N]\})}{T \cdot N}.$$

where t_i and n_j indicate i^{th} time slot in T and j^{th} channel in N. Therefore, if we could define function X appropriately, then it could summarize CR networks' spectrum availability *SHM* set $\{S_{t_i,n_j} | t_i \in [0,T], n_j \in [0,N]\}$, and *communication efficiency* factor δ could be quantized.

At last, the first question of *communication efficiency* quantization has been changed to be the function X definition, which would be introduced in details at the following part of this section in this paper.

On the other hand, the solution of paths selection could be settled by '*Multi-layer based Multi-path Routing Algorithm*' (*MMRA*) which we have briefly introduced above. By utilizing *MMRA*, the selected paths' *SHM* could be increased to maximum. Hence, the *communication efficiency* $\delta_{T,N}$ of this CR network in T time period with N channels could also be maximized. While in the next T' period, the paths chosen by *MMRA* in T could also have most probabilities to be disjoint, so the disjoint routing problem could be solve to some extent.

Now, we define the novel sub-optimal modified problem formmaly as follows:

Problem 1 *Given a $\mathcal{N}$ nodes weighted CR network graph $G(V, E, S)$ with N communication channels in T period, V indicates node's information, E indexes edge's information and S represents each node's SHM knowledge. The problem should be solved is finding a mathematical operation X and a routing algorithm MMRA to select R multiple paths,*

$$\text{Maximize} \quad \delta_{T,N} = \frac{X(\{S_{t,n} | t \in [0,T], n \in [0,N]\})}{T \cdot N}$$
$$\text{Subjectto} \quad S \propto V, \; V \in R.$$

3.2 Spectrum history matrix

In this part, we provide the *Spectrum History Matrix* mechanism and mathematical function X in detail.

3.2.1 Spectrum history matrix

In order to collect sensed discrete spectrum information which is distributed in all CR nodes, the *Spectrum History Matrix* (*SHM*) mechanism would be presented by employing periodically broadcasting RREQ and RREP messages. So that overall CR network's *SHM*s could be converged to source for calculation.

Then, for the detailed definition of *SHM*, suppose a long-term PUs' movements sensing information is obtained by a N channels CR network, if we split the long-term information into T time slots. Obviously, for a single spectrum channel n at a fixed time slot t, there may be multiple PUs which interfere the same SU. However, these interferences would only be sensed as *ON* in the SU's *SHM* unit $s_{t,n}$ since SU could not distinguish different PUs' features. Hence, the PUs' appearances could only be 2 statements $ON - OFF$. While although there exist interferences among PUs, which have little impacts on the spectrum sensing results by SUs. So $s_{t,n}$ could be described as

$$s_{t,n} = \begin{cases} 1, & \text{PU is arriving.} \\ 0, & \text{PU is absent.} \end{cases} \tag{1}$$

where $s_{t,n}$ represents the n^{th} channel's t^{th} time slot PUs appearances. As a result, for the whole T time slots and N channels, the *SHM* M_s could be depicted as

$$M_s = \left\{ \begin{matrix} s_{1,1}, s_{1,2}, \cdots, s_{1,N} \\ s_{2,1}, s_{2,2}, \cdots, s_{2,N} \\ \ddots, \ddots, \ddots, \ddots \\ s_{T,1}, s_{T,2}, \cdots, s_{T,N} \end{matrix} \right\}. \quad (2)$$

Apparently, the spectrum availability under PUs' interference could be pictured by M_s in time and spectrum dimension. However, the role which *SHM* plays in relationships between nodes and paths in CR networks, and the calculation from M_s to δ both have not been proposed.

3.2.2 Function X

Thus, for the purpose of computing M_s and δ, the details of function X would be stated in this part.

As we know, in a CR network, all nodes could sense the same channels at the same time. Then, for node i, it's *SHM* which is represented by $\mathbf{s}_i$ could have the same matrix size as M_s. So for all nodes, paths and networks, this characteristic is all suitable.

Therefore, if a path with k nodes is selected in this network for data transmission, the path's *SHM* could be summarized as

$$\mathbf{S}_j = \mathbf{s}_1 \cup \mathbf{s}_2 \cup \cdots \cup \mathbf{s}_k. \quad (3)$$

As shown in Eq. 3, $\mathbf{S}_j$ represents j^{th} path's *SHM* which contains k nodes, $\mathbf{s}_i$ is the *SHM* M_s of a single node in the k nodes. So the k nodes' combined *SHM* is the logical bit level 'OR' set between nodes' *SHM*s. Because path's *SHM* is designed to describe the available channels which have not be occupied by PUs through employing this path. If one channel is occupied by PUs in one time slot at one node in the path, this spectrum time slot should be marked out for suggesting PUs movements. So that the potential channels and time slots which may be under the same PUs in other paths could be figured out by paths' comparisons.

While for multi-path *SHM* calculation, as multiple paths which are not under the same PUs are needed, logical 'AND' bit-operation between different paths is equipped since 1 could not be calculated out in multiple *disjoint* paths on a certain spectrum time slot.

$$M_m = \mathbf{S}_1 \cap \mathbf{S}_2 \cap \cdots \cap \mathbf{S}_m. \quad (4)$$

In Eq. 4, multi-path *SHM* M_m is presented as an 'AND' set of m paths. Hence, the channels which could not be interfered by PUs at the same time between paths would be shown.

Consequently, the *SHM* of selected paths could be figured out, so that the operation X would be described as follow and the *communication efficiency* δ could be formulated.

$$X(\{S_{t,n} | t \in T,\ n \in N\}) = T \cdot N - ||M_m||$$

where $||M_m||$ represents the amount of occupied units in multiple paths' *SHM*, so the remaining amount in $T \cdot N$ is the available spectrum, which could describe *communication efficiency* δ.

Therefore, if the $||M_m||$ could be minimized, a maximum *communication efficiency* δ would be obtained. So the Problem 1 could be settled by minimizing $||M_m||$ as shown in Problem 2.

Problem 2 *Given a $\mathcal{N}$ nodes weighted CR network graph $G(V, E, S)$ with N communication channels in T period, V indicates node's information, E indexes edge's information and S represents each node's SHM knowledge. Select R paths in this network to solve the following problem for maximizing network's communication efficiency.*

$$\text{Minimize} \quad ||\mathrm{M_R}|| = \left\| \begin{matrix} \mathrm{s_{1,1}, s_{1,2}, \cdots, s_{1,N}} \\ \mathrm{s_{2,1}, s_{2,2}, \cdots, s_{2,N}} \\ \ddots, \ddots, \ddots, \ddots \\ \mathrm{s_{T,1}, s_{T,2}, \cdots, s_{T,N}} \end{matrix} \right\|$$

$$\text{Subject to} \quad M_R = \mathbf{S}_1 \cap \mathbf{S}_2 \cap \cdots \cap \mathbf{S}_R.$$

3.2.3 Example

Besides the detailed introduction on *SHM* and function X, an example would be presented in this part for easy understanding.

As shown in Fig. 2, there are 2 paths from source S to destination T. Then, the *SHM* details of Node 1 and Node 2 in path 1 are shown in Fig. 3. In 5 time slots, they have sensed 3 spectrum channels. So that their *SHM*s are depicted out, the 'blue' block represents corresponding channel in specific time slot is blocked by PUs, and oppositely a 'white' block means $SHM = 0$.

So, the Path 1 in Fig. 4 which consists of Node 1 and Node 2 has described how to construct a path's *SHM*. When we combine Path 1 and Path 2 in Fig. 4, we could find out that there are only 2 time slots in channel 3 occupied. Which means if we select these 2 paths, all others time slots except the 2 may be interfered by PUs' movements simultaneously, these 2 paths have a $\frac{13}{15}$ probability to be *disjoint*. Hence, if we could select multiple paths could form complementation and obtain least time slots occupied, the final multi-path route could have most probability to transmit real-time data correctly in other period. Then, network's spectrum availability and *communication efficiency* could be maximized.

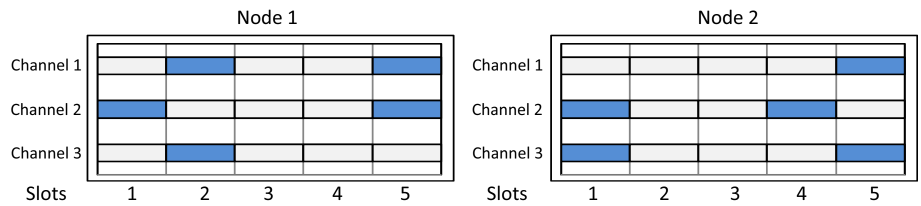

Fig. 3 SHMs of nodes

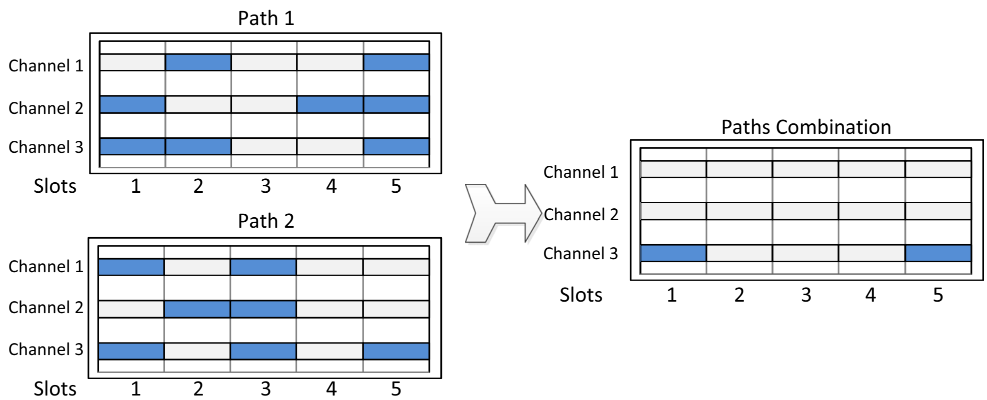

Fig. 4 SHMs of paths

4 Multi-layer based multi-path routing algorithm

After a comprehensive introduction of *Spectrum History Matrix* (*SHM*) and *communication efficiency* quantization mechanism in Sect. 3, the main problem of this paper is proposed. Then, for minimizing multi-path's *SHM M*, a *Multi-layer based Multi-path Routing Algorithm* (*MMRA*) would be presented in this section.

4.1 Motivation

Before *MMRA* presentation, the motivation of this algorithm should be explained.

As introduced in Sect. 3, the main problem has been changed to Problem 2 to find multiple paths which could obtain minimum *SHM* (most idle channels in all time slots). However, the problem is hard to be settled since a similar problem has been proved as a NP-Complete problem in [17, 18]. Hence, we should proposed a novel solution to minimize *SHM*.

However, before the presenting of solution, a key question should be settled. As we know, there are multiple types of wireless signal transceivers have been equipped in CR networks practically. In brief, we could simply distinguish them into 3 types by receiving and sending technology utilization, included *Multiple Input Multiple Output* (MIMO) with infinite interfaces, MIMO with finite interfaces, *Single Input Single Output* (SISO), which all have important impacts on routing method proposition. Actually, the MIMO with finite interfaces and SISO types could only be found in real life. Whereas, the MIMO with finite interfaces type networks are too hard to be analysed since the random constraints of interfaces could construct too many obstacles, especially in the routing mechanism designing scenario of this paper. And if the solutions on infinite interfaces and SISO scenarios could be provided, the MIMO with finite interfaces could also be taken out by combining them. Thus, we would only consider solutions on these 2 types of CR networks. While because the MIMO with infinite interfaces and SISO types solutions on Problem 2 may be too different, the infinite interfaces MIMO routing scenario would be employed in this paper without consideration of nodes and links uniqueness for convenience.

Therefore, as shown in Fig. 4, when paths are combined to form a multi-path *SHM M*, the white block in *M* represents there is one path at least which is completely idle at this specific spectrum time slot. Thus, for the multiple selected paths' *SHM M*, if there exists a single unit $s_{t,n}$ in *M* which is 0, there must exists 1 path k whose *SHM* unit $\mathbf{S}^k_{t,n} = 0$. Then, for all nodes in the k path, there must be

$$\forall\ \mathbf{s}^p_{t,n} = 0,\ p \in Path(k).$$

where n and t index the number of channel and time slot in *SHM*.

Then, considering Problem 2 conversely, it is obvious that minimization of $\|M\|$ is to find multiple paths which have maximum 0 in their *SHM*. So, for each *SHM* unit, suppose there exists one path in which all nodes are idle, the amount of 0 in their *SHM* should be maximized.

Hence, given a weighted CR network $G(V, E, S)$ with N communication channels in T period. By copying and reconstructing original $G(V, E, S)$ according to it's *SHM*, we could get that

$$G_{t,n}(V', E', S') = \{G(V, E, S) | S_{t,n} = 0,\ V \propto S_{t,n}\}.$$

Through selecting nodes which have 0 in corresponding *SHM* unit, multiple new graphs $G_{t,n}(V', E', S')$ have been reconfigured. So, if one path *Path*(*t*, *n*) could be routed in $G_{t,n}(V', E', S')$, the *SHM* unit $\mathbf{S}_{t,n}^{t,n}$ of this path *Path*(*t*, *n*) must be 0. Thus, for all the new graphs $G_{t,n}(V', E', S')$, the path routing approach is changed to ordinary routing mechanism without consideration of *SHM*, and their *communication efficiency* δ would become

$$\delta_{T,N} = 1 - \frac{||M||}{T \cdot N} = 1 - \frac{||\{\mathbf{S}_{t,n}^{t,n} = 0 | t \in [0, T],\ n \in [0, N]\}||}{T \cdot N}.$$

Therefore, Problems 1 and 2 could be settled by the maximization of δ.

Consequently, as shown in the above equations, if we could split the long-term spectrum sensing knowledge into different layers with corresponding idle nodes according to channels and time slots distribution, and find idle paths in each layer respectively. The multiple paths which we select at each layer must be able to obtain minimum *SHM*, and the *communication efficiency* δ should also be maximum. Then, the most steadily continuable communication from source to destination in this CR network under PUs interference could be guaranteed.

4.2 MMRA

After motivation introduction stated previously, we would like to present *MMRA* in this part.

As stated above, *MMRA* should be able to split network into pieces according to it's *SHM* distribution, and find paths in different layers. Therefore, *MMRA* could be divided into two parts: '*Multi-layer Dividing Algorithm*' and '*Path Selected Mechanism*'. *Multi-layer Dividing Algorithm* is responsible for generating multiple layer graphs according to CR network's *SHM*s. And *Path Selected Mechanism* whose core algorithm is '*Dijkstra Algorithm*' is provided to select paths in multiple layers with repeated paths reduction since there may be same paths in selected paths.

4.2.1 Multi-layer dividing algorithm

By utilizing the methods of graph theory, we could split a CR network graph into individual network layers, so that it would be easy to find paths which is idle in specific channel and time slot. Therefore, we could describe the *Multi-layer Dividing Algorithm* in Algorithm.1:

Algorithm 1 Multi-layer Dividing Algorithm

```
Input: G(V, E, S);
Output: {G_{t,n}(V', E', S')};
Collect Channel amount 'Camount', Time Slot amount 'Tamount' and the number of nodes 'Namount' from
   original network graph G(V, E, S);
Copy G(V, E, S) Camount · Tamount times, and number them as 'G_{t,n}(V, E, S)' according to channels and
   slots;
for n = 1 : Camount do
  for t = 1 : Tamount do
    for p = 1 : Namount do
      if s^p_(tn) == 1 then
        Delete V_p in G_{t,n}(V, E, S);
      end if
    end for
  end for
end for
Combine all the processed G_{t,n}(V', E', S') into layered network graph set {G_{t,n}(V', E', S')}.
```

(1) At first, the amount of channels '*Camount*', time slots '*Tamount*' and nodes '*Namount*' should be obtained from original network graph *G*(*V*, *E*, *S*);
(2) Then, $Camount \cdot Tamount$ copies of original graph *G*(*V*, *E*, *S*) would be generated to be multiple layers and numbered as $G_{t,n}(V,E,S)$ according to channels and time slots distribution;
(3) For each layer, nodes distribution in corresponding graph $G_{t,n}(V,E,S)$ must be reallocated according to their *SHM*s. If the node's *SHM* in this layer is 1, deletion could not be avoided since completely idle path is wanted;
(4) After $Camount \cdot Tamount \cdot Namount$ iterations of nodes' redistribution, the Multi-layer network graph set $\{G_{t,n}(V',E',S')\}$ could be gained.

4.2.2 Path selection mechanism

As the network is divided into different idle layers in $\{G_{t,n}(V',E',S')\}$, multiple paths should be selected in these layers. Then, the *Path Selection Mechanism* could be shown in Algorithm.2, the detailed processes are the follows:

(1) At first, we must count out the layers amount in network set $\{G_{t,n}(V',E',S')\}$;
(2) For each layer, *Dijkstra* algorithm is utilized to find path in each layer, and put the generated path into PATH list;
(3) As there may exist repeated paths in PATH list after paths selection in multiple layers, the repeated paths would be deleted, and paths in PATH list are the final paths which could maximize spectrum availability.

Algorithm 2 Path Selection Mechanism

Input: $\{G_{t,n}(V',E',S')\}$, Source, Destination;

Output: PATH;

```
Obtain the amount of layers 'Lamount' from network set {G_{t,n}(V',E',S')};
for i = 1 : Lamount do
    Utilize Dijkstra algorithm to find path_{t,n} in G_{t,n}(V',E',S') and add it into PATH;
end for
Delete repeated paths in PATH;
```

4.3 Time complexity

Through detailed introduction and motivation of *MMRA* presented above, the maximizations of *communication efficiency* δ and spectrum availability *SHM* by *MMRA* have been illustrated. However, the time complexity of *MMRA* which is a very important parameter for an algorithm has not been stated out. Hence, we would like to analyze time complexity of *MMRA* in this part.

As the *MMRA* introduction stated previously, there are 2 parts in *MMRA*. Hence, Assuming the 'Multi-layer Dividing Algorithm' as `MultilayerDividing` and 'Path Selection Mechanism' as `PathSelection`. Then, their time complexities could be represented by $T_{Multilayer}$ and T_{Path}, which could be depicted as Eq. 5.

$$T_{MMRA} = T_{Multilayer} + T_{Path} \tag{5}$$

And for these 2 parts of *MMRA*, the detailed processes are presented in Algorithm.1 and Algorithm.2. Their time complexities could be calculated easily according to their algorithm procedures. So we would calculate their time complexities separately in 2 parts.

Suppose a weighted graph *G*(*V*, *E*, *S*) has *n* nodes, *c* channels and *s* time slots in long-term spectrum sensing information. Then, for `MultilayerDividing` process, there are only $c \cdot s \cdot n$ iterations in different layers, so $T_{Multilayer}$ could be depicted as $O(c \cdot s \cdot n)$.

Whereas, for the `PathSelection` process, there are 2 different computation processes ('*Dijkstra Routing Algorithm*' and '*Repeated Path Deletion*'), whose time complexities could be described as $T_{Dijkstra}$ and $T_{Pathdelete}$. As we know, time complexity of ordinary *Dijkstra* Routing Algorithm could be easily summarized as $O(n^2)$, while in different layers, the maximum amount of nodes is *n*, so the $T_{Dijkstra}$ could be calculated as Eq. 6

$$T_{Dijkstra} \leq O(c \cdot s) \cdot O(n^2) = O(c \cdot s \cdot n^2). \tag{6}$$

Furthermore, it is hard to calculate time complexity of *RepeatedPath Deletion* since there may not exists fixed amount of repeated paths which should be deleted, but maximum repeated comparisons and deletion iterations could be estimated, so $T_{Pathdelete}$ could be presented as Eq. 7

$$T_{Pathdelete} \leq O((c\cdot s-1)+(c\cdot s-2)+\cdots+1) = O\left(\frac{c\cdot s\cdot(c\cdot s+1)}{2}\right). \quad (7)$$

Consequently, because amounts of channels and time slots are fixed constant values before processing, which could not be calculated in time complexity, T_{MMRA} could be shown as:

$$\begin{aligned} T_{MMRA} &= T_{Multilayer} + T_{Path} = T_{Multilayer} + T_{Dijkstra} + T_{Pathdelete} \\ &\leq O(c\cdot s\cdot n) + O(c\cdot s\cdot n^2) + O(\frac{c\cdot s\cdot(c\cdot s+1)}{2}) \\ &= O(n) + O(n^2) = O(n^2). \end{aligned}$$

Therefore, the time complexity of *MMRA* must be less than $O(n^2)$, so that the disjoint routing algorithm presented in this paper is polynomial time complexity.

5 Performance evaluation

Through the introduction and analysis of *MMRA* which stated above, the details and advantages of *MMRA* has been presented clearly. Hence, for a better presentation of *MMRA*, we would evaluation the simulation performance in this section. However, because no related routing algorithm is suitable for this disjoint routing scenario, we would utilize the *Closeness Routing* mechanism proposed in [14] for comparison, which select disjoint paths by comparing overlap areas between them. As the *Closeness Routing* mechanism needs priori routing information, we added an all-path routing algorithm before this mechanism which costs most of the time on simulation. Then, we would comprehensively compare *MMRA* and *Closeness Routing* mechanism in 5 different aspects.

5.1 Nodes variation

In this scenario, we would compare *MMRA* and *Closeness Routing* with various nodes' amounts.

As we know, different nodes' amounts are employed in fixed size space would cause different densities of CR nodes' distribution, which would lead to diverse difficulties of route. Hence, we would apply 70–70 m^2 as simulation space, for each node, 25 m power range is equipped with 4 spectrum channels and 5 time slots *SHM*; for PUs, they have 40 m interference range and 20 amount, each PU could access random channels and time slots. While the CR nodes' amount would be accumulated from 10 to 100, and for each amount comparison scenario, the simulations would be repeated for 100 times with randomly distribution reconstitution of simulation's parameters.

Thus, as shown in Fig. 5, in 100 nodes scenario, *MMRA* which is indexed by 'o' line has better performance than *Closeness Routing* on spectrum availability obtainment. Especially on the average spectrum availability, *MMRA* is about 30% higher than *Closeness Routing* mechanism.

And in Fig. 6, the comparison between *MMRA* and *Closeness Routing* mechanism with various nodes amounts is depicted out. The bars indicate spectrum availability expectations under different nodes amounts. Hence, it is apparent that spectrum availability decrease between 10 and 30 nodes since the densities of nodes are too low to generate more nodes under the same PUs, and nodes amounts increase causes huge route environment change. However, from 30 to 100 nodes amounts, *MMRA* could maintain a steady increasing average spectrum availability means that *MMRA* could always find brilliant disjoint paths selection, and *Closeness Routing* mechanism's spectrum availability maintains at the same level generally in this range because more nodes would make lower opportunities

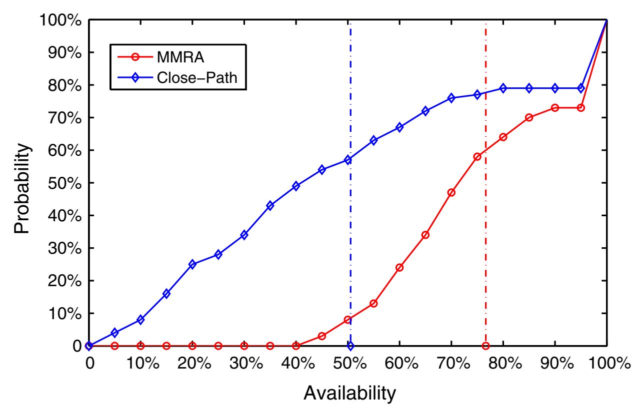

Fig. 5 Comparison with 100 nodes

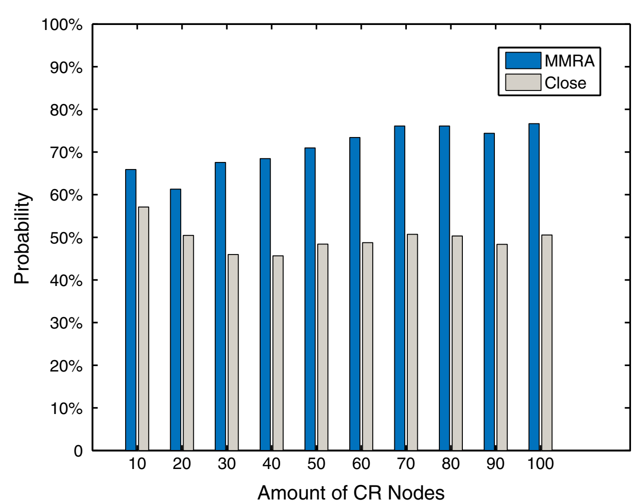

Fig. 6 Comparison of various nodes

than *MMRA* to find disjoint paths by employing lowest closeness paths.

Consequently, for different nodes amounts, *MMRA* could always obtain better disjoint paths selection than *Closeness Routing* mechanism.

5.2 Channels and time variation

In this scenario, a comprehensive comparison based on various channels and time slots amounts setting between *MMRA* and *Closeness Routing* mechanism would be simulated.

Dynamical channels and time slots amounts distribution would cause changes on access channels probabilities of SUs and interference accuracies of PUs. Hence, in a 70–70 m^2, we would vary standby channels from 1 to 5 and time slots from 2 to 10, with 50 nodes and 20 PUs, while other settings are the same as Nodes Variation. Then, the performance is depicted in Fig. 7.

As shown in Fig. 7, the average availability distribution in various channels and time slots is shown out. The dashed surface represents *MMRA* and solid surface indicates *Closeness Routing* mechanism. It is apparent that the fewer channels and time slots amounts are, the lower average availabilities are in the 2 different routing mechanism, since limited channels and time slots amounts would cause more PUs access into same *SHM* slot, and fewer disjoint routing opportunities could be found. Whereas, the performance of *MMRA* is always better than *Closeness Routing* mechanism. Therefore, varying channels and time slots amounts could not change the advantages of *MMRA*.

5.3 PUs variation

After the comparisons above, *MMRA* always has more spectrum availabilities than *Closeness Routing* mechanism. Then we would like to simulate these 2 mechanisms under different PUs amounts.

In this scenario, PUs amount would be arranged from 10 to 100, each simulation under the same PUs' amount would be iterated for 100 times for a reliable result, so there are total 1000 iterations of this comparison. And SUs' nodes amount is 50 with 25 m transmission power range. For *SHM*, 4 channels and 5 time slots distribution is employed. Besides, PUs have 40 m interference range and each PU could only occupy 1 slot in each iteration for easier arrangement and calculation.

In Fig. 8, the comparison between *MMRA* and *Closeness Routing* mechanism on different PUs' amounts is described out. As shown in Fig. 8 which is box-plot and average value of spectrum availabilities, the downward trends of these 2 mechanism could be figured out easily since it would be more difficult to find disjoint paths under high PUs' density. On the other hand, the *Q*1, *Med* and *Q*3 points of box-plot in this figure revealed out that most of the spectrum availabilities obtained by *MMRA* are mainly higher than *Closeness Routing* mechanism on different PUs distributions. While the average values of *MMRA* which are represented by 'o' lines are higher than *Closeness Routing* mechanism also indicates that.

Hence, *MMRA* could receive a better performance on spectrum availability than *Closeness Routing* mechanism on diverse PUs amounts.

5.4 PUs' ranges variation

In this scenario, comparison between *MMRA* and *Closeness Routing* mechanism would be held under different PUs' interference ranges.

As standby settings of simulation stated previously, 50 CR nodes would be randomly distributed in a 70–70 m^2 with 25 m transmission power range, and 20 PUs are equipped as interference sources. A 4 channels and 5 time slots *SHM* would be employed, while for each PU range selection there are 100 iterations of simulation. Then, the

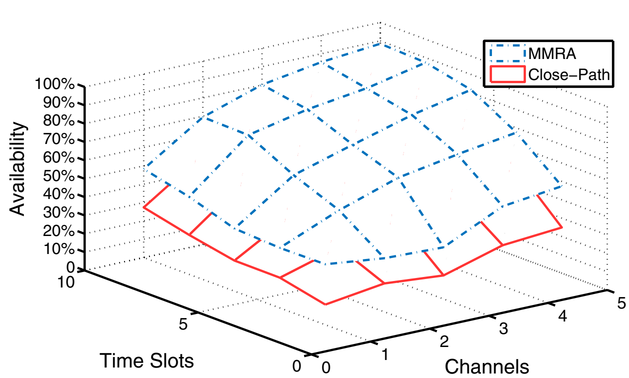

Fig. 7 Comparison of various channels and time slots

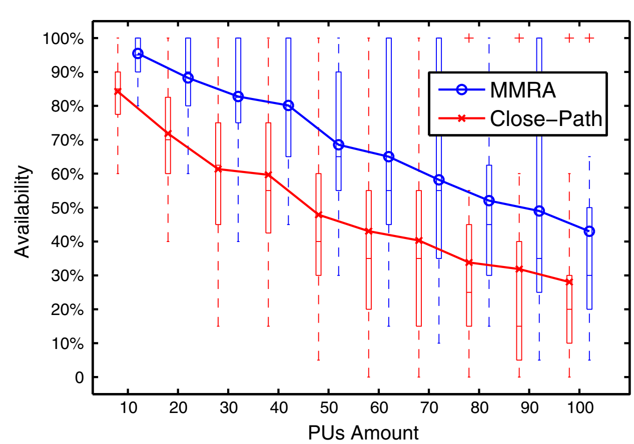

Fig. 8 Comparison of various PUs amounts

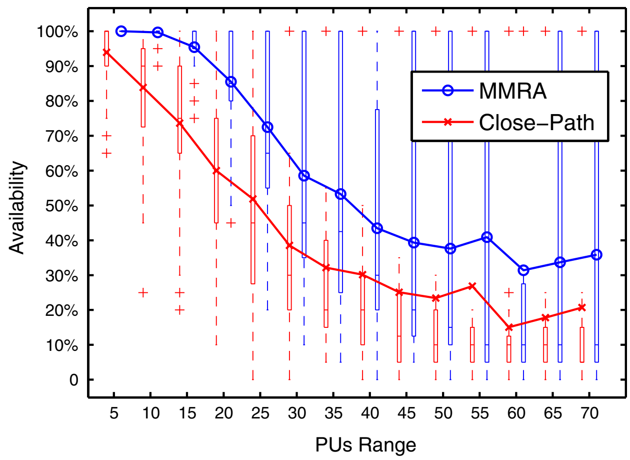

Fig. 9 Comparison of various PUs ranges

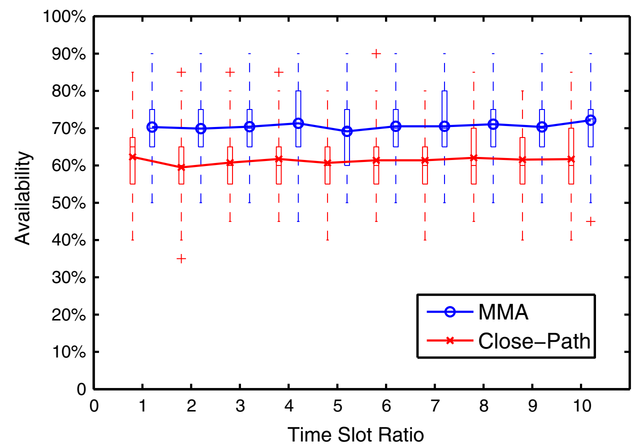

Fig. 10 Comparison under different time ratio

PUs' ranges would be picked from 5 to 70 m where most of CR nodes would be under the same PU's interference.

The simulation performance is depicted as Fig. 9, in which box-plot and average spectrum availability are shown out. Obviously, both *MMRA* and *Closeness Routing* mechanism's results are decreasing generally when PUs' range is increasing. That is because it would become more difficult to find disjoint paths with the growing PUs' range. On the other side, it is apparently that the average availability line of *Closeness Routing* mechanism which is indexed by 'x' lines is separated from *Q*3 point in the box-plot from PUs range 40–70 m, since there exist some extreme outliers of *Closeness Routing* mechanism. Whereas, no matter the average availabilities or box-plots, *MMRA* always has a better performance than *Closeness Routing* mechanism.

5.5 Time ratio variation

After the simulations stated above, the advantages of *MMRA* are undoubtable. However, should the *MMRA* pay much time on the reroute after *SHM* sensing period, and does it have impacts on final communication outputs when PUs' statements change under the process of *MMRA* reroute?

Superficially, routing mechanism's output should have a close relationship with it's cost time and networks' statements. But this rule is not suitable for solutions on *disjoint multi-path routing problem in CR networks*, because the target of *MMRA* is to find *distributed* paths which have little impact from time.

Therefore, the comparison between *MMRA* and *Closeness Routing* mechanism would be held with different time ratios (*SHM* time slots and route time) scenarios. For convenience, suppose routing time lengthes of *MMRA* and *Closeness Routing* mechanism are the same as *T*. And ordinary *SHM* sensing period is the basic time unit *t*. Then, the time ratio $\mathcal{K}$ should be $\frac{T}{t}$. So, in 50 CR nodes networks whose nodes would be randomly distributed in a 70–70 m^2 with 25 m transmission range, while 20 PUs would be employed, *SHM* has 4 channels and 5 time slots.

The first simulation has employed the same fixed CR nodes location distributions for the 2 mechanisms after they randomly distributed at beginning, while PUs and *SHM* distributions would randomly change with *t*. Hence, the comparison with different time ratio $\mathcal{K}$ could be depicted as Fig. 10. *K* would increase from 1 to 10, which means the last routing pattern would be utilized in the next 1*t* to 10*t* with PUs' changes. For each time ratio, the simulation would last for 100*t*.

As shown in Fig. 10, the boxplot indicates spectrum availabilities distribution in 100*t*, and the line indexes average spectrum availability of each 100*t*. It is clear that the outputs of *MMRA* and *Closeness Routing* mechanism mainly maintain the same level in different time ratios, which revealed these 2 mechanisms' performances had little relationship on routing time they cost. But the divergences of boxplots are a little large suggests that there exist some shadow areas they could not cover. Nevertheless, the performance of *MMRA* is still better than *Closeness Routing*.

A more precise result has been stated in the second simulation, in which *MMRA* would be equipped in 2 different routing scenarios, '*non changeable*' and '*changeable*' scenarios. The '*non changeable*' scenario means that the paths has been selected by *MMRA* and fixed at beginning, and '*changeable*' scenario is the same as above in which *MMRA* could reroute with *T*. While time unit is *t*, $\mathcal{K}$ would increase from 1 to 10 with each 100*t*. So, in Fig. 11, it is obvious that no matter the routing mechanism has been utilized or not when PUs' statements are changing, the average spectrum availabilities (indexed by lines) would not produce big fluctuations.

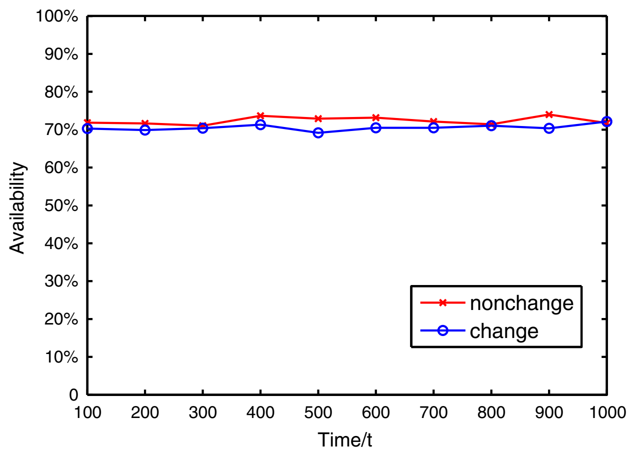

Fig. 11 Comparison of routing scenarios

Consequently, after the series of simulations, all in all, *MMRA* could find paths which have more and spectrum availabilities and *communication efficiency* than *Closeness Routing* mechanism, and which would not change too much with time.

6 Conclusion

In this paper, we have provided a time and spectrum based '*Spectrum History Matrix*' mechanism to define CR nodes' long-term spectrum sensing information, so that the more idle slots paths obtained, the more probabilities to guarantee communication traffic, and *communication efficiency* would be improved. Then, a *Multi-layer based Multi-path Routing Algorithm* is proposed to divide long-term spectrum sensing information into multiple layers and find paths in them. Hence, multiple paths which have most idle spectrum time slots could be obtained, so that the *communication efficiency* of CR network could be maximized. Although the paths which selected by *MMRA* may not be completely '*disjoint*' or exclusive with each other, they could have a huge probability to maintain continuous communication without interruption, and the simulations results indicate that *MMRA* is workable and has better performance than other paths selection mechanisms.

Though *MMRA* has a brilliant performance on the *disjoint multi-path routing problem in CR networks*, there also exist some weak points waiting for addressing. By employing infinite interfaces MIMO scenario, the same nodes and links would have probability on reselection in different paths, which may be potential trouble when networks traffic load exceeds single node's affordable ability. Hence, the multi-path routing problem with nodes and links selection constraint should be study in future. While the complete routing protocol and a more comprehensive comparison with other routing mechanism would be researched under practical environments.

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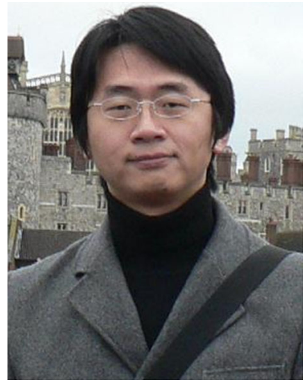
Duzhong Zhang is a Ph.D. Candidate of Information and Communication Engineering in Wuhan University of Technology. He received B.E. and M.E. degrees from the School of Information Engineering, Wuhan University of Technology, in 2009 and 2012. His research interests include cognitive radio dynamic access technology, multi-path routing algorithm, heterogeneous networks coexistence etc.

Quan Liu received her bachelor degree from the Department of Electronic and Information, Huazhong University of Science and Technology, in 1985, the M.E. degree from the Department of Automation, Wuhan University of Technology, in 1991, and the Ph.D. degree from the School of Mechanical and Electronic Engineering, Wuhan University of Technology, in 2004. She is currently a Professor in the School of Information Engineering at Wuhan University of Technology. Her research interests include signal processing, signal detection, digital manufacturing, etc.

Lin Chen received his B.E. degree in Radio Engineering from Southeast University, China in 2002 and the Engineer Diploma, Ph.D. from Telecom ParisTech, Paris in 2005 and 2008, respectively. He also holds a M.S. degree of Networking from the University of Paris 6. He currently works as associate professor in the department of computer science of the University of Paris-Sud XI. His main research interests include modeling and control for wireless networks, security and cooperation enforcement in wireless networks and game theory.



Wenjun Xu received his bachelor degree in information engineering from the School of Information Engineering, Wuhan University of Technology, in 2005, the M.E. and Ph.D. degrees in communication and information system from the School of Information Engineering, Wuhan University of Technology, in 2007 and 2010 respectively. He is currently an Associate Professor in the School of Information Engineering at Wuhan University of Technology. His research interests include service-oriented manufacturing, sensor networks, future internet, etc.

Kehao Wang received the B.S. degree in Electrical Engineering, M.S. degree in Communication and Information System from Wuhan University of Technology, Wuhan, China, in 2003 and 2006, respectively, and Ph.D. in the Department of Computer Science, the University of Paris-Sud XI, Orsay, France, in 2012. He currently works as associate professor in the department of Information Engineering of the Wuhan University of Technology His research interests are cognitive radio networks, wireless network resource management, and data hiding.