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***Abstract*—Cognitive radio is an efficient technique to relieve the tense of wireless spectrum scarcity by allowing unlicensed secondary users (SUs) to access the licensed band opportunistically without causing interference to primary users (PUs). Although Federal Communications Commission (FCC) recently ruled that the data of PU activity schedule is accessible to SUs 24 hours ahead, which relieves SUs from heavy sensing or interruption by sudden PU activity, however, multi-hop wireless cognitive radio networks (MWCRN) suffers a unique problem caused by the fact that the spectrum resources are not unified in different areas affected by different PUs. In other words, an SU origin-destination (OD) pair transmission would meet the bottleneck in bandwidth when crossing areas with different available spectrum resources. To solve this problem, we formulate an optimization problem to maximize the number of connection bridges to cross different areas. Moreover, we introduce channel bonding technique into the MWCRN for network performance improvement. We also propose a distributed algorithm for practical application. Simulation results verifies the better performance of our proposed scheme.**

I. Introduction

Wireless spectrum resource becomes extremely scarce due to the vast growing wireless devices and diversity of wireless applications. However, some existing licensed bands are highly under utilized. For example, the usage of TV band is lower than 30% even in metropolitan areas [1]. Cognitive radio (CR) technology provides a method to take advantage of this white space (unused TV band) [2] by letting unlicensed secondary users (SUs) access the licensed bands when primary users (PUs) are inactive on that particular bands [3].

Since *IEEE* 802.22 [4] was standardized in 2009, it has become more practical to build up multi-hop wireless cognitive radio networks (MWCRN) [5] [6] in white space for low cost rural area network communications. However, it was always hard for real practical MWCRN applications because of the unpredictable PU activity. Recently, the Federal Communications Commission (FCC) set a rule that a database must exist for aggregating PU activity (such as occupied spectrum, active duration, time schedule, etc.) over the coming 24 hours [7]. This rule would significantly relieve SU from heavy sensing duty [8][9], it also pushes MWCRN to the edge of real applications.

Although the spectrum resources for SUs in MWCRN can be viewed as semi-stationary based on the rule mentioned above, MWCRN is yet special from traditional multi-hop wireless mesh networks. In an MWCRN with multiple PUs, each PU would affect a certain area with its unique activity, therefore the whole network is then divided into several areas (not necessarily mutually exclusive to each other) considering available spectrum resources for SUs. In other words, the spectrum resource is not unified in MWCRN, therefore a long distance SU OD pair transmission would have to go through different areas with different available spectrum resources. This fact makes it hard to implement routing and channel allocation mechanisms for traditional multi-hop wireless mesh networks [10][11] to MWCRN for high network performance.

In this paper, we define each affected area by a particular PU as a *zone*. It is clear that with semi-stationary but un-unified spectrum resource, the bottleneck for long distance OD pair transmission is the crossing-zone (we name it *Xing-zone* hereafter) areas. For better description, we analogize a connection between two zones to a *Xing-zone* bridge. The bandwidth and number of Xing-zone bridges may vary according to different SU OD pair application requests. Instead of considering special OD pair cases, we study the problem which aims to construct Xing-zone bridges with a predefined bandwidth request. This predefined bandwidth is fair enough to meet different OD pair application requests with different number of Xing-zone bridges. To provide better service for Xing-zone area communications, we introduce multi-interface into our MWCRN network model. More specifically, multi-interface enables the ability of multi-path routing, which enhances the network performance for wireless mesh networks [12] [13]. Multi-path ability also enables two users to communicate through separate transmission flows. Therefore, each Xing-zone bridge may have multiple entrances and multiple exits. To further improve the network performance, we also introduce *channel bonding* technique into our MWCRN. Channel bonding technique has been proved to have a great improvement on network performance over *IEEE* 802.11n [14] [15][16].

Our main contributions in this paper include: first, we formulate an optimization problem to maximize the number of feasible Xing-zone bridges which would improve the Xing-zone communication performance. Since the problem is NP-hard which cannot be solved in large scale, we also propose a distributed algorithm for practical application. In the end, we give simulation results that verify our proposed scheme. The rest of this paper is organized as follows. We present our network model and problem formulation in section II. We propose a Xing-zone bridge construction algorithm in section III. We show the performance evaluation results in section IV. We give the conclusion and future work in section V.

II. System Model and Problem Formulation

A. General Network Model

We first give the definition of *Xing-zone communication* and *single-zone communication* used in this paper.

Definition 2.1: Xing-zone communication is defined as a one-way transmission between two groups of boarder routers located in two zones, and none of them is located in any overlapped areas.

Definition 2.2: Single-zone communication is defined as a one-way transmission which the origin and the destination are located in the same zone and they obtain the same PU activity such that they share the spectrum resources.

Definition 2.3: Boarder router is defined as a router which is at most 1-hop away from another zone. More specifically, the boarder routers are either located in non-overlapped section but 1-hop away from the overlapped area or located in the overlapped area already.

Lemma 1. *1-hop is far enough for choosing boarder routers in Xing-zone communication routing.*

Proof: Any 2-hop (or more hops) router initiate the communication to transmit across the zone must go through the 1-hop routers so that the transmission can pass into another zone. The transmission between them are single-zone communication. Therefore, any routers 2 (or more) hops away from the other zone are not necessary to be considered in Xing-zone communications. ■

For an OD pair application request, the actual application request might differ due to different transmission protocols or methods. For simplicity, we assume the transmission request is based on the bandwidth $\mathbf{B}_{OD}$ needed in half-duplex scenario, either $Origin \Rightarrow Destination$ (up stream), or $Origin \Leftarrow Destination$ (down stream). Generally, the Xing-zone communication is a part of a specific OD pair transmission, and it can be roughly classified into two categories, *direct Xing-zone communication* and *indirect Xing-zone communication*. More specifically, direct Xing-zone communication indicates that the communication happens between the two neighbor zones (in most cases overlapped) directly. On the other hand, the indirect Xing-zone communication indicates that the communication can be completed only when a third or even more neighbor zones are introduced into this communication.

Definition 2.4: $\mathbf{B}_X$ is defined as the bandwidth request unit for direct Xing-zone communication, which is predefined to fulfill any direct or indirect Xing-zone communications with different combinations.

Lemma 2. *Any indirect Xing-zone communication is a combination of several direct Xing-zone communications with unit Xing-zone bandwidth $\mathbf{B}_X$, and single-zone communications for interconnections.*

Proof: The indirect Xing-zone communication is necessary only when direct Xing-zone communication cannot support the original bandwidth request, e.g., $\mathbf{B}_{OD}$. Since the network supports multi-path transmission, it is able to use several paths which involve different direct Xing-zone communications (an example is shown in Fig. 1). The interconnection of these direct Xing-zone communications is a single-zone communication problem. With a predefined $\mathbf{B}_X$ which is agreed to be the Xing-zone communication bandwidth unit, it will fulfill any indirect Xing-zone communications using different combinations of direct Xing-zone communications even though Xing-zone communication requirements between different zones may not be unified. Take an extreme example, the combination of communications with unit bandwidth $\mathbf{B}_0$ can fulfill all the bandwidth requirements. ■

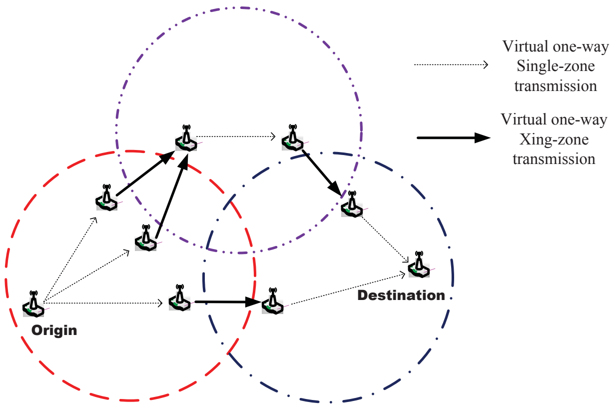

Fig. 1. An example of Xing-zone communication.

According to Lemma 2 and the fact that the single-zone communication is similar to wireless mesh network, we rule out indirect Xing-zone communication problems in our discussion. And the network model can be limited within the Xing-zone area. In the Xing-zone area, there exists 2 PUs, thus we have two zones Z_O and Z_D. We want to clarify that the Xing-zone area only contains parts of the zones, however each PU may affect larger size area in reality. Moreover, the zones are not mutually exclusive to each other, thus we have three subsections in the Xing-zone area as $Z_O \bigcup Z_D \setminus Z_D$, $Z_O \bigcap Z_D$, and $Z_D \bigcup Z_O \setminus Z_O$. We also have N routers r_i, $i \in [1, N]$, and a total of $\mathbf{K}$ channels spectrum resources. For simplicity, we assume the channels are contiguous c_i, $i \in [1, \mathbf{K}]$. The PUs and routers are fixed and the locations are known to each other. Among all the N border routers, we have $\mathbf{O}$ routers located in $Z_O \bigcup Z_D \setminus Z_D$, and $\mathbf{D}$ routers located in $Z_D \bigcup Z_O \setminus Z_O$.

We define $\mathbb{S}\{\mathbb{X}_{i,j}\}$ as the set of Xing-zone bridges. Where the subset $\mathbb{X}_{i,j} = \{\mathbb{O}_i, \mathbb{D}_j\}$ indicates the Xing-zone bridge $\{i, j\}$. Recall that the Xing-zone communication is part of the OD pair transmission, however, it may not have a unique origin router or a unique destination router due to the multi-path capability and the relatively small Xing-zone bandwidth unit $\mathbf{B}_X$. Therefore, we have the origin of $\mathbb{X}_{i,j}$ with multiple entrance routers $\mathbb{O}_i = \{r^{(O)}_{i_1}, r^{(O)}_{i_2}, \ldots\}$, and the destination with multiple exit routers $\mathbb{D}_j = \{r^{(D)}_{j_1}, r^{(D)}_{j_2}, \ldots\}$. Where $r^{(k)}_i$ indicates whether router i is located in Z_k or not. For the

Xing-zone bridge $\mathbb{X}_{i,j}$, $\mathbb{O}_i$ is located in $Z_O \bigcup Z_D \setminus Z_D$, and $\mathbb{D}_j$ is located in $Z_D \bigcup Z_O \setminus Z_O$ for this Xing-zone bridge.

Since the network has multi-path capability, each router (e.g., r_i) is equipped with $\mathbf{I}$ interfaces, defined as $It_k^{(i)}$, for $k \in [1, \mathbf{I}]$. We assume all the interfaces are the same following a *disk connectivity* model. Besides, we introduce *channel bonding* technique to further improve the network performance by assuming that each interface has the ability to do channel bonding with up to $\mathbf{C}$ *contiguous channels*. One interface from one router can only communicate with one interface of another router. We want to emphasize that one router has the ability to communicate with multiple routers using different channels through multiple interfaces, it also has the ability to communicate with another router with different channels using multiple interfaces. Each router is equipped with an extra special interface which operating as long-range Wi-Fi to exchange control information with other routers. We then give the problem formulation in the next subsection.

B. Problem Formulation

Since we have $\mathbf{O}$ candidate routers for the origin router groups, the number of possible group $\mathbb{O}_i$ is

$$N_{\mathbf{O}} = \binom{\mathbf{O}}{1} + \binom{\mathbf{O}}{2} + \ldots + \binom{\mathbf{O}}{\mathbf{O}} = 2^{\mathbf{O}} - 1 \quad (1)$$

And the number of possible destination router groups $\mathbb{D}_j$ is

$$N_{\mathbf{D}} = \binom{\mathbf{D}}{1} + \binom{\mathbf{D}}{2} + \ldots + \binom{\mathbf{D}}{\mathbf{D}} = 2^{\mathbf{D}} - 1 \quad (2)$$

Therefore, the number of total possible Xing-zone bridges $\mathbb{X}_{i,j}$ is

$$N_X = N_{\mathbf{O}} \times N_{\mathbf{D}} \quad (3)$$

If a Xing-zone bridge $\mathbb{X}_{i,j}$ is connected and it can provide transmission bandwidth over or equal to $\mathbf{B}_X$, then we conclude that this bridge $\mathbb{X}_{i,j}$ is feasible, and we define $\mathcal{X}_{ij} = 1$ to indicate this status. When $\mathcal{X}_{ij} = 0$, it indicates that $\mathbb{X}_{i,j}$ is not a feasible Xing-zone bridge. Our objective is to maximize the number of feasible Xing-zone bridges. Mathematically, we form the following maximization problem.

$$\max \sum_{i=1}^{N_{\mathbf{O}}} \sum_{j=1}^{N_{\mathbf{D}}} \mathcal{X}_{ij} \quad (4)$$

s.t.

$$\mathcal{X}_{ij'} \cdot \mathcal{X}_{ij} = 0,\ for\ \mathcal{X}_{ij} = 1,\ \forall j' \in [1, N_{\mathbf{D}}] \setminus \{j\} \quad (5)$$

$$\mathcal{X}_{i'j} \cdot \mathcal{X}_{ij} = 0,\ for\ \mathcal{X}_{ij} = 1,\ \forall i' \in [1, N_{\mathbf{O}}] \setminus \{i\} \quad (6)$$

$$c_{k,n}^{r_i} \cdot c_k^{r_i} = 1, \quad \forall c_{k,n}^{r_i} = 1 \quad (7)$$

$$\sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i} \leq \mathbf{C}, \quad \forall i \in [1, N] \quad (8)$$

$$\prod_{k=k_0}^{k_0+k_1} c_{k,n}^{r_i} = 1, \quad \forall c_{k_0,n}^{r_i} = 1,\ c_{k_0+k_1,n}^{r_i} = 1 \quad (9)$$

$$\begin{aligned} c_{k_0,n_1}^{r_i} \neq c_{k_0,n_2}^{r_j}, \quad &\text{for } \overrightarrow{r_{i,j}} = \overrightarrow{r_{i,j}} = 0, \\ \forall\, 0 < |r_i r_j| < R_I,\ &k \in [1, \mathbf{K}], \\ n_1 \in [1, N],\ &n_2 \in [1, N] \end{aligned} \quad (10)$$

$$\begin{aligned} &\sum_{r_o \in \mathbb{O}_i} \sum_{x=1}^{N} \sum_{n=1}^{\mathbf{I}} (It_n^{(o)}|_{\overrightarrow{r_{o,x}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_o}) \\ &= \sum_{r_d \in \mathbb{D}_j} \sum_{x=1}^{N} \sum_{n=1}^{\mathbf{I}} (It_n^{(d)}|_{\overrightarrow{r_{d,x}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_d}) \\ &\geq \mathbf{B}_X, \quad \forall \mathcal{X}_{ij} = 1 \end{aligned} \quad (11)$$

$$\sum_{x=1}^{N} \sum_{n=1}^{\mathbf{I}} (It_n^{(i)}|_{\overrightarrow{r_{x,i}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i}) = \sum_{x=1}^{x=N} \sum_{n=1}^{\mathbf{I}} (It_n^{(i)}|_{\overrightarrow{r_{i,x}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i}), \quad \forall r_i \notin \{\mathbb{O}_i, \mathbb{D}_j\} \quad (12)$$

$$\sum_{n=1}^{\mathbf{I}} \left(\sum_{x=1}^{N} It_n^{(p)}|_{\overrightarrow{r_{x,p}}} + \sum_{x=1}^{N} It_n^{(p)}|_{\overrightarrow{r_{p,x}}} \right) \leq I, \quad \forall r_p \notin \{\mathbb{O}_i, \mathbb{D}_j\} \quad (13)$$

$$\sum_{n=1}^{\mathbf{I}} \left(\sum_{x=1}^{N} It_n^{(p)}|_{\overrightarrow{r_{x,p}}} + \sum_{x=1}^{N} It_n^{(p)}|_{\overrightarrow{r_{p,x}}} \right) \leq \lceil I/2 \rceil, \quad \forall r_p \in \{\mathbb{O}_i, \mathbb{D}_j\} \quad (14)$$

Eq. 5 and Eq. 6 indicate that $\mathbb{O}_i$ and $\mathbb{D}_j$ can only be assigned once if the Xing-zone bridge $\mathbb{X}_{i,j}$ is feasible. That is to say, the entrance and the exit of a Xing-zone bridge might be multiple, but the bridge in between is unique.

In Eq. 7, $c_{k,n}^{r_i}$ indicates the status whether channel k is assigned for $It_n^{(i)}$ or not, and $c_k^{r_i}$ indicates the status whether channel k is available for r_i or not. This constraint ensures that the channel assigned to $It_n^{(i)}$ is available to r_i.

Eq. 8 indicates that the total number of channels assigned to one interface cannot exceed the channel bonding limit $\mathbf{C}$ for one interface. And for each interface, all the assigned channels must be contiguous due to the technical limit of channel bonding. This is shown in Eq. 9.

In Eq. 10, $\overrightarrow{r_{i,j}} = 1$ indicates that r_i and r_j are one-hop away, and one-way transmission $r_i \Rightarrow r_j$ is established. And Eq. 10 is the constraint for channel reuse. More specifically, if a channel is assigned to an operating link of two routers r_i and r_j, then all the other routers within the interference range R_I of either r_i or r_j cannot reuse the same channel. We do not consider CDMA, FDMA or other protocols which allow to use the same channel for transmission within interference range in our network model, because this will significantly reduce the effective bandwidth of the transmission.

Eq. 11 illustrates the transmission flow bandwidth constraint for the entrance and the exit of a feasible Xing-zone bridge $\mathbb{X}_{i,j}$. In other words, the entrance transmission flow (outgoing transmission flow of $\mathbb{O}_i$) is equal to the exit transmission flow (incoming transmission flow of $\mathbb{D}_j$) of Xing-zone bridge $\mathbb{X}_{i,j}$, and moreover, the total bandwidth is greater or equal to $\mathbf{B}_X$.

For each intermediate router constructing a Xing-zone bridge, it must balance the incoming transmission flow and the outgoing transmission flow so that the communication can be passed on. This constraint is shown in Eq. 12.

Moreover, the total number of interfaces in use for each intermediate router has a physical limit $\mathbf{I}$ as shown in Eq. 13. However, for the entrance and exit routers, we cannot use all the available interfaces because they need to be available for further connection. Since we only consider these boarder routers, therefore we do not have more information about the other routers, it would be hard to decide how many interfaces left for further usage. In this case, we intentionally constrain it to less than half of the available interfaces to be used for Xing-zone bridge construction as shown in Eq. 13.

Mathematically, each $\mathbb{X}_{i,j}$ sequence, for example $(\mathbb{X}_{1,1},\ \mathbb{X}_{1,2},\ldots,\ \mathbb{X}_{2,1},\ldots,\ \mathbb{X}_{N_{\mathbf{O}},N_{\mathbf{D}}})$ forms a sub maximization problem with a sub optimal solution. In the worst case, we have to get all the sub optimal solutions of $\binom{N_X}{N_X} \times N_X!$ sequences so that we can finally decide what the best combination of $\mathbb{S}$ is. In most cases, solving this formulation with standard solvers (e.g., CPLEX) is infeasible if the network scale is large. The main problem is the large number of variables and constraints. Therefore, we propose a distributed algorithm to construct Xing-zone bridges for practical applications in the next section.

III. Xing-zone bridges Construction Algorithms

Given the Xing-zone bandwidth request $\mathbf{B}_X$, the basic idea of this algorithm is to use the same number of routers for entrance and exit sets. The routing between them is then one-to-one multi-hop routing with evenly assigned bandwidth $\lceil \mathbf{B}_X/n \rceil$. Where n is the smallest number of routers within an $\mathbb{O}_i$ set or $\mathbb{D}_j$ set to satisfy the limited number of $\mathbf{C}$ and $\mathbf{I}$, and it can be calculated by Eq. 15. The intermediate routers may be reused for different transmission paths.

$$n = \lceil \lceil \frac{\mathbf{B}_X}{\mathbf{C}\mathbf{B}_0} \rceil / \lfloor \mathbf{I}/2 \rfloor \rceil \qquad (15)$$

Since we do not have enough spectrum resources or enough intermediate routers, we may not construct all the bridges with the smallest number of routers for the entrance or exit set. However, to construct the Xing-zone bridge, we start with n routers from both ends of the bridge intuitively. The Xing-zone bridge construction algorithm is summarized in Algorithm 1. In total we have $\binom{\mathbf{O}}{n}$ possible entrance sets, and $\binom{\mathbf{D}}{n}$ possible exit sets with n routers. Pick up one pair of entrance and exit sets and try to form them as a Xing-zone bridge by connecting them with end-to-end bandwidth equal to or greater than $\mathbf{B}_X$. If successful, we then pick up another pair from $\binom{\mathbf{O-n}}{n}$ and $\binom{\mathbf{D-n}}{n}$. If failed, we stick with the same entrance set, but pick another exit set from $\binom{\mathbf{D}}{n}$. If no feasible bridge can be found until all $\binom{\mathbf{D}}{n}$ exit sets are tested, we will move on to another entrance set. Once all possible pairs with n sets are tested, we will start another iteration round with the unchosen routers using $n = n + 1$. The algorithm ends when the remaining routers in either side is less than n.

The one-to-one multi-hop routing algorithm is summarized in Algorithm 2. Parameter $\mathbb{C}_{r_p}$ is the set of available channels of r_p. The basic idea of Algorithm 2 is to pair each two routers that one is from $\mathbb{O}_i$ and the other one is from $\mathbb{D}_j$ according to shortest distance (number of hops) sequence. After establishing the route, we attempt to assign operating channels with total bandwidth $\lceil \mathbf{B}_X/n \rceil$ to each pair of routers. Two routers may be assigned with a channel (e.g., c_i) for direct transmission only when no other router within the interference range of either of the two routers is currently assigned with c_i. If the channel assignment succeeded, we will start from another pair; if the channel assignment failed, we will conclude

Algorithm 1 Xing-Zone Bridge Construction

Input: $\mathbf{B}_X,\ r_i \in Z_O \bigcup Z_D \setminus Z_D,\ r_j \in Z_D \bigcup Z_O \setminus Z_O,\ n;$
Output: Feasible Xing-zone bridge $\mathbb{X}_{i,j},\ \sum_{i=1}^{N_{\mathbf{O}}} \sum_{j=1}^{N_{\mathbf{D}}} \mathcal{X}_{ij};$

while No. of remaining routers on either side $> n$ **do**
  Pick one entrance set and one exit set with n routers independently, e.g., $\mathbb{O}_i$ and $\mathbb{D}_j$;
  while No. of remaining candidate entrance routers $> n$ **do**
    while No. of remaining candidate exit routers $> n$ **do**
      One-to-one multi-hop routing (Algorithm 2);
      if Successful **then**
        $\mathcal{X}_{i,j} = 1$;
        Rule out $\mathbb{O}_i$ and $\mathbb{D}_j$;
      else
        $\mathcal{X}_{i,j} = 0$;
        Keep $\mathbb{O}_i$ but choose another $\mathbb{D}_j$;
      end if
    end while
    Pick another entrance set $\mathbb{O}_i$ with n routers from remaining candidate entrance routers, use $\mathbb{D}_j$ from last failed assignment;
  end while
  $n = n + 1$
end while

Algorithm 2 One-to-one multi-hop routing

Input: $\lceil \mathbf{B}_X/n \rceil,\ \mathbb{X}_{i,j},\ \mathbb{C}_{r_p}\ \forall p \in [1, N];$
Output: One-to-one routing status and detailed assignment, updated $\mathbb{C}_{r_p}\ \forall p \in [1, N];$

Initial $\mathcal{X}_{i,j} = 1$;
Set up n one-to-one pairs according to least-hop sequences;
while $\mathcal{X}_{i,j} = 1\ \&\ n > 0$ **do**
  Do channel assignment for one pair with bandwidth $\lceil \mathbf{B}_X/n \rceil$;
  if Successful **then**
    Update $\mathbb{C}_{r_p}\ \forall p \in [1, N]$; $n = n - 1$; pick another pair;
  else
    $\mathcal{X}_{i,j} = 0$
  end if
end while

that routing for is $\mathbb{X}_{i,j}$ failed and $\mathbb{X}_{i,j}$ is not feasible. We can have the conclusion of infeasible bridge based on single pair routing failure is due to the fact that $\lceil \mathbf{B}_X/n \rceil$ is the lower bound of bandwidth for each pair, with one failure pair, the total end-to-end bandwidth would not achieve $\mathbf{B}_X$. Therefore, we can confirm that the bridge is infeasible based on single pair of routing failure.

IV. Performance Evaluation

In the simulation setting, we have a 5×5 (25 boarder routers) grid network located in a $10\ km \times 10\ km$ area with two overlapped zones Z_O and Z_D (involving 2 independent PUs), as shown in Fig. 2. The communication range of each router is set to $R_C = 1.5\ km$. Generally, the interference range should be 1.8 to 2 times of the communication range. However, in order to get the exact optimal solutions of a small scale networks for analysis, the interference range of each router is set to $R_I = 1.8\ km$. Besides, the spectrum pool holds 50 contiguous channels. We assume that the two PUs use the same amount of spectrum resources but not the same part.

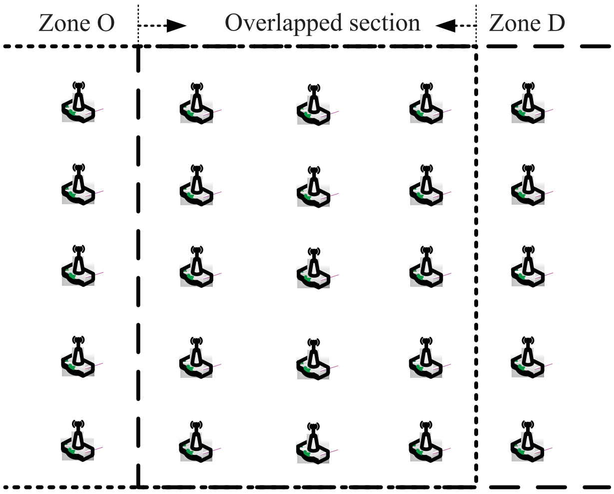

Fig. 2. A grid network for simulations.

Channel availability (CA) is defined as the percentage of available channels for routers under one PU. For Xing-zone communication, the common channel availability will decrease since the boarder routers need to obey both of the PUs. More specifically, in this model, the portion of available channels for each router is roughly $CA \times CA$. In this case, we are able to give the optimal solutions to show the impact of CAs, limit number $\mathbf{C}$ of channels for channel bonding, and interface number limit $\mathbf{I}$ on Xing-zone bridge construction.

In Fig. 3 we show the impact of CA on feasible Xing-zone bridge construction with different $\mathbf{B}_X$. It is clear that with larger CA, there would be more feasible Xing-zone bridges with a given $\mathbf{B}_X$. Moreover, larger CA also let the network support larger $\mathbf{B}_X$. However, the achievable $\mathbf{B}_X$ is upper bounded because the total available spectrum resources are limited.

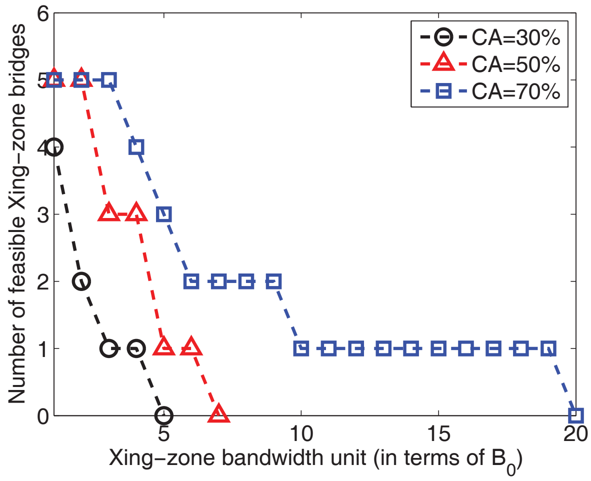

Fig. 3. Impact of CA on feasible Xing-zone bridges.

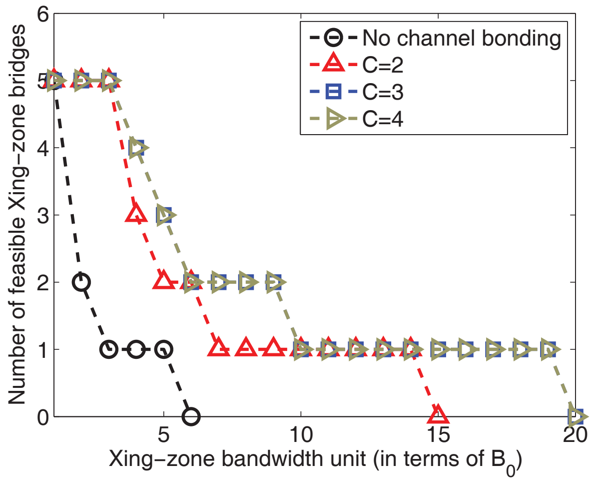

Fig. 4. Impact of $\mathbf{C}$ on feasible Xing-zone bridges.

Then we set $CA = 70\%$ and $\mathbf{I} = 4$ to show the impact of channel bonding technique. From Fig. 4 we can see that by introducing channel bonding (even bonding 2 channels only), the system has better performance in both number of feasible Xing-zone bridges and achievable $\mathbf{B}_X$ than traditional transmission technology without channel bonding technique. Moreover, larger number of channels for channel bonding provides even better performance. However, similar to the impact of CA, the increasing performance of larger $\mathbf{C}$ is upper bounded. This is due to the insufficient number of available channels for large $\mathbf{C}$ to establish transmission.

After that, we set $CA = 70\%$ and $\mathbf{C} = 4$ to show the impact of $\mathbf{I}$. Obviously, the number of interfaces directly influences the ability of multi-path routing. The results in Fig. 5 show that with more interfaces, the system would

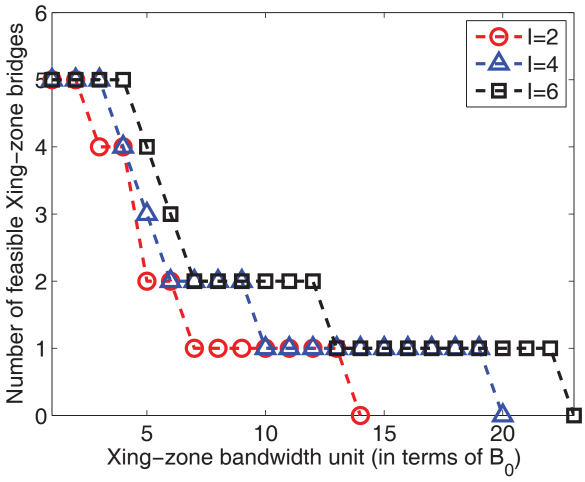

Fig. 5. Impact of $\mathbf{I}$ on feasible Xing-zone bridges.

have better network performance with more feasible Xing-zone bridges and higher achievable $\mathbf{B}_X$. It is because that the higher multi-path routing ability given by more interfaces creates more options to establish transmissions, which will in turn end up with better optimal solutions. Unexceptionally, increasing $\mathbf{I}$ cannot have positive infinite effects due to the limited spectrum resources.

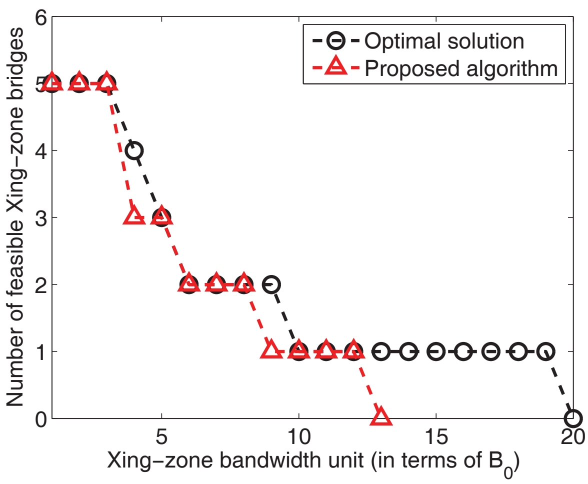

Fig. 6. Results of proposed algorithm.

Finally, we test our proposed Xing-zone bridge construction algorithm in the same network topology with $CA = 70\%$, $\mathbf{C} = 4$, and $\mathbf{I} = 4$. As shown in Fig. 6, although our proposed algorithm cannot achieve the same highest $\mathbf{B}_X$ as the optimal solution does since it is not able to fully utilize the available spectrum resources, the proposed algorithm produces near optimal solution when $\mathbf{B}_X \leq 12\mathbf{B}_0$. In practice, only 2 or at most 3 channels are supported for channel bonding in a router based wireless transmission with low cost MIMO (multiple-input and multiple-output) antenna. In this case, with $\mathbf{I} = 4$, it can provide a service with $\mathbf{B}_X = \mathbf{C} \times \lfloor \frac{\mathbf{I}}{2} \rfloor = 6\mathbf{B}_0$ at most. Therefore, we believe our proposed algorithm is good enough for practical applications in the near future.

V. Conclusion and Future Work

In this paper we formulated the optimization problem for Xing-zone bridge construction. The Xing-zone communication is the bottleneck for OD pair transmission in MWCRN across different areas with different available spectrum resources due to different PU activities. For practical applications, we also proposed a distributed algorithm which heuristically maximize the number of feasible Xing-zone bridges according to different requests of $\mathbf{B}_X$. In the future work, we plan to further discuss how to decide this Xing-zone bandwidth unit $\mathbf{B}_X$ based on different application requests with the consideration of the entire OD pair transmission.

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