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Application-Aware Routing for Multi-hop Cognitive Radio Networks with Channel Bonding

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***Abstract*—Due to the unequal spectrum resources in different areas, multi-hop wireless cognitive radio network (MWCRN) faces the challenge of a relatively poor performance. In this paper, we propose an application-aware routing scheme with channel bonding technique to help improve the efficiency and performance of a MWCRN network. More specifically, we formulate an optimization problem aiming to meet the application request, as well as operating at low transmission cost. To solve this problem, we first study the greatest lower bound of transmission cost named as Utopian cost, as well as an upper bound of transmission cost. Moreover, we propose two distributed algorithms for practical applications. Simulation results show that the proposed application-aware scheme achieves low transmission cost in MWCRN while satisfying demands of application requests.**

I. Introduction

The explosive growth of wireless devices and diversity of wireless applications almost congest the unlicensed industrial, scientific and medical (ISM) bands. However, the usage of some existing licensed bands is quite low. For instance, the usage of TV band is lower than 30% in most areas [1]. Cognitive radio (CR) [2] technology, which allows secondary users (SUs) opportunistically access the licensed bands when primary users (PUs) are inactive on that portion of spectrum resource [3], provides a possibility to take advantage of the white space (unused TV band) [4] in establishing a network.

The Federal Communications Commission (FCC) issued *IEEE* 802.22 [5] a few years ago. Since then, multi-hop wireless cognitive radio networks (MWCRN) [6] [7] has become a hot topic. The objective of establishing a MWCRN using licensed bands but without licensed contract is to build an economic network which saves transmission cost. Recently, the FCC has ruled that a central database must exist for aggregating the PU activity (such as occupied spectrum, active duration, starting time, etc.) over the coming 24 hours [8]. This rule relieves SUs from keeping sensing or applying complicated dynamic spectrum access protocols, and the reliability issue of cognitive radio network (CRN) has been significantly reduced [9] [10].

In this paper, we apply the pre-knowledge of PU activity into MWCRN in order to improve the performance of the network, and provide better service for O-D (origin to destination) pairs with various application requests. To jointly consider the network performance and transmission cost, we introduce both multi-interface and channel bonding technique into a MWCRN network model for the first time. Although the MWCRN with predictable spectrum information is similar to traditional multi-hop wireless mesh networks, the existing routing and channel allocation mechanisms for traditional ones [11] [12] can hardly be implemented into MWCRN for high network performance. Because the various activities of different PUs causes unequal available spectrum resource for SUs in different areas.

In order to deal with this problem of unequal spectrum resource, we equip each router with multiple interfaces. More specifically, multi-interface enables the ability of multicasting for one user (in terms of multi-path routing), it also enables two users to communicate with multiple transmission flows operating at different channels. Multi-path routing would increase the applicable common available spectrum resource when crossing different areas. Moreover, multi-path routing also takes advantage of channel reuse to serve a high volume of application requests of O-D (origin to destination) pairs.

For MWCRN, the transmission cost highly depends on the number of operating routers. However, due to the assumption that each router is equipped with multiple interfaces, it is more reasonable to count the number of transmission flows as transmission cost instead of the number of operating routers in our MWCRN. Therefore, to further improve the network performance by taking transmission cost into consideration, we introduce channel bonding technique into our MWCRN. Channel bonding technique enables one interface operating at several contiguous channels. It is obvious that if a single interface can operate at several channels, the O-D pair's application request is more likely to be fulfilled with fewer transmission flows. On the other hand, using multiple channels instead of a single channel can improve throughput greatly in wireless networks [16].

Our main contributions in this paper include: first, we formulate an optimization problem for a centralized MWCRN to minimize the transmission cost when fulfilling the application request for each O-D pair with best effort, we also study the greatest lower bound and the upper bound of transmission cost; second, we propose two distributed algorithms for practical usage in large scale networks; In the end, we give simulation results that verify the improvement brought by multi-interface and channel bonding technique.

The rest of this paper is organized as follows. We present our system model and problem formulation in section II. Two distributed algorithms for finding optimal paths are proposed in section III. We present the performance evaluation results in section IV. Conclusion and future work are given in section V.

II. System Model and Problem Formulation

A. The General Network Model

The whole network consists of M fixed PUs and N SUs (named as routers hereafter). We assume the locations of PUs and routers can be detected through GPS. For each PU, its activity affects a certain area. We define this area as a *zone* for this PU. Therefore, we have M zones, Z_k, for $k \in [1, M]$, with respect to each PU$_k$. The zones are not necessarily mutually exclusive for some PUs may locate within the interference range of each other. For simplicity, we assume that PUs have some protocols or agreement to use the same licensed spectrum resource even if their zones have overlapped areas. For the area with no PU activity, we define it as Z_0. We define $\mathbb{C}_i$, for $i \in [0, M]$ as the available spectrum resource (channels) for routers in Z_i. Specifically, $\mathbb{C}_0$ is equal to the pool of whole spectrum resource in the network.

Each router locates in one or multiple zones, $r_i^{(k)} = 1$ indicates that r_i locates in Z_k. Note that a router (e.g., router i denoted as r_i) has to know all the PUs which affect it. Thus, if a router locates in several zones (e.g., $r_i^{(k_1)} = 1$, $r_i^{(k_2)} = 1$, and $r_i^{(k_3)} = 1$), then the available channels for r_i is $\mathbb{C}_{k_1} \bigcap \mathbb{C}_{k_2} \bigcap \mathbb{C}_{k_3}$. Each router equips with $\mathbf{I}$ interfaces, and each interface of a router (e.g., r_i) is denoted as $It_k^{(i)}$, for $k \in [1, \mathbf{I}]$. We assume all the interfaces are the same following a *disk connectivity* model. Besides, each interface has the ability to do channel bonding with up to $\mathbf{C}$ *contiguous channels*. One interface can only communicate with another interface at a time. The transmission between two interfaces is defined as a *transmission flow*. Each router has the ability to use multiple interfaces to communicate with one or multiple routers.

Since the FCC rules that unlicensed users (SUs) must be given access to a predictive database which details the times when the licensed users (PUs) will be active/inactive over the coming 24 hours [8], therefore, $\mathbb{C}_i$, for $i \in [1, M]$ is predicable, and routers would have enough time for routing and transmission flow establishment, and finally finish the transmission requests from applications. We consider one O-D pair application request from origin router (e.g., r_O) to destination router (e.g., r_D), with bandwidth request $\mathbf{B}_{OD}$. For simplicity, we assume that the transmission at each interface is half duplex.

Definition 2.1: Let L_{OD} be the transmission cost of an O-D pair application. L_{OD} is computed as the total number of transmission flows used by an O-D pair application.

For simplicity, we use Lemma 1 to convert transmission flow number computing into interface number computing.

Lemma 1. *L_{OD} can be counted as the total number of interfaces used for one-way transmission (either $r_O \Rightarrow r_D$ or $r_D \Rightarrow r_O$).*

Proof: Each transmission flow consists of one interface for outgoing transmission and another interface for incoming transmission. Interfaces cannot be reused for other transmission flows. Therefore, L_{OD} can be counted as the total number of interfaces used for one-way transmission (either $r_O \Rightarrow r_D$ or $r_D \Rightarrow r_O$). ■

B. Problem Formulation

According to Lemma 1, the total number of O-D route transmission flows can be counted as

$$L_{OD} = \sum_{\forall (i,j) \in \mathbb{H}^1} \sum_{k=1}^{I} It_k^{(i)}|_{\overrightarrow{r_{i,j}}} \tag{1}$$

Where $\mathbb{H}^1$ is the set of 1-hop router pairs, and $It_k^{(i)}|_{\overrightarrow{r_{i,j}}}$ indicates the status of $It_k^{(i)}$ for transmission $r_i \Rightarrow r_j$.

Since our MWCRN targets to minimize the transmission cost, the objective function is simply

$$\min \ L_{OD} \tag{2}$$

Along with the objective function, we have several constraints due to the characteristics of MWCRN as indicated from Eq. 3 to Eq. 10.

Assigning a channel to one transmission flow is indeed assigning this channel to the two interfaces, one on each of the two routers at two ends. Both routers must have this channel available in their channel pool, as shown in Eq. 3, where $c_k^{r_i}$ is availability of k^{th} channel for r_i, and $c_{k,n}^{r_i}$ is the status of k^{th} channel for It_n^i.

$$c_{k,n}^{r_i} \cdot c_k^{r_i} = 1, \quad \forall c_{k,n}^{r_i} = 1 \tag{3}$$

Eq. 4 indicates that the number of assigned channels for one interface cannot exceed the limit $\mathbf{C}$. One interface can do channel bonding with maximum $\mathbf{C}$ contiguous channels,

$$\sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i} \leq \mathbf{C}, \quad \forall i \in [1, N] \tag{4}$$

Eq. 5 indicates that the assigned channels for one interface have to be contiguous.

$$\prod_{k=k_0}^{k_0+k_1} c_{k,n}^{r_i} = 1, \quad \forall c_{k_0,n}^{r_i} = 1, \ c_{k_0+k_1,n}^{r_i} = 1 \tag{5}$$

In order to accommodate the application request, we tend to use different channels for each hop if the assignment does not cause interference to existing assignments, as indicated in Eq. 6. Where $\overrightarrow{r_{i,j}}$ indicates that r_i and r_j are one hop away from each other, and $r_i \Rightarrow r_j$, $|r_i r_j|$ is the geographical distance between r_i and r_j, R_I is the interference range for a router.

$$\begin{aligned} c_{k_0,n_1}^{r_i} \neq c_{k_0,n_2}^{r_j}, \quad &\text{for } \overrightarrow{r_{i,j}} = \overrightarrow{r_{i,j}} = 0, \\ &\forall \ 0 < |r_i r_j| < R_I, \ k \in [1, \mathbf{K}], \\ &n_1 \in [1, N], \ n_2 \in [1, N] \end{aligned} \tag{6}$$

To provide a service targeting the bandwidth request $\mathbf{B}_{OD}$, both the outgoing transmission flows from origin router r_O and the incoming transmission flows to destination router r_i must satisfy this request or provide with its best supported service. We define $B_{max}^{r_i}$ as the maximum bandwidth supported for one way transmission of r_i. The constraint for this statement is shown in Eq. 7.

$$\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(D)}|_{\overrightarrow{r_{O,x}}}\cdot\sum_{k=1}^{\mathbf{K}}c_{k,n}^{r_O})\geq min\{\mathbf{B}_{OD},B_{max}^{r_O},B_{max}^{r_D}\} \tag{7}$$

However, since all the outgoing transmission flows from r_O would finally transmit to r_D, we only need to ensure that

$$\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(D)}|_{\overrightarrow{r_{O,x}}}\cdot\sum_{k=1}^{\mathbf{K}}c_{k,n}^{r_O})=\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(D)}|_{\overrightarrow{r_{x,D}}}\cdot\sum_{k=1}^{\mathbf{K}}c_{k,n}^{r_D}) \tag{8}$$

For an intermediate router (e.g., r_i), it needs to balance the bandwidth of incoming flows with that of outgoing transmission flows, calculated in term of interfaces as shown in Eq. 9.

$$\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(i)}|_{\overrightarrow{r_{x,i}}}\cdot\sum_{k=1}^{\mathbf{K}}c_{k,n}^{r_i})=\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(i)}|_{\overrightarrow{r_{i,x}}}\cdot\sum_{k=1}^{\mathbf{K}}c_{k,n}^{r_i}) \tag{9}$$

Moreover, each router has a limited number $\mathbf{I}$ of interfaces. Therefore, the total number of interfaces in use is bounded by this limitation, formed as Eq. 10.

$$\sum_{n=1}^{\mathbf{I}}\left(\sum_{x=1}^{N}It_n^{(i)}|_{\overrightarrow{r_{x,i}}}+\sum_{x=1}^{N}It_n^{(i)}|_{\overrightarrow{r_{i,x}}}\right)\leq I,\quad\forall i\in[1,N] \tag{10}$$

We will discuss the greatest lower bound and an upper bound of transmission cost for each O-D application in the next two subsections.

C. Utopian Transmission Cost

Definition 2.2: We define Utopian scenario with the assumption that the spectrum resource for each router is the same and unlimited.

Definition 2.3: Utopian transmission cost is the optimization result obtained in Utopian scenario.

Lemma 2. *Utopian transmission cost is the greatest lower bound of transmission cost.*

Proof: If there exists a result from a practical scenario lower than Utopian transmission cost, it suggests that the practical scenario has better spectrum resource for each router than that of Utopian scenario. However, the spectrum resource for each router in Utopian scenario is unlimited. Therefore, Utopian transmission cost is the greatest lower bound of transmission cost. ■

In Utopian scenario, the least number of outgoing transmission flows (in terms of necessary interfaces) for r_O equals to the least number of incoming transmission flows for r_D satisfying $\mathbf{B}_{OD}$, as shown in Eq. 11. Suppose channel bandwidth unit is B_0 (e.g., $6MHz$ for a TV band channel in the U.S.).

$$\sum_{k=1}^{\mathbf{I}}It_k^{(O)}=\sum_{k=1}^{\mathbf{I}}It_k^{(D)}=\lceil\frac{\mathbf{B}_{OD}}{B_0\cdot C}\rceil \tag{11}$$

For an intermediate router r_i ($i\neq O$ and $i\neq D$) in Utopian scenario, the least number of incoming transmission flows and outgoing transmission flows to achieve its maximum throughput are the same, as shown in Eq. 12.

$$\sum_{k=1}^{\mathbf{I}}It_k^{(i)}|_{\overrightarrow{r_{j,i}}}=\sum_{k=1}^{\mathbf{I}}It_k^{(i)}|_{\overrightarrow{r_{i,j}}}=\lfloor\mathbf{I}/2\rfloor,\quad\forall j\in[1,N] \tag{12}$$

According to Eq. 12, each path from $O\Rightarrow D$ consists of up to $\lfloor\mathbf{I}/2\rfloor$ transmission flows. Then, we can calculate the minimum number of paths from $O\Rightarrow D$ as,

$$\mathcal{N}_{\mathcal{P}}=\lceil\lceil\frac{\mathbf{B}_{OD}}{B_0\cdot C}\rceil/\lfloor\mathbf{I}/2\rfloor\rceil \tag{13}$$

It is noticeable that no two paths would use the same intermediate router in Utopian scenario. Although the intermediate router may have one spare interface in this congested scenario, it is not enough to balance one more incoming transmission or outgoing transmission flow.

We define $\mathcal{P}_k^{(O,D)}$ as the k^{th} shortest path (excluding the routers which have been chosen in other paths) from $r_O\Rightarrow r_D$. $\mathcal{P}_k^{(O,D)}$ consists of all the routers along the path. Among the $\mathcal{N}_{\mathcal{P}}$ shortest paths, $\mathcal{P}_k^{(O,D)}$, for $k\in[1,\mathcal{N}_{\mathcal{P}}-1]$ consists of $\lfloor\mathbf{I}/2\rfloor$ interfaces for one way transmission in each link. $\mathcal{P}_{\mathcal{N}_{\mathcal{P}}}^{(O,D)}$ consists of $\left(\lceil\frac{\mathbf{B}_{OD}}{B_0\cdot C}\rceil-((\sum\mathcal{P}_k^{(O,D)})_{min}-1)\cdot\lfloor\mathbf{I}/2\rfloor\right)$ interfaces for one way transmission in each link. There exists a transmission flow for every two sequential routers in $\mathcal{P}_{\mathcal{N}_{\mathcal{P}}}^{(O,D)}$ doing channel bonding with $\lceil(\mathbf{B}_{OD}-\lfloor\mathbf{B}_{OD}/\mathbf{C}\rfloor\cdot\mathbf{C})/B_0\rceil$ contiguous channels at each interface. Except for those transmission flows, all other transmission flows do channel bonding with $\mathbf{C}$ contiguous channels. Therefore, Utopian transmission cost $\overline{\mathcal{L}}_{OD}$ is obtained in Eq. 14.

$$\overline{\mathcal{L}}_{OD}=\lfloor\mathbf{I}/2\rfloor\cdot\left(\sum_{k=1}^{\mathcal{N}_{\mathcal{P}}-1}(\sum_{i=1}^{i=N}(r_i\in\mathcal{P}_k^{(O,D)})-1)\right)+(\lceil\frac{\mathbf{B}_{OD}}{B_0\cdot C}\rceil-(\mathcal{N}_{\mathcal{P}}-1)\cdot\lfloor\mathbf{I}/2\rfloor)\cdot(\sum_{i=1}^{N}(r_i\in\mathcal{P}_{\mathcal{N}_{\mathcal{P}}}^{(O,D)})) \tag{14}$$

D. An Upper Bound of Transmission Cost

In order to find the lowest transmission cost, any achievable transmission cost can be defined as a cost upper bound. As discussed before, the practical bandwidth from $O\Rightarrow D$ is $\min\{\mathbf{B}_{OD},B_{max}^{r_O},B_{max}^{r_D}\}$. For simplicity, we take the example where $\mathbf{B}_{OD}$ is achievable from both end.

In this case, r_O is able to transmit $\mathbf{B}_{OD}$ through $\lceil\mathbf{B}_{OD}/\mathbf{C}\rceil$ paths outside its interference range R_I. Similarly, r_D is available to receive $\mathbf{B}_{OD}$ through $\lceil\mathbf{B}_{OD}/\mathbf{C}\rceil$ paths within the range of R_I. Among all the paths, there would be one transmitting with the bandwidth of $\mathbf{B}_{OD}-\mathbf{C}\lfloor\mathbf{B}_{OD}/\mathbf{C}\rfloor$, while

Algorithm 1 Upper bound of transmission cost

Input: $\mathbf{B}_{OD}, B^{r_O}_{\max}, B^{r_D}_{\max}, R_O, R_D$, and $\mathbb{C}^{r_i}$, $\forall\ i \in [1, N]$.
Output: Transmission cost;
1: Establish least-paths routes to $r_O \Rightarrow r_D$;
2: Each router of one path outside R_I towards r_O and r_D is outside the R_I towards all the routers belong to other paths.

the others would transmit with the bandwidth of $\mathbf{C} \cdot B_0$. When transmitting outside the interference range of r_O or r_D, each path should be outside the interference range of other paths. The way to compute a feasible transmission cost is summarized in Algorithm 1. It is clear that any routing will result in a closed area. If the two boundary paths go through z_0 and the two zones where r_O and r_D locate only, then the lowest cost of transmission can be found within the closed area because any path outside the closed area would have more hops.

III. Distributed Algorithms

In the previous section, we have formulated the optimization problem to minimize transmission cost. Although we may reduce the size of the problem by finding a closed area through the upper bound, solving this problem is infeasible if the network scale is large. Moreover, although a centralized network might work in some certain circumstances, we agree that distributed networks are more practical in large area. Therefore, we introduce the distributed algorithms, where each router only has the knowledge of neighbor routers in a limited area.

In distributed network, each router would detect the PUs which cause interference to it, and label itself with those PUs as zone label. With zone label, routers can exchange zone spectrum information more efficiently. Although the new rule from the FCC requires PU to provide a full schedule of activity for the next 24 hours, due to the lack of centralized computing system, each router only can retrieve the activity of the PU in the same zone where it locates. We assume the routers use long-range Wi-Fi to support the control channel exchanging spectrum information and other control messages with neighbor routers. Therefore, the spectrum information in different zones can be exchanged from crossing-zone communication. We assume the PUs do not change their occupied licensed spectrum very often, thus, there would be enough time for routing and transmission in most cases.

A. Algorithm for One-Way Routing and Transmission Flow Assignment

We first introduce the *transmission flow balance check algorithm* (Algorithm 2). For the intermediate routers, when assigning channels to the link between two routers (e.g., $r_i \Rightarrow r_j$), we have to ensure that r_i would have enough resources to form incoming flows to balance the pre-assigned outgoing transmission flows, as indicated in Eq. 15.

$$\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(i)}|_{\overrightarrow{r_{x,i}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i}) + \overrightarrow{B_{n_{r_i}}^{(i)}} \geq \sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(i)}|_{\overrightarrow{r_{i,x}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_i}) \tag{15}$$

Where n_{r_i} is the number of remaining unassigned interfaces of r_i, as it can be calculated as,

$$n_{r_i} = \mathbf{I} - (\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}} It_n^{r_i}|_{\overrightarrow{r_{i,x}}} + \sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}} It_n^{r_i}|_{\overrightarrow{r_{x,i}}}) \tag{16}$$

And $\overrightarrow{B_{n_{r_i}}^{(i)}}$ is the maximum potentially achievable outgoing bandwidth from r_i to all the neighbors of r_i, using the remaining unassigned interfaces and spectrum resources.

As a reminder, all the checking processes in Algorithm 2 are based on the assumption that the input $\overrightarrow{r_{i,j}}$ has been assigned with candidate transmission flows. Moreover, $\mathbb{C}^{r_k}_{temp}$, $\forall k \in [1, N]$ is the temporary spectrum resources information for all the routers after the pre-assignment for $r_i \Rightarrow r_j$.

Algorithm 2 Possible transmission flow balance check

Input: Pre-assignment (e.g., for $\overrightarrow{r_{i,j}}$), and $\mathbb{C}^{r_k}_{temp}, \forall k \in [1, N]$
Output: $check$;
1: $check = 0$;
2: Calculate the remaining number of interfaces n_{r_i} for r_i, and n_{r_j} for r_j;
3: **if** ($i = O$, and $n_{r_i} \geq 0$), or, ($j = D$, and $n_{r_j} \geq 0$) **then**
4: $check = 1$; //check passed
5: **else**
6: **if** Both Eq. 15 and Eq. 17 are satisfied **then**
7: $check = 1$; //check passed
8: **else**
9: $check = 0$; //check failed
10: **end if**
11: **end if**

Similarly, we need to ensure that r_j would have enough resources to form outgoing flows to balance the newly-assigned incoming transmission flows, as indicated in Eq. 17.

$$\sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(j)}|_{\overrightarrow{r_{j,x}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_j}) + \overleftarrow{B_{n_{r_j}}^{(j)}} \geq \sum_{x=1}^{N}\sum_{n=1}^{\mathbf{I}}(It_n^{(j)}|_{\overrightarrow{r_{x,j}}} \cdot \sum_{k=1}^{\mathbf{K}} c_{k,n}^{r_j}) \tag{17}$$

Where $\overleftarrow{B_{n_{r_j}}^{(j)}}$ is the maximum potentially achievable incoming bandwidth to r_j from all the neighbors of r_j, using the remaining unassigned interfaces and spectrum resources.

For the origin router r_O and the destination router r_D, the balance check for their pre-assigned transmission flows would be simplified as the check for number of their remaining unassigned interfaces, n_{r_O} and n_{r_D} respectively.

Based on Algorithm 2, we propose a *one-way routing and transmission flow assignment algorithm* (Algorithm 3) for one O-D pair from $r_O \Rightarrow r_D$ with bandwidth request $\mathbf{B}_{OD}$. For simplicity, we assume that $\mathbf{B}_{OD} = n_{OD}B_0$, where n_{OD} is a non-negative integer. Therefore, to achieve $\mathbf{B}_{OD}$ is equal to assign n_{OD} channels to outgoing transmission flows to r_O with respect to Eq. 8 and Eq. 9.

Algorithm 3 Single-path one-way routing and transmission flow assignment

Input: $\mathbb{C}^{r_i}$, $\forall\ i \in [1, N]$, $\mathbf{n}_{OD}$, R_O, and R_D
Output: Assignment for each router pairs;
Find shortest path without chosen routers, and establish r_{seq}
Calculate n_{path} according to Eq. 18
$k = 0$;
while $k < K$ **do**
  $\overrightarrow{r_{i_k,i_{k+1}}} \longleftarrow \min\{n_{\max}^{(i_k,i_{k+1})},\ n_{path}\}$;
  $k = k + 1$;
end while

We first find the shortest path from $r_O \Rightarrow r_D$ as the shortest path $r_O \Rightarrow r_D$, obtain a sequence of routers as $r_{seq} = [r_{i_1}, r_{i_2}, \ldots, r_{i_D}]$. The path bandwidth request is,

$$n_{path} = \min\{n_{\max}^{i_0,i_1}, n_{\max}^{i_{K-1},i_K}, n_{OD}\} \tag{18}$$

Then we determine transmission flows and assign $min\{n_{max}^{(i_k,i_{k+1})},\ n_{path}\}$ to $\overrightarrow{r_{r_k,r_{k+1}}},\ k \in [1, K-1]$ sequentially. Where $n_{max}^{(i_k,i_{k+1})}$ is the largest achievable bandwidth for $\overrightarrow{r_{r_k,r_{k+1}}},\ k \in [1, K-1]$. For each assignment, we need to call Algorithm 2 to do the transmission flow balance check.

After one application of Algorithm 3, we may have the router pairs which have achieved less bandwidth. We then find two routers (e.g., r_i, and r_j), where the incoming transmission flows are balanced with outgoing transmission flows for all the intermediate routers of $\overrightarrow{r_{i,j}}$, but with the same least achieved bandwidth (e.g., n_{ij}). We define $r_i \Rightarrow r_j$ as a sub O-D pair with a sub bandwidth request $n_{sub} = n_{OD} - n_{ij}$, run Algorithm 3 for this sub O-D pair. After that, we check the routers from the original path again, and find a new sub O-D pair. The iteration would end when n_{path} is achieved.

Then we go back to original O-D pair with new bandwidth request $n_{OD} = n_{OD} - n_{path}$, and work on another path. The whole one-way routing and transmission flow assignment stops when $n_{OD} = 0$, or when r_O cannot find any new path, including that r_O/r_D cannot support anymore outgoing/incoming transmission flows.

B. Algorithm for Meet-in-The-Middle Routing and Transmission Flow Assignment

Similar to one-way routing and transmission flow assignment algorithm, *meet-in-the-middle routing and transmission flow assignment* (meet-in-the-middle hereafter) is also a path-based algorithm. However, meet-in-the-middle starts from both ends of the path and ends in the middle, as shown in Algorithm 4.

Algorithm 4 Single path meet-in-the-middle routing and transmission flow assignment

Input: $\mathbb{C}^{r_i}$, $\forall\ i \in [1, N]$, $\mathbf{n}_{OD}$, R_O, and R_D
Output: Assignment for each router pairs;
Find shortest path without chosen routers, and establish r_{seq}
Calculate n_{path} according to Eq. 18
$k = 0$;
while $k < (K + 1)/2$ **do**
  $\overrightarrow{r_{i_k,i_{k+1}}} \longleftarrow \min\{n_{\max}^{(i_k,i_{k+1})},\ n_{path}\}$;
  $\overrightarrow{r_{i_{K-k-1},i_{K-k}}} \longleftarrow \min\{n_{\max}^{(i_{K-k-1},i_{K-k})},\ n_{path}\}$;
  $k = k + 1$;
end while

IV. Performance Evaluation

A. Optimization Results for Centralized Network

In the simulation setting, there are 100 routers located in an 100 $km\times$ 100 km area. Although the interference range should be 1.8 to 2 times of the communication range, that would be a must to model a large scale network to show the effect of each parameter. Therefore, for obtaining the optimization results for centralized network, the communication range of each router is set as $R_C = 15\ km$, where the interference range of each router is set as $R_I = 18\ km$. Moreover, we apply grid topology for routers in order to get exact optimization results. There are 2 PUs (PU_1, PU_2) in this network. Thus, there are three zones Z_0, Z_1, and Z_2 in the network. We assume that both PUs occupy same portion of the spectrum resource (e.g., 30% or 50%) at a time, but they do not necessarily occupy the same spectrum resource. The whole spectrum pool is set as 30 contiguous channels. If not specified, set $\mathbf{I} = 4$, $\mathbf{C} = 4$, and each PU occupies 50% of the spectrum resource (15 channels) independently.

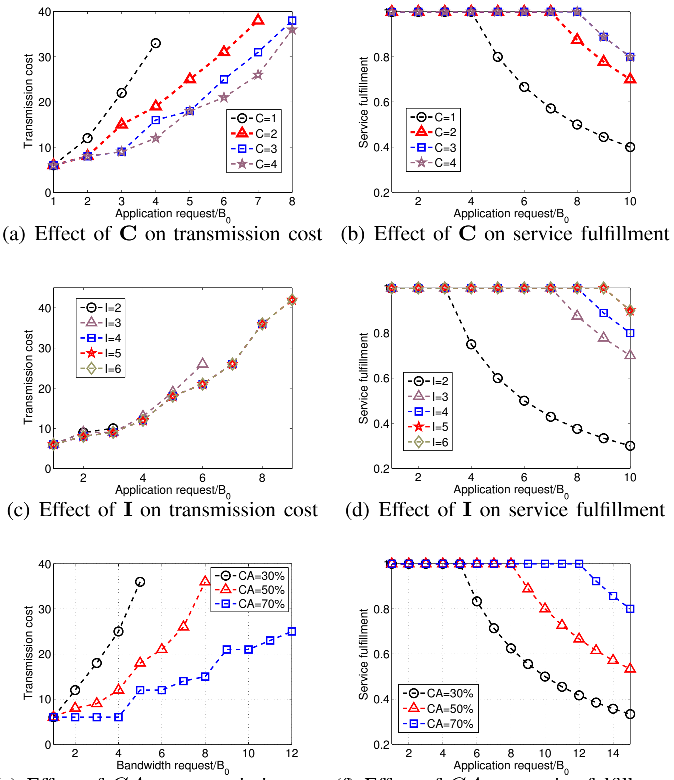
The results in Fig. 1(a) and Fig. 1(b) show the effect of different $\mathbf{C}$. It is obvious that with the increase of $\mathbf{C}$, the optimized transmission cost of centralized network decreases and the service provided can fulfill a higher number of application request. However, since the available number of contiguous channels for each router is limited, the improvement of performance is bounded.

The results in Fig. 1(c) and Fig. 1(d) show the effect of different $\mathbf{I}$. As we can see, higher $\mathbf{I}$ would lower the optimization cost of a centralized network, but the effect is marginal. On the other hand, the network would be able to fulfill higher application request with a higher $\mathbf{I}$. Due to the limited spectrum resources, all the improvements are bounded.

The results in Fig. 1(c) and Fig. 1(d) show the effect of different channel availability (CA). We can see that with higher CA for routers, the optimized transmission cost of centralized network is lower, and the service provided is better.

B. Results of Distributed Algorithms

To compare the performance of the distributed algorithms, we set the interface number $\mathbf{I} = 4$, channel bonding number $\mathbf{C} = 4$. Both PU_1 and PU_2 occupy 50% channels from the channel pool independently, the network area is the same as the centralized one. The results of the grid network topology with 100 routers are shown in Fig. 2(a) and Fig. 2(b). The



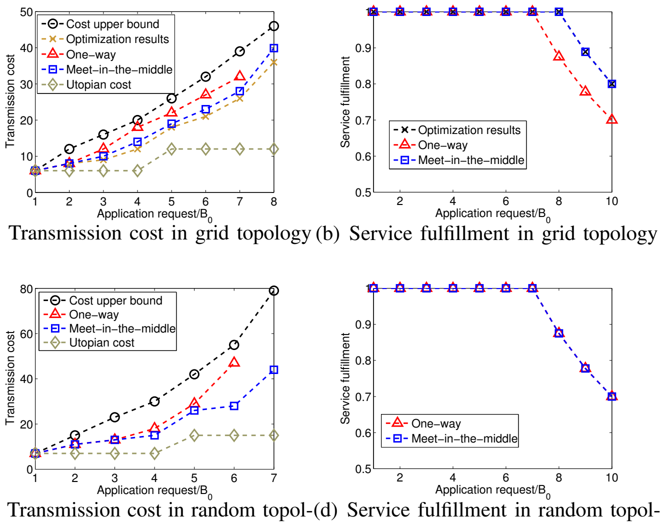
(a) Effect of $\mathbf{C}$ on transmission cost (b) Effect of $\mathbf{C}$ on service fulfillment

(c) Effect of $\mathbf{I}$ on transmission cost (d) Effect of $\mathbf{I}$ on service fulfillment

(e) Effect of CA on transmission cost (f) Effect of CA on service fulfillment

Fig. 1. Optimization Results for Centralized Network

results of a random network topology with 200 routers are shown in Fig. 2(c) and Fig. 2(d).



(a) Transmission cost in grid topology (b) Service fulfillment in grid topology

(c) Transmission cost in random topology (d) Service fulfillment in random topology

Fig. 2. Results of distributed algorithms

We can see that meet-in-the-middle assignment algorithm again provides a lower cost and a higher service compared with one-way assignment algorithm in both network topologies. However, meet-in-the-middle assignment algorithm is harder to put into practice because the assignment starts from both ends, and the information has to be sent to the other end before and after each assignment.

V. Conclusion

In this paper we introduced channel bonding technique into MWCRN to deal with different application requests at a low transmission cost. We formulated the optimization problem for transmission cost in a centralized network, and studied the greatest lower bound and upper bound of the transmission cost. Finding an upper bound of the transmission cost would help reduce the scale of the problem, in turn we are able to find the optimization results for some specific scenarios. To solve practical problems, we also proposed two distributed algorithms which heuristically minimize the transmission cost while satisfying application request at the same time.

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