BAR: Bandwidth-Aware Opportunistic Localized-Routing for Cognitive Radio Networks

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***Abstract*— In this paper, we propose the bandwidth-aware localized-routing that can sense the available spectrum bands within two-hop neighboring for choosing the highly opportunistic routes. Based on the mixed-integer linear programming (MILP) and through our proposed algorithm, we can determine the maximum of minimization bandwidth possible of links pairs through bandwidth approximation of relaxed variables, leading to reduce the computational complexity in the network. This allows selected routes corresponding to maximize bandwidths possible between CR users, which are based on behaviors of primary services, can be utilized the links pairs effectively. Simulation results show the efficiency of our proposed algorithm in CRNs.**

I. Introduction

In recent years, cognitive radio (CR) technology is predominated as one of the promising issues in wireless communications. In fact, the tradition of fixed spectrum sharing to licensed communication network results in spectrum utilization without efficiency [1]. In addition, due to the emerging demand of the spectrum for mobile communications of the licensed spectrum bands, CR is widely considered to resolve spectrum bands scarcity and meet requirements of wireless services [2]. These problems lead to the concepts of opportunistic spectrum sharing that allow CR users to opportunistically exploit the spectrum bands efficiently throughout the network [3][4][5].

As regarded to the opportunistic spectrum sensing we expect to utilize, it is varying over time and space. Hence, the integration between spectrum awareness and route optimization is totally the key challenge for spectrum awareness routing to deal with the spectrum utilization in the CR network [6][7][8][9][10].

In this paper, we propose a bandwidth-aware opportunistic localized-routing for CRNs. Basically, we cope with the problem which comes from the fact that when the spectrum aware opportunistic routing is considered for the entire network, it totally requires a high computational complexity, since there are enormous exponential variables corresponding to the different network conditions. Thus, to make more practical concerns, we came up with the bandwidth awareness based on the localized routing solution. In particular, our proposal algorithm manages the bandwidth awareness within two-hop neighboring routing for optimal routes. Thereby, the network load can be reduced since the computational complexity can be decreased significantly. To this end, we build the problem formulation which issues how to find the optimal solutions for localized routing through the minimization of bandwidth-utilized of links.

The proposed algorithm is based on the bandwidth approximation process (BAP) and the branch-and-bound (B&B) search algorithms. After solving LP relaxation from the problem formulation in Section III to determine the lower bound (LB), infeasible solutions have to be sorted in order to reduce the computational complexity for the whole network. The BAP algorithm filters the approximation solutions (upper bound solutions) that satisfy the condition which is within the vicinity of [LB, (1+ε)LB]. Hence, the outcoming solutions can be feasible and infeasible solutions. If a feasible solution is found, it is called an optimal solution, otherwise, infeasible solutions are divided into sub-problems for searching a feasible solution through the B&B algorithm. The procedure is iterative until an optimal solution is found. Simulation results show that solutions achieved through the proposed algorithm.

The rest of this paper is organized as follows. System model and problem formulation are issued in Section II and III, correspondingly. The proposed algorithm shows how to solve the problem in Section IV. Finally, simulation results and conclusion are given in Section V and VI, respectively.

II. System Model

To avoid the interference between transmission and reception among nodes in the network, all nodes in the network have to listen its surrounding local environment when they want to transmit. As illustrated in Fig. 1, we can see that nodes C and A can send data to nodes K and F, respectively. This is because nodes C and A can simultaneously send data to nodes K and F, respectively, on the same band h. However, this will be interfered by their mutual interference ranges if they had not listened for transmission, thereby, the same band utilization can result in the interference among nodes C and A. In addition, each node in the network uses spectrum sensing techniques to obtain the available spectrum bands through medium access control layer as discussed in [11][12]. Therefore, we model the network that each node can listen available bandwidths before transmission.

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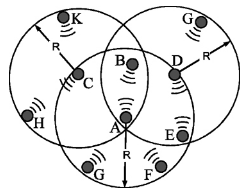

Fig. 1. Interference range between nodes in the network.

As in the scope of this paper, we consider the bandwidths of links pairs which are relied on the relationship of time utilization on bandwidths T_{on} and T_{off} in order to optimize the bandwidth-utilized on links in the CR network. Note that T_{on} is the time that the primary user is busy for transmission, while T_{off} means that the secondary user can utilize the bands for transmission [13]. Based on this characteristic, we can determine the maximum bandwidth possible for opportunistic routing. Thus, we have:

$$\mathcal{C}_{ij\,max}^{\,hk} = \frac{T_{on}}{T_{on} + T_{off}} \times \mathcal{C}_{ij}^{hk} = Pb \times \mathcal{C}_{ij}^{hk}, \tag{1}$$

where $\mathcal{C}_{ij\,max}^{\,hk}$ is the maximum bandwidth possible of link pairs depending on T_{off} and T_{on}; $\mathcal{C}_{ij}^{hk}$ is the available link capacity from node i to j, in which will be defined in (12); Pb is the fraction of time which the primary user is busy.

As in Fig. 1, we can see that if node H needs a certain bandwidth for forwarding, it listens the spectrum sensing information from nodes A, B, C, and K, then determines the minimum bandwidth-utilized on link pairs $\{l_{HC}, l_{CK}\}$, $\{l_{HC}, l_{CB}\}$, $\{l_{HC}, l_{CA}\}$. Thereby, we can determine a set of minimum bandwidth between links' pairs and then decide the maximum of one in such set of minimum bandwidth between links pairs. Hence, we formulate the optimal bandwidth for routing at node H as follows:

$$l_H = \mathbf{Max}\{\mathbf{Min}\{l_{HC}, l_{CK}\}; \mathbf{Min}\{l_{HC}, l_{CB}\}; \mathbf{Min}\{l_{HC}, l_{CA}\}\}, \tag{2}$$

where $l_{HC}, l_{CK}, l_{CB}, l_{CA}$ are available bandwidths on links HC, CK, CB, and CA, respectively. l_H is the maximum bandwidth possible on the set of minimum bandwidths on links pairs which have a source routing from node H.

Accordingly, we can obtain a set of maximum available bandwidth in the set of minimum available bandwidths of two-hop neighboring routing from (2) as follows:

$$BW_{optimal} = \mathbf{Max}\{\sum_{i \in \mathcal{A}} l_i\}, \tag{3}$$

where $BW_{optimal}$ is the maximum bandwidth possible on link pairs for routing from node i.

Based on abovementioned issues, we describe an example as follows. Assume that node A wants to make a decision for routing to node K, it obviously has two optional links including links pairs (l_{AC}; l_{CK}) and (l_{AB}; l_{BK}). These links pairs have spectrum sensing information about bandwidths following to (20; 15) and (30; 35), respectively. First, node A minimizes those links pairs, then it gets the minimum bandwidths $15Mbps$ for the first link pairs and $30Mbps$ for the second one. Then, it maximizes those minimum links pairs, thereby, it can obtain the maximum bandwidth possible that is $30Mbps$. Thus, node A will choose link pairs (l_{AB}; l_{BK}) for routing.

Note that the equations (1), (2), (3), are introduced to show briefly the idea of this paper. While (2), (3) will be obtained by solving problems that are mentioned in Section III and IV, respectively, the equation (1) is defined to evaluate the maximum bandwidth possible for opportunistic routing based on various behaviors of primary services.

TABLE I
SYSTEM MODEL NOTATION

Symbol	Definition
$\mathcal{A}$	Set of nodes in the network
$\mathcal{S}$	Set of available bands among all nodes in the network
$\mathcal{S}_i$	Set of available bands at node i in the network
$\mathcal{W}_h$	Bandwidth of band $h \in \mathcal{S}$
$\mathcal{K}_h$	Band h is divided into sub-bands with unequal bandwidths
$\mathcal{F}_{hk}$	Bandwidth fraction for a sub-band k in band h
$\mathcal{R}_i^T$	Transmission range of node i
$\mathcal{R}_i^I$	Interference range of node i
$\mathcal{T}_i^h$	Set of available nodes that are using band h and within the transmission range of node i
$\mathcal{I}_j^h$	Set of nodes which can interfere at node j on band h
$\mathcal{PS}^T$	Power spectral density of transmission range
$\mathcal{PS}^I$	Power spectral density of interference range
z_{ij}^{hk}	Switching mode that sub-band k in band h can either be utilized or not between node i and j
$\mathcal{L}$	Set of available links in the localized-routing area

From the abovementioned issues, we denote that $\mathcal{S}$ is the set of available bands among all nodes in the network and $\mathcal{S}_i \subseteq \mathcal{S}$ is the set of available bands at node $i \in \mathcal{A}$. Note that node $j \in \mathcal{A}$ has $\mathcal{S}_j \neq \mathcal{S}_i$. In addition, let $\mathcal{W}_h$ be the bandwidth of band $h \in \mathcal{S}$, and band h can be divided into $\mathcal{K}_h$ sub-bands with unequal bandwidths.

However, the problem comes from how to assign sub-bands at a node for transceiving without interference among nodes. We suppose that the scheduling on bands and sub-bands must be guaranteed in such problem. Hence, we aim that band h can be used in nodes i and j if satisfying this condition:

$$z_{ij}^{hk} = \begin{cases} 1 & \text{if } i \text{ sends data to } j \text{ on sub-band } k \in h, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Note that band $h \in \mathcal{S}_{ij}$, where $\mathcal{S}_{ij} = \mathcal{S}_i \cap \mathcal{S}_j$, means that band h is available at node i and j. Node $i \in \mathcal{A}$ and it uses sub-band k in band h that is within its transmission range, then we have:

$$\mathcal{T}_i^h = \{j : j \neq i, h \in \mathcal{S}_j, d_{ij} \leq \mathcal{R}_i^T\}, \tag{5}$$

where $\mathcal{T}_i^h$ means the set of nodes which can use available band h within the transmission range of node i, $\mathcal{R}_i^T$; d_{ij} is the distance between node i and j.

We note that node i cannot transmit to multiple nodes simultaneously on the same sub-bands, since it will occur the bottleneck phenomenon in the communication links. Therefore, we can make a constraint as follows:

$$z_{ij}^{hk} + \sum_{p \in \mathcal{T}_j^h} z_{jp}^{hk} \leq 1. \tag{6}$$

According to the constraint (6), if z_{ij}^{hk} is equal to 1, then $\sum_{p \in \mathcal{T}_j^h} z_{jp}^{hk}$ must be 0, then node j cannot use sub-band k for transmission. Otherwise, if z_{ij}^{hk} is equal to 0, then $\sum_{p \in \mathcal{T}_j^h} z_{jp}^{hk} \leq 1$, and node j can transmit to node p on sub-band k in band h, but only use if node $p \in \mathcal{T}_j^h$.

On the other hand, scheduling constraints can be considered since the interference between nodes in the network. It is clear that if node i uses sub-band k in band h for transmission to node j, then any node which can interfere at node j will be eliminated to use this sub-band. In order to build this constraint, let $\mathcal{I}_j^h$ be the set of nodes which can interfere at node j on sub-band k in band h, we have:

$$\mathcal{I}_j^h = \{p : p \neq j, h \in \mathcal{S}_p, d_{pj} \leq \mathcal{R}_j^I\}. \tag{7}$$

Note that $\mathcal{R}^T$ and $\mathcal{R}^I$ have mutual relation with the power spectral density (PS) of nodes in the network. When $\mathcal{PS}^T > \mathcal{PS}^I$, it means $\mathcal{R}^T < \mathcal{R}^I$ as mentioned in [12]. Then, we can formulate:

$$z_{ij}^{hk} + \sum_{q \in \mathcal{T}_p^h} z_{qp}^{hk} \leq 1, \tag{8}$$

where $p \in \mathcal{I}_j^h$ and $p \neq i$. If $z_{ij}^{hk} = 0$, the interference of two nodes at node j but apart from each other can use the same sub-band k in band h for their transmission. As illustrated in Fig. 1, when node A uses sub-band k in band h for transmission, other nodes cannot use this sub-band, e.g. node C, D, E, F, G cannot use for their transmission. When node A does not use this sub-band for transmission to node B, all surrounding nodes B, C, D, E, F, G can use sub-band k for transmission. In particular, it can be seen that while node C can use this sub-band for transmission to either node H or node K, node D can use such sub-band for transmission to either node G or node E. That means both node C and D can use the sub-band k in band h at the same time without interference. Therefore, Fig. 1 illustrates an example that it totally follows to the constraints (7), (8) as abovementioned.

When a source node transmits data to the destination node, it could probably need a number of hops from intermediate nodes to approach the destination node. However, which routes could be the appropriate routes for routing, it is needed to be approximated via the flow rates on each radio link, which cannot exceed the capacity of link. Moreover, when node i is transmitting to node j on sub-band k in band h, their neighboring nodes[1] have to avoid to use such sub-band k in band h for transmission. At the network level, we denote that l_{ij} is the link data rate from node i to node j, where $l_{ij} \in \mathcal{L}$ and belongs to the set of available nodes that are using band h and within the transmission range of node i, $\mathcal{T}_i^h$.

[1]The neighboring nodes are within the transmission range of nodes i and/or j.

Denote that if node i is a source node or destination node of link l, its rate is defined as $r_{src}(l)$ or $r_{dst}(l)$, respectively. Hence, we have:

$$\sum_{j \in \mathcal{T}_i^h} l_{ij}(l) = r_{src}(l), \tag{9}$$

$$\sum_{p \in \mathcal{T}_i^h} l_{pi}(l) = r_{dst}(l), \tag{10}$$

Then, we formulate the constraint for two-hop routing which is mentioned as a localized-routing as follows:

$$\sum_{j \in \mathcal{T}_i^h} \sum_{i \neq j} l_{ij}(l) = \sum_{p \in \mathcal{T}_i^h} \sum_{i \in r_{src}(l)} \sum_{p \notin \{r_{dst}(l)|i\}} l_{ip}(l)$$
$$+ \sum_{j \in \mathcal{T}_i^h} \sum_{j \in r_{dst}(l)} \sum_{p \notin \{r_{src}(l)|j\}} l_{pj}(l). \tag{11}$$

Note that node p in (11) plays a role as an intermediate node in the proposed model.

Unlike in [12], the authors aimed to make computational complexity of links through the whole network, this apparently results in the routing overhead of the network. Thus, it is generally impractical in real networks. In this paper, we suppose a two-hop neighboring that is applicable to the network, in which satisfies the condition (11).

In addition, each link data rate cannot exceed the capacity of link. Thus, the capacity of link l_{ij} via sub-band k in band h can be described as [14]:

$$\mathcal{C}_{ij}^{hk} = z_{ij}^{hk} \times \mathcal{F}_{hk} \times \mathcal{W}_h \times log_2(1 + \frac{\mathbf{P}}{\sigma}), \tag{12}$$

where $\mathbf{P} = g_{ij} \times PS$; g_{ij} is a power propagation gain; and PS is the power spectral density of a CR node; σ is the Gaussian noise density. In addition, we assume that all CR nodes have the same PS for transmission. Note that these parameters have been mentioned in [12], therefore will not be elaborated in this paper.

From (11) and (12), we have:

$$\sum_{l \in \mathcal{L}} \sum_{i \notin r_{dst}(l)} \sum_{j \notin r_{src}(l)} l_{ij}(l) \leq \sum_{h \in \mathcal{S}_{ij}} \sum_{k=1}^{k=\mathcal{K}_h} \mathcal{C}_{ij}^{hk}. \tag{13}$$

III. Problem Formulation

In a multi-hop CR network, the available spectrum bands at a node could be utilized by another node in the network. Moreover, a given set of available frequency bands at a node is completely different from other nodes in the CR network. Hence, the large diversity bandwidth of the sets of available bands need to be allocated into sub-bands for utilizing such bands more flexible in various network conditions.

Mathematically, we formulate the optimization problem based on the minimization of bandwidth-utilized in the network. Thus, we have:

$$\textbf{Min} \quad \sum_{i\in\mathcal{A}}\sum_{h\in\mathcal{S}_{ij}}\sum_{j\in\mathcal{T}_i^h}\sum_{k=1}^{k=\mathcal{K}_h}\mathcal{F}_{hk}\times\mathcal{W}_h\times z_{ij}^{hk}. \quad (14)$$

$$\text{s.t.} \quad z_{ij}^{hk}+\sum_{q\in\mathcal{T}_p^h}\sum_{p\in\mathcal{I}_j^h}\sum_{p\neq i}\sum_{i\in\mathcal{A}}\sum_{h\in\mathcal{S}_{ij}} z_{qp}^{hk}\leq 1. \quad (15)$$

$$\sum_{l\in\mathcal{L}}\sum_{i\notin r_{dst}(l)}\sum_{j\notin r_{src}(l)} l_{ij}(l)-\sum_{h\in\mathcal{S}_{ij}}\sum_{k=1}^{k=\mathcal{K}_h}\mathcal{C}_{ij}^{hk}\leq 0. \quad (16)$$

Note that the aforementioned problem in (14) is a non-linear problem. However, such non-linear problem can be converted to a linear problem by using the method that is proposed in [15]. We denote binary variables $D_{ij}^{hk}=z_{ij}^{hk}\mathcal{F}_{hk}$, which have to satisfy following constraints:

$$D_{ij}^{hk}\leq z_{ij}^{hk} \quad (17)$$

$$D_{ij}^{hk}\leq \mathcal{F}_{hk} \quad (18)$$

$$D_{ij}^{hk}\geq z_{ij}^{hk}+\mathcal{F}_{hk}. \quad (19)$$

To sum up, the problem is to minimize in (14), subject to constraints (4), (6), (7), (8), (9), (11), (13), (17), (18), (19), where $\mathcal{W}_h$, $\mathbf{P}$, σ, $r_{src}(l)$, $r_{dst}(l)$ are constants, and all optimization variables are z_{ij}^{hk}, $l_{ij}(l)$. Consequently, we have:

$$\textbf{Min}\sum_{i\in\mathcal{A}}\sum_{h\in\mathcal{S}_{ij}}\sum_{j\in\mathcal{T}_i^h}\sum_{k=1}^{k=\mathcal{K}_h}\mathcal{W}_h\times D_{ij}^{hk}. \quad (20)$$

$$\text{s.t.} \quad (15),(16),(17),(18),(19). \quad (21)$$

IV. Proposed Algorithm

The proposed algorithm is based on the bandwidth approximation process (BAP) and the branch-and-bound (B&B) search algorithms. After solving LP relaxation from conditions (20) and (21) in Section III to determine the lower bound (LB), infeasible solutions need to be sorted in order to reduce the computational complexity for the entire network. To this end, the BAP algorithm filters the approximation solutions[2] that satisfy the condition which is within the vicinity of [LB, (1+ε)LB] in terms of the lower bound[3]. The outcoming solutions can be feasible and infeasible solutions. If a feasible solution is found, it is called an optimal solution, otherwise, infeasible solutions are divided into sub-problems for searching a feasible solution through the B&B search algorithm. The procedure is iterative until an optimal solution is found.

The operation of proposed algorithm is based on the iterative steps as follows:

- First step: a lower bound solution is obtained by solving LP relaxation through the polynomial time. However, the outcoming solutions can be infeasible solutions since they are fractional. The BAP algorithm is applied to determine the upper bound solutions which are potential optimal solutions.
- Second step: the condition of lower bound with the range of [LB,(1+ε)LB] is used to sort the number of infeasible solutions that do not satisfy such condition. Hence, the set of satisfied feasible solutions, which are obtained in the vicinity of [LB, (1+ε)LB], is maximized the minimum set of such solutions obtained to select the optimal solution. Otherwise, if no feasible solution is found, the procedure turns to the third step.
- Third step: Since there is no feasible solution after the second step, the B&B algorithm is used to divide the infeasible solutions into sub-problems for the next iterative loops until an optimal solution is found out.

According to the discussion as above, we denote that LB_i and UB_i are the lower bound and upper bound of problem i, respectively. In terms of LB_i and UB_i, the minimum lower bound and upper bound can be determined as follows.

$$LB_{min}=\min_{i\in\mathcal{SP}}\{LB_i\}, \quad (22)$$

$$UB_{min}=\min_{i\in\mathcal{SP}}\{UB_i\}, \quad (23)$$

where $\mathcal{SP}$ is the set of problems. Note that the purpose of (22) and (23) is to shorten the computational complexity by obtaining $(1+\varepsilon)$ optimal solution. A problem can be removed from the set of problems if it satisfies:

$$(1+\varepsilon)LB_i\geq UB_i. \quad (24)$$

The optimal solution will not be removed if the minimum upper bound solution from selected problems, which are not be removed from the constraint (24), is not better than the current optimal solution. Otherwise, the current optimal solution will be replaced by the minimum upper bound solution, which is $(1+\varepsilon)$ optimal solution, as the latest optimal solution.

V. Simulation Performance

In this section, we perform simulations under network scenarios to verify the effectiveness of the proposed algorithm by using MATLAB. Initially, network topology is deployed with 100 nodes randomly in the area of 1000×1000 m^2. Transmission range of the nodes is 100 meters for CR networks, for example, wireless microphones with small transmission range as mentioned in [16]. In addition, random bandwidth values are uniformly distributed in the interval of [0, 35](Mbps). The tolerant accuracy ε is set at 5%. The bandwidth-utilized of CR users is considered by the busy-idle time T_{on} and T_{off}. In fact, T_{on} and T_{off} are random variables depending on the primary users [17], such as mobile communication services. Moreover, T_{on} and T_{off} are independent and exponential distributions with λ_{on} and λ_{off} are the expected lengths of ON and OFF states corresponding to T_{on} and T_{off}, respectively. Assume that T_{on} and T_{off} are obtained in the ceasing process, then we can evaluate the throughput with the different behaviors of T_{on}

[2]Approximation solutions are the potential optimal solutions as well as upper bound solutions.

[3]Note that ε is the tolerant accuracy within the range of $0\leq\varepsilon\ll 1$.

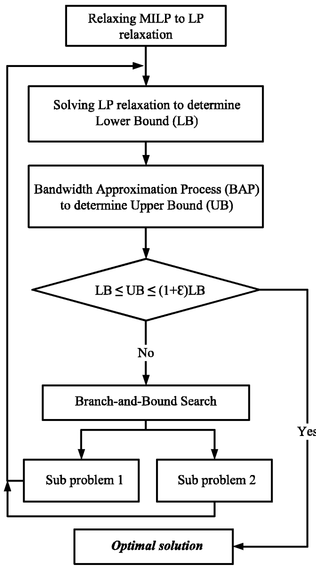

Fig. 2. Proposed algorithm.

and T_{off} from primary services. Note that $T_{on} = \frac{1}{\lambda_{on}} e^{-\frac{t}{\lambda_{on}}}$, and $T_{off} = \frac{1}{\lambda_{off}} e^{-\frac{t}{\lambda_{off}}}$.

From simulation results, we did not compare with prior results because they are near-optimal, thus, a direct comparison between near-optimal results and our approach is not applicable. We can see that Figs. 4, 6, 8 illustrate average throughputs corresponding to network topologies 3, 5, 7, respectively. Although network topologies have the same size 1000×1000 m^2 and the number of nodes, nodes are randomly distributed and the network's bandwidth-utilized is relied on the expected lengths λ_{on} and λ_{off}. In this paper, we simulated with (λ_{on}; λ_{off}) following to a set of value [(2.6; 3.6), (1.6; 2.6), (3.6; 4.6)], respectively. As can be recognized that when λ_{on} and λ_{off} are decreased to 1.6(s) and 2.6(s) from 2.6(s) and 3.6(s) [17], the links pairs are maintained to the maximum bandwidth possible based on T_{on} and T_{off} which are statistically random variables. However, when λ_{on} and λ_{off} are increased to 3.6(s) and 4.6(s) from 2.6(s) and 3.6(s), the minimum upper bound is greater than the previous one because of being occupied by primary user for transmission.

On the other hand, it is apparent that the number of solutions is filtered remarkably through the proposed algorithm, since it minimizes the number of links pairs for routing as well as utilizes the maximum bandwidth possible on links pairs in different network scenarios as can be seen in Figs. 4, 6, 8. Therefore, our approach shows that the proposed algorithm can adapt dynamically to network conditions according to T_{on} and T_{off} behaviors in primary services through the bandwidth approximation capability in order to reduce significantly the number of infeasible solutions for routing. Thereby, the network can avoid the hot areas such as traffic congestion.

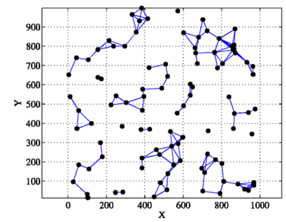

Fig. 3. Network topology 1000×1000 m^2 with 100 nodes randomly, λ_{on} = 2.6(s), λ_{off} = 3.6(s) [17].

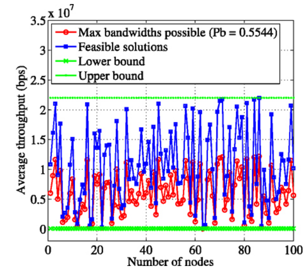

Fig. 4. Average throughput corresponding to 100 nodes, λ_{on} = 2.6(s), λ_{off} = 3.6(s).

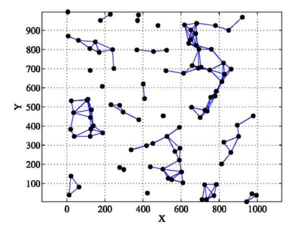

Fig. 5. Network topology 1000×1000 m^2 with 100 nodes randomly, λ_{on} = 1.6(s), λ_{off} = 2.6(s).

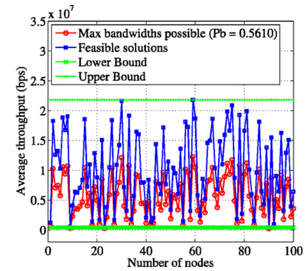

Fig. 6. Average throughput corresponding to 100 nodes, λ_{on} = 1.6(s), λ_{off} = 2.6(s).

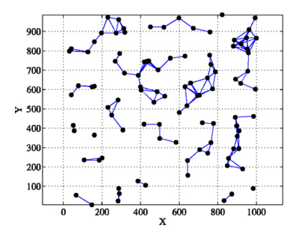

Fig. 7. Network topology 1000×1000 m^2 with 100 nodes randomly, λ_{on} = 3.6(s), λ_{off} = 4.6(s).

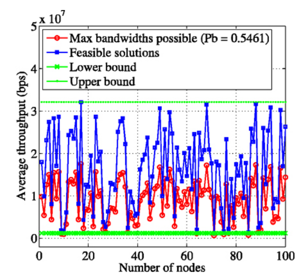

Fig. 8. Average throughput corresponding to 100 nodes, λ_{on} = 3.6(s), λ_{off} = 4.6(s).

VI. Conclusion

In this paper, a bandwidth-aware opportunistic localized routing in CRNs is proposed. We proved that the bandwidth-aware localized routing, which is within two-hop neighboring, can reduce the high computational complexity in the network by maximizing the minimum set of links pairs' bandwidths. Simulation results showed our proposed algorithm that can be utilized for opportunistic routing with large networks under various conditions.

In future work, we will conduct the optimization routing toward to queueing lengths, interference features that are concerned about the behaviors of primary services.

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