IAN: Interference-Aware Routing Geometry on Proximity for Cognitive Radio Networks

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***Abstract*—In this paper, we propose the interference-aware routing geometry algorithm that can approximate the interference percentage of the multiple overlapping transmissions between primary network and secondary network in cognitive radio networks for balancing routing costs. This algorithm allows selected routes that are corresponding to the fair costs for routing performance in cognitive networks. We also utilize the cumulant of the aggregate interference as the interference model in order to analyze the impact of overlapping interference in terms of varying distances in the network. Simulation results demonstrate the efficiency of our proposed algorithm and distance-based analysis in CRNs.**

***Index Terms*—Interference-aware, overlapping transmissions, geometry routing, cognitive radio networks.**

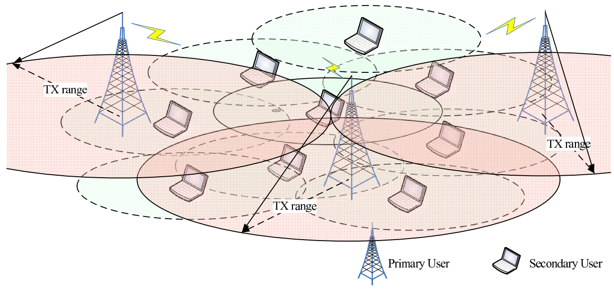


Fig. 1: Multiple overlapping transmissions in a CRN.

I. Introduction

Cognitive radio (CR) technology is introduced to manage the resource allocation toward the drastic increase in demand for licensed spectrum frequency bandwidth. Moreover, CR technology has contributed to the recent scarcity of available bandwidth. CR technique is the best solution to efficiently utilize the unoccupied licensed bandwidth. [1]. In addition licensed spectrum bands are able to be exploited and adaptively adjusted according to bandwidth demands which vary over time and distance [2], [3], [4], [5]. In reality, CR technology is definitively feasible for many applications. For instance, first responders such as firefighters, emergency medical crews, and police officers are deployed instantaneously at the same time to rescue people from disaster circumstances. Hence, they could probably utilize the CR technology in their licensed bands to reuse frequency bands in their existing networks [6]. In another scenario, various wireless communication bands are used in battlefield communications within different military units. In this scene, CR capabilities can possibly aid in maintaining timely transmission communications among all of the units. Therefore, it is obvious that the CR technology may play an important key in overcoming the scarcity of spectrum frequency bands in cognitive radio networks (CRNs).

To ensure the efficient routing performance in CRNs, channel interference also is one of the factors that can affect routing performance and it is harmful in both the primary and secondary networks of CRNs due to the overlaps in transmission. Consequently, optimizing the routing performance cost is an open challenge in CRNs. Even though many researchers have been studied the interference constraints in CRNs [3], [7], [8], [9], [10], [11], [12], [13], [14], to minimize the costs, to the best of our knowledge, there is no study that focuses on the optimal routing flows in CRNs under the adverse effect of multiple overlapping transmissions to analyze its impacts on routing performance.

This paper proposes the interference-aware routing geometry algorithm to approximate the interference percentage of multiple overlapping transmissions. The proposed algorithm is used in cognitive radio networks for balancing routing costs between primary and secondary networks. It allows selected routes that are corresponding to the fair costs for routing performance in cognitive networks. In addition, the paper uses the cumulant of the aggregate interference as the interference model in order to analyze the influence of overlaps in transmission through varying distances. Simulation results show the effectiveness of the proposed algorithm and distance-based analysis in terms of average throughput, end-to-end delay, and packet delivery ratio, on routing performance in CRNs.

The rest of this paper is organized as follows. The proposed algorithm in Section III discusses a fairness solution for selecting the routes that ensure optimal routing performance. Section IV shows the proposed algorithm provides the best performance in comparison with other algorithms. Finally, the conclusion shows a summary of the proposed method as well as potential plans for future work in Section V. Now, the paper describes the system and the interference models of the cognitive network in the next Section II.

II. SYSTEM MODEL

In cognitive networks, multiple overlapping transmissions phenomenon during routing performance is still a challenge in CRNs. Thus, this section focuses on the investigation of how secondary users consider the challenging interference features of these transmissions to approximate minimized costs for routing performance. The transmission model and the interference model are described as follows.

TABLE I: Notations

Symbol	Notation
$\mathcal{A}$	Set of nodes in the CRN
$\mathcal{S}$	Set of secondary nodes (SUs) in the network
$\mathcal{L}$	Set of links established among SUs with its neighbors in the CRN
$\mathcal{P}$	Set of primary nodes (PUs) in the network
$\mathcal{O}$	Network extension in a unit square
$\mathcal{X}_m$	Position of m^{th} PU in the network
$\mathcal{Y}_n$	Position of n^{th} SU in the network
X_i^p	Subset of active PUs in the network
Y_j^s	Subset of active SUs in the network
P_i^p	Uniform power level of the primary network
P_j^s	Power level chosen by the secondary node $\mathcal{Y}_j^s$
N	Ambient noise
γ	Minimum required SINR necessary for successful reception in the PUs
δ	Minimum required SINR necessary for successful reception in the SUs
α	Amplitude path loss exponent

A. Transmission Model

Suppose that a SU s_i transmits data over sub-band k to a SU s_j, but the transmission could fail or collide with other factors such as noise or interference. Hence, to determine whether transmissions are successfully received or not, we investigate the results of the transmission by following the well-known physical model proposed by Gupta *et al.* in [15]. Let P_i^p be the uniform power level of a primary network, and P_j^s be the power level chosen by a secondary node Y_j^s, for $j\in\mathcal{S}$. Moreover, X_i^p and Y_j^s, for $i\in\mathcal{P}$ and $j\in\mathcal{S}$, respectively, are the subsets of nodes transmitting simultaneously over certain sub-channels in the CR network. Then, the transmission **for primary networks** is denoted from node X_i^p to node X_k^p, where $k\in\mathcal{P}$, is successfully received if,

$$\frac{P_i^p K(\left|X_i - X_j\right|)}{N + \sum\limits_{j,k\in X_i^p} P_k^p K(\left|X_k - X_j\right|) + \sum\limits_{j,h\in Y_j^s} P_h^s K(\left|Y_h - X_j\right|)} \geq \gamma, \tag{1}$$

where $K(|.|)$ is the gain of a normalized channel between the transmission of the two nodes with $\alpha > 2$, in terms of $K(|X - Y|) = |X - Y|^{-\alpha}$.

For secondary networks, the transmission from node Y_i^s to node Y_k^s, for $k\in\mathcal{S}$, is successfully received if,

$$\frac{P_i^s K(\left|Y_i - Y_j\right|)}{N + \sum\limits_{j,k\in Y_i^s} P_k^s K(\left|Y_k - Y_j\right|) + \sum\limits_{j,h\in X_j^p} P_h^p K(\left|X_h - Y_j\right|)} \geq \delta. \tag{2}$$

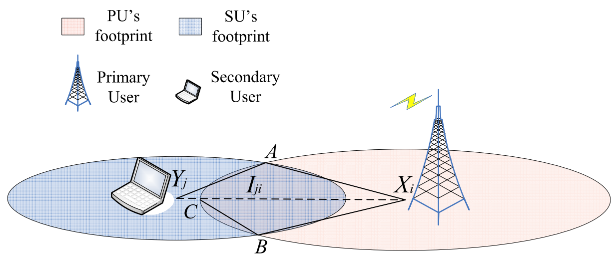


Fig. 2: An example of overlapping transmission between a primary receiver and a secondary user in the CRN, where I_{ji} is the interference area.

The description of the overlapping nodes among SUs and PUs is illustrated in Fig. 2. Since the PUs' behaviors are completely unpredictable, the context of the interference interactions involving the SUs are also influenced by behaviors of the PUs, because PUs have the right to access the spectrum bands at any time.

B. Interference Model

Denote that the transmission of every node X_k, which transmits simultaneously over the same sub-channel, is satisfied as

$$|X_k - X_j| \geq (1 + \Delta_{gp})\,|X_i - X_j|\,, \forall k \in X_i^p, \tag{3}$$

where Δ_{gp} is the guard zone for the primary network.

1) Interference between a Primary Receiver and a Secondary Interferer: In this sub-section, the interference constraints are initiated within the primary network in which are generated by the secondary interferer.

Suppose that two adjacent neighborhoods overlap, it comes out a common area that exists I_{ji}, as in Fig. 2. The first research of this case was initiated by Rabbachin *et al.* in [3]. The following formula describes the interference at the primary receiver, which is generated by the j^{th} secondary interferer,

$$\mathcal{I}_j^s = \sqrt{P_I^{s(j)}}\left|Y_j - X_i\right|^{-\alpha}\mathcal{F}_j^s, \tag{4}$$

where $P_I^{s(j)}$ is the interference power level at the j^{th} secondary interferer, $\left|Y_j - X_i\right|^{-\alpha}$ is the distance between the primary receiver and the j^{th} secondary interferer, α is the amplitude path loss exponent, and $\mathcal{F}_j^s$ is the per-dimension fading channel path gain from the j^{th} secondary interferer to the primary receiver. Furthermore, $\mathcal{F}_j^s = \Re\{H_i\}$, where H_i is the complex path gain of the channel from the j^{th} secondary interferer to the primary receiver, and $\mathcal{F}_j^s$ is independent and identically distributed (IID) with the common probability density function (PDF) $f_{\mathcal{F}}(.)$. Note that $I_{ji} = \mathcal{I}_j^s$.

Note that $\mathcal{I}_j^s = \mathcal{D}_{Y_j} \cap \mathcal{D}_{X_i}$, where $\mathcal{D}_{Y_j}$ and $\mathcal{D}_{X_i}$ is the disk of Y_j and X_i, respectively, A and B are two intersection points, and C is a cross point between the arc of ACB and the line X_iY_j. It is clear that $\angle X_iCB = \angle X_iCA \in \left[\frac{\pi}{3}, \frac{\pi}{2}\right)$. Thus, if such two points are coincident, $C \equiv Y_j$, the area of $\mathcal{I}_j^s$ is at least one third of the disk $\mathcal{D}_{Y_j}$.

2) Interference between a Primary Receiver and Multiple Secondary Interferers: In terms of active SUs, the full aggregate of the interference generated by all secondary users towards a primary receiver, which is also an interferer, in the area A is given as

$$\mathcal{I}_{fi}^{s}=\sqrt{P_{I}^{s(j)}}\sum_{i\in X_{i}^{p};j\in Y_{j}^{s}}\left|Y_{j}-X_{i}\right|^{-\alpha}\mathcal{F}_{j}^{s}. \tag{5}$$

Note that $\mathcal{G}_{fi}{=}\sum_{i\in X_{i}^{p};j\in Y_{j}^{s}}\left|Y_{j}-X_{i}\right|^{-\beta}\mathcal{F}_{j}^{s}$; then, the characteristic function (CF) of $\mathcal{G}_{fi}(jw,\ A)$ is formulated by using *Theorem 3.1* in [7], and it is described as follows

$$\Theta_{\mathcal{G}_{fi}^{s}}(jw,A)= \exp\left(-2\pi\lambda\int_{\mathcal{F}}\int_{\mathcal{D}_{min}}^{\mathcal{D}_{max}}\left(1-\exp\left(jwr^{-\alpha}\mathbf{y}\right)\right)\times f_{\mathcal{F}}\left(\mathbf{y}\right)d\mathbf{y}rdr\right), \tag{6}$$

where λ is the spatial density, $\alpha>1$, $\mathcal{D}_{min}$ and $\mathcal{D}_{max}$ are the min and max disks[1] of the primary receiver, $j=\sqrt{-1}$, and $f_{\mathcal{F}}(\mathbf{y})$ is the PDF of $\mathcal{F}_{j}^{s}$.

From Eq. (6), the m^{th} cumulant of the interference $\mathcal{G}_{fi}(jw,\ A)$ is given as below.

$$\begin{aligned}\mathcal{C}_{\mathcal{G}_{fi}}(m)&=\frac{1}{j^{m}}\left(\frac{d}{dw}\right)^{m}\ln\Theta_{\mathcal{G}_{fi}^{s}}(jw,A)\bigg|_{w=0}\\ &=2\pi\lambda\int_{\mathcal{F}}\int_{\mathcal{D}_{min}}^{\mathcal{D}_{max}}\mathbf{y}^{m}r^{(1-m\alpha)}f_{\mathcal{F}}(\mathbf{y})drd\mathbf{y}\\ &=\frac{2\pi\lambda}{m\alpha-2}\left(\mathcal{D}_{min}^{(2-m\alpha)}-\mathcal{D}_{max}^{(2-m\alpha)}\right)\times\mu_{\mathcal{F}}(m).\end{aligned} \tag{7}$$

Hence, the m^{th} cumulative of the full aggregate of the interference in the CR network $\mathcal{I}_{fi}^{s}$, as follows.

$$\mathcal{C}_{\mathcal{I}_{fi}^{s}}=\sqrt{P_{I}^{m}}\mathcal{C}_{\mathcal{G}_{fi}}(m). \tag{8}$$

From the fomulae abovementioned, transmission distances of the CR users are utilized to consider multiple overlapping transmissions in CRNs, and such overlaps in varying transmission distances will be utilized and be analyzed in the next Section.

III. Proposed algorithm

In this section, the proposed algorithm is described based on the percentage of interference approximation algorithm (PIA) to sort the feasible links with under 40% percentage of interference, and then minimizing such feasible links for establishing the flows routing. After computing the links with the percentages of interference, the PIA is processed to sort the infeasible links in which the percentages of interference are greater than[2] 40%. Then, the outcomes are minimized by the distance between adjacent nodes and the links with the lowest percentage of interference. Thereby, the optimal solutions are selected with fairness, and the flows routing to the network are obtained. The operation of the proposed algorithm is demonstrated as follows.

- **First step:** Since there are mutually overlaps in primary and secondary networks, the links are computed with the percentages of interference and through this step, the outcomes are achieved with various values of interference that are generated from the overlapping transmission ranges in the network.
- **Second step:** The outcomes obtained from the previous step are processed to be sorted through the PIA process. The links with percentages of interference that are greater than 40% will be sorted via the PIA process, and the outcomes after sorting are less than 40%.
- **Third step:** In order to ensure the routes with a low probability of packet loss, the selected routes should be achieved by using the minimum distance between adjacent nodes to minimize the fading propagation conditions. Therefore, this step is used to minimize the distances between nodes, and as a result, the probability of packet delivery between these nodes is more likely to be higher than between other nodes.
- **Fourth step:** After sorting the minimized distances of the links and the under 40%-interference outcomes, it is necessary to minimize these interfering links and distances to increase the probability of packets being received at CR receivers. This step is important because it considers the lowest interference possible during routing to eliminate the possibility of retransmissions, which can occur for sufficiently high percentages of interference. After solving the problem in this step, routing flows can be established to the network.

IV. Simulation Performance

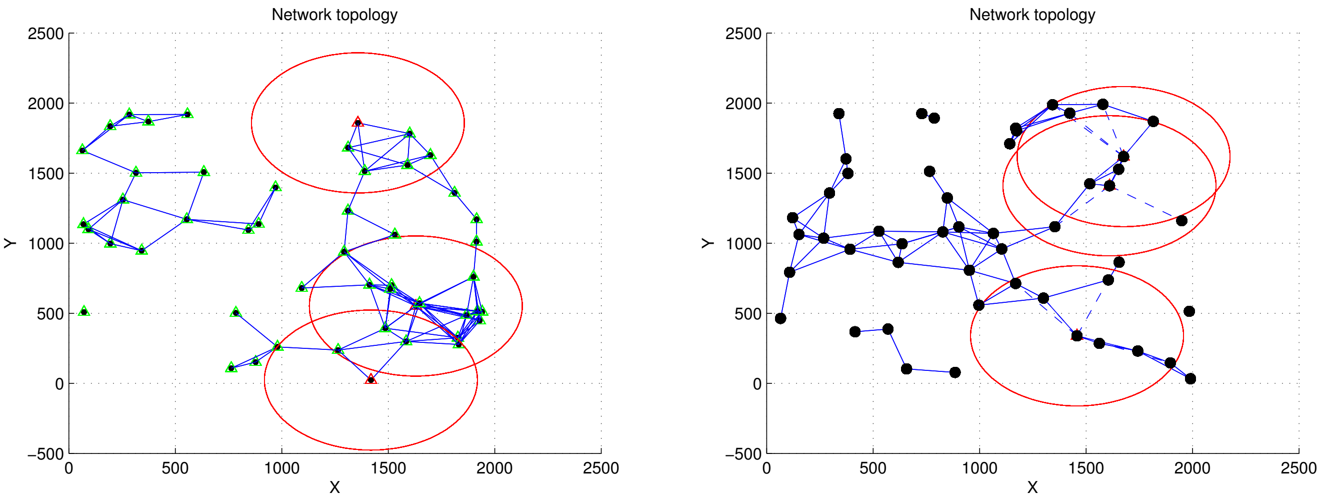
A. The Proposed Algorithm in the Network Topology

In this sub-section, the simulation results are achieved by using MATLAB. The network scenario is represented with 50 CR nodes that are deployed, including 3 PUs and 47 SUs with a size of 2000×2000 m^2. As can be shown in Fig. 3a, routing performance does not consider overlapping transmissions with respect to each other and as well as the primary network. Therefore, the operation directly affects routing performance in terms of average throughput, end-to-end (ETE) delay, and packet delivery ratio (PDR).

In addition, in Fig. 3b, the effect of the proposed algorithm results in the avoidable ability in higher percentages of interference by sorting the percentages of interference, which are over 40%, to determine its routes. Moreover, this helps reducing the probabilities of both packet losses and retransmissions.

[1]The min/max disks are defined as the min/max radii of the primary receiver, respectively.

[2]Note that 40% is a relative percentage that is based on the interference level when the area of $\mathcal{I}_{j}^{s}$ is at least one third of the disk $\mathcal{D}_{Y_j}$ in the case of $C\equiv Y_j$ in Fig. 2, as discussed in sub-section II-B1.



(a) A random network topology without the proposed algorithm.

(b) A random network topology with the proposed algorithm.

Fig. 3: Simulation results of (a) without the proposed algorithm and (b) with the proposed algorithm in the network topology of 2000×2000 m^2 with 50 CR nodes deployed randomly in terms of different behaviors of primary services.

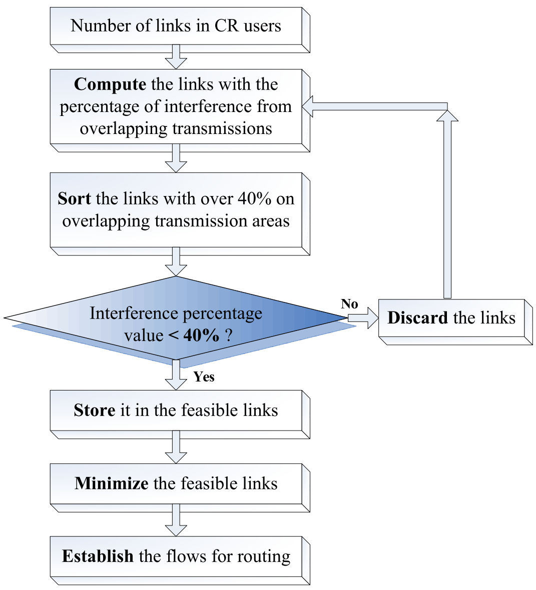


Fig. 4: Flowchart of the proposed algorithm.

The proposed algorithm is therefore applicable for improving the routing performance in CRNs.

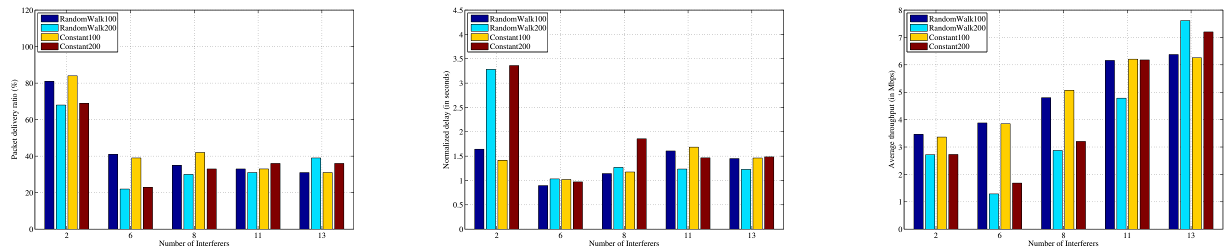
B. Network Performance Setting

In this sub-section, the network performance is simulated by using Network Simulator (NS-3) [16]. The network topology is deployed with a size of 2000 × 2000 m^2 to investigate how the uncertain behavior of primary services has an impact on the secondary network in terms of multiple overlapping transmissions for 13 PUs and 37 SUs. In terms of the footprints of the CRs, the coverage of the PUs is 500 m, and the coverage of the SUs is 350 m. These transmission ranges are calculated by using the Friis transmission range formula [17]. The IEEE 802.11b standard for the 2.47-Hz frequency band is implemented for simplicity with a path loss exponent (α) of 3. In simulation results, 50 nodes are deployed using the random-walk-mobility and constant-mobility models with distances of 100 m and 200 m between the nodes, respectively. Constant speed propagation delay model and Friis propagation loss model are used for the network performance setting.

C. Results and Analysis

Simulation results are obtained in the following figures that show the interference for the case of multiple overlapping transmissions in terms of PDR, ETE delay, and the average throughput versus the number of interferers. Fig. 5a illustrates the PDR versus the number of interferers with 50 nodes deployed in the network. Note that the legends in the figures that indicate RandomWalk100, RandomWalk200, Constant100, Constant200, are the random-walk-mobility and constant-mobility models at distances of 100 m and 200 m between nodes. When the number of interferers is 2, the PDR is up to over 80% for the random-walk-mobility and constant-mobility models at a distance of 100 m between nodes. This ratio is nearly 70% at a distance 200 m between nodes, and the PDR for the random-walk-mobility model dropped lower to approximately 10% owing to the lower probability of a packet being received. This ratio significantly goes down to around 40% when the number of interferers went up to 6, 8, 11, and 13, continuously. The increase occurred because the footprint of the interferers overlapped with the SUs, and thus, this interference resulted in high packet loss in the secondary network.

As far as the delay is concerned, Fig. 5b shows that the ETE delay vacillates for a small number of nodes from 10 to



(a) PDR vs Interferers. (b) ETE delay vs Interferers. (c) Avg. throughput vs Interferers.

Fig. 5: The different number of interferers in terms of PDR, ETE delay, and average throughput, respectively.

40 and it indicates that the number of nodes has a significant influence on relaying hops for routing performance. Hence, when the number of interference coverage areas increase, the probability of retransmissions is high, and therefore, SUs need to discover alternative routes for successful transmissions. It is apparent that this results in higher routing costs. Nevertheless, for a low number of nodes, it is hardly to seek alternative routes for routing, and thus, the ETE delay also generates a high cost. The delay saturates at 50 nodes even when the impact of multiple overlapping transmissions between nodes is changed from 100 m to 200 m, especially for the random-walk-mobility model at a distance of 200 m.

Fig. 5c shows that the random-walk-mobility nodes at the larger transmission distances have a good throughput for a higher number of nodes, even when the number of interferers were at 13 nodes, as compared with the other types of models, due to the probability of packet loss over the communication channel is low, as the alternative routes are available for routing performance with relatively low costs. As a result, the average throughput increased mostly 40% from 10 to 50 nodes as demonstrated in Fig. 5c.

V. Conclusion

In this research, the effectiveness of the proposed algorithm is shown through the interference awareness on routing performance in CRNs. In addition, different guard transmission distances have also been demonstrated to validate the influence of this algorithm on routing performance between CR nodes in terms of different costs to performance parameters, consisting of throughput, ETE delay, and PDR.

In our future work, an investigation into the complex circumstances for CRNs may be taken into account in terms of the impact of overlapping interference in 3D geographic routing aspect.

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