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PERFORMANCE ENHANCEMENT IN MULTI HOP COGNITIVE RADIO WIRELESS MESH NETWORKS

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Abstract. *Cognitive Radio technology is an emerging technology which enables the temporary use of the unused licensed spectrum without interfering with the transmissions of other users, thereby improving spectrum utilization. The spectrum is dynamically reused by the alteration of its power, frequency, modulation, and other operating parameters after sensing its radio frequency environment. Since cognitive radio is envisaged to solve the problem of scarcity of the spectrum by making use of a large under-utilized spectrum, it can be applied in wireless mesh networks' paradigm for a larger network capacity with high-quality services for the end user. Interference is a critical issue in cognitive radio wireless mesh networks (CR WMNs) performance. In this work, first an analytical model was developed for link scheduling in CR WMNs considering scheduling constraints. Then a novel scheduling algorithm was proposed and implemented to minimize interference in CR WMNs. Simulation results show effectiveness of our proposed algorithm as the results are very close to the near optimum solution.*
Keywords: CR-WMN, IEEE 802.22, Scheduling, Cognitive capability

1. **Introduction.** The radio spectrum resources usage is controlled by national regulatory bodies such as the Federal Communication Commission (FCC). The FCC assigns radio spectrum to licensed holders also known as primary users on a long-term basis over vast geographical regions. There are portion of the assigned spectrums which are congested so much that there is interference while, on the other hand, large portions of the allocated spectrum are sporadically used, as shown in Figure 1.

Due to the inefficient usage of a spectrum, there exists a scarcity of the spectrum which has given rise to the development of dynamic spectrum access (DSA) techniques. FCC has recently approved the use of unlicensed users, also called as Secondary Users to use the unutilized licensed band temporarily. Cognitive radio is the technology that enables DSA networks to make use of the radio spectrum efficiently without disturbing the transmission of primary users.

The IEEE 802.22 standard for wireless regional area network standard has recently been finalized. It is the first standard for cognitive radio that attempts to utilize the idle or under-utilized spectrum allocated for TV bands. There are many frequency bands between 54 MHz and 862 MHz, which are licensed to operators but are sporadically used. IEEE 802.22 systems will provide broadband access to wide regional areas around the world and bring reliable and secure high-speed communications to under-served and un-served communities.

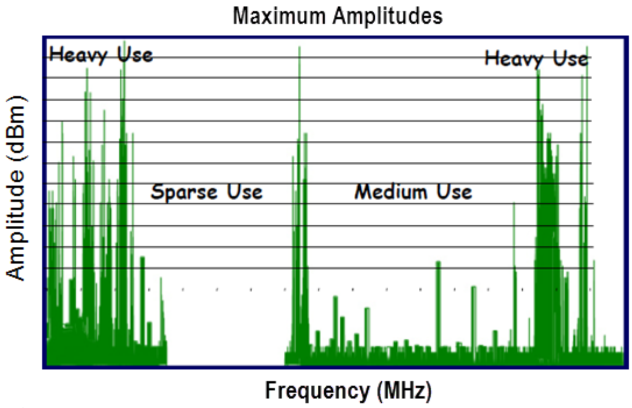

FIGURE 1. Spectrum usage [4]

This new standard for Wireless Regional Area Networks (WRANs) takes advantage of the favorable transmission characteristics of the VHF and UHF TV bands to provide broadband wireless access over a large area up to 100 km from the transmitter. Each WRAN will deliver up to 22 Mbps per channel without interfering with the reception of existing TV broadcast stations, using the so-called white spaces between the occupied TV channels. This technology is especially useful for serving fewer densely populated areas, such as rural areas, and developing countries where most vacant TV channels can be found. IEEE 802.22 incorporates advanced cognitive radio capabilities, including dynamic spectrum access, incumbent database access, accurate geolocation techniques, spectrum sensing, regulatory domain dependent policies, spectrum etiquette and coexistence for optimal use of the available spectrum.

The Cognitive radio (CR) term was first coined by Mitola and Maguire in 1999 [1]. A cognitive radio is defined as a radio that can change its transmitter parameters based on interaction with the environment in which it operates [2]. It is a promising approach to utilize TV spectrum in an efficient and opportunistic way [3]. It differs from conventional radio devices that it has cognitive capability and reconfigurability [3,4]. Cognitive capability is the capability of the radio technology to sense and gather information from the surrounding environment. The information it tries to sense can be about transmission frequency, bandwidth, power, modulation, etc. Based on these sensed information the best spectrum is chosen by the secondary users. Reconfigurability quality is the ability that how rapidly the operational parameters adapt to the sensed information for achieving optimum performance. So by exploring the spectrum in an opportunistic manner, the cognitive radio allows secondary users to use the unused spectrum, choose the best available channel, coordinate spectrum access with other secondary users and jump to another channel on the arrival of primary user. If the secondary users are allowed transmissions along with the primary users (overlay cognitive model) secondary users should not cross the interference temperature threshold [5].

We can say that the ultimate goal of the cognitive radio is to achieve the best spectrum through cognitive capability and reconfigurability, as defined above. Through CR, the unused spectrum is accessed temporarily, which is called white space or spectrum hole [4], as shown in Figure 2.

The remainder of this paper is organized as follows. In Section 2, the research related to this work has been presented. Section 3 describes the network model to be considered for classic WMN, extending it to incorporate CR capabilities. In Section 4, we describe the scheduling constraints and our proposed optimizing scheduling algorithm. Section 5

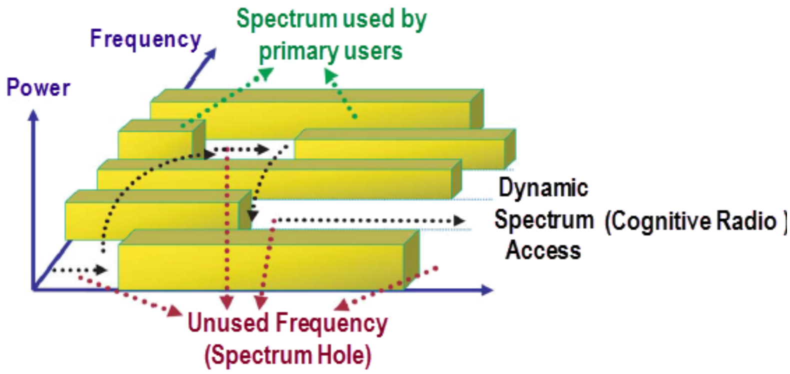

FIGURE 2. Spectrum holes in cognitive radio [4]

presents simulation results. Finally, Section 6 concludes this paper and discusses future work.

2. **Related Work.** There has been an extensive research activity going on in the CR technology in the field of spectrum sharing. However, not much research has been done in CR WMN. In a recent study, it was analyzed that capacity increased when the nodes of WMN were given CR capability by using the two way switched models [6]. Researchers have also suggested the use of cognitive radio as a means of increasing throughput [7,8]. In [9], the authors proposed a new scheme called Cognitive Mesh Network (COMNET). This scheme was used for channel assignment between the users and their respective mesh gateways and used for spectrum sensing for identifying the primary users' frequency. Furthermore, a mathematical model was proposed by them for estimation of power received by the cognitive users in that particular channel.

In [10], impact of the licensed channels on CR WMNs network performance was studied by developing an analytical model, and the impact of the number of licensed channels and channel utilization on the network performance was evaluated. The performance was evaluated by considering a two hop neighbor as an interfering node without link scheduling.

Chen et al. [11] studied CR WMNs in the context of topology management where the network was distributed. They termed a group of neighbor nodes existing in the networks who shared a common channel as a cluster (sub-network). Each cluster had a cluster head which coordinated between different clusters. The network was formed by interconnecting clusters after the neighbor discovery process. They had proposed a distributed management algorithm and studied its performance under various channel conditions. It was a DSA problem but lacked the elaboration of assigning common control channel for the clustered mesh nodes. In [12] authors proposed a mathematical model to minimize the required system resources in context of multiple layers. The algorithm proposed by them was based on sequential fixing where the integer variables were determined iteratively. The objective was to minimize the required spectrum for CR WMNs, the main focus being on spectrum sensing. A cross layer multi-channel MAC protocol [13] was proposed, which utilized the unused frequency in such a way that interference to the primary users is constrained by suggesting that each cognitive user, to use two trans receivers. One was tuned to the dedicated control channel while the other worked in an opportunistic way to sense unused channels. Siraj and Shebeilli [14] proposed a cross layer multi-channel MAC protocol for route discovery. It had the ability of switching the channels opportunistically according to the channel availability. Its performance was evaluated in terms of an end to end delay, packet delivery ratio and throughput. In [15], the authors demonstrated how the WMN performance could be enhanced using CR technology. Performance was studied using metrics like probability of acceptation of flows and spectrum reuse. Performance comparison was done between classic, virtual private networks and CR-enabled networks. It was seen that utilizing CR technology in WMNs improves QoS and fewer channel resources are used. The drawback with their demonstration was that the model used by the authors was not a generalized model. Siraj and Bakar [16] demonstrated the impact of interference on Multi-hop Wireless Mesh Network. They showed how the performance is degraded due to interference. In [17], an algorithm was proposed, which was based on the interference temperature model. This algorithm main work was just to do channel (homogenous) selection for the mesh nodes. In [18], an algorithm to cancel inter-channel interference, to control channel allocation by minimizing false alarm and missed detection in spectrum sensing was proposed. In this algorithm, the multiple control channels were used for the transmission of the sensed data from the cognitive users to the access points. This algorithm also focused on inter channel interference cancellation technique only. In most of the above mentioned research, CR performance evaluation was not done and the major thrust was on spectrum sensing and interference cancellation techniques. Some work which was on performance evaluation of CR did not effectively made use of channel assignment. Our scheduling approach is more realistic in comparison to the above approaches, as we consider all scheduling constraints including inter channel interference for problem formulation to segregate interfering and non-interfering links before applying our proposed algorithm to minimize interference in CR WMNs by optimizing the network flows.

3. **Network Model.** We represent a Wireless mesh network with n nodes distributed arbitrarily by a directed graph. $G = (V, E)$, where V is the set of vertices representing nodes of WMN. E is the set of directional edges, which represent radio links between nodes. d_{ij} is the distance between nodes j and k, and each node of the WMN is equipped with radio, which has r_t as the transmission range r_i as the interference range and $r_i > r_t$.

There exists a link $\{i, j\}$ between node i and j provided $d_{ij} \leq r_{ij}$ and $i \neq j$.

Thus, the link between two neighbor nodes i and j of WMN is represented by the directed edge $\{I, j\} \in E$.

For the above directed graph $G(V, E)$, a connectivity matrix T can be constructed based on the vertices V depending on the connectivity between links. In the connectivity matrix presence of 1 indicates directly connected and presence of 0 not connected.

A node i can successfully transmit to node j if the following two conditions are met.

a)

$$d_{ij} \leq r_t \tag{1}$$

b)

$$d_{kj} \leq r_{ik} \text{ where } n_k \text{ is the neighbor node.} \tag{2}$$

Figure 3 shows presence of six nodes in WMN. Node 2 is transmitting. If node 4 wants to transmit it cannot transmit because of the above constraint as node 4 is in the interference range of node 3. In this condition node 1, 2, 4 cannot transmit whereas node 5 and 6 can transmit. It is seen that node 4 is not able to connect but causes interference.

Based on the above approach an Interference graph G_i can be constructed. An interference graph can be represented by $G_i = (Vi, Ei)$. The vertex set is identical to the directed graph G representing nodes of WMN. There exists a directed edge from node j to node k if

a) a signal from node j is strong enough to disturb node k but

b) it cannot be decoded correctly by k.

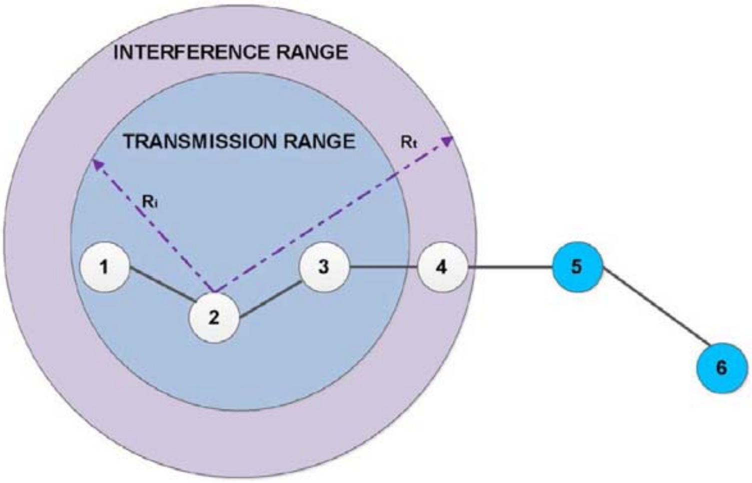

Figure 3. Nodes constraint diagram

Table 1. Interference set

	L12	L21	L23	L32	L13	L31	L34	L43	L45	L54	L46	L64	L56	L65
L12	1	1	1	1	1	1	0	1	0	0	0	0	0	0
L21	1	1	1	1	1	1	0	1	0	0	0	0	0	0
L23	1	1	1	1	1	1	0	1	0	0	0	0	0	0
L32	1	1	1	1	1	1	1	1	0	1	0	1	0	0
L13	1	1	1	1	1	1	1	1	0	0	0	0	0	0
L31	1	1	1	1	1	1	1	1	0	1	0	1	0	0
L34	1	1	1	1	1	1	1	1	1	1	1	1	0	0
L43	0	0	1	1	1	1	1	1	1	1	1	1	1	1
L45	0	0	1	0	1	0	1	1	1	1	1	1	1	1
L54	0	0	0	0	0	0	1	1	1	1	1	1	1	1
L46	0	0	1	0	1	0	1	1	1	1	1	1	1	1
L64	0	0	0	0	0	0	1	1	1	1	1	1	1	1
L56	0	0	0	0	0	0	1	0	1	1	1	1	1	1
L65	0	0	0	0	0	0	1	0	1	1	1	1	1	1

Here, 1 indicates interference and 0 indicates no interference.

So if there are two communication links $\{j, k\}$ and $\{l, m\}$, and if they are not able to transmit, it indicates that there exists an edge between them. So an edge for the interference graph G_i can be drawn between $\{j, k\}$ and $\{l, m\}$ based on the following conditions, i.e., $d_{jm} \leq r_j$ or $d_{lk} \leq r_l$. With the help of interference graph, G_i and vertex set Ei, an interference vector can be defined between any given link say link $\{i, j\}$ and all the links in E. If $\{k, l\} \neq \{i, j\}$ and there is a link between link $\{i, j\}$ and link $\{k, l\}$ then $I\ \{i, j\}, \{k, l\} = 1$ otherwise it is 0. Similarly interference vector for all the links can be computed and an interference constraint matrix $|E| \times |E|$ can be constructed.

The interference set of each link can be constructed as shown in Table 1, i.e., n_k does not transmit where n_i is transmitting. This constraint is shown by Figure 3. Suppose node i wants to transfer to node j on channel q of spectrum band p, the nodes i and j should neither transmit nor receive data on channel q. Further node i should not be in the vicinity of the interference range of node k on channel q and spectrum band p. During this time not only the nodes in the interference range should not transmit but also the hidden nodes nearby i should also be silent.

The status of channel q of spectrum band p can be defined by Equation (3)

$$C_{ij}^{(p,q)} = \left\{ \begin{array}{c} 1 \\ 0 \end{array} \right\} \tag{3}$$

If there is a transmission from node i to node j, it is 1 otherwise 0, where $C_{ij}\,(p,q)$ is the status of the channel q. Therefore,

$$C_{ij}^{(p,q)} \leq T_{ij} \tag{4}$$

where T_{ij} is the connectivity matrix for node i and node j. From Equations (1) and (2), it is very clear node i cannot transfer to its one hop neighbor j on channel p of the spectrum band q because of the presence of node k close to the interference range of node i ($j \neq i$). This can be written as

$$C_{ij}^{(p,q)} + \sum_{l \in V} I_{(k,i)} T(k,l) C_{ij}^{(p,q)} \leq 1 \tag{5}$$

Equation (5) shows the Interference Constraint.

3.1. **The cognitive scenario.** Figure 4 below shows a conceptual model of cognitive wireless mesh network. Cognitive WMNs are self-organizing, self-healing and self-forming. Mesh routers and mesh clients are the elements of WMNs, as shown in Figure 3. The mesh nodes maintain connectivity with the other nodes of the network automatically. The network is reliable because of the mesh structure through which multiple paths are feasible to each of the mesh nodes. The coverage area can be increased by addition of more routers and clients. Though the network coverage is increased, throughput at each node decreases with the increase in node density. By incorporating CR functionality in WMN, an enhancement in the network performance is seen.

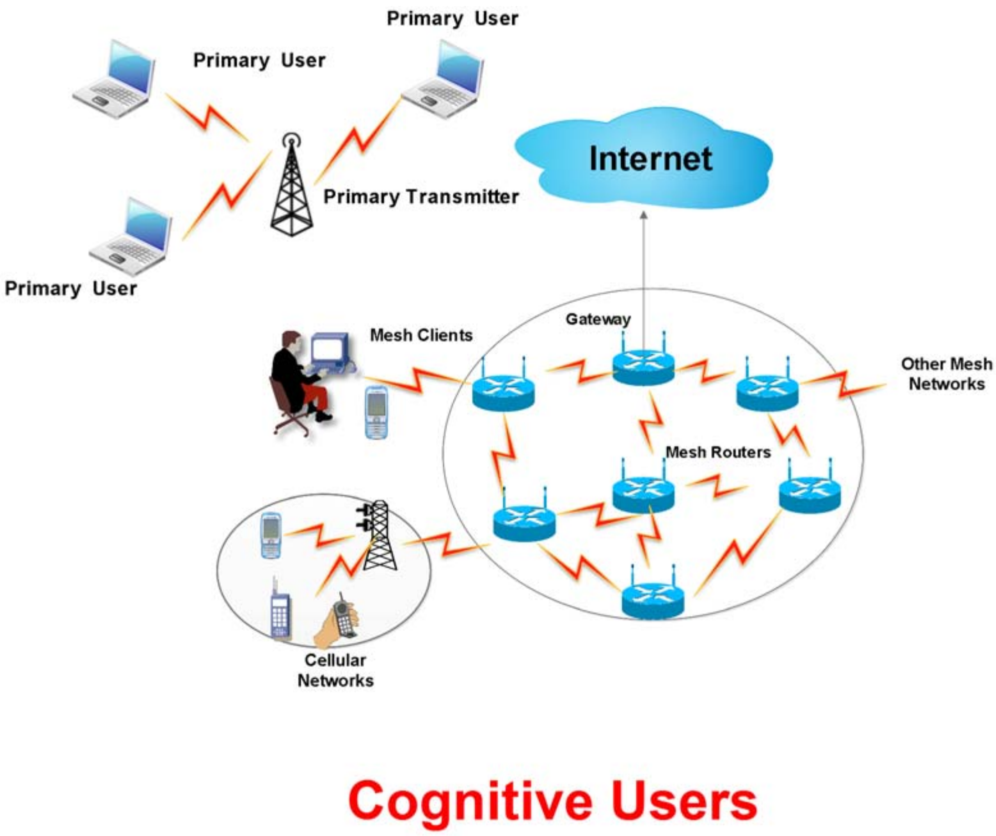

FIGURE 4. A conceptual model of cognitive wireless mesh networks

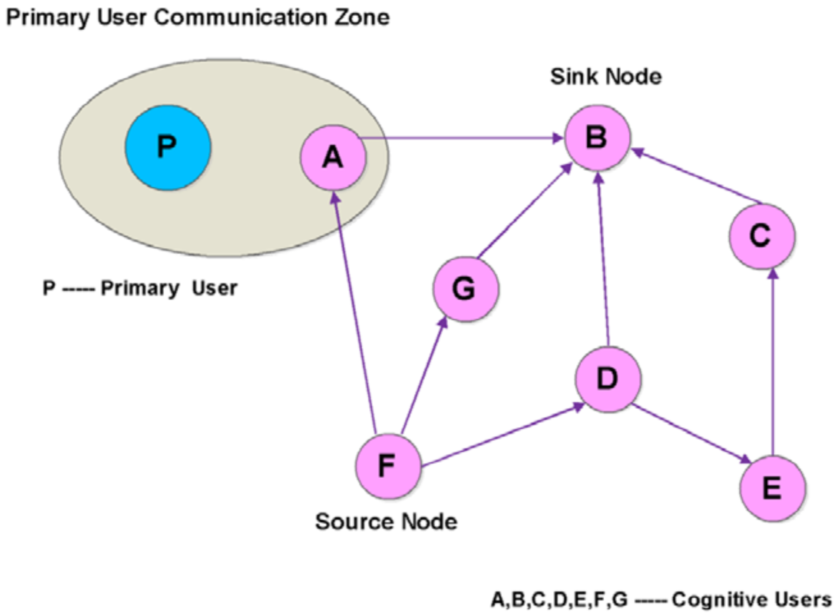

FIGURE 5. Interference model of cognitive wireless mesh networks

3.2. **Interference model.** For optimum routing in CR-WMNs, cognitive users should cause minimal interference to the primary users. When the cognitive users are few, they may be in the bare interference threshold range but as the number of CU increases, the total interference is more than the allowed threshold. To see the bounds of interference, we use the interference temperature model here [5]. We have used this model to enumerate and control interference. This is identical to that of noise temperature. The model is

$$T_i\left(f_c, B\right) = \frac{Pi(f_c, B)}{kB} \tag{6}$$

where $Pi(f_c, B)$ is the average interference power in watts centered f_c, at covering bandwidth B measured in Hertz. Boltzmann's Constant k is 1.38×10^{-23} Joules per kelvin degree.

To illustrate this model let us consider Figure 5. Nodes A, B, C, D, E and F are the cognitive users. Node P is the primary user. As the node A is in the vicinity of node P communication range, the temperature level of A will be higher than the rest of the nodes. So utmost care should be taken to avoid interference to primary users. In CR-WMN the total temperature from the cognitive users should be accounted. The routing among cognitive users should be such that the cognitive nodes falling in the primary user communication range should be avoided due to the high temperature. If node F wants to communicate with node B, they can communicate, either through G, which is the shortest path or through D, which is a longer path. To avoid interference to the primary user it is suggested to take the path F $\rightarrow$ D $\rightarrow$ B because the cumulative temperature level of F $\rightarrow$ G $\rightarrow$ B will be more and may cause interference to P.

4. **Scheduling Constraint.** Link scheduling can be applied to the cognitive mesh networks in either of the two ways, i.e., in time domain or frequency domain. In this paper, we consider time domain. Scheduling is successful only, when it does not cause interference to the cognitive user who is transmitting or to the nearby cognitive users present.

Let us imagine that frequency band p is available for cognitive user i and j, i.e., $p \in P_i \cap P_j$. This relation can be seen from Equation (1).

Let $P_i \subseteq P$ be the set of available bands (spectrum hole or whitespace) at node $i \in N$. This may or may not be the same for another node, say $j \in N$ where N is total number of cognitive user nodes present.

We can say that $P_i = P_j$ when P_i and P_j consist of the same bands.

Or $P_i \neq P_j$ when P_i and P_j consist of different bands.

For a node $i \in N$ and a band $p \in P_i$. Let T_i^p represent the set of mesh nodes that use band p and are within the transmission range of node i.

$$T_i^p = \{j : d_{ij} \leq r_t, j \neq i, p \in P_j\} \tag{7}$$

As the mesh node i cannot transmit to multiple mesh nodes on the same frequency band due to the interference constraint (Equation (5)), therefore,

$$\sum_{k \in T_i^p} C_{ik}^{(p,q)} \leq 1 \tag{8}$$

Furthermore, the mesh node i cannot use the same frequency band for reception and transmission as it will lead to self-interference. That is if $C_{ij}^{(p,q)} = 1$, then for $k \in T_i^p$, $C_{jk}^{(p,q)}$ should be 0.

We can write the above statement

$$C_{ij}^{(p,q)} + \sum_{k \in T_j^p} C_{jk}^{(p,q)} \leq 1 \tag{9}$$

In Equation (9), j is the node to which i is transmitting. If $C_{ij}^{(p,q)} = 1$, then

$$\sum_{k \in T_j^p} C_{jk}^{(p,q)} = 0$$

In other words, we can say that node j cannot use the frequency band (p, q) for transmission. On the other hand, if $C_{ij}^{(p,q)} = 0$, then $\sum_{k \in T_j^p} C_{jk}^{(p,q)} \leq 1$, i.e., node j may use the frequency band (p, q) for transmission, but is restricted for one-time use for node $k \in T_j^p$, the same as Equation (8).

Besides the above discussed interference constraints, scheduling constraint should also be taken care of. Under this category of interference, hidden node problem is a special case.

To realize the scheduling constraint, let the set of mesh nodes producing this constraint at mesh node j be represented by

$$S_j^p = \{u : d_{uj} \leq u \neq j, T_u^p \neq 0\} \tag{10}$$

In the above equation, $T_u P \neq 0$ implies that the mesh node u can use the frequency band p to transmit in T_u^p.

Then,

$$C_{ij}^{(p,q)} + \sum_{k \in T_u^p} C_{jk}^{(p,q)} \leq 1 \ \ (u \in S_j^p, u \neq i) \tag{11}$$

In Equation (11) if $C_{ij}^{(p,q)} = 1$, i.e., mesh node i uses the frequency band (p, q) to transmit to mesh node j, then any mesh node u should not transmit on this band $\sum_{k \in T_u^p} C_{jk}^{(p,q)} = 0$.

So any communication to mesh node j can only be through the channel p provided time slots are available.

The problem formulation discussed above will be solved by a standard linear programming (SLP) considering the constraints. The solution obtained by SLP will yield optimized network flows.

This time sharing can be seen in context of Figure 3. Suppose mesh node 2 is transmitting to mesh node 3 on channel p. Those nodes that can produce interference cannot make use of the same channel. In this case if mesh node 4 wants to transmit to mesh node 5 on channel p it cannot transmit as it will cause interference to node 4. This is accomplishable as per our proposed algorithm where it is realizable for the mesh nodes to transmit in different time slots without causing interference to each other. If the mesh nodes have CR capability, they will be in a position to manage the spectrum effectively and time scheduling. Thus, they are able to do cross layer optimization (between Network and MAC Layer) resulting in performance enhancement. Extending this scheme to CR WMNs will result in transmission of more mesh nodes at the same time using the same channel thereby minimizing interference. The network flow between the mesh nodes will be optimized using the optimized time scheduling algorithm below.

Table 2. Optimized scheduling algorithm

```
Let p be the set of all channels under q spectrum band and L be the set of links between
mesh nodes.
For all the links (1 : L) and for all the network flows
If the links are in the interference range
Assign Interfering links C_jk^(p,q) = 0
Else
    C_jk^(p,q) = 1
end if
```

After the implementation of the above algorithm, we have the complete information of interfering and non-interfering links. We can schedule interfering links in the different time slots in the same channel. Thus both the network flows and time scheduling will be optimized.

5. **Simulation Scenario and Results.** In this section we discuss the simulation scenario and results. We consider maximum number of cognitive users as 30 spread in a 500×500 area. The data rate was taken as 54 Mbps and the maximum transmission range r_t is 90 m and the maximum interference range r_i is 160 m. Random topology was selected. Each mesh node had the capability of acting as a gateway node. Number of channels was 8. 100 data sets were generated randomly for the simulation. The time slots, availability of frequency channels for the mesh nodes and link pair were randomly generated. In the simulation number of primary users was fixed and interference was observed when the number of cognitive users was varied. We had considered two scenarios. In the first scenario effect of interference to the primary users was not considered during application of the proposed optimized algorithm. In the second scenario interference to the primary users was considered during the application of the proposed optimized algorithm. From Figure 6 it is observed that with an increase in number of mesh nodes, interference increases in CR WMN's due to the bandwidth limitation and congestion as number of hops is increased. This results in performance degradation. However, with the application of our proposed optimized algorithm interference is minimized and remains at the optimum level. The interference value ranges from 0.3 to 0.6 which shows that our proposed algorithm performs well and is able to mitigate interference in CR WMNs.

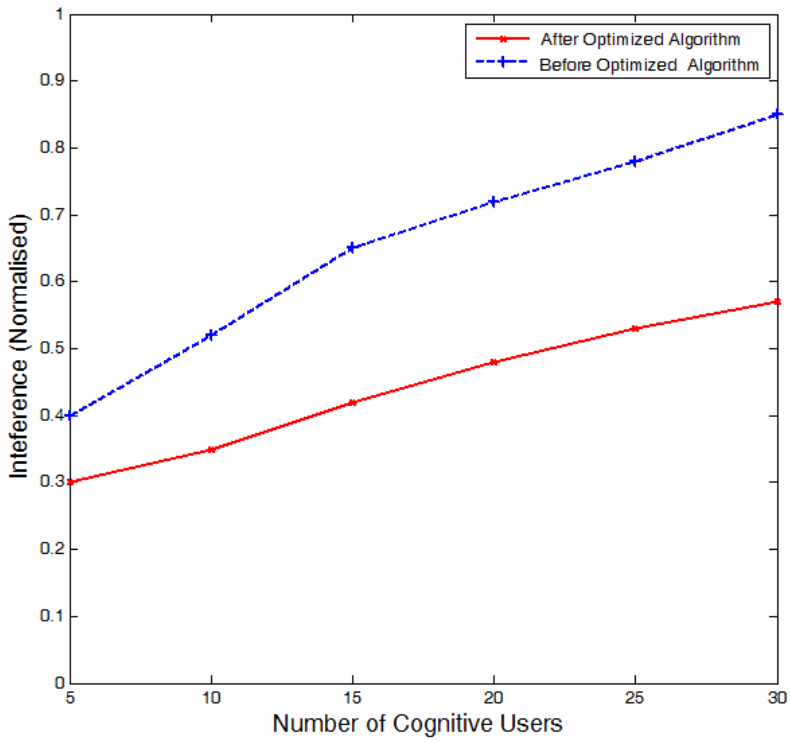

FIGURE 6. Normalized interference vs. cognitive users

6. **Conclusion and Future Work.** Interference is a critical factor hampering the performance of wireless mesh networks. In this paper, we have made an attempt to extend CR capability to multi hop mesh nodes to address this issue. An algorithm to optimize network flow and time scheduling for minimizing interference is proposed. Interference, scheduling and spectrum constraints were modeled considering cross layer approach. Simulation results indicate that the results obtained by the proposed algorithm are very close to the optimum value. This approach is suitable for medium size mesh networks. In the future we will investigate the performance of our algorithm for large mesh networks.

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