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14. ABSTRACT
This research studies the current IEEE 802.22 system architecture and investigates the limitations in creating wireless back-haul mesh networks due to its lack of knowledge about the spectrum bands to be used. In this regard, a coordinated distributed scheme for IEEE 802.22 enabled devices to is proposed establish a mesh network with reduced interference. The coordination is initiated by the base station and is followed by the iterative joining of the IEEE 802.22 consumer premise equipment to the mesh network in a distributed manner. A graph coloring approach is taken, and an algorithm called Maximum Utility Graph Coloring (MUGC) is proposed to allocate spectrum to the mesh network, enabling higher spectrum utilization and reduced collisions. Two objective functions are explored: maximize utility and proportional fair utility to allocate spectrum efficiently.

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ABSTRACT

Since static spectrum allocation has proved to be ineffective in maximizing spectrum utilization over time and space, *dynamic spectrum access* is clearly the best alternative for efficient usage of radio spectrum. In order to take advantage of the flexibilities presented by dynamic spectrum access, the newly proposed IEEE 802.22 standard based on cognitive radio is seen as one of the solutions that can harness the unused or under-utilized spectrum. Also, the recent success of wireless mesh networks is creating the possibility of availing wide-area wireless back-haul networks without the infrastructure cost that will have increased network resource utilization and greater performance characteristics at low cost.

In this research, we study the current IEEE 802.22 system architecture and investigate the limitations in creating wireless back-haul mesh networks due to its lack of knowledge about the spectrum bands to be used. In this regard, we propose a coordinated distributed scheme for IEEE 802.22 enabled devices to establish a mesh network with reduced interference. The coordination is initiated by the base station and is followed by the iterative joining of the IEEE 802.22 consumer premise equipments to the mesh network in a distributed manner. We take a graph coloring approach and propose an algorithm called *Maximum Utility Graph Coloring* (MUGC) that allocates spectrum to the mesh network, enabling higher spectrum utilization and reduced collisions. We explore two objective functions: maximize utility and proportional fair utility to allocate spectrum efficiently. Through extensive simulation experiments, we demonstrate how the proposed algorithm helps reduce collisions and most importantly, increase spectrum utilization among IEEE 802.22 devices.

1. Introduction

There have been conclusive experimental evidence that spectrum utilization is typically time and space dependent [9]. Thus, it is intuitive that static spectrum allocation may not be the optimal solution towards efficient spectrum sharing and usage. In static spectrum allocation, large parts of the radio band are allocated to the military, government, private, and public safety systems. However, the utilization of these bands is significantly low. Often times, the usage of spectrum in certain networks is lower than anticipated, while there might be a crisis in others if the demands of their users exceed the network capacity. Though it might be argued that the implementation and administration is very easy, the fact remains that the current allocation policy is ineffective and the penalty trickles down as an increased cost to the end user.

The problem of static spectrum allocation worsens due to the modification of old technologies. For example, in case of VHF, UHF bands reserved for television broadcast in the United States, allocation of 6 MHz per TV channel was based on old analog NTSC system even though better quality video can be now broadcast with almost 50% less spectrum per channel [1]. Given the pervasive penetration of cable–TV, this precious spectrum, though allocated and owned for TV transmissions, remains unused in most locations.

In order to break away from the constraints imposed by static allocation, FCC recently defined provisions to open the sub–900 MHz TV bands for unlicensed services also. Though it is mandated for the unlicensed devices to detect and avoid interference with the licensed users (primary incumbents) in a timely manner [8]. The newly proposed IEEE 802.22 standard, commonly known as wireless regional area network (WRAN), based on cognitive radios (CRs) is targeted to provide a solution to this problem [7]. The aim of IEEE 802.22 is to use spectrum bands dynamically through incumbent sensing and avoidance. For this reason, much of the standard of the IEEE 802.22 is dependent on cognitive radio. The basic operating principle relies on the cognitive radio being able to sense whether a particular band is being used and, if not, utilize the spectrum without interfering with the transmission of other users (primary incumbents). Cognitive radios can be viewed as an electromagnetic spectrum detector, which can find an unoccupied band and adapt the carrier to that band. The layer functionalities of cognitive radios can be separated into physical and medium access control layers. The physical layer includes sensing (scanning the frequency spectrum and process wideband signal), cognition (detecting the signal through energy detector), and adaptation (optimizing the frequency spectrum usage such as power, band and modulation). The medium access layer cooperates with the sensing measurement and coordinates in allocating spectrum. Cognitive radio systems continuously perform spectrum sensing, dynamically identify unused spectrum, and operate in the spectrum band when it is not used by the primary incumbent radio systems. Upon detecting incumbents, cognitive radio enabled devices are required to switch to another channel or mode.

The primary entities in the cognitive radio based IEEE 802.22 system are the base stations (BSs) and the Consumer Premise Equipments (CPEs) [2]. BS controls the on-air activity in the cell, including admission control, access to the medium by CPEs, allocations to achieve quality of service (QoS), and network security mechanisms. The IEEE 802.22 system can operate in two modes: point–to–multipoint and point–to–point (mesh). In the point–to–multipoint mode, transmission is directed from the BS to the CPEs or vice-versa. All the transmissions are centrally coordinated by the BS, and thus, the BS might become a bottleneck. Moreover, in the case of hidden incumbent problem [6], primary incumbent detection might be difficult leading to high detection time, or worse, no detection at all. In such scenarios, the interference level for the primary incumbents from the IEEE 802.22 device might exceed the allowed thresholds [8]. Therefore, instead of providing a centralized access through the BS, the alternative of point–to–point (mesh) architecture can be used. In the mesh mode, communications can be established among the CPEs directly. This will not only increase the wireless coverage, but will also lower the backhaul deployment cost.

However, unlike other wireless mesh networks (IEEE 802.11 or 802.16), one major problem in IEEE 802.22 is the allocation of spectrum band. In IEEE 802.22, there is no pre-defined channel for the BS or CPEs to establish connection with other CPEs. This is because IEEE 802.22 networks share the spectrum bands dynamically with licensed devices. This gives rise to a complication in establishing mesh networks: how do BS/CPEs decide on the set of channel(s) that can be used for communication across the entire network so that interference in the mesh network is minimized and the spectrum utilization is maximized?

In the mesh network, when multiple CPEs and BS operate in close proximity, each of their rationality is to capture as much spectrum as possible for data transmission without coordinating with other CPEs. In areas with high analog/digital TV transmissions and wireless microphone services, unused channels are already commodities of demand. Therefore, when numerous unlicensed CPEs are operating using a small available band of frequency, there is a chance that the CPEs will try to act greedy and hog the available bandwidth. As all the CPEs will act in the same way, this may result in interference among 802.22 networks themselves. Thus an efficient spectrum allocation method needs to be proposed in order to use the channels with least interference.

In this paper, we attempt to answer the above mentioned question of self-coexistence among the devices in the mesh network. In this regard, we propose a coordinated distributed scheme for efficient spectrum allocation to increase the spectrum utilization and reduce the interference. The coordinated strategy has a cognitive BS, which controls the CPEs and their dynamic spectrum access. The spectrum allocation procedure is initiated when no CPE is connected to the mesh and repeated whenever new CPE(s) connect to the mesh or some change in spectrum usage report occurs due to primary incumbents. The CPEs connected to mesh in turn become special type of CPEs called pseudo-BS. The pseudo-BSs can adaptively broadcast their uplink frequency information for other CPEs which are still not connected to the mesh and can thus expedite the process of mesh establishment. To address the issue of self-coexistence among WRAN devices, we propose a graph theory based network controlled spectrum access mechanism where WRAN devices behave collaboratively to minimize interference and increase the utility obtained from the system. We show how the collaborative approach among WRAN devices outperforms the greedy non-collaborative approach. In this regard, we investigate two objective functions: maximize utility and proportional fair. For the former objective, the spectrum allocation is aimed at maximizing the utility obtained from the system while for the latter, the spectrum is allocated under a proportional fairness criteria. Jain's fairness index is also studied for these objectives. Through simulation experiments, we demonstrate that the proposed techniques help IEEE 802.22 systems to increase spectrum utilization.

The rest of the paper is organized as follows. In section 2, we formulate the problem using graph theoretic framework. Spectrum allocation for self-coexistence for different objectives are presented in section 3. We use the principles of graph coloring to efficiently allocate the spectrum. In section 4, simulation models and results are presented. Conclusions are drawn in the last section.

2. Problem formulation for spectrum allocation in IEEE 802.22 mesh

We define an undirected graph $G = \{V, E, \mathcal{B}\}$ to model the wireless mesh network, where V is the set of vertices denoting all CPEs and BS in the region, E is the set of all undirected edges denoting the links among the CPEs/BS, and $\mathcal{B}$ is the total available spectrum band not used by the incumbents and therefore, usable by the IEEE 802.22 network. Moreover, without loss of generality, we assume that through the beacon broadcasting and control signaling in each beacon period, topology information (potential neighbors and interferers of each CPE connected to the mesh) becomes global at the end of each FBP. In order to make the mesh spectrum allocation efficient, we propose few constraints such as, all CPEs transmit with the same power, i.e., the transmission and receiving range is fixed ($r > 0$) and interference range is also fixed ($R > r$). We use a *graph coloring* technique for spectrum allocation and study the spectrum access problem under different objectives.

The key concept behind efficient spectrum allocation is to find appropriate chunks of spectrum in such a manner so that BS/CPEs can coexist without interfering neighboring CPEs and the required objectives are met. We discuss about the objectives in section 3.1.

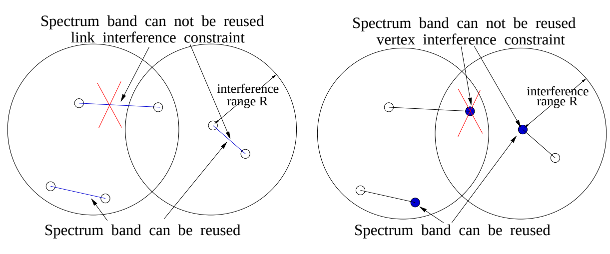
We consider that the utility achieved, depends directly on the throughput obtained, which in turn depends on the bandwidth of the frequency band(s) assigned. Thus we define utility achieved by CPE i as,

$$U_i = \sum_j (b_{ij_2} - b_{ij_1}); \tag{1}$$

where, $(b_{ij_2} - b_{ij_1})$ are the spectrum ranges that CPE i is operating on and no other interfering neighbor is using that. b_{ij_1} and b_{ij_2} are the lower and upper bounds respectively of the jth spectrum band.

We focus on the iterative channel assignment problem in the mesh network. The channel assignment problem can be partitioned into two sets. A channel assignment $\mathcal{G}_{\mathcal{E}} \in G$ assigns spectrum bands to each existing link $e \in E$ such that the interference constraint among the links are maintained. The link interference constraint is defined such that if two vertices are connected via a link of certain frequency, then no other vertices or links can use the same frequency channel within the interference range of those two connected vertices as shown in Fig. 1(a).

Similarly, a channel assignment $\mathcal{G}_{\mathcal{V}} \in G$ assigns spectrum bands to each pseudo-BSs $v \in V$ as shown in Fig. 1(b). The reason behind assigning spectrum bands to pseudo-BSs in addition to the spectrum allocated to the links is that the pseudo-BSs can adaptively broadcast their uplink frequency information for other CPEs which are still not connected to the mesh.



(a) (b)

Figure 1. a) Link interference constraint; b) Vertex interference constraint

However, $\mathcal{G}_{\mathcal{E}}$ and $\mathcal{G}_{\mathcal{V}}$ are not mutually exclusive as these subgraphs have overlaps. The optimization problem is to combine these two assignments. Thus we formulate a new undirected graph $G_{\mathcal{A}} = \{V_{\mathcal{A}}, E_{\mathcal{A}}, \mathcal{B}\}$ from the existing graph G combining the constraint of $\mathcal{G}_{\mathcal{E}}$ and $\mathcal{G}_{\mathcal{V}}$ using line graph mechanism [10]. The vertices $v_{\mathcal{A}} \in V_{\mathcal{A}}$ in $G_{\mathcal{A}}$ now denote the interference constrained links and vertices from the original graph G together, while $e_{\mathcal{A}} \in E_{\mathcal{A}}$ denote the interference constraint information, i.e., if two distinct vertices in $G_{\mathcal{A}}$ have an edge $e_{\mathcal{A}}$ in between them, they have the risk of interfering with each other if using the same frequency band at the time of transmission.

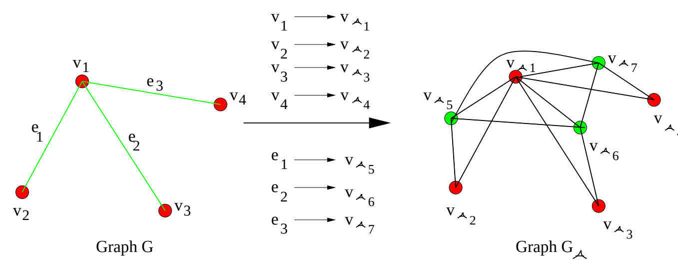


Figure 2. An example of creating $G_{\mathcal{A}}$ from G

In Fig. 2, we present a simple example of creating $G_{\mathcal{A}}$ from G. We see that the links (edges) in graph G are converted to the new vertices in the graph $G_{\mathcal{A}}$ and the interference constraint among these new and existing vertices are now depicted as edges in graph $G_{\mathcal{A}}$. Thus the spectrum allocation problem is to assign frequency bands to $V_{\mathcal{A}}$ such that spectrum utilization is maximized and interference is minimized.

3. Spectrum Allocation for Self-coexistence in IEEE 802.22 mesh

With the graph model for the problem known, we try to solve the problem through graph coloring. In doing so, we first define the objective functions and then propose the algorithms to achieve maximized spectrum utilization.

3.1 Objective functions

We define two kinds of objective functions.

1. **Maximize utility:** The aim is to maximize the total utility achieved by all the vertices $v_{\mathcal{A}} \in V_{\mathcal{A}}$ in $G_{\mathcal{A}}$. The constraint we follow is that each $v_{\mathcal{A}}$ must get at least a certain amount of spectrum to be functional, which we denote as b_{min}. The objective function is given by

$$maximize \quad \sum_{i=1}^{|V_{\mathcal{A}}|} U_i \tag{2}$$

$$\text{such that} \quad \sum_j (b_{ij_2} - b_{ij_1}) \geq b_{min}$$

2. **Proportional fair utility:** The aim is to divide the spectrum bands under some proportional fairness criteria. The criteria we follow is to prioritize the vertices $v_{\mathcal{A}} \in V_{\mathcal{A}}$ which interfere with the least number of other CPEs and thus maximize the utility achieved. This mechanism of allocating spectrum will demand cooperation from the CPEs and thus the CPEs will not follow any greedy approach that may harm the system.

3.2 Spectrum Allocation Mechanism

We model the spectrum assignment problem using the graph coloring technique. The traditional graph coloring problem [3] is to color each vertex using a color taken from existing color list. The constraint in such coloring is that if an edge exists between any two distinct vertices, then those two vertices can not be same colorable. With this constraint, the aim of the traditional algorithm is to minimize the number of colors to color all the vertices.

We propose an extension to the graph coloring algorithm: *Maximum Utility Graph Coloring* (MUGC). The aim is to find divisions of spectrum band under the objective functions defined. In contrast to the traditional graph coloring algorithm where each color is equal in its weightage, in MUGC, we consider heterogeneity in the colors. We associate spectrum bands with the color assigned to a vertex. The proposed MUGC algorithm is divided into two parses.

Parse 1: In this parse, we follow the traditional graph coloring heuristic (coloring the vertices in decreasing order of degrees) to find the minimum number of colors to cover all the vertices. We do not associate any value to the colors at this point and thus keep colors homogeneous. Let us assume, $C_1, C_2, \cdots, C_m$ are m minimum colors to color all the vertices. This implies m minimum non-interfering divisions of the available spectrum band are necessary.

Parse 2: In the next parse, we take the output from parse 1 and follow the mechanism of MUGC. The algorithm of MUGC is presented below. The aim here is to increase (maximize) the *reuse* of colors keeping the total number of colors fixed as obtained in parse 1. If the bandwidths assigned to the higher occurring colors are more than the rest of the colors, then it is obvious that the maximum chunk of the spectrum is used the most number of times implying the increase in spectrum reuse through MUGC.

Note that, while traditional graph coloring aims at minimizing the number of colors, it does not care for the number of occurrence of any color. MUGC focuses on the increased reuse of l colors with higher appearance than the rest of the colors. l is an implementation dependent parameter and can be controlled by coordinator.

In Fig. 3, we present an illustrative example to explain operation of MUGC. With the traditional graph coloring heuristic (left hand side), we find that C_1 appears 3 times, C_2 appears 2 times, and C_3 appears 2 times, where C_1, C_2 and C_3 denote three different colors. With the MUGC

Algorithm 1 Maximum utility graph coloring algorithm

INPUT:
Graph $G_{\mathcal{A}}$
PARSE 1:
1. Color $G_{\mathcal{A}}$ with traditional graph coloring heuristic
2. $G_{\mathcal{A}}$ is m colorable

PARSE 2:
1. FOR (each color i) {
check each vertex if it can be made color i without conflict to the neighboring vertices' colors made from PARSE 1
2. Count and store occurrence of colors after iteration i
}
3. Choose the iteration with total maximum occurrence of l ($l < m$) highest appearing color(s) among all iterations and assign bandwidths to the vertices accordingly under the objective functions defined

algorithm in effect (right-hand side), we find that the color appearances have changed. Now, C_1 appears once, C_2 appears 2 times, and C_3 appears 4 times. As C_3 appears maximum number of times, maximum amount of spectrum chunk can be associated with C_3 after division of the available spectrum bands. Thus through maximization of occurrence of C_3, the *reuse* of spectrum increases, making MUGC a better choice for higher spectrum utilization. In

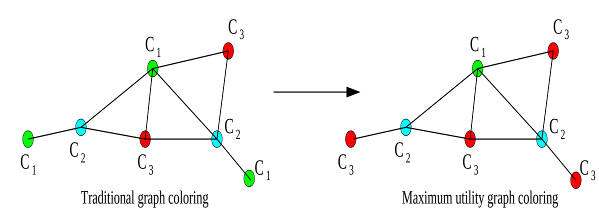


Figure 3. MUGC mechanism for spectrum allocation

general, depending on the objective functions, the actions taken for spectrum allocation are as follows.

For objective function 1: The essence of MUGC under objective 1 is to maximize the spectrum utilization with the constraint that each of the vertices get at least the minimum band (b_{min}). The whole spectrum band is divided into m chunks such that the vertices associated with the l highest appearing colors are favored *the most* till a certain bandwidth is left to assign b_{min} to each of the rest of the vertices regardless of the color. This mechanism clearly reduces the interference to the least, as the vertices with interference risk (vertices with existing edges between them) operate on different parts of the spectrum band. Moreover, the spectrum utilization is also maximized. The only drawback in this scheme is that fairness is not maintained among the vertices associated with lowest appearing colors ($m - l$).

For objective function 2: For this objective, we divide spectrum bands into m different parts in the ratio of $N_1^* : N_2^* : \cdots : N_m^*$ and assign them to vertices with color bands $C_1, C_2, \cdots, C_m$ respectively, where $N_1^* : N_2^* : \cdots : N_m^*$ are the number of occurrence of colors $C_1, C_2, \cdots, C_m$ respectively. Thus we maintain a proportional fairness criteria through a simple trade-off. As the vertices are now ranked according to number of neighbors they are interfering with, this mechanism will not let CPEs be greedy.

4. Simulation Experiments and Results

We have conducted simulation experiments to evaluate the improvements achieved by the proposed graph theoretic mechanism of spectrum allocation in IEEE 802.22. We present how the proposed maximum utility graph coloring algorithm (MUGC) can outperform standard spectrum allocation.

4.1 Simulation model and parameters

We have developed our simulation model in C under UNIX environment. The experiments have been carried out extensively and averaged over 1000 runs to evaluate the improvements due to the MUGC algorithm. For the topology, we assume a 50 km x 50 km region where IEEE 802.22 network and licensed incumbents reside and share the spectrum from the licensed spectrum band. In our licensed incumbent network model, the TV transmitters and receivers are stationary, while receivers of the FM radio are mobile. Depending on TV and/or radio channel requests, the inter-arrival times of these request streams and their duration vary. For our simulation model, we have followed the TV and radio usage traffic based on the data provided in [4], which suggests the inter-arrival times to be exponentially distributed. For the IEEE 802.22 network, we assume random topology with BS and CPEs' location as stationary in any single run of the simulation and use directional antenna for transmission/receiving purpose and omni-directional antenna for incumbent sensing. The locations of the CPEs change uniform randomly across the simulation runs. The number of CPEs are varied in the range of $5 - 30$. In table 1, we present rest of the simulation parameters.

4.2 Simulation results

In Fig. 4, we compare the performance of MUGC with the traditional graph coloring heuristic of spectrum allocation for objective functions 1 and 2. It is clear that proposed MUGC mechanism outperforms the traditional graph coloring in maximizing spectrum reuse.

In Fig. 5, we compare the total system utility achieved under MUGC and greedy non-collaborative spectrum hogging. In the non-collaborative approach, most of the spectrum bands are wasted due to interference among the

Table 1. Simulation parameters for IEEE 802.22 system

Simulation parameters	**Values**
Total licensed spectrum band	54 - 806 MHz
BS/CPE receiving radius	30 - 35 km
BS/CPE sensing radius	30 - 35 km
TV transmission receiving radius	30 km
b_{min}	7 MHz
Control signal frequency	1 - 2 MHz
Data signal frequency	1 - 18 MHz
Broadcast control signaling interval	10 time units
Number of control frequency information transmitted	1 - 3

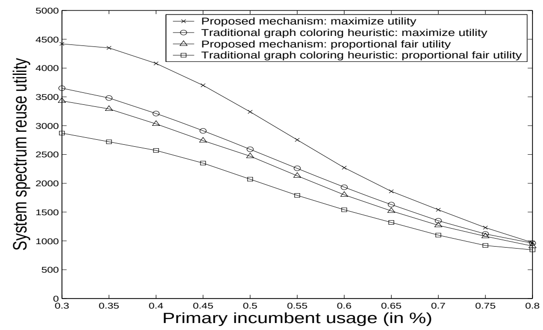


Figure 4. Total spectrum utilization achieved for MUGC and traditional graph coloring heuristic

greedy and selfish CPEs, whereas under the collaborative mechanism, system utility is improved. For a comprehensive performance evaluation of the proposed scheme, we present the results under both the objective functions and show that system utility is always better for the proposed scheme.

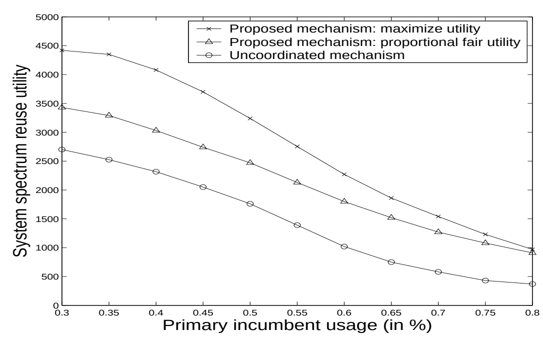


Figure 5. Total spectrum utilization achieved for MUGC and greedy non-collaborative approach

Figure 6 compares the proposed MUGC algorithm with the separate spectrum assignment mechanism for links and pseudo-BS (recall figure 1(a) and 1(b)). In the separate spectrum assignment, conflicts among the links and conflict among the nodes (pseudo-BSs) are considered separately and available spectrum chunk is divided between links and nodes statically before the allocation begins. This can not take advantage of the maximum spectrum reuse (e.g., a link and a node may be geographically located such that they can use the same spectrum band without interfering each other but separate spectrum assignment mechanism will not let them do so). While through MUGC technique, the spectrum bands can be reused at its best with both the links and nodes.

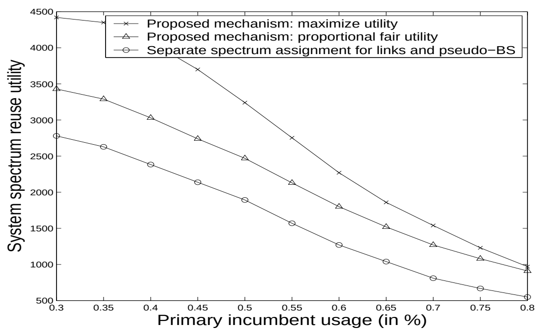


Figure 6. Total spectrum utilization achieved for MUGC and for separate spectrum assignment for links and pseudo-BS

Last, but not the least is the fairness criteria that we investigated in figure 7 for MUGC objective functions 1 and 2 for which we use Jain's fairness index [5]. After taking average from 1000 simulation runs, we find that in addition to providing better system utility than any other spectrum allocation mechanisms, both the objective functions show fairness index more than 0.5, which is considered to be a good fairness index. (This fairness index lies between 0 and 1 with 0 being most unfair and 1 being absolutely fair.) Moreover, the objective function for proportional fair utility maintains an excellent fairness index of 0.86 which exceeds the fairness index provided by maximum utility objective function.

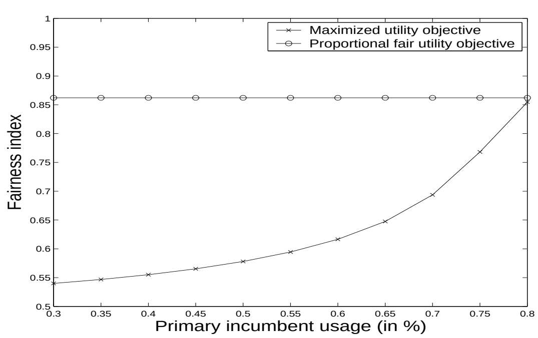


Figure 7. Jain's fairness index for maximized utility objective function and proportional fair utility objective function

5. Conclusion

In this research, we study the problems related to the construction of cognitive radio based IEEE 802.22 mesh networks. We addressed the issue of self-coexistence among WRAN devices. With the help of dynamic allocation of spectrum at multiple non-interfering frequencies, we reduced the interference resulting in quicker mesh initialization. We proposed a graph coloring technique called MUGC that allocates spectrum bands to the various links such that interference is minimized and spectrum utilization is maximized. Through simulation experiments, we found that the proposed enhancements increased the spectrum utilization obtained from the system.

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