Self-coexistence Among Interference-aware IEEE 802.22 Networks with Enhanced Air-interface

S. Sengupta, S. Brahma, M. Chatterjee and N. Sai Shankar

Abstract

IEEE 802.22 is a cognitive radio based Wireless Regional Area Network (WRAN) standard that allows opportunistic access to idle or under-utilized sub–900 MHz TV bands by unlicensed (secondary) networks. Though most of the standard has been laid out, there is still no consensus on the channel access policies for the uncoordinated secondary networks. Hence, the possibility of interference always exists. Moreover, in the absence of any control channel, the problem of establishing a connection becomes even more challenging, more so in the presence of hidden incumbents.

In this paper, we address the above mentioned self-coexistence problem among the IEEE 802.22 networks and provide novel solutions to improve the IEEE 802.22 air-interface. We use an interference-aware graph theoretic technique and propose utility graph coloring (UGC) for allocating spectrum to different IEEE 802.22 base stations such that they can co-exist with the least interference, thereby maximizing the system spectrum utilization. We also consider allocation fairness among the networks in terms of minimal fairness, proportional fairness, and complete fairness. With the spectrum allocated to the IEEE 802.22 networks, we propose enhancements to the IEEE 802.22 MAC layer to maximize spectrum usage efficiency. In particular, we make use of aggregation and fragmentation of channel carriers, dynamic multiple broadcast messages, and aggressive contention resolution. Through simulation experiments, we show how the proposed techniques can increase the spectral efficiency and spectrum utilization, and still maintain fairness. We show that the spectral efficiency obtained with UGC is more than three times compared to the existing standard. The average number of collisions among the IEEE 802.22 enabled devices are significantly reduced resulting in low connection set-up delay, enhanced system performance, and higher spectrum allocation for data transmissions.

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S. Sengupta is with the Department of Mathematics and Computer Science, John Jay College of Criminal Justice, CUNY, New York, NY 10019. Email: ssengupta@jjay.cuny.edu. S. Brahma is with the Department of Electrical Engineering and Computer Science at Syracuse University, Syracuse, NY 13244. Email: skbrahma@syr.edu. M. Chatterjee is with the Department of Electrical Engineering and Computer Science at University of Central Florida, Orlando, FL 32816. E-mail: mainak@eecs.ucf.edu. N. Sai Shankar is with Tensorcom, Carlsbad, CA 92008. E-mail: nsai@tensorcom.com.

I. Introduction

Radio spectrum are usually statically allocated for various wireless networking services for the military, government, commercial, private and public safety systems. Though such long-term static allocations have certain advantages in terms of oversight and management, it has been demonstrated through experimental studies that spectrum utilization is time and space variant. Thus, conventional static spectrum allocation results in suboptimal use of the spectrum– over-utilization in some bands and under-utilization in others [1]. Another problem static spectrum allocation often faces is 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 [2]. Given the pervasive penetration of cable–TV, this precious spectrum, though allocated and owned, remains unused in most locations. This observation has led to spectrum usage and access policy reforms [3] and *dynamic spectrum access* (DSA) based on *cognitive radio* (CR) [4] is seen as a viable option that can help the current reforms.

One of the efforts that is seen as a solution to the current spectrum scarcity problem is the proposition of the *IEEE 802.22* standard. IEEE 802.22 is a cognitive radio-based wireless regional area networks (WRANs) standard that would allow the unused, licensed sub–900 MHz TV bands to be used by unlicensed users on a non-interfering basis [5]. To protect the licensed services (primary incumbents), IEEE 802.22 devices are required to perform periodic spectrum sensing and evacuate promptly upon the return of the licensed users (spectrum etiquettes).

Even though the primary user protection mechanisms (primary-secondary spectrum etiquettes) have been predominantly studied and designed in IEEE 802.22 standard [6], the critical issue of ensuring quality of service (QoS) among IEEE 802.22 networks themselves, i.e., in other words, maintaining *self-coexistence* (secondary-secondary spectrum etiquettes) have not been addressed. In a system where unlicensed devices share the spectrum under the presence of licensed incumbents, the issue of self-coexistence among multiple CR operators in an overlapping region is very significant. In areas with analog/digital TV transmissions and wireless microphone services, unused channels are already commodities of demand. The challenge of self-coexistence becomes even tougher as the networks do not have information about which bands other secondary CR networks will choose. Different from other IEEE 802 standards where self-coexistence issues are only considered after the specification essentially is finalized, it is required for IEEE 802.22

to take the proactive approach and mandate to include self-coexistence protocols and algorithms for enhancing the medium access control (MAC) as a revision to the initial standard [8]-[10].

In this paper, we focus on the self-coexistence of IEEE 802.22 networks by designing new enhancements to the existing IEEE 802.22 air-interface. We investigate this problem using a two-tier architecture (macroscopic and microscopic tiers). First, we use a novel graph theoretic technique to dynamically allocate spectrum to the IEEE 802.22 networks such that interference across the networks is minimized (macroscopic tier – self-coexistence among multiple networks). However, even with the allocated spectrum to a BS, the CPEs within the coverage area of the BS would not know how to communicate with that BS. This is because, there is no predefined channel for the CPEs to establish connection with the BS or other CPEs as the IEEE 802.22 networks share the spectrum bands dynamically with the TV transmissions. Thus in the microscopic tier, we investigate and propose flexible MAC layer features for dynamic connection establishment through reduced control signaling and increased spectrum usage for data communication. More specifically, the contributions of this paper are:

• We address the issue of self-coexistence among multiple overlapping 802.22 networks. We formulate it as a *graph coloring* model on spectrum allocation and study the spectrum access problem in a time and space variant manner. We study a coordinated spectrum allocation approach instead of the greedy approach taken by the BSs.

• In this regard, we propose a network controlled spectrum access mechanism called *Utility Graph Coloring (UGC)* where 802.22 BSs behave collaboratively to minimize the interference obtained from the system. Three different constraint functions are considered while allocating spectrum among BSs through UGC: minimum fairness, proportional fairness and complete fairness. Jain's fairness index is also studied for these allocations.

• We show how the spectrum allocation among 802.22 BSs through UGC mechanism outperforms any other spectrum allocation mechanism. We analyze the spectral efficiency in the IEEE 802.22 networks in this regard.

• With the spectrum allocated to the IEEE 802.22 networks, we propose novel MAC functionalities for IEEE 802.22 BSs and CPEs that are effectively used to increase allocated spectrum usage efficiency, i.e., increased spectrum usage for data communication through significantly reduced control signaling. We also focus on the problem of hidden incumbent (defined later) sensing and avoidance by IEEE 802.22 networks.

• We propose a beacon based dynamic multiple broadcasting scheme and enhance the con-

tention resolution mechanism among IEEE 802.22 enabled devices with the help of aggressive contention resolution protocol. Analysis shows that the enhanced IEEE 802.22 MAC outperforms the existing legacy IEEE 802.22 MAC.

• We conduct simulation experiments to demonstrate that the proposed mechanisms help IEEE 802.22 systems in significantly increasing spectrum utility and spectral efficiency. Hidden incumbents are detected quickly with the enhanced flexible MAC layer and dynamic connection is established with less delay. Control signaling is also greatly reduced increasing spectrum utilization for data transmission from the allocated spectrum.

The rest of the paper is organized as follows. In section II, we provide a brief discussion on the related works for dynamic spectrum access and cognitive radio networks. In section III, we present an overview of the existing system architecture of IEEE 802.22 and its MAC air-interface. The problems of self-coexistence and hidden incumbent avoidance are also discussed here. In section IV, we formalize the problem of self-coexistence with graph theoretic technique and propose a collaborative spectrum allocation algorithm called *Utility Graph Coloring*. Spectral efficiency for IEEE 802.22 networks following UGC is analyzed in section V. In section VI, we address the issue of hidden incumbent problem. In section VII, simulation models and results are presented. Conclusions are drawn in the last section.

II. Related work

As far as dynamic spectrum sensing and access are concerned, there is an emerging body of work that deal with different decision making aspects, issues and challenges in cognitive radio network setting. Energy detection have been largely used in [11], [12], [13], [14] to monitor primary spectrum usage activity. Spectral correlation based signal detection for primary spectrum sensing in IEEE 802.22 WRAN systems is presented in [15]. Signature-based spectrum sensing algorithms are presented in [16] to investigate the presence of Advanced Television Systems Committee (ATSC) DTV signals. In a similar effort, sequential pilot sensing of Advanced Television Systems Committee (ATSC) DTV signals is carried out in [17] to sense the primary usage in IEEE 802.22 cognitive radio networks. In [18], a novel frequency sensing method is proposed known as dynamic frequency hopping (DFH). In DFH, neighboring WRAN cells form cooperating communities that coordinate their DFH operations where WRAN data transmission is performed in parallel with spectrum sensing without interruptions. The aim here is to minimize interrupts due to quiet sensing. In [19], a novel metric called Grade-of-Service (GoS) is defined

and the trade-off between miss-detection and false alarm is studied for optimizing spectrum sensing performance.

Though most of the above mentioned works focus on primary spectrum usage sensing, however, the issue of self-coexistence among multiple CR networks are not considered. Such interferences can largely be modeled using conflict graphs and graph coloring formulation (e.g., see [20], [21]). A broad survey on resource allocation in cellular networks and WLAN though graph coloring mechanisms can be found in [22], [23], [24], [25], [26] and in the references therein. However, most of these works do not consider the dynamic availability of spectrum bands due to the presence of primary users and thus can not be directly applied to IEEE 802.22 network spectrum sharing. The research in [27] investigates the channel assignment problem in a multi-radio wireless mesh networks using graph-coloring such that a given set of flow rates are schedulable. In [28], the dynamic channel allocation problem is formulated as graph coloring problem where dynamic channel availability is observed by the secondary users. In [29], spectrum allocation and scheduling problems are studied jointly in cognitive radio wireless networks with the objectives of achieving fair spectrum sharing. However, all channel divisions are treated equally here. In [30], a distributed, real-time spectrum sharing protocol called On-Demand Spectrum Contention (ODSC) is proposed that employs interactive MAC messaging among the coexisting 802.22 cells. However, control signaling is greatly increased through extensive MAC messaging. Game theoretic approaches are recently being investigated in [31], [32] for distributed coexistence. In these research, channel assignment problem is formulated as a multi-player, non-cooperative, incomplete information game that attempt to converge to a Nash Equilibrium point.

III. The IEEE 802.22 System

Before proceeding further, let us briefly discuss some of the features of IEEE 802.22 networks and their shortcomings that are relevant for this research.

A. Architecture of IEEE 802.22

The core components of the IEEE 802.22 system are the base stations (BSs) and the Consumer Premise Equipments (CPEs) as shown in figure 1. A BS typically manages its own cell by controlling on-air activity within the cell, including access to the medium by CPEs, allocations to achieve quality of service (QoS) and admission to the network based on network security mechanisms. In order to provide primary-protection, the 802.22 system follows a strict

masters/slave relationship, wherein the BS performs as master and the CPEs as the slaves. No CPE is allowed to transmit before receiving proper authorization from a BS. The operations of BS/CPEs can be divided into two major categories: sensing and transmitting/receiving data. If any of the channels used by 802.22 network is accessed by the licensed incumbents, the primary task of 802.22 devices is to vacate the channels within the channel move time (2 seconds) and switch to some other channel. To get the knowledge of the presence of licensed incumbents and their usage of channels, BS and CPEs periodically perform channel sensing. Depending on the incumbent detection algorithms proposed and their efficiencies, the general spectrum sensing process in divided into two categories: *fast sensing* and *fine sensing* [6].

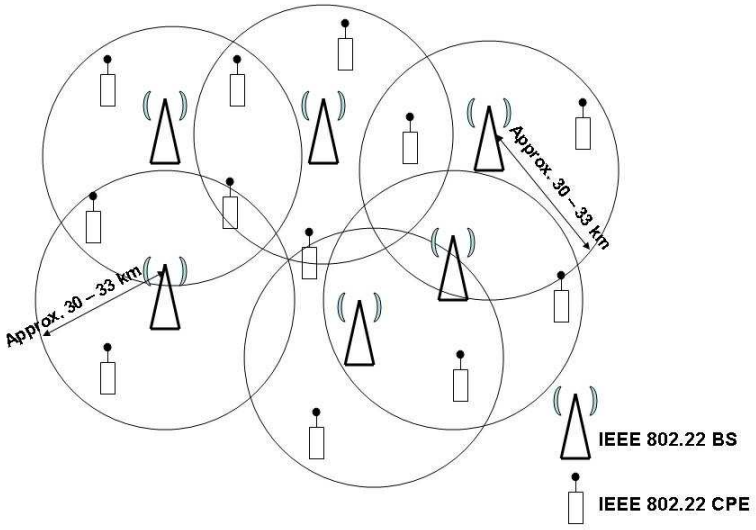


Fig. 1. An example of IEEE 802.22 system

B. MAC Layer of IEEE 802.22

The standard as detailed in [6] defines both PHY and MAC layers; we focus on the MAC layer in this research. The existing MAC of IEEE 802.22 has most of the features similar to the MAC of 802.11 and 802.16. However, few distinguishing features make the 802.22 MAC worth mentioning.

Initial connection establishment

Initial connection establishment in IEEE 802.22 differs from that of the previous IEEE 802 standards such as 802.11 or 802.16. Though connection establishment in a true centralized network, should be simple, it is not so for IEEE 802.22 because there is no pre-defined channel

for the CPEs to establish connection with BS as these networks share the spectrum band with licensed devices. Thus there is no way for a CPE to know what channel to use to establish the initial connection with a BS.

In IEEE 802.22, when a CPE is switched on, it follows the mechanism of *listen before talk* by scanning all the channels in the licensed TV band to determine the presence of any incumbent in the interfering zone and builds a spectrum usage report of vacant and occupied channels. The BS, on the other hand, also follows the same mechanism of sensing spectrum and periodically broadcasts using an unused frequency channel. The broadcast from the IEEE 802.22 BS is differentiated from other TV broadcasts by the preamble sent at the start of each OFDMA frame. If a CPE can locate the broadcast sent from the BS, it then tunes to that frequency and then transmits back in the uplink direction with an unique identifier; BS thus becomes aware of the existence of the CPE. Authentication and connection registration is then done gradually.

Frequency of operation and service capacity

In the typical standard version, the 802.22 system operates/transmits using the 6 MHz channels (TV bands in US are typically 6 MHz). The spectral efficiency ranges from 0.5 bit/sec/Hz to 5 bit/sec/Hz, thus resulting in an average data rate of 18 Mbps and maximum upto 30 Mbps in a single 6 MHz TV band [5], [6]. However, different channel sizes are also supported by the IEEE 802.22 standard. The architecture consists of one or more PHY/MAC air interface module and are empowered with capability to take advantage of the simultaneous availability of multiple vacant TV channels– contiguous or not. Moreover the architecture allows fragmenting carriers to selectively tune to partial channels avoiding interference and cross-talk.

The current standard defines provisions for aggregating/bonding up to three 6 MHz channels thus making it up to 18 MHz. Separate sets of OFDMA carriers are used on each channel to increase the data transmission rate at the time of channel bonding/aggregation. In general, approximately 2K carriers are used for each channel of 6 MHz, thus making it 6K carriers to transmit data at a high rate while aggregating/bonding 3 channels together.

Spectrum usage report

Once the initial connection is established, the spectrum usage report is then sent back to the BS from the CPE in the form of feedback. The BS upon acceptance of the feedback takes decision on spectrum usage. When more than one CPE tries to establish an initial connection, then contention-based connection setup similar to that of the IEEE 802.11 takes place after all the CPEs tune to the broadcasted channel.

C. Shortcomings of existing IEEE 802.22 MAC

Since IEEE 802.22 networks share the spectrum bands with licensed devices, the devices cannot know a priori what frequency bands other devices are operating on. Therefore, dynamic spectrum access among IEEE 802.22 networks is of utmost importance so that the interference among IEEE 802.22 networks can be minimized; else the throughput and quality of service (QoS) would be compromised and the whole purpose of DSA will be beaten [31], [32], [33]. Different from other IEEE 802 standards where self-coexistence issues are only considered after the specification essentially is finalized, IEEE 802.22 and FCC therefore took the proactive approach and planned to include self-coexistence protocols and algorithms for enhanced MAC as revision of the initial standard conception and definition [6], [7]. This gives birth to two very important inter-related problems: (i) how does BS in one IEEE 802.22 network decide on the set of channel(s) that can be used for communication across the entire network so that interference to/from *other IEEE 802.22 networks* is minimized (self-coexistence) and (ii) how can these channels be chosen such that interference to/from *other primary networks* is avoided (hidden incumbent avoidance).

Self-coexistence: In a system like 802.22 where unlicensed devices are sharing the spectrum under the presence of licensed incumbents, the issue of self-coexistence among multiple 802.22 operators in an overlapping region is very significant. In areas with analog/digital TV transmissions and wireless microphone services, unused channels are already commodities of demand. In such a scenario, when multiple IEEE 802.22 networks operated by multiple operators (or, service providers), overlap, it is highly probable that the operators will try to act greedy and hog the available bandwidth. As all the operators will act in the same way, this may result in interference among 802.22 networks themselves. Thus an efficient channel allocation method needs to be used such that the interference is minimized. Although the exact methodology for interference mitigation in 802.22 networks is yet unknown, we propose an algorithm that increases the spectrum utilization.

The hidden incumbent problem: If an incumbent (e.g. TV transmitter) starts up with the same frequency near the CPE but outside the BS sensing region, the BS has no way of sensing this TV transmission. The BS thus is hidden to the incumbent TV transmitter but one or more CPEs associated to it are not hidden to the incumbent (refer Fig. 2 – hidden incumbent region). This scenario is referred to as hidden incumbent problem. The CPE can detect the incumbent transmission in-band, but the BS can not. The BS will continue transmission and might create

interference to the devices in the hidden incumbent region. The CPE will have no way to report this licensed incumbent. If it transmits at the same frequency with which it is connected to the BS, it will result in harmful interference to the incumbent. On the other hand, due to the centralized nature of the IEEE 802.22 network (on-air activities of CPE is controlled by BS), the CPE can not choose any other channel to connect to the BS as it is not permitted by the BS to use any other channel.

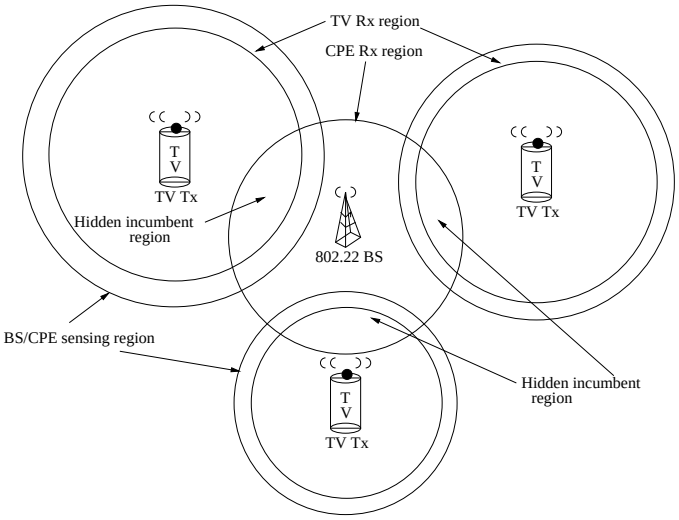


Fig. 2. IEEE 802.22 hidden incumbent scenario

Similarly, if a CPE switches on and desires to connect to a BS, the CPE will scan all the channels for periodic broadcast. But if there is a nearby incumbent already transmitting with the same frequency as the BS periodic broadcast frequency, and is outside the BS sensing region but inside the CPE receiving region (hidden incumbent region as shown in Fig. 2), the CPE will not be able to decode the BS broadcasting frequency. This results in a three-fold problem. The CPE might think that there is no IEEE 802.22 BS transmitting at that time and might switch off. Similarly, if the BS does not receive any feedback from the CPE, it might think that there is no CPE alive and might stop broadcasting after a certain number of broadcasting periods. Last but not the least, for the duration of the broadcasting period, the BS will cause harmful interference to the primary receiver.

IV. Inter-Cell Spectrum Allocation for Self-coexistence

When multiple 802.22 networks (BSs) operate in close proximity in an overlapping region, each BS's aim is to grab as much spectrum as possible to serve its corresponding CPEs without coordinating with other BSs. This greedy approach leads to increased interference to the operating BS and the neighboring BSs thus degrading the performance of the system. To alleviate the problem of rise in interference, we propose an efficient spectrum allocation algorithm to increase the spectrum utilization and reduce the interference.

A. Assumptions and Problem formulation

We assume that there are N 802.22 BSs competing for unused licensed spectrum. The amount of the unused spectrum is time variant. The key concept behind efficient spectrum allocation is to find appropriate chunks of spectrum in such a manner so that BSs can coexist without interfering neighboring networks.

We consider that the utility, U_i achieved by the BS i depends directly on the throughput obtained, which in turn depends on the spectral bandwidth the BS is operating on. We assume a simple interference model among the overlapping BSs. When two BSs are within a certain physical proximity and transmitting using the same frequency band or overlapping frequency bands, interference will occur. If their interference exceeds the SINR requirements, both transmissions will fail resulting in zero utility achieved by both the BSs.

We consider multiple overlapping 802.22 networks using a graph theoretic model. We define an undirected graph $G = \{V, E, B\}$, where V is the set of vertices denoting all BSs in the region. E is the set of all undirected edges denoting the interference constraints among the BSs, i.e., if any two distinct vertices have an edge between them, they are in the risk of interfering with each other if using the same frequency band. B is the total available spectrum band not used by the incumbents and is usable by the 802.22 networks. Moreover, without loss of generality, we assume that the topology information of this overlapping region is known to all the 802.22 BSs (as BSs are static) and the BSs will be honest in providing all their acquired graph information.

We investigate the self-coexistence problem from a *centralized controller* perspective. This model is consistent with the dynamic spectrum allocation process that is controlled by a centralized spectrum manager (SM) [6], [2] as shown in the upper half of Fig. 3. Since the SM is responsible for collecting and distributing the spectrum availability, there is no need for the BSs to directly exchange information with other BSs.

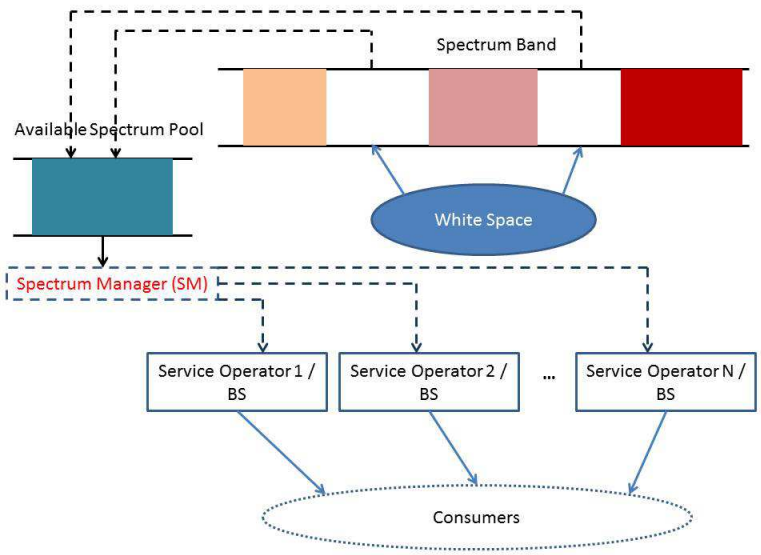


Fig. 3. Spectrum allocation architecture using Spectrum Manager (SM)

Apart from the technical standard defined for SM, there are other reasons why we prefer a centralized mechanism than a distributed one. As shown in [30], a distributed, real-time spectrum sharing protocol called On-Demand Spectrum Contention (ODSC) is investigated that employs interactive MAC messaging among the coexisting 802.22 cells. However, control signaling is greatly increased through extensive MAC messaging thus reducing the effective spectrum utilization. Moreover, distributed graph coloring is performed in number of iterations (by back and forth message passing) [34]. With increase in the number of nodes or spectrum bands participating in the distributed mechanism, the lack of scalability is often a concern.

B. System constraint functions

Before proceeding any further with the spectrum allocation, let us briefly explain various system constraints that we consider and then we explain how proposed algorithm works with each of the system constraints. The objective of the spectrum allocation problem among IEEE 802.22 networks is to maximize the system utility expressed as

$$maximize \quad \sum_{i=1}^{N} U_i \tag{1}$$

under any of the various system constraints as follows. In this work, we assume three different system constraints and study how our proposed design would operate under each of these

constraint functions.

1) Minimum fairness: The aim is to maximize the total utility achieved by all the BSs under the constraint that all the BSs must get at least a certain amount of spectrum, which we denote as B_{min}.
2) Proportional fairness: The aim here is to maximize the total utility achieved by all the BSs under the constraint of some proportional fairness criteria. The criteria for proportional fairness that we follow in this work is to prioritize the BSs most, which interfere with least number of other BSs and so on. This mechanism of allocating spectrum will help BSs to be cooperative with other BSs and not follow any greedy approach that may harm the system performance.
3) Complete fairness: Under this constraint, all the BSs are treated equally. The problem in this approach is known as *tragedy of the commons* [35].

C. Spectrum Allocation through Utility Graph Coloring

We model the spectrum allocation process among BSs using the graph coloring technique. The graph coloring problem [36] 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. Though the optimal graph coloring problem (i.e., proving that number of colors needed to color the graph is indeed minimum) is known to be NP-hard in searching and NP-complete in decision, it can be solved in reasonable time with the traditional graph coloring heuristic [37]. Moreover, the number of BSs that coexist and compete with each other is in the order of 10's due to the high area coverage capacity. Thus the complexity of the graph coloring problem does not hinder the proposed mechanism. The working of the traditional graph coloring heuristic algorithm is as follows. The vertices (initially uncolored) are sorted in non-increasing order of degree and are then colored in that order, maintaining the graph coloring constraint that if an edge exists between any two distinct vertices, then those two vertices can not be same colorable.

We propose an extension of the above graph coloring algorithm and call it *Utility Graph Coloring* (UGC). The aim is to find divisions of spectrum, such that, *reuse* of spectrum bands and thus *system utility* can be maximized under various *system constraint functions* defined for the system. In contrast to the traditional graph coloring algorithm where the colors do not carry any weight and thus all colors are equal, in the UGC, we consider heterogeneity in the colors.

A color assigned to a vertex (BS) becomes associated with a spectrum chunk [1] assigned to the BS. The bandwidth of that spectrum chunk denotes the weight of the color which is also the utility achieved by the BS if the chunk is not interfered.

The implementation of the proposed UGC algorithm is divided into two phases.

Phase 1: In this phase, we follow the principle of traditional graph coloring algorithm to find the number of colors to color all the vertices. We do not associate any value to any color at this phase and thus keep colors homogeneous. Let us assume, $C_1, C_2, \cdots, C_m$ are m colors to color all the vertices. With the completion of first phase, we get to know that the graph is m-colorable and the available spectrum band needs to be divided into m chunks to allocate spectrum to all the BSs. Note that, bandwidth of each of the chunks is yet unknown.

Phase 2: In this phase, we follow the mechanism of UGC. We find the *occurrence* of the colors in the graph. Let us assume the occurrence of the colors $C_1, C_2, \cdots, C_m$ are $N_1, N_2, \cdots, N_m$ respectively, where, $N_1 + N_2 + \cdots + N_m = N$, the total number of base stations. Then for each of the colors, we run UGC parsing (the complete UGC algorithm is presented in Algorithm 1). For each iteration, we keep the information which color has occurred the maximum number of times and how many times. Let us assume that after all the color iterations, we find that, color C_m has the maximum occurrence of N_m^* in iteration i. We then choose iteration i and redefine the occurrences of colors $C_1, C_2, \cdots, C_m$ as, $N_1^*, N_2^*, \cdots, N_m^*$ respectively.

Note that, traditional graph coloring aims to find the minimum number of colors needed. The physical significance is that, in this way we can find the divisions of the unused spectrum needed to avoid interference. But traditional graph coloring does not focus on maximizing reusing (occurrences) of a color and thus can not maximize the spectrum utilization. UGC provides major improvement over the traditional graph coloring in terms of increased system utility through maximized reusing of a color even under various system constraint functions. In phase 1, the traditional graph coloring provides the number of divisions of available spectrum required that are used in phase 2 to manipulate their *number of occurrences*.

Let us consider an example to illustrate how UGC works. For the graph shown in Fig. 4, with the traditional graph coloring algorithm, we find that the graph is 3-colorable and we have colored the vertices accordingly. The left-hand graph (traditional graph coloring) in Fig. 4 shows that C_1, C_2 and C_3 appearing 2, 3 and 1 times respectively. For example, if the current system

[1]Note that, a spectrum chunk signifies a set of spectrum bands

Algorithm 1 Utility graph coloring algorithm

INPUT: Graph G

Phase 1:
- Color G with traditional graph coloring heuristic of coloring nodes with descending order of degree
- G is m colorable

Phase 2:
- FOR (each color i) {
  check each node in G if it can be made color i without conflict to the other nodes' colors made from Phase 1

  Store the information of occurrences of each color after this iteration i
  }
- Select the iteration with maximum occurrence of a color among all iterations and assign bandwidths to the nodes accordingly under the constraint functions defined

operates in the 402-405 MHZ band, then the total available spectrum is 3 MHz (i.e., 3000 KHz). A proportional fair allocation results in a bandwidth 1000 KHz corresponding to color C_1, 1500 KHz corresponding to color C_2 and 500 KHz corresponding to color C_3. The total system utility is given by

$$U = 2B(C_1) + 3B(C_2) + B(C_3), \tag{2}$$

where $B(C_i)$ is the bandwidth assigned to color C_i. Intuitively, a higher value of utility indicates larger available data rate in the network. In this case, the system utility can be obtained as 7000 units from (2). Parsing this graph with our proposed UGC algorithm, it is observed that C_1 appears once, C_2 appears once, and C_3 appears 4 times. This corresponds to a bandwidth 500 KHz corresponding to color C_1, 500 KHz corresponding to color C_2 and 2000 KHz corresponding to color C_3. The system utility for the UGC is

$$\hat{U} = B(C_1) + B(C_2) + 4B(C_3), \tag{3}$$

which yields a system utility of 9000 units, thus resulting in an improved data rate of 28%. Hence, it is observed that the UGC mechanism, maximizes spectrum reuse while avoiding interference among the secondary networks.

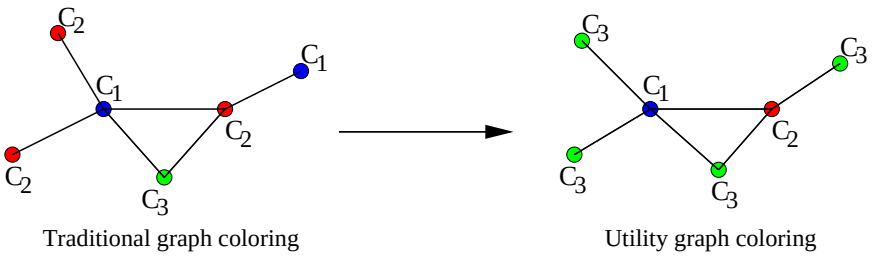


Fig. 4. An illustrative example of UGC for 802.22 networks

In general, depending on the constraint functions, the actions taken for spectrum allocation are as follows. We assume the graph is m-colorable.

For constraint function 1: The whole spectrum band is divided into m chunks such that the vertices with the color label C_m (maximum number of vertices in the graph) are assigned the maximum possible spectrum as they would interfere least. The essence of UGC here is to maximize the system utility under constraint of minimum fairness. The rest of the vertices (BSs) will be assigned the minimum threshold frequency (B_{min}) to operate on. This mechanism minimizes interference as the BSs with interference risk (vertices with existing edge between them) now operate on different parts of the spectrum band. Moreover, as maximum number of BSs in the graph obtain the maximum possible spectrum band, the system utility is maximized. The only drawback in this scheme is that fairness is minimized and the BSs with other color labels, i.e., $C_1, C_2, \cdots, C_{m-1}$ are all treated equally.

For constraint function 2: Here, we try to maximize the system utility under the constraint of proportional fairness. Let us assume that after the UGC parsing is completed, the occurrences of colors $C_1, C_2, \cdots, C_m$ are redefined as, $N_1^*, N_2^*, \cdots, N_m^*$ respectively. Then the available spectrum is divided in m different parts in the ratio of $N_1^* : N_2^* : \cdots : N_m^*$ and are assigned to vertices with color bands $C_1, C_2, \cdots, C_m$ respectively.

For constraint function 3: Here, our aim is to provide complete fairness among all the BSs. Thus in this mechanism, we divide the available spectrum band in m equal parts and assign each part to each of the non-interfering BSs.

Note that, though our proposed mechanism for self-coexistence, viz., Utility Graph Coloring (UGC) is aimed at IEEE 802.22 WRANs, the principles are generic enough and can be extended to any resource-conflict environment.

V. Spectral Efficiency for IEEE 802.22 networks using UGC

With UGC explained, we now analyze the spectral efficiency achieved through UGC in the IEEE 802.22 networks. Spectral efficiency, measured in bits/sec/Hz, is defined as the amount of information that can be transmitted over a given bandwidth in a specific digital communication system. It provides an indication of how efficiently a limited frequency spectrum is utilized by the physical layer protocol and/or the media access control. In other words, we can assume spectral efficiency as a quantitative degree of measurement for self-coexistence among the interfering IEEE 802.22 networks. Let us show how the average spectral efficiency increases with UGC.

We start with Shannon's formula for the capacity of a band-limited channel with additive white Gaussian noise (AWGN) [38]. In our case, we are concerned with not only the noise but the interference caused by other IEEE 802.22 interferers which occupy the same spectral band as the network under consideration. Shannon's capacity C can be written as

$$C = B\ log_2(1 + SINR) \tag{4}$$

where, B is the bandwidth in Hz and SINR is the signal to interference and noise ratio. The spectral efficiency for bandwidth B can then be written as $E = \frac{C}{B}$ bits/sec/Hz.

With the definition of spectral efficiency given, we now try to find the average spectral efficiency where N IEEE 802.22 networks with N BSs are competing for limited spectrum. We compare both the spectrum allocation mechanisms, with and without UGC. With UGC, spectrum is allocated such that the available spectrum band is divided into several non-interfering chunks and these chunks are allocated to IEEE 802.22 networks following interference constraints such that interference among the networks is minimized. Note that, with this mechanism, though the available spectrum band for each of the networks is actually reduced, average number of interferers will also be reduced which will eventually increase the channel capacity and also spectral efficiency. To obtain the interference distribution at any IEEE 802.22 node, we consider node w as the receiver under consideration as shown in Fig. 5.

The *receiving distance* r_R for node w is defined as the maximum distance from which a receiving node can correctly recover a transmitted signal. Similarly, the *interference distance* r_I is defined as the maximum distance from which a receiving node can sense a carrier. We also consider a distance r_0 to represent the near field of node w. When $r_0 \ll r_R$ we can safely assume that the spatial distribution of the active nodes remains uniformly random. If we assume that all nodes operate with omni-directional transmit and receive antennas, then node w will be

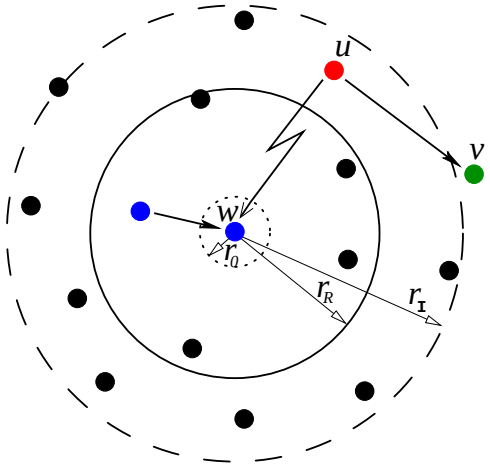


Fig. 5. Interference at node w from a local neighbor u

interfered by all nodes within the circle of radius r_I. For example, node u, while transmitting to node v, acts as an interferer to node w. By considering the spatial distribution of all the potential interferers, we can compute the distribution of the interference power as done in [39]. We use the interference equation from [39], where the *mean* value of the collected interference power η from an interfering transmitter is given by,

$$\eta = \frac{4\ P_r\ (r_R^{\alpha+2} - r_0^{\alpha+2})\ (r_I^{\alpha-2} - r_0^{\alpha-2})}{(\alpha^2-4)\ r_0^{\alpha-2}\ r_I^{\alpha-2}\ (r_I^2 - r_0^2)\ (r_R^2 - r_0^2)} \tag{5}$$

where, P_r is the desired receive power threshold. We also assume that signal power in wireless media decays proportionally to the distance raised to the power of α.

To find the number of potential interfering IEEE 802.22 BSs in the interference area $a_I = \pi r_I^2$, we proceed in the following way. We consider that there are N BSs that are uniformly randomly scattered over a region of area A. Then the probability that a IEEE 802.22 network has n neighbors in the interference range can be calculated using binomial distribution

$$Prob[\text{n neighbors}] = \binom{N-1}{n} (\frac{a_I}{A})^n (1 - \frac{a_I}{A})^{N-n-1} \tag{6}$$

The expected number of BSs within the interference range of one IEEE 802.22 network can then be given by

$$N_I = \sum_{n=0}^{N-1} n \times Prob[\text{n neighbors}] \tag{7}$$

Note that not all these BSs will create the interference for the BS under consideration. Out of the many potential interferers only the ones that acquired the same frequency bands or partial non-orthogonal frequency bands as BS i, will be the interferers for network i. With this assumption, the expected number of interferers for network i can be given by

$$N_I^* = \sum_{n=0}^{N_I} n \times Prob[\text{n BSs using same or non-orthogonal channel as network i}] \quad (8)$$

Using the interference distribution and average number of interferers from equations (5) and (8), we calculate the spectral efficiency for network i as

$$E_i = log_2(1 + \frac{S_i}{\mathcal{W} + N_I^* \times \eta}) \quad (9)$$

where $\mathcal{W}$ is the additive white Gaussian noise and is given by $\mathcal{W} = B_i \times \mathcal{W}_0$. B_i is the frequency bandwidth being used by network i.

Considering spectral efficiencies over N IEEE 802.22 competing networks, we express the average spectral efficiency per IEEE 802.22 network as

$$E_{average} = \frac{\sum_{i=1}^{N} E_i}{N} \quad (10)$$

Note that, the key concern in achieving better spectral efficiency and better system capacity is choosing the frequency bands B_i's for the IEEE 802.22 networks in vicinity such that N_I^*, the actual number of interferers, can be minimized. UGC takes into account the interference constraints with desired received power threshold while allocating spectrum bands to neighboring BSs such that the spectrum bands can be reused the maximum number of times. With the UGC in effect, we find that $N_I^* \to 0$; thus minimizing the possibility of actual interferers and maximizing the possibility of increased spectral efficiency.

VI. Enhanced MAC for Efficient Spectrum Usage

In Section IV, we have shown how the proposed UGC mechanism allocates spectrum to the IEEE 802.22 networks (BSs) such that interference across the networks is minimized. The UGC mechanism essentially finds the spectrum for each of the BSs, i.e., e.g., we get the right-side of Fig. 4. However, even with the allocated spectrum to a BS, the CPEs within the coverage area of the BS would not know how to communicate with that BS. This is because, there is no predefined channel for the CPEs to establish connection with the BS or other CPEs as the IEEE 802.22 networks share the spectrum bands dynamically with the TV transmissions. A CPE

would not know what frequency bands other CPEs are operating on. As a result, the challenge for the WRAN devices is to discover other WRAN devices and establish connection. This is illustrated in Fig. 6, where the left side is the outcome of the UGC mechanism (i.e., ***macroscopic tier spectrum allocation***) and the right side shows the network clouds where the dynamic and real-time connection establishment need to be investigated through reduced control signaling and increased spectrum usage for data transmission (i.e., ***microscopic efficient spectrum usage***). Thus, it is important to delve into the MAC layer features and understand how the time-frame structures can be manipulated to abide by FCC incumbent avoidance guideline and yet increase effective spectrum utilization. In Section VI.A., we address hidden incumbent avoidance by dynamic multiple broadcasting. In Section VI.B., we propose a novel aggressive contention resolution with the help of multiple broadcasting to reduce collisions among CPEs in network initialization which reduces control signalling and startup delay to a great extent and increases effective spectrum utilization for data transmission.

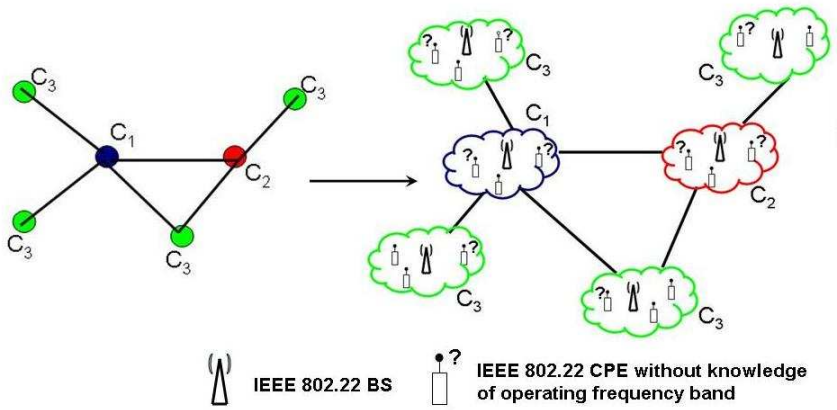


Fig. 6. Macroscopic spectrum allocation to microscopic efficient spectrum usage

A. Using foreign beacon period dynamically with multiple broadcasting: Hidden incumbent avoidance

In the existing standard, both TV transmitters (primary users) and WRAN BS (secondary users) broadcast control signals for connection establishment before actual data transmission

starts. This period of broadcasting control signals is known as beacon period (BP). Beacon period provides a mechanism for coordination of TV transmission and WRAN devices. Each beacon period consists of three separate periods: *network beacon period* (NBP), *foreign beacon period* (FBP) and *Sense/Sleep/Beacon Period* (SSBP). NBP is used by primary incumbents for broadcasting pilot signals carrying channel and power information while WRAN devices sense in this period. FBP is used by WRAN devices for broadcasting beacons. During SSBP, both primary incumbents and WRAN devices stop broadcasting. In the existing IEEE 802.22 standard, beacon periods are pre-defined and BS periodically broadcasts using only single frequency channel.

Unlike the existing IEEE 802.22 standard, we propose using the foreign beacon period duration dynamically. To cope with the primary incumbents, we use dynamic multiple outband broadcasting in different frequencies (*candidate frequencies*) periodically. The BS will coordinate the adaptive FBP and will announce the largest FBP duration in each iteration. The number of broadcast messages by BS is updated dynamically depending on the feedback received from the CPEs. BS decreases the number of candidate channels if all the candidate channels are decodable by the CPEs (implying low probability of hidden incumbent situation) and increases the number of broadcasting channels changing the candidate frequencies, if most of the previous candidate channels are not tuned up by CPEs. The reason behind broadcasting at multiple frequencies is that even if a CPE encounters an in-band licensed incumbent transmission (hidden to the BS), it still has ways to report this incumbent transmission to the BS using other candidate channels. The BS then changes the service channel to some other unused band thus overcoming the problem of hidden incumbent. In Fig. 7, we illustrate an example of beacon broadcasting where the first superframe has the FBP length of 2 units, whereas the second superframe has the FBP length of 5 units.

Moreover, we divide the BS/CPE transmissions in two categories: (1) connection establishment or channel hopping with the help of control signaling and (2) data transmission with the help of data signaling. For control signaling, we use fragmentation of channel carriers to minimize the wastage of spectrum band[2] and aggregation of channel carriers for data transmission to maximize

[2]Note that channel carriers are not narrow bands and are sufficiently spaced to take care of narrow band fading. This is done by means of calculating the coherence bandwidth. So one would select carriers that are beyond the coherence bandwidth so that different carriers have different fading characteristics. Now coding in frequency domain can be done to make sure that even if the CPE/BS synchronize over a subset of carriers, we will have synchronization.

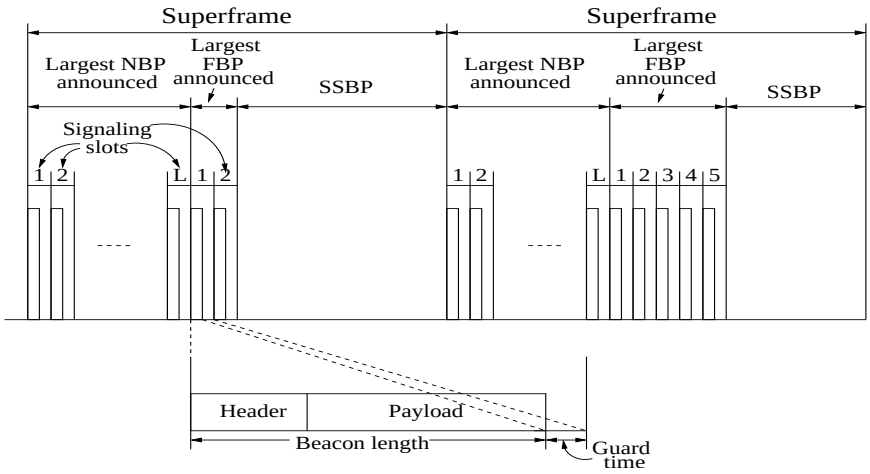


Fig. 7. Dynamic beacon period

the bandwidth and data rate. In our simulation of IEEE 802.22 network (discussed later), we use typical 1 or 2 MHz bands for control signaling.

B. Contention resolution among CPEs through spectrum usage report

Another functionality that we propose to the IEEE 802.22 MAC is the addition of spectrum usage report within the periodic broadcasting from BS to the CPEs. Currently, the spectrum usage reports traverse from the CPEs to the BS but not the other way. We mirror the spectrum usage report in all the multiple broadcasting from the BS. This spectrum usage report contains the information of all control frequencies that the CPEs can tune to in the uplink. Thus, in contrast to the existing connection establishment procedure of IEEE 802.22 where CPEs must tune to the single broadcasting frequency and then follow the contention resolution mechanism, we propose that CPEs obtain information about all control frequencies for uplink. Obtaining information about all control frequencies for uplink will help the CPEs in quick connection establishment through reduced contention.

In this mechanism, CPEs sense the broadcast beacons from the BS during connection initiation. Upon receiving the broadcast beacons, the CPEs intending to connect to the BS, measure the signal to interference and noise ratio (SINR) to evaluate the link quality. The SINR measured at receiver (CPE) j associated with transmitter (BS) i can be expressed as additive white Gaussian

noise

$$SINR_{ij} = \frac{p_i G_{ij}}{\mathcal{W} + \sum_{k \neq i} p_k G_{kj} H(k,j)} \tag{11}$$

where p_i is the transmission power of i, G_{ij} is the link gain between i and j and $\mathcal{W}$ is the additive white Gaussian noise. $H(k,j)$ is the interference function characterizing the interference created by any other transmitting node k to node j and is defined as

$$H(k,j) = \begin{cases} 1 & \text{if } k,j \text{ operating on the same frequency band} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

If the SINR (link quality) is below a certain pre-defined threshold (Q_1) (which may be due to primary incumbents), the broadcast is assumed to be not decodable. If the SINRs in all the broadcastings are not decodable, the CPEs discard the frequency bands and keep quiet. This way, BS does not receive any connection request from the CPEs; the round-trip timer expires and a different frequency band(s) is selected for broadcast in the next FBP. On the other hand, if the SINR of a broadcast frequency channel is better than the threshold Q_1, then the frequency channel in the downlink is assumed to be available [3]. CPEs, which are able to decode the signal, update their spectrum usage table, obtain the available uplink frequency information from the beacon payload, and contend among themselves to connect to the BS. In this regard, we propose a unique aggressive contention resolution mechanism among IEEE 802.22 enabled devices.

Aggressive contention resolution

As mentioned above, the CPEs tuning to the same uplink frequency contend among themselves with the contention resolution protocol similar to IEEE 802.11. The only difference in this aggressive contention resolution protocol lies in generating the differentiated random backoff number for collision avoidance. Instead of starting with the same random backoff range for all the CPEs (as used in IEEE 802.11, e.g., $[0, 7]$ before first transmission), we propose to use the initial random number generation range as an inverse step function of the SINR received. For this purpose, we choose another SINR threshold Q_2 which is greater than Q_1. Now, CPEs with SINR greater than Q_2 acts aggressively in choosing a smaller initial random backoff range than

[3]We assume that the channel is free from incumbent transmission explicitly.

the CPEs with SINR below Q_2. Note that all the CPEs considered in this contention algorithm receive SINR above Q_1.

Let us present an example to illustrate the case. Let two CPEs A and B receive SINR as q_1 and q_2 from one particular beacon broadcast. We assume $Q_1 < q_1 < Q_2 < q_2$. According to the proposed MAC, B's initial random backoff range for example, would be $[0, 3]$, while A's initial random backoff range would be $[0, 7]$. If A and B still collide and generate random backoff interval for next transmission, B's interval will be $[0, 7]$ and A's interval will be $[0, 15]$ and so on. The justification behind such discriminatory range is that we want CPEs with higher SINRs (or in other words, CPEs closer to the source of the beacon broadcast) to be favored than the CPEs far from the source. In other words, we are prioritizing the CPEs with low latency to lower the total system latency in establishing connection[4].

We analyze the probability of winning a contention by a CPE to synchronize to a BS under the presence of existing and proposed random backoff values. We assume M CPEs contend in the uplink while N of those CPEs ($N < M$) are close to the source of the beacon broadcasting in the particular period, i.e., N CPEs receive SINR above Q_2. B is one such CPE (with SINR above Q_2) whose probability of winning is to be determined. Let the initial random number generation interval for all the CPEs in the existing MAC be $[0, (y-1)]$. While with the proposed MAC, N CPEs generate initial random backoff number in the range of $[0, (x-1)]$, where $x < y$. Then the probability of successful transmission (or probability of winning the contention in the first transmission attempt) by B in a particular slot with existing MAC can be given by

$$P_{existing} = \Big(\frac{1}{y}\Big)\Big(\frac{y-1}{y}\Big)^{(M-1)} \tag{13}$$

The probability of success with proposed MAC is

$$P_{proposed} = \Big(\frac{1}{x}\Big)\Big(\frac{x-1}{x}\Big)^{(N-1)}\Big(\frac{y-1}{y}\Big)^{(M-N)} \tag{14}$$

We define P_{gain} as the ratio of $P_{proposed}$ to $P_{existing}$ as

$$P_{gain} = \frac{P_{proposed}}{P_{existing}} = \frac{\big(\frac{x-1}{y-1}\big)^{(N-1)}}{\big(\frac{x}{y}\big)^{N}} \tag{15}$$

[4]Note that, the aggressive contention resolution is used only for the quick connection establishment process and not for the purpose of data communications among the CPEs and BS. Thus once a CPE has tuned to a BS, it cannot take part in the aggressive contention resolution mechanism any further for its data transfer. Rather, it will then revert back to the normal contention resolution mechanism.

If x and y are large numbers such that we can assume $x-1 \approx x$ and $y-1 \approx y$ then equation (15) can be reduced to

$$P_{gain} = \frac{(\frac{x}{y})^{(N-1)}}{(\frac{x}{y})^{N}} = \frac{y}{x} \tag{16}$$

$P_{gain} > 1$ as $y > x$. Thus probability of successful transmission of a CPE with proposed MAC is greater than that with existing MAC.

If x and y are not large numbers such that $x - 1 \neq x$ and $y - 1 \neq y$, even then we find that

$$P_{gain} > 1 \quad \text{for} \quad N \leq N_{max} \tag{17}$$

where, N_{max} is the upper bound on how many CPEs can act aggressively simultaneously. For example, in the initial transmission attempts, say, $(x-1) = 3$ and $(y-1) = 7$, after exhaustive search we found that the upper bound of N is 5.

VII. Simulation Model and Results

We conducted extensive UNIX based simulations to evaluate the improvement due to the enhanced MAC air-interface and UGC spectrum allocation. Evaluations for enhanced and existing schemes were done for a fair comparison. We also present how the utility graph coloring algorithm (UGC) outperforms any other existing spectrum allocation mechanism. We compare our proposed UGC algorithm under all three system constraint functions.

A. 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 performance. We consider a topology of 100 km radius region where multiple overlapping IEEE 802.22 networks and licensed incumbents reside simultaneously. We present the simulation parameters for our experiments in table I.

B. Simulation results

In Fig. 8, we compare the total system utility achieved by the IEEE 802.22 BSs under utility graph coloring spectrum allocation mechanism and greedy non-collaborative spectrum hogging. Licensed spectrum usage by incumbents are varied from 30% to 75% of the total available

Simulation parameters	Values
Total licensed spectrum band	54 - 806 MHz
Number of overlapping BSs	8
BS/CPE receiving radius	30 - 33 km
BS/CPE sensing radius	30 - 50 km
$B_{i_{min}}$	30 MHz
Control signal frequency	1 - 2 MHz
Data signal frequency	1 - 18 MHz
Broadcast control signaling interval	20 ms
Number of broadcast control signals	2 - 6
Received power threshold	-35 dBm
Path loss exponent α	3.0

TABLE I

SIMULATION PARAMETERS FOR 802.22 SYSTEM

spectrum. In the greedy non-collaborative approach, most of the spectrum bands are wasted due to interference among the greedy and selfish base stations, whereas under the collaborative utility graph coloring mechanism, system utility is improved. Moreover, it is clear from Fig. 8 that with the increase in usage of the licensed spectrum band, the proposed utility graph coloring method produces better result than the non-collaborative approach. For a comprehensive performance evaluation of the proposed scheme, we present the results under all three constraint functions and show that system utility is always better under the proposed scheme than the non-collaborative approach.

In Fig. 9, we compare the performance of utility graph coloring with the traditional graph coloring method of spectrum allocation. It is clear that proposed utility graph coloring mechanism outperforms the traditional graph coloring under both the constraint functions 1 and 2. For constraint function 3, i.e., the complete fairness, any of the either methods would provide same result.

We present the fairness achieved with UGC in Fig. 10 for all the system constraint functions 1, 2 and 3 with changing primary incumbent usage. We use Jain's fairness index [40] to measure

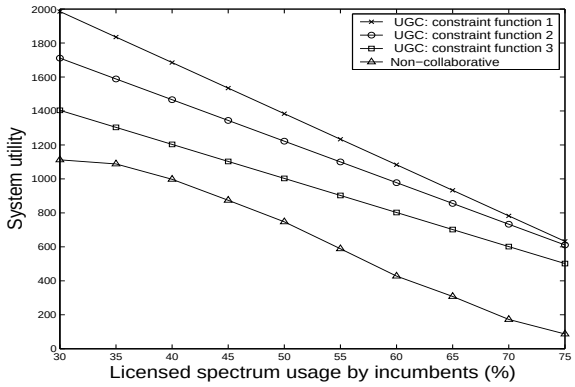


Fig. 8. Total utility achieved by all the BSs under the proposed collaborative approach and greedy non-collaborative approach

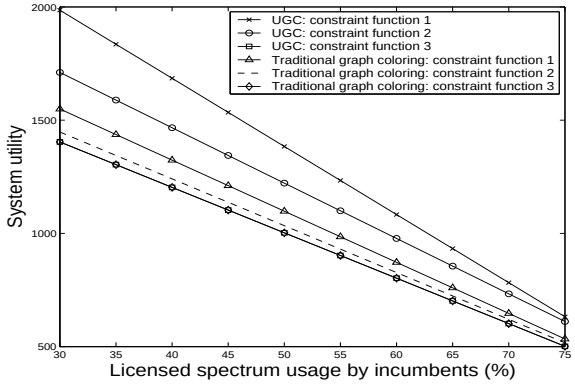


Fig. 9. Total utility achieved by all the BSs under the proposed collaborative approach and greedy, traditional graph coloring approach

the fairness parameter achieved by UGC. We find that in addition to providing better system utility than any other spectrum allocation mechanisms, proposed UGC mechanism shows fairness index more than 0.5, even with the minimal fairness constraint, which is considered to be a good fairness index. (This fairness index lies between 0 and 1; 0 being most unfair and 1 being absolutely fair.) Moreover, the system constraint function of proportional fair utility maintains an excellent fairness index of 0.86 with the proposed mechanism of proportional fairness. As obvious from the nature of system constraint function 3 of complete fairness, Jain's fairness index calculation indicates fairness parameter of 1 treating all the BSs equally.

In figure 11, we show the average spectral efficiency with increase in number of BSs (IEEE 802.22 networks). We find that spectrum allocation with UGC achieves better spectral efficiency

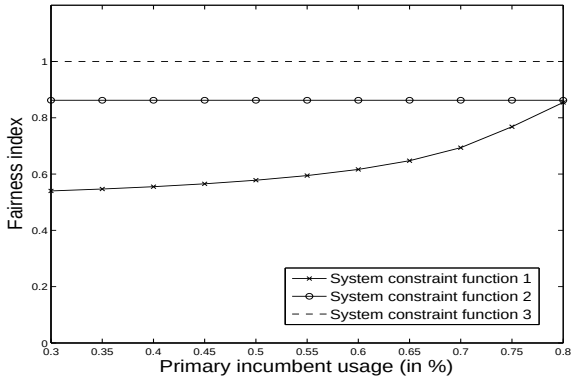


Fig. 10. Jain's fairness index for maximized utility objective function and proportional fair utility objective function

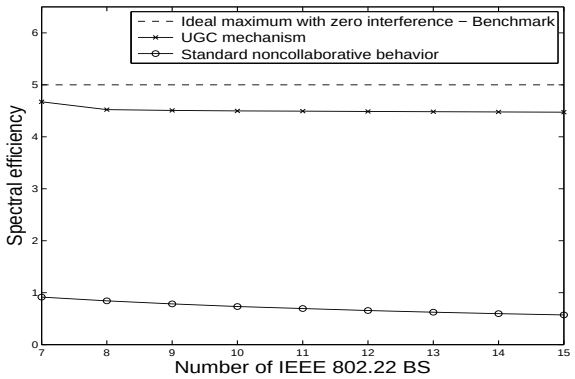


Fig. 11. Average spectral efficiency with increase in number of IEEE 802.22 networks

(almost close to ideal 5 bits/sec/Hz, which is the maximum spectral efficiency [41] that can be achieved in the presence of zero interference – benchmark). Also, with increase in number of BS the difference between UGC and non-UGC increases. This proves the fact that allocating spectrum efficiently following interference constraints in UGC plays a key role for self-coexistence and achieves better system performance. Next, the licensed spectrum usage is varied dynamically and spectral efficiency is calculated. In figure 12, we show the average spectral efficiency with increase in licensed spectrum usage. Note that, when primary incumbent usage is low, both UGC and standard non-collaborative spectrum access produces better spectral efficiency (though UGC produces slightly better results). This is due to the fact that with low primary usage, unused spectrum for secondary usage is sufficient so that even uncoordinated access to the spectrum hardly produces overlapping of the bands and thus interference is low. But with increase in

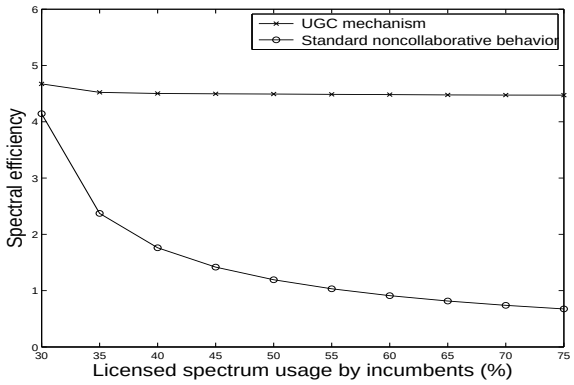


Fig. 12. Average spectral efficiency with increase in licensed incumbent usage

primary usage, spectrum bands for secondary usage gets low. Standard, non-collaborative access produces more and more overlapping of the bands and thus creates more interference. While with UGC, spectrum is allocated considering interference constraints and maximization of spectrum reusage; thus minimizing the interference from other IEEE 802.22 networks, which eventually produces high spectral efficiency even with high primary usage.

Next, we present the results to provide more insights on how our enhanced air-interface would improve the performance. In Fig. 13, we present the probability of a CPE (which just switched on) to connect to a BS. For this scenario, we assumed there is no contention from other CPEs but licensed incumbents (hidden and revealed) are active and operating. As seen from the figure, the probability of successfully connecting to a BS with the dynamic multiple candidate channels is more than the existing single frequency broadcast signaling.

The average initial delay (under no contention from other CPE) to tune to a BS broadcasting signal frequency against the licensed spectrum usage by incumbents is shown in Fig. 14. As expected, with increase in licensed spectrum usage by incumbents (e.g., TV transmission, wireless microphones etc.), the average delay increases, but the average delay with the proposed scheme is always less than the average delay with the existing MAC.

Next, we present the results in the presence of collisions from other IEEE 802.22 enabled devices. In Fig. 15, we show average number of collisions encountered in initializing the network connection against primary incumbents usage. In the existing standard, BS broadcasts single beacon, enabling all the CPEs to snoop on the broadcast beacon to initialize transmission. This results in an increase in the number of contending CPEs for the same broadcast resulting

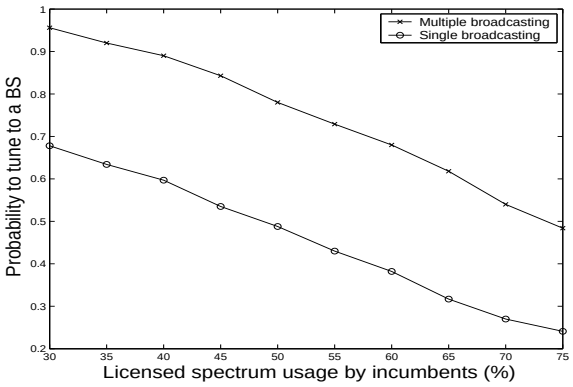


Fig. 13. Probability to tune to a BS (no contention)

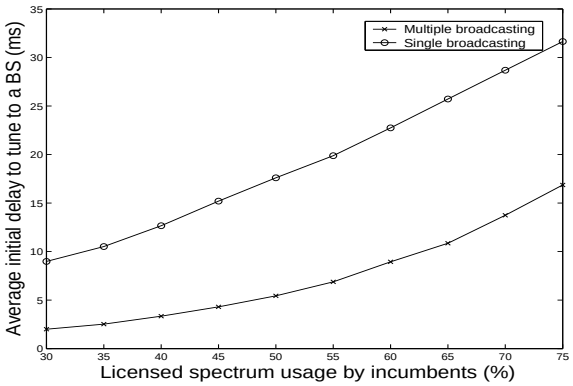


Fig. 14. Average initial delay to tune to a BS broadcasting frequency (no contention)

in increased number of collisions. The proposed MAC with dynamic multiple broadcasting distributes the initialization among multiple frequency channels and thus reduces the number of contending CPEs for each broadcast beacon.

In figures 16(a) and 16(b), we present a more comprehensive result of connection establishment delay (delay between switching on and start of data transmission and receiving) with varying licensed spectrum usage and contention with other CPEs. We calculate the combined delays to tune to a BS broadcasting frequency signal and then successful uplink transmission (transmission of connection identifier and spectrum usage report) through contention resolution mechanism. It is evident from the figures that enhanced MAC (Fig. 16(b)) provides better result in terms of delay to initiate data transmission.

Last but not the least, Fig. 17 presents very important result in terms of system spectrum

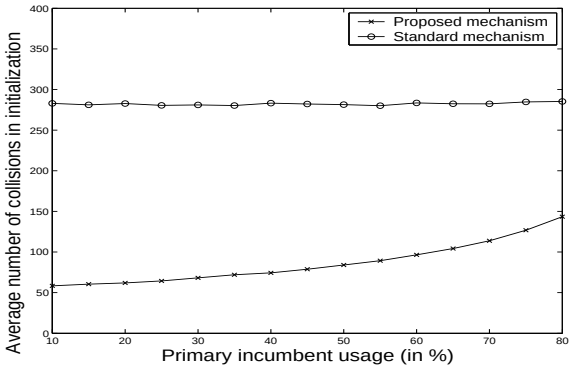
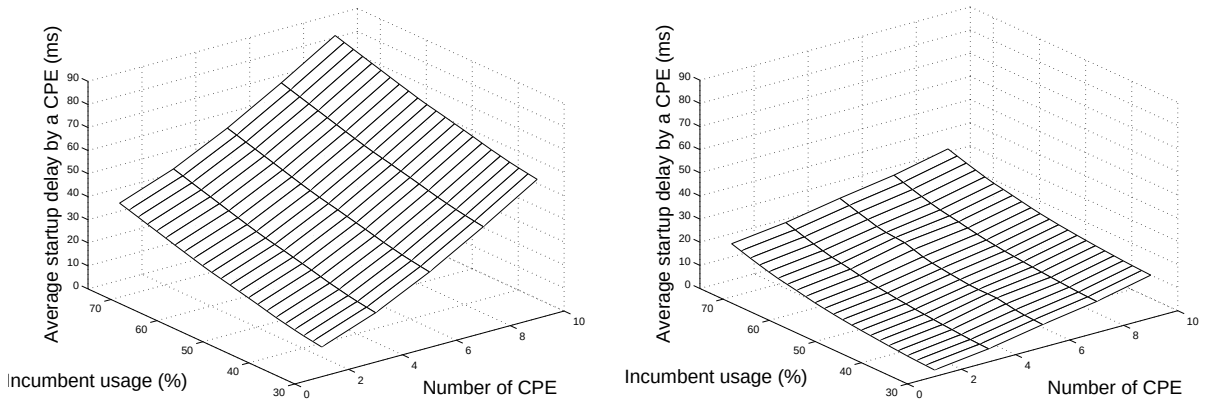


Fig. 15. Average number of collisions among the CPEs



(a) (b)

Fig. 16. a) Average startup delay for existing MAC, and b) Average startup delay for proposed MAC

utilization (in percentage) for data transmission (y-axis) from the residual spectrum for secondary usage. As evident from the figure, in comparison to the existing standard, the enhanced MAC layer functionalities increase the spectrum utilization for data transmission significantly, thus justifying the design of the proposed system for efficient spectrum usage.

VIII. Conclusions

In this research, we provided insights to the workings of the cognitive radio based IEEE 802.22 networks which are meant to harness the under-utilized TV bands. We discussed the problem of self-coexistence (secondary-secondary spectrum etiquettes) and present an interference aware

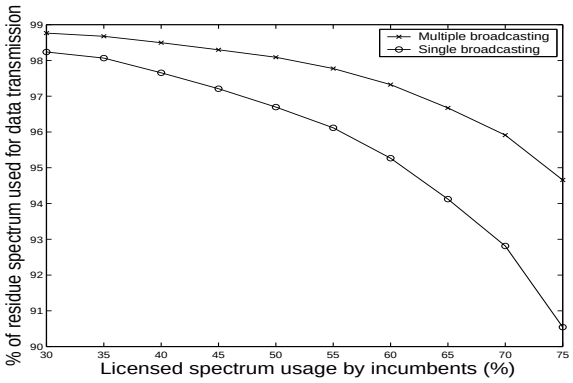


Fig. 17. Spectrum utilization efficiency

framework for IEEE 802.22 air-interface. We propose a utility graph coloring technique for allocating spectrum to multiple IEEE 802.22 networks so that interference across the networks can be minimized. The allocations are done so as to satisfy the desired constraint functions such as minimized fairness, proportional fairness or complete fairness. We analyze the spectral efficiency of the IEEE 802.22 networks and find that with the help of proposed UGC mechanism, spectral efficiency is greatly increased resulting in highly efficient self-coexistent networks. To address the interference issue to/from the primary incumbents and establish dynamic and fast connection in IEEE 802.22 network, we provided enhancements to the flexible MAC features that greatly improved the performance compared to the existing IEEE 802.22 MAC standard mechanisms. With the help of dynamic allocation of foreign broadcast beacons at multiple non-interfering frequencies, we were able to use available spectrum efficiently even in the presence of hidden primary incumbents. We also reduced the number of collisions among the IEEE 802.22 enabled devices resulting in quicker connection initialization. Simulation results have demonstrated that the proposed mechanisms provide better system utility, high Jain's fairness index along with efficient spectrum utilization for data transmission and less connection establishment delay.

REFERENCES

[1] [Online]. Available: http://www.sharedspectrum.com/papers/spectrum-reports/

[2] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum," *Sixth IEEE International Symposium on World of Wireless Mobile and Multimedia Networks (WoWMoM)*, pp. 78–85, June 2005.

[3] Federal Communications Commission (FCC), “Notice of proposed rule making”, ET Docket no. 04-113, May 2004.

[4] J. Mitola and G. M. Jr., “Cognitive radio: making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[5] “IEEE 802.22 Working Group on Wireless Regional Area Networks.” [Online]. Available: http://www.ieee802.org/22/

[6] “IEEE P802.22 draft standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV bands,” 2006.

[7] Federal Communications Commission (FCC), “In the matter of unlicensed operation in the TV broadcast bands,” Second Report and Order and Memorandum Opinion and Order, no. FCC-08-260A1, Nov. 2008.

[8] A. Attar, S. A. Ghorashi, M. Sooriyabandara, and A. H. Aghvami, “Challenges of real-time secondary usage of spectrum,” *Computer Networks*, vol. 52, no. 4, pp. 816–830, 2008.

[9] H. Liu and S. Li, “Research on the mechanism of wran self-coexistence,” *International Symposium on Electromagnetic Compatibility, EMC*, pp. 67–70, 2007.

[10] S. Sengupta, S. Brahma, M. Chatterjee, and S. Shankar, “Enhancements to cognitive radio based ieee 802.22 air-interface,” *IEEE International Conference on Communications (ICC)*, pp. 5155–5160, 2007.

[11] G. Ganesan and Y. Li, “Cooperative spectrum sensing in cognitive radio networks, part i: Two user networks and part ii: Multiuser networks,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 6, pp. 2204–2222, June 2007.

[12] A. Ghasemi and E. S. Sousa, “Spectrum sensing in cognitive radio networks: the cooperation-processing tradeoff,” *Wireless Communications and Mobile Computing*, vol. 7, no. 9, pp. 1049–1060, 2007.

[13] X. Liu and N. Sai-Shankar, “Sensing-based opportunistic channel access,” *Mobile Networks and Applications*, vol. 11, no. 4, pp. 577–591, 2006.

[14] A. Sahai, N. Hoven, and R. Tandra, “Some fundamental limits on cognitive radio,” *Forty-second Allerton Conference on Communication, Control and Computing*, Oct. 2004.

[15] N. Han, S. Shon, J. Chung, and J. Kim, “Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems,” *8th Intl. Conference on Advanced Communication Technology (ICACT)*, vol. 3, pp. 1–6, 2006.

[16] H.-S. Chen, W. Gao, and D. Daut, “Signature based spectrum sensing algorithms for IEEE 802.22 wran,” *IEEE International Conference on Communications (ICC)*, pp. 6487–6492, June 2007.

[17] N. Kundargi and A. Tewfik, “Sequential pilot sensing of atsc signals in ieee 802.22 cognitive radio networks,” *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 2789–2792, 2008.

[18] W. Hu, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, “Cognitive radios for dynamic spectrum access - dynamic frequency hopping communities for efficient IEEE 802.22 operation,” *IEEE Communications*

Magazine, vol. 45, no. 5, pp. 80–87, May 2007.

[19] X. Gelabert, I. F. Akyildiz, O. Sallent, and R. Agustí, "Operating point selection for primary and secondary users in cognitive radio networks," *Computer Networks*, vol. 53, no. 8, pp. 1158–1170, 2009.

[20] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *9th annual international conference on Mobile computing and networking (MobiCom)*, pp. 66–80, 2003.

[21] I. Katzela, and M. Naghshineh, "Channel assignment schems for celluar mobile telecommunication systems," *IEEE Personal Communications*, vol. 3, pp. 10–31, 1996.

[22] S. Khanna and K. Kumaran, "On wireless spectrum estimation and generalized graph coloring," *IEEE INFOCOM*, vol. 3, pp. 1273–1283 vol.3, Mar-2 Apr 1998.

[23] A. Koster, "Frequency assignment: Models and algorithms," Ph.D. dissertation, Universiteit Maastricht, Maastricht, The Netherlands, 1999.

[24] L. narayanan, "Channel assignment and graph multicoloring," *Handbook of wireless networks and mobile computing*, pp. 71–94, 2002.

[25] A. Safwat, "Distributed connection admission control and dynamic channel allocation in ad hoc-cellular networks," *International Conference on Digital Telecommunications (ICDT)*, pp. 52–52, Aug. 2006.

[26] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted coloring based channel assignment for WLANs", *SIGMOBILE Mobile Computer Communication Rev.*, pp. 19–31, 2005.

[27] S. Avalallone, I. Akyldiz, "A channel assignment algorithm for multi-radio wireless mesh networks", *Computer Communications*, pp. 1343–1353, 2008.

[28] W. Wang and X. Liu, "Dynamic channel sharing in open-spectrum wireless networks," *IEEE VTC Fall 2005*, Sep. 2005.

[29] J. Tang, S. Misra, and G. Xue, "Joint spectrum allocation and scheduling for fair spectrum sharing in cognitive radio wireless networks," *Computer Networks*, vol. 52, no. 11, pp. 2148–2158, 2008.

[30] W. Hu, M. Gerla, G. Vlantis, and G. Pottie, "Efficient, flexible, and scalable inter-network spectrum sharing and communications in cognitive ieee 802.22 networks," *First International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART)*, pp. 1–5, Feb. 2008.

[31] V. Gardellin, S. K. Das, and L. Lenzini, "A Fully Distributed Game Theoretic Approach to Guarantee Self-Coexistence among WRANs," *In IEEE INFOCOM-2010 Workshop on Cognitive Wireless Communications and Networking*, San Diego, CA, USA, 19 Mar. 2010.

[32] S. Sengupta, R. Chandramouli, S. Brahma, and M. Chatterjee, "A Game Theoretic Framework for Distributed Self-Coexistence Among IEEE 802.22 Networks," *In Proc. of IEEE GLOBECOM 2008*, pp. 1–6, 2008.

[33] H. Liu, S. Li, "Research on the Mechanism of WRAN Self-Coexistence International Symposium on Electromagnetic Compatibility," EMC 2007, pp. 67-70.

[34] F. Kuhn and R. Wattenhofer, "On the complexity of distributed graph coloring," *Proceedings of the twenty-fifth annual ACM symposium on Principles of distributed computing*, pp. 7–15, 2006.

[35] D. Fudenberg and J. Tirole, *Game Theory*. MIT Press, 1991.

[36] T. Cormen, C. Leiserson, R. Rivest, and C. Stein, *Introduction to Algorithms*. The MIT Press and McGraw-Hill, 2001.

[37] D. Welsh and M. Powell, "An upper bound for the chromatic number of a graph and its application to timetabling problems," *Computer Journal*, Sep. 1967-68.

[38] C. E. Shannon, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, pp. 379–423, 1948.

[39] S. De, C. Qiao, D. Pados, and M. Chatterjee, "Topological and mai constraints on the performance of wireless cdma sensor networks," *IEEE INFOCOM*, vol. 1, pp. 256–265, March 2004.

[40] R. Jain, *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation and Modeling*. New York, USA: John Wiley & Sons.

[41] C. Cordeiro, K. Challapali, D. Birru, and S. Shankar, "IEEE 802.22: the first worldwide wireless standard based on cognitive radios," *IEEE DySPAN*, pp. 328–337, 2005.