A coordinated distributed scheme for cognitive radio based IEEE 802.22 wireless mesh networks

Shamik Sengupta
Department of Electrical and
Computer Engineering
Stevens Institute of Technology
New Jersey 07030
Email: Shamik.Sengupta@stevens.edu

Mainak Chatterjee
School of Electrical Engineering and
Computer Science
University of Central Florida
Orlando, FL 32816-2450
Email: mainak@eecs.ucf.edu

Rajarathnam Chandramouli
Department of Electrical and
Computer Engineering
Stevens Institute of Technology
New Jersey 07030
Email: mouli@stevens.edu

***Abstract*—The IEEE 802.22 standard based on cognitive radio is envisioned as one of the solutions that can harness the unused or under-utilized spectrum that was primarily been allocated for licensed TV services. This allows the cognitive radio enabled devices to opportunistically use the spectrum without spatial and temporal interference with the licensed devices. Alongside, the success of wireless mesh networks is enabling the possibility of creating wide-area wireless back-haul networks that will have increased network resource utilization and better performance.**

In this paper, we study the limitations of the current IEEE 802.22 MAC in mesh establishment and propose a coordinated distributed scheme for IEEE 802.22 enabled devices to establish a mesh network with reduced latency and control signaling. The coordination is initiated by the base station and is followed by the gradual joining of the IEEE 802.22 consumer premise equipments to the mesh network in a repeated, distributed manner. Through extensive simulation experiments, we demonstrate how the proposed mesh creation algorithm helps minimize mesh initialization latency, reduce control signaling, reduce start-up delay, reduce collisions during network initialization, and most importantly, increase spectrum utilization among IEEE 802.22 devices.

I. INTRODUCTION

Spectrum allocations for various wireless services such as the military, government, private and public communications systems are usually static in nature. Moreover, these allocations are long-term and any changes are made under the strict guidance of a governmental agency, e.g., Federal Communications Commission (FCC) in United States of America. An experimental study conducted during the 2004 Republic National Convention [10] found that spectrum utilization is typically time and space dependent and there is a great amount of “white space” (unused bands) available sparsely in the entire spectrum. Similar results were published in [4] for public safety bands. As a result, it is intuitive that static spectrum allocation may not be the optimal solution toward efficient spectrum access for both licensed and unlicensed services.

As far as the sub–900 MHz TV bands are concerned, the VHF and UHF bands are 6 MHz per TV channel. This was based on old analog NTSC system even though better quality video can now be broadcasted with almost 50% less spectrum per channel [1]. With the ever growing penetration of cable–TV and the phase out of old technologies, the limitations of static spectrum allocation is even more evident. Thus FCC defined provisions to open the sub–900 MHz TV bands for unlicensed services, though it is mandated for the unlicensed devices to detect and avoid interference with the licensed users (primary incumbents) in a timely manner [9]. 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 [8]. The aim of IEEE 802.22 is to use spectrum bands dynamically through incumbent sensing and avoidance. 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 radio systems perform spectrum sensing, dynamically identify unused spectrum, and operate in the spectrum band when it is not used by the primary incumbent radio systems [5], [6]. Upon detecting incumbents, cognitive radio enabled devices are required to switch to another channel or mode.

The core components of the cognitive radio based IEEE 802.22 system are the base stations (BSs) and the Consumer Premise Equipments (CPEs) [2]. In such a network, a BS typically manages its own cell by controlling the on-air activity, 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) mode. In the point–to–multipoint mode, traffic is directed from the BS to the CPEs or vice-versa. All the traffic is centrally coordinated by the BS, and thus, the BS might become a bottleneck. Moreover, in the case of hidden incumbent problem [7], 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 [9]. Therefore, instead of providing a centralized access through the BS, the other alternative of point–to–point architecture that can create a wide-area wireless backhaul mesh network can be used. In the mesh mode, traffic can flow among the CPEs directly. However, unlike other wireless mesh networks (IEEE 802.11 or 802.16), IEEE 802.22 faces a unique problem during connection establishment. In IEEE 802.22, there is no predefined 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. Thus the devices cannot know a priori what frequency bands other devices are operating on. This gives rise to two very important questions: (i) how do CPEs identify other CPE neighbors and communicate with them to build the wireless mesh network, and (ii) how is the communication done across the entire network so that interference in the mesh network is minimized and the spectrum utilization is maximized? To the best of our knowledge, this research is the first attempt to address these issues in IEEE 802.22 mesh network.

In this paper, we attempt to answer the above mentioned questions. In this regard, we propose a beacon-based coordinated distributed scheme to create and handle the mesh architecture. The coordinated strategy has a cognitive BS, which controls the CPEs and their dynamic spectrum access through beacon handshaking. The subset of CPEs upon receiving control packets and successfully establishing initial connection with the BS become pseudo-BSs. The process is iterated for rest of the CPEs. We adaptively manipulate the foreign beacon period (FBP), where beacon broadcasts from the BS and pseudo-BSs occur in a time divisioned collision free manner. We find that through the coordinated distributed scheme, BS/CPEs can create IEEE 802.22 wireless mesh network quickly and if needed, can switch channel. We show how the collaborative approach among WRAN devices outperforms the greedy non-collaborative approach. Through simulation experiments, we demonstrate that the proposed techniques help IEEE 802.22 systems to lower mesh initialization latency and increase spectrum utilization.

The rest of the paper is organized as follows. The IEEE 802.22 mesh architecture is explained in section II. In section III, we address the issue of mesh initialization through control signaling and dynamic allocation of broadcasting beacon periods. In section IV, simulation models and results are presented. Conclusions are drawn in the last section.

II. IEEE 802.22 MESH ARCHITECTURE

In the mesh network, when multiple CPEs and BS operate in close proximity, each of the CPEs' ideal aim would be to grab 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 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 mesh initialization method needs to be invoked. The mesh establishment 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.

We propose a simple yet elegant way to iteratively create a mesh network. An illustrative example of how CPEs dispersed randomly over a region join the mesh network is shown in Fig. 1. We present four snapshots of the gradual mesh network creation to show how the CPEs get connected to the mesh. In the iteration 0, no CPE is connected to the mesh and we assume BS to initiate the coordination by broadcasting beacons. In the iteration 1, CPEs listening to the broadcasts, contend among themselves. The winners connect to the BS, request for pseudo-BS id and upon receiving pseudo-BS id, broadcast beacons with coordination with BS. In this research, we focus on choosing the winners efficiently with the objective of reduced mesh initialization latency. Unconnected CPEs continue to listen to multiple broadcasts and try to connect to the mesh and the process iterates as shown in iteration 2 and 3.

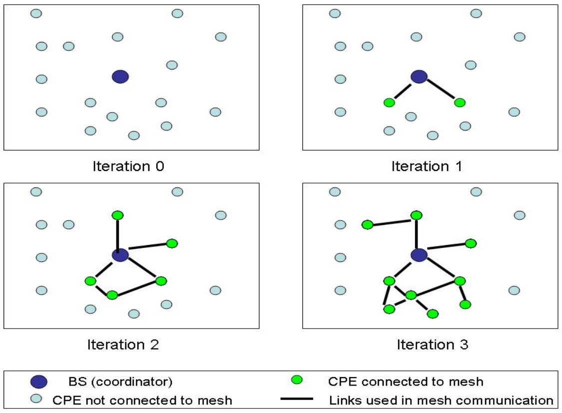


Fig. 1. Iterative mesh creation

III. ESTABLISHING MESH WITH ENHANCED MAC

In an IEEE 802.22 mesh network, communications can be facilitated by (i) dynamically selecting spectrum bands for the CPEs to exchange control information, (ii) adaptively determining and using alternate spectrum bands for control channels if the original control channel is not usable due to the primary incumbent return or hidden incumbent, and (iii) allocating a set of channels to each CPE so that it can initiate data transmission with minimum latency. In this regard, we present four enhancements that are used simultaneously to improve the MAC performance for mesh establishment.

A. Allocating beacon period dynamically

In sub-900 MHz spectrum range, TV transmitters (primary users) and WRAN BS (secondary users) broadcast beacons 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 beacons 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 beacons.

Unlike the existing standard, where beacon periods are pre-defined, we propose using the foreign beacon period duration dynamically. To cope with the primary incumbents, IEEE 802.22 BS will coordinate the adaptive foreign beacon period and will announce the largest FBP duration in each iteration depending on the number of psedo-BSs. Moreover, as we are dealing with initial connection establishment of mesh network, we no longer confine foreign beacon period with BS broadcasting. In addition, we propose to use pseudo-BSs also to broadcast beacons in a TDMA manner within the FBP coordinated by BS. In Fig. 2, we illustrate an example of beacon broadcasting. The first superframe has the FBP length of 2 units, whereas the second superframe has the FBP length of 5 units.

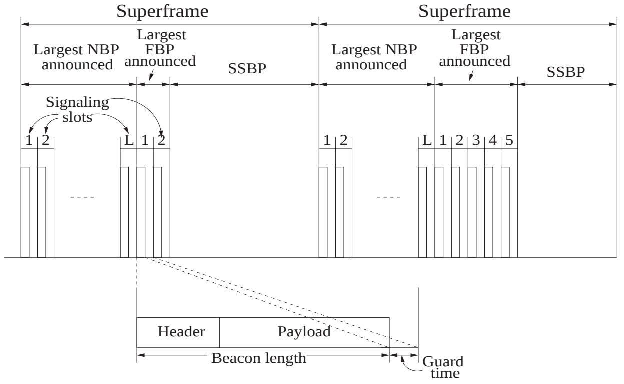


Fig. 2. Beacon period

CPEs not connected to the mesh will try to tune to the BS/pseudo-BSs after obtaining frequency information from the broadcasts. (The mechanism of how the pseudo-BSs are created will be presented in subsection III-B.) The advantage of broadcasting beacons from multiple CPEs with special permission (pseudo-BS) in addition to BS broadcasting is that CPEs not yet connected to the mesh will have more opportunities to connect to the mesh as it can connect to any of the broadcasters. This is in contrast to the existing standard where CPEs must tune to the BS first to connect to any other neighboring CPE. Thus existing standard would lead to higher contention among CPEs and higher latency in mesh building.

In the proposed enhancement, the number of pseudo-BSs is increased with each FBP until all the CPEs are connected to the mesh, thus requiring dynamic FBP interval in each iteration. Each of these foreign beacon periods occurs after a certain interval called *BSS_Interval*. The same downlink frequency band is used for broadcasting in TDMA manner by all BS/pseudo-BSs to reduce control frequency usage. We use separate uplink frequencies for each of the BS and pseudo-BSs, which is different from the broadcast beacon frequency. As separate uplink frequencies are used for BS and each of the pseudo-BSs, the number of collisions among the CPEs contending for the uplink control channel will greatly reduce.

B. Initial mesh establishment through pseudo-BS

With the control frequencies and beacon periods defined, we present the two step process of mesh establishment.

1) Initial beacon broadcast phase: All CPEs wait for the very first mesh broadcast from the BS during mesh initiation. Upon receiving the broadcast beacon, the CPEs intending to connect to the mesh, measure the signal-to-interference ratio (SIR) to evaluate the link quality. The signal-to-interference ratio measured at receiver (CPE) j associated with transmitter (BS) i can be expressed as additive white gaussian noise

$$SIR_{ij} = \frac{p_i G_{ij}}{\mathcal{W} + \sum_{k\neq i} p_k G_{kj} H(k,j)} \tag{1}$$

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

$$H(k,j) = \begin{cases} 1 & \text{if } k,j \text{ operating on same frequency band} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

If the SIR (link quality) is better than a certain pre-defined threshold (Q_1), then the frequency channel with which the BS is broadcasting in the downlink, is assumed to be available. Otherwise, if the SIR is below the threshold (which may be due to primary incumbents), the broadcast is assumed to be not decodable. The CPEs discard the frequency band and keep quiet. BS or the sender do not receive any connection request from the CPEs, the round-trip timer expires and chooses different frequency band for broadcasting in the next FBP.

2) Mesh establishment through coordinated distributed handshaking: The CPEs, which are able to decode the signal update their potential 1-hop and 2-hop neighbor table, obtain the uplink frequency information from the beacon payload, and contend among themselves to connect to the BS with the contention resolution protocol similar to IEEE 802.11. The CPE(s) winning the contention, tune to the BS with the uplink frequency with unique identifier(s) of the CPE(s), the spectrum usage report, potential 1-hop and 2-hop neighbors information and pseudo-BS identifier request; BS then becomes aware of the existence of the CPE(s). Note that at the beginning, a CPE may have no potential neighbor other than the BS (as it can hear only 1 broadcast). The BS upon acceptance of the feedback, coordinates on spectrum usage for data transmission and provides unique pseudo-BS identifier(s) and global timestamp(s) to the CPE(s). The global timestamp indicates which slot in the FBP the pseudo-BS will broadcast.

Rest of the CPEs which were not able to connect to the BS, observe multiple broadcasts and connect to the broadcaster(s) provided the SIR is above threshold (Q_1) and follow the same mechanism. As there are multiple beacon broadcasts each with separate uplink frequency, multiple CPEs can connect to the mesh simultaneously in a coordinated distributed manner. The process is repeated until all the CPEs are connected to the mesh and after that periodical mesh beacon broadcasting is continued for allocation of spectrum maintenance. This mechanism reduces the number of collisions among the contending

CPEs and thus minimizes the latency for a CPE to connect to the mesh. Moreover, as each of the beacon broadcasts from the BS and pseudo-BS contains information of potential 1-hop and 2-hop neighbors in the payload, each WRAN device will also obtain at least 2-hop topology information of the network, which would be advantageous in data spectrum allocation.

C. Aggressive contention resolution

As mentioned above, the CPEs tuning to the same broadcaster in the uplink contend among themselves with the contention resolution protocol similar to IEEE 802.11. The only difference in the contention resolution protocol lies in generating the 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 SIR received. For this purpose, we choose another SIR threshold Q_2 which is greater than Q_1. CPEs with SIR greater than Q_2 acts aggressively in choosing a smaller initial random backoff range than the CPEs with SIR below Q_2. Note, all the CPEs considered in this contention algorithm receive SIR above Q_1.

Let us present an example to illustrate the case. Let two CPEs A and B receive SIR as q_1 and q_2 from one particular beacon broadcast. We assume $Q_1 < q_1 < Q_2 < q_2$ for the CPEs. 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 SIRs (or in other words, CPEs closer to the source of the beacon broadcast) to be favored in connecting to the mesh than the CPEs far from the source. This would help in gradual mesh expansion with CPEs with higher SIRs becoming pseudo-BS early.

In this regard, we analyze the probability of winning a contention by a CPE to synchronize to a BS/pseudo-BS under the presence of existing and proposed random backoff values. We assume M CPEs contend in the uplink while N of those CPEs ($M > N$) are close to the source of the beacon broadcasting in the particular period, i.e., N CPEs receive SIR above Q_2. B is one such CPE (with SIR 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

$$P_{existing} = \Big(\frac{1}{y}\Big)\Big(\frac{y-1}{y}\Big)^{(M-1)} \tag{3}$$

The probability of success with proposed MAC is

$$P_{proposed} = \Big(\frac{1}{x}\Big)\Big(\frac{x-1}{x}\Big)^{(N-1)}\Big(\frac{y-1}{y}\Big)^{(M-N)} \tag{4}$$

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

$$P_{gain} = \frac{P_{proposed}}{P_{existing}} = \frac{(\frac{x-1}{y-1})^{(N-1)}}{(\frac{x}{y})^{N}} \tag{5}$$

If x and y are large numbers such that we can assume $x-1 \approx x$ and $y-1 \approx y$ then equation (5) can be reduced to

$$P_{gain} = \frac{(\frac{x}{y})^{(N-1)}}{(\frac{x}{y})^{N}} = \frac{y}{x} \tag{6}$$

$P_{gain} > 1$ 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

$$P_{gain} > 1 \quad \text{for} \quad N \leq N_{max} \tag{7}$$

where, N_{max} is the upper bound on how many CPEs can act aggressively. 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.

IV. SIMULATION EXPERIMENTS AND RESULTS

We have conducted simulation experiments to evaluate the improvements achieved by the enhanced MAC of IEEE 802.22. We compare our proposed mechanism with the existing standard version of IEEE 802.22. In the existing standard version, only BS is allowed to broadcast beacons and there is no concept of pseudo-BS.

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 improvements due to the enhanced PHY/MAC air-interface. 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 [3], 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 I, we present rest of the simulation parameters.

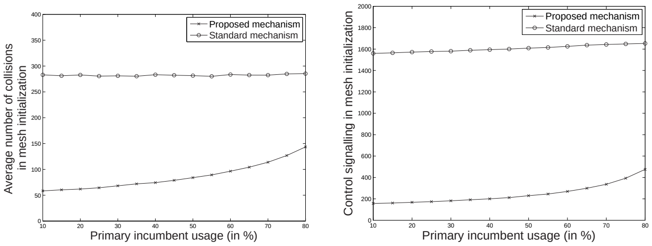
TABLE I

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	1 - 3

B. Simulation results

In Fig. 3(a), we show the comparison of average number of collisions encountered in initializing the mesh against primary incumbents usage. In the existing standard, only BS broadcasts periodic beacons, enabling all the CPEs to snoop on the broadcast beacons to initialize transmission. This results in an increase in the number of contending CPEs for the same broadcast resulting in increased number of collisions. The proposed MAC with dynamic multiple broadcasting distributes the initialization among multiple pseudo-BSs and thus reduces the number of contending CPEs for each broadcast beacon. Though with increase in primary incumbents usage, the number of collisions increases slightly for proposed scheme, proposed scheme still provides better result than the existing scheme. Fig. 3(b) shows similar trend of improvement for the proposed MAC in terms of total amount of control signaling.



(a) (b)

Fig. 3. a) Average number of collisions among the CPEs; b) Average number of control signal messages in mesh initialization

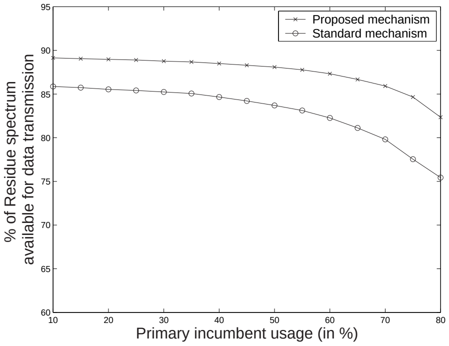
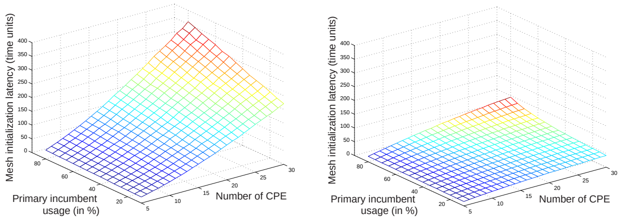


Fig. 4. Spectrum utilization efficiency

Fig. 4 presents an important result in terms of spectrum utilization for data transmission in IEEE 802.22 mesh. As total amount of control signaling in mesh initialization is much lesser for proposed scheme than the standard scheme, the proposed mechanism of enhancing the MAC layer obtains better data spectrum utilization than the existing MAC layer.

In figures 5(a) and 5(b), we present mesh initialization latency under contention with both CPEs and licensed incumbents. The average startup latency (delay between switching on and start of data transmission and receiving) is compared for both existing and proposed MAC. It is evident from the figures that enhanced MAC (Fig. 5(b)) provides better results in terms of delay to initiate data transmission with an almost three-fold decrease in the mesh initialization latency.



(a) (b)

Fig. 5. a) Average startup delay for existing MAC; b) Average startup delay for proposed MAC

V. CONCLUSIONS

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 initial topology discovery and mesh establishment among WRAN devices. With the help of dynamic allocation of broadcast beacon periods at multiple non-interfering frequencies and introduction of pseudo-BS concept, we reduced the number of collisions resulting in quicker mesh initialization. Through simulation experiments, we found that the proposed enhancements to the IEEE 802.22 MAC could reduce control signals, number of collisions, mesh initialization latency and also increased the spectrum utilization obtained from the system.

REFERENCES

[1] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan and J. Evans, “DIMSUMnet: New Directions in Wireless Networking Using Coordinated Dynamic Spectrum Access”, IEEE WoWMoM 2005, pp. 78-85.

[2] C. Cordeiro, K. Challapali, D. Birru, Sai Shankar, “IEEE 802.22: the first worldwide wireless standard based on cognitive radios”, IEEE DySPAN 2005, pp. 328 - 337.

[3] J. Gong, D. Reed, T. Shaw, D. Vivanco, and J. Martin, “QAM Resource Allocation in Mixed-Format VoD Systems”, JOURNAL OF COMMUNICATIONS (JCM), vol. 2, Issue 1, 2007, pp. 1-9.

[4] S. D. Jones, E. Jung, X. Liu, N. Merheb, I-J. Wang, “Characterization of Spectrum Activities in the U.S. Public Safety Band for Opportunistic Spectrum Access”, IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2007, pp. 137-146.

[5] M. Pitchaimani, B. J. Ewy, J. B. Evans, “Evaluating Techniques for Network Layer Independence in Cognitive Networks”, IEEE International Conference on Communications, June 2007, pp. 6527-6531.

[6] D. Raychaudhuri, N. Mandayam, J. Evans, B. Ewy, S. Seshan, P. Steenkiste, “CogNet An Architectural Foundation for Experimental Cognitive Radio Networks within the Future Internet”, Proceedings of ACM/IEEE MobiArch 2006, San Francisco, December 2006.

[7] S. Sengupta, S. Brahma, M. Chatterjee and Sai Shankar N, “Enhancements to cognitive radio based IEEE 802.22 air-interface”, IEEE International Conference on Communications (ICC) 2007.

[8] http://www.ieee802.org/22/

[9] Federal Communications Commission (FCC), “Notice of Proposed Rule Making”, ET Docket no. 04-113, May, 2004.

[10] http://www.sharedspectrum.com/inc/content/measurements/nsf/NYC_report.pdf.