Dynamic Frequency Hopping Communities for Efficient IEEE 802.22 Operation

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***Abstract*— One of the key challenges of the emerging Cognitive Radio based IEEE 802.22 Wireless Regional Area Networks (WRAN) is to address two apparently conflicting requirements: assuring QoS satisfaction for WRAN services, while providing reliable spectrum sensing for guaranteeing licensed user protection. To perform reliable sensing, in the basic operation mode on a single frequency band (the non-hopping mode), one has to allocate Quiet Times, i.e. periodically interrupt data transmission which could impair the QoS of WRAN. This critical issue can be addressed by an alternative operation mode proposed in 802.22 called Dynamic Frequency Hopping (DFH) where WRAN data transmission is performed in parallel with spectrum sensing without interruptions. DFH Community, as described in this paper, is a mechanism that coordinates multiple WRAN cells operating in the DFH mode such that efficient frequency usage and reliable channel sensing are achieved. The key idea of DFH Community is that neighboring WRAN cells form cooperating communities which coordinate their DFH operations.**

I. INTRODUCTION

Cognitive Radio [1] has been considered as an enabling technology that allows unlicensed radio transmitters to operate in the licensed bands at locations where that spectrum is temporally not in use. Based on cognitive radio technology, IEEE802.22 [2][3], following an FCC NPRM (Notice of Proposed Rulemaking) in 2004 [4], is an emerging standard for Wireless Regional Area Networks (WRANs) operating on license-exempt and non-interference basis in the spectrum allocated to TV broadcast services (between 47-910 MHz). It aims at providing alternative broadband wireless Internet access in rural areas without creating harmful interference to licensed TV broadcasting.

As depicted in Figure 1. an 802.22 WRAN cell consists of a Base Station (BS) and the associated Customer Premise Equipments (CPEs) that communicate to the BS via a fixed point-to-multi-point radio air interface. The typical radius of the coverage area is 33 km [5]. Apart from coexisting with Digital TV (DTV) services, 802.22 cells also have to be aware of Part 74 devices (such as wireless microphones) and other licensed devices in the TV bands. It is envisioned that channel (frequency) availability for data transmission of a WRAN cell is determined by referring to an up-to-date incumbent database augmented by distributed spectrum sensing performed continuously both by the BS and the CPEs. A preliminary overview on IEEE 802.22 systems can be found in [6].

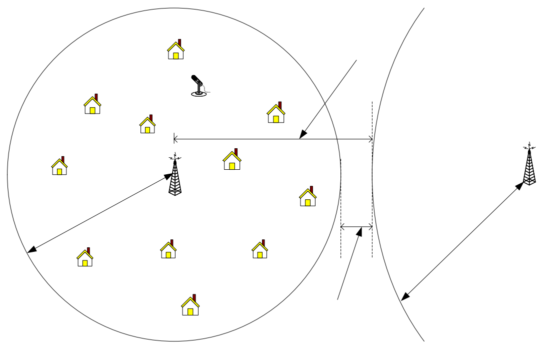

Figure 1. A Typical 802.22 WRAN Cell coexisting with DTV and Part 74 Devices

WRAN operations need to satisfy two apparently conflicting requirements: assure the Quality of Service (QoS) satisfaction for WRAN services while providing reliable and timely spectrum sensing for guaranteeing the licensed user protection. In fact 802.22 requires that the maximum transmission delay is 20ms in order to support VoIP and other delay-sensitive services [5]. On the other hand, the sensing reliability required by DTV incumbents is quite high (i.e. WRAN devices shall be able to detect DTV signals above a detection threshold of -116dBm with at least 90% probability of detection and at most 10% probability of false alarm [5]). Analyses of well-known sensing technologies show that the sensing task takes up to several tens of milliseconds per channel [7], given the required reliability. For example, the DTV energy detection at 6MHz requires 69.43ms per channel. In fact, because of out-of band interference, a channel can be considered to be free only if its adjacent channels are also free, making it necessary to sense several channels. Hence, a sensing period can range from tens of milliseconds up to more than 100 milliseconds. In addition, it is required that licensed incumbent signals shall be detected by WRAN devices with no more than 2 seconds "delay", starting from the time the licensed signal exceeds the detection threshold on a TV channel [5]. In other words, a WRAN cell has to perform sensing on a working channel at least every 2 seconds.

A channel which is to be sensed cannot be used for data transmission. Thus, a WRAN cell operating consistently on a single channel has to interrupt data transmission every 2 seconds for sensing and continue to transmit on that channel only if no incumbent was detected. This so called *non-hopping mode* is the basic mode of 802.22 systems [3]. Such periodic interruptions of data transmission however decrease the system throughput and can significantly impair the QoS of 802.22 systems (e.g. interruption of more than 20ms is usually considered to be harmful for voice transmission).

In order to mitigate this phenomenon Dynamic Frequency Hopping (DFH) has been proposed recently in IEEE 802.22 [3][8]. In the DFH mode a WRAN cell hops over a set of channels. During operation on a working channel, sensing is performed in parallel on the intended next working channels. After 2 seconds, a channel switch takes place: one of the intended next working channels becomes the new working channel; the channel previously used is vacated. Hence, no interruption is required any longer for sensing. Obviously, efficient frequency usage and mutual interference-free spectrum sensing can only be achieved if multiple neighboring WRAN cells operating in the DFH mode coordinate their hopping behavior.

Motivated by this requirement we propose in this paper the concept of DFH Communities (DFHC) [9] and assess its advantages. The key idea of DFHC is that neighboring WRAN cells form cooperating communities which choose their hopping channels and perform DFH operation in a coordinated manner. The further major contribution of this paper is to develop concepts of fundamental mechanisms for managing such cooperative communities.

The reminder of this paper is organized as follows. In Section II we describe the principle of DFH. Section III presents and discusses the concept of DFHC in detail. Section IV introduces mechanisms and protocols for initiating and maintaining a DFHC and Section V proposes mechanisms for the coexistence of multiple DFHCs. A performance analysis is given in Section VI. Section VII concludes the paper.

II. Dynamic Frequency Hopping

The following is a brief description of the principle of Dynamic Frequency Hopping.

A. *Simultaneous Sensing and Data Transmission*

A WRAN cell in the DFH mode uses the working (in-band) channel for data transmission and performs spectrum sensing on out-of-band channels simultaneously as shown in Figure 2. We refer to this operation as Simultaneous Sensing and Data Transmissions (SSDT). Guard bands between the in-band and out-of-band channels are allocated to mitigate adjacent interference caused by data transmission to the out-of-band sensing. An out-of-band channel sensed to be vacant is considered to be validated.

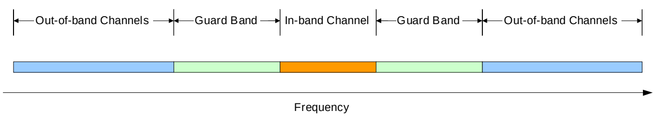

Figure 2. Simultaneous Sensing and Data Transmission

B. *Dynamic Frequency Hopping Operation*

As previously mentioned a WRAN cell can use a working channel for up to two seconds before it has to perform spectrum sensing in order to re-validate the channel.

The DFH mode works as follows: The time axis is divided into consecutive operation periods, in each of which a WRAN is operating on a validated channel, while simultaneously sensing – and validating – out-of-band channels as explained above (SSDT). A WRAN system in the DFH mode thus, as shown in Figure 3, dynamically selects one of the channels validated in a previous operation period for data transmission in the next operation period. This channel can be used for data transmission for up to two seconds (the maximum channel detection time [5]) after the time it was validated.

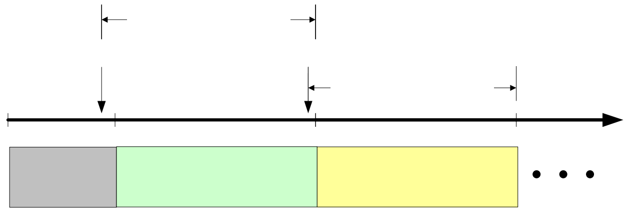

Figure 3. Dynamic Frequency Hopping Operation

C. *Fast Channel Switching*

DFH is justified only, if the channel switching can be executed quickly enough. Recognizing that hardware channel switching delays are negligible in today's evolving technologies – e.g. in the range of tens of microseconds in current 802.11 wireless cards [10]. – a novel fast channel switching technique has been proposed [3]. Applying the proposed mechanism, a WRAN system performs periodic channel maintenance on a set of hopping channels that are initially setup, such that switching delays for channel setup and channel availability check are eliminated. No details will be given here due to lack of space.

D. *Frequency Requirements for DFH*

In order to perform reliable sensing in the DFH mode, the channel being sensed cannot be used for data transmission by the WRAN cell. This implies that a single WRAN cell operating in the DFH mode needs at least two channels in order to perform data transmission and reliable sensing in parallel (in further considerations we will, for the sake of simplicity, assume that there is no out of band interference of the WRAN cells). By simple extension of this scheme, 2**N** free channels would be needed to support **N** totally uncoordinated, mutually interfering cells without collisions in channel usage among them.

If, however, spatially overlapping cells decide to cooperate, the channel usage can be significantly reduced. In the following we prove by construction that only **N**+1 vacant channels (i.e., channels free of both incumbents and other WRANs) are enough.

Figure 4. illustrates the Phase-shifting DFH operation [3] of **N**=3 overlapping WRAN cells over (**N**+1)=4 vacant channels. Each WRAN cell shifts its DFH operation phase by one Quiet Time (QT) against the operation phase of the previous WRAN cell as shown in Figure 4. For instance, WRAN2 shifts its operation by one QT against the operation of WRAN1, and WRAN3 shifts by one QT against that of WRAN2. During a QT, channel sensing is performed. This implies that a QT has to be at least equal to the minimum time required for reliable channel sensing.

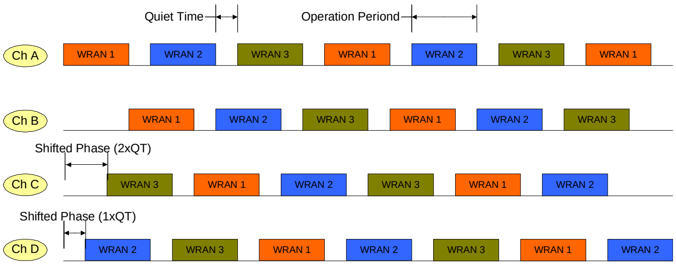

Figure 4. Phase-shifting DFH Operation

We have demonstrated that a set of **N** overlapping cells can operate continuously using (**N**+1) channels as long as the length of a single transmission is larger than the product **N***QT. We will further refer to this observation as the "**N**+1" rule [3]. Imposing the above explained hopping pattern of time shifted jumps is, however, possible in case of strict coordination, which motivates the concept of DFH Community (DFHC) as described in Section III.

III. Dynamic Frequency Hopping Communities

Dynamic Frequency Hopping Community (DFHC) is a non-empty set of neighboring WRAN cells following a common protocol that supports a coordinated DFH operation in order to ensure mutual interference-free channel sensing and to minimize the channel usage, applying the DFH phase-shifting explained above.

A DFHC has one leader and, possibly, some community members. The DFHC leader is responsible for decisions about community membership, calculating the hopping patterns (phase-shifting sequences) for all members and distributing this information within the community. Members provide the leader with their neighborhood and channel availability information, i.e. information about their sensing results and observed channel usage of the neighboring WRAN cells.

For a group of WRAN cells to create a DFHC the following requirements should be satisfied:

- Community members are able to communicate with the community leader.
- Each community member is able to perform the SSDT operation as described in Section II.A.
- Community members have reasonably synchronized clocks. (up to a given accuracy)
- The community members share a joint notion of a Quiet Time of a channel X – a time period during which no community member is allowed to transmit on that channel.

In the 802.22 draft, a best effort method called Coexistence Beacon Protocol (CBP) is proposed for over-the-air inter-cell communication. The basic mechanism of CBP works as follows. BSs of neighboring cells schedule a coexistence window at the end of every MAC frame (synchronized among BSs). During a coexistence window, neighboring BSs communicate using coexistence beacons. Note that CBP has been developed for constant channel assignments while in DFHC mode the channel assigned for transmission to individual cells does strongly vary in time. Therefore we introduce for the support of the inter-cell communications within a community an abstraction of a Communication Management Channel (CMC) on which the CBP is executed. While different implementations of CMC are possible, the detailed discussion of this issue exceeds the scope of this paper.

IV. DFHC Management

DFHC initialization and maintenance are supported by numerous activities which will be referred to as community management. We begin its discussion with a set of operational principles:

- A WRAN cell is represented by its BS, having a unique IEEE 802 MAC address and a priority.
- WRAN cells attempt to create or join communities whenever possible. Nevertheless a single cell that has lost the association with a community will always **temporarily** falls back to the non-hopping mode.
- The association with a community is based on a soft state principle, subject to renewal within a life-time period determined by a TIMER value. Lack of renewal will lead to fallback into the non-hopping mode on the last used channel.

In the following we present an outline of the mechanisms for DFHC management.

A. *Neighborhood Discovery*

Each BS periodically broadcasts announcement messages (BSANN) on the CMC. Two cells are called one-hop neighbors if control messages (e.g. BSANNs) of one of the cells can be received by the other cell. A BSANN message contains the state of the BS (Non-hopping, DFHC leader or DFHC member), a list of actually known neighbors, a hopping channel list, and the priority of the community leader (if belonging to a community).

B. *DFHC Creation*

To create a DFHC, a community leader is selected first. The community leader of a DFHC is defined as a BS with the highest priority value (and smallest MAC address within equal priorities). Each BS believing to fulfill this condition within its neighborhood declares itself a DFHC leader. The declared leader selects a set of hopping channels and broadcasts its leadership using leader announcement (LDRA) messages on the CMC. An LDRA message contains a list of community members (at the beginning just the leader itself) and the selected hopping channels with the hopping pattern of the community.

A WRAN cell in the non-hopping mode might decide to create a community if no LDRA message is heard. Upon receiving LDRA messages from (possibly multiple) leaders, a BS, however, can decide to join one of the advertised communities. These decisions are based on policies not discussed in this paper.

To join a community, a BS transmits a membership request message (MBRA) on the community's CMC. An MBRA message contains the targeted community leader's identification, and the neighborhood and channel availability information of the requesting BS. Upon receiving the MBRA, the leader decides whether to accept or reject the joining request and sends an acknowledgement containing the decision. This might have to be preceded by a proper maintenance of the existing community to assure that the joining station fits into the hopping behavior.

C. *DFHC Maintenance*

Each channel hopping pattern calculated and distributed by the community leader has a lifetime. A community member can use the hopping pattern only during this lifetime. The leader periodically renews the hopping pattern by broadcasting an LDRA containing the renewed hopping pattern for the community. The start time for using the new hopping pattern is set to the expiration time of the previous hopping pattern. The reception of a new hopping pattern is acknowledged by all members. If some member did not receive a new hopping pattern from the leader before the old pattern's lifetime is expired, it cannot stay in the DFH mode and has to return to the non-hopping mode.

The neighborhood and channel availability information of a community are updated by all members of the community. For this purpose, each community member performs spectrum sensing, tracks BSANN messages from neighboring cells, and reports to the leader if needed, by sending MBRA messages.

The leader recalculates the channel hopping pattern for the community based on the received MBRA messages. The new hopping pattern can be distributed in two possible ways: either by *renewing the hopping pattern* at the end of the old hopping pattern's lifetime or by *sequential switching* of all members to the new hopping pattern.

The first option ensures a collision free switching between the two hopping patterns. Even if some community member does not receive the new hopping information it cannot use the old one any more since it is expired. This approach, however, lacks the flexibility of distributing new hopping pattern in the middle of the old hopping pattern's lifetime without causing pattern conflicts, in case some members fail to receive the new hopping pattern and continue to use the old one.

This hopping pattern confliction issue can be avoided by *sequential switching*. In this approach the leader switches each member individually to the new hopping pattern (which is selected to be collision-free with the patterns of members not switched yet) and verifies whether the recommended switching really took place by sensing newly assigned channel. Thus we introduce an "implicit confirmation by acting" for adopting of the new pattern. Sequential switching is performed such that even if some member does not switch to the new hopping pattern as ordered, all members already switched can use the new hopping pattern without collisions.

Sequential switching for adding a new member is demonstrated in Figure 5. The old assignment is shown in the background. First, all members are switched to the new hopping pattern which means shifting their hopping pattern by one Quiet Time on channel 4. Additionally, the operation periods on channel 1 are shortened by one Quiet Time during the switching procedure. After all members have switched, there is enough space to add the new member (last slot in channel 4). This approach thus ensures no collision between the old and the new hopping patterns.

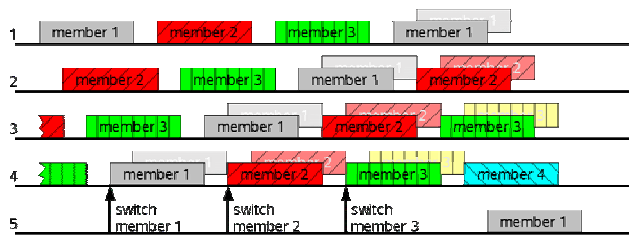

Figure 5. Sequential switching: Add a new member

Whenever a community member detects an incumbent on a channel, it cannot utilize that channel for the next hops. The member should inform the leader by sending an MBRA message containing the new channel information. Until the leader calculated and distributed a new hopping pattern, the cell should use some backup channel for the time period it is scheduled to use the interfering channel.

V. DFHC Coexistence

The mechanisms introduced so far support the management of one DFHC. In a large network of WRAN cells, however, multiple such communities might exist, which have to coexist. As creation of communities as described above is a distributed process following appearing/disappearing of cells as well as changes of their connectivity, it is easy to see that rearrangements of established communities might occasionally be useful. In particular it might help in

- reducing total number of channels used,
- resolving channel usage conflicts among communities,
- reducing communication overhead for community management.

This section introduces mechanisms to shift cells between communities, and to split and merge communities. Whether and when to rearrange communities depends on polices that are beyond the scope of this paper. In addition we will discuss how to avoid and resolve collisions between communities.

A. *Community Rearrangement*

We propose three operations for rearrangement: cell shifting, community splitting and community merging.

A cell shifts from one community to a new one by first requesting to join the new community. If the leader of the new community accepts the joining request, the cell may explicitly leave the old community. The cell then starts to use the hopping pattern received from the new community.

In contrast to shifting of a cell, multiple cells are involved in splitting and merging of communities leading to consistency problems discussed in Section IV.C. These potential collisions of different hopping patterns can be avoided by always performing the splitting and merging at the end of the lifetime of a channel hopping pattern as described below.

If a leader decides to split its community, it divides the community into two and selects two new leaders (where it may become one of the new leaders). The leader first announces the intention to split the community. This intention contains the member lists of the new communities and the new leaders. The designated new leaders and all members of the community shall acknowledge this announcement (where some acknowledgements may get lost). Upon reception of (at least some of) these acknowledgements the old leader may – if it wants to continue the split – schedule the new leaders to announce the new communities starting operation upon expiration of the lifetime of the old community. Note that if some members are lost, they might request later to join one of the new communities.

A WRAN cell can initiate a merger of two communities with itself being the leader of the new community. Note that the initiating cell might be one of the two old leaders or a normal member. When deciding to merge two communities, a cell assures that all members of the old communities can still be a member of the new community and there are sufficient available channels for the new community. The cell then announces the intention of community merging to leaders of communities to be merged. If both leaders agree, the expiration times of their hopping patterns have to be synchronized, i.e. the leader with the earlier expiration time renews its hopping pattern after the hopping pattern of the other community expires. The dedicated new leader then announces the new community on CMCs of both to-be-merged communities by setting the new community's start time to the synchronized expiration time of the old communities. Once the new community has been announced, all members acknowledge the announcement on the CMC of the new community, which then starts to operate using the hopping pattern calculated by the new leader.

B. *Collision Avoidance and Resolution*

BSANN messages are used to announce channel availability and neighborhood information. Channels being included in a BSANN from another community or a non-hopping BS are labeled occupied by the receiving BS. It might nonetheless occur that two neighbor communities select an overlapping channel set as working channels. In this case priority values (transmitted via BSANN messages) of community leaders or non-hopping BSs are used to resolve this conflict. A BS, which detects such collision and has a lower community (or non-hopping BS) priority, releases the overlapping working channels.

VI. PERFORMANCE ANALYSIS

In this section we study the DFHC performance regarding the achievable system throughput and the channel usage. For the throughput analysis we compare the non-hopping mode to the DFH mode. For the channel usage analysis we compare the number of channels used in the DFHC mode with the global minimum (computed by an optimization tool).

A. *Throughput Analysis*

The main advantage of the DFH mode compared to the non-hopping mode is the non-interrupted data transmission. Equation (1) shows the throughput **T** as function of the sensing time **X** and the used bit rate **b** (ignoring the channel switching overhead).

$$T(x) = b * 2 s / (2 s + X s) \quad (1)$$

In the DFH mode the throughput does not depend on the sensing time (**X**=0) and is always equal to **b**, since sensing is performed in parallel to data transmission. Therefore the DFH mode can achieve a higher throughput than the non-hopping mode (X>0).

B. *Channel Usage Analysis for a group of Communities*

In Section II.D we have derived the upper bound of 2**N** and the lower bound of **N**+1 channels for a set of **N** mutually interfering cells following the phase-shifted DFH principle as a single community.

It can, however, be expected, that if numerous cells cover a larger area not ALL of them will mutually interfere (not all cells will be one-hop neighbors). In fact, grouping those cells into **several** communities with limited interference among those communities, and utilizing the possibility of spatial frequency reuse provide a potential for reducing the total number of required frequencies.

Let us assume that **M** cells are randomly distributed in a square normalized to the size 1 by 1 with a normalized interference distance **d<1** (i.e. cells being in distance larger than **d** do not interfere). This assumption leads to a random interference graph.

These cells are split into communities in such a way that all cells belonging to a single community are one-hop neighbors. Obviously, there exist numerous alternative groupings of cells into communities. We use two different approaches to generate communities, one where we minimize the **total number of communities** and another one where the **total number of connections** between communities is minimized.

The optimal number of channels required is based on the assumption that all cells follow a global hopping pattern generated by a central controller. This number can be computed by solving a standard graph coloring problem, so called "chromatic number" +1 channels being the minimum. We use a standard Integer Programming solver (CPLEX [11]) for computing this chromatic number.

Figure 6. shows the analysis results for **M**=10 and **M**=20 cells. These results are an average over 40 independently generated graph instances per **M**.

As expected, splitting into numerous communities is advantageous, and the number of required channels is lower than 2**N**. Moreover, our intuition about not aiming for the minimal number of communities but minimal connectivity among communities has been confirmed (admittedly, we do NOT consider the overhead for community management). In fact, the total number of channels could be further reduced by relaxing the community definition such that all members are only required to be one-hop neighbors of the leader instead of being mutually one-hop neighbors. This would allow for further channel reuse within a community and offer greater flexibility in the community creation.

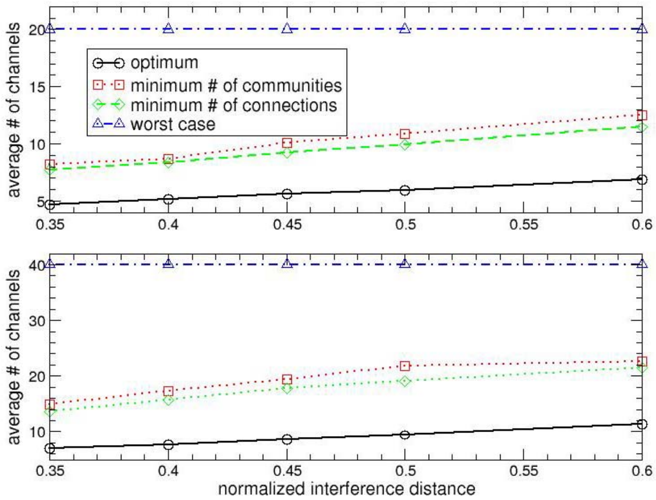

Figure 6. Number of Channels used for **M**=10 (top) and **M**=20 (bottom)

VII. CONCLUSIONS

The emerging IEEE 802.22 standard is defining one of the first cognitive radio based wireless systems to become reality. When operating on a single channel, the QoS of WRAN cells degrades due to sensing interuptions. This can be mitigated by Dynamic Frequency Hopping, where data transmission is performed without interruptions in parallel with spectrum sensing. However, in a bigger cluster of cells, frequency hopping could lead to significant problems if no coordiniation scheme is employed. Dynamic Frequency Hopping Community is a concept introducing coordination among cells. As shown, it leads to a better QoS and throughput behavior, while requiring a modest amount of channels for hopping. It enables coexisistence of multiple communities. In fact DFHC could also be used to coordinate channel usage of cells operarting in the non-hopping mode. In this paper we have presented principles of mechanisms for dynamic rearrangement adapting to changes of cluster topology. As future work we will focus on detailed specification and analysis of protocols suporting these mechanisms as well as various aspects related to policies driving evolution of such communities.

REFERENCES

[1] Joseph Mitola, “Cognitive radio: An integrated agent architecture for software defined radio”, PhD Dissertation, Royal Institute Technology (KTH), Stockholm, Sweden 2000

[2] IEEE802.22 working group “IEEE802.22 Project Homepage” [Online]. Available: http://www.ieee802.org/22/

[3] IEEE P802.22/D0.1 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

[4] FCC. ET docket no. 04-113. Notice of Proposed Rulemaking, May 2004

[5] Carl R. Stevenson, Carlos Cordeiro, Eli Sofer, Gerald Chouinard. “Functional Requirements for the 802.22 WRAN Standard r47”

[6] Carlos Cordeiro, Kiran Challapali, Dagnachew Birru, Sai Shankar. “IEEE 802.22: The First Worldwide Wireless Standard based on Cognitive Radios”, Proceedings of the 1st IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005), 2005, 328-337

[7] Gerald Chouinard, Danijela Cabric, Monisha Gosh. “Sensing Thresholds r8”, Technical proposal submitted to the IEEE 802.22 WG

[8] Wendong Hu, Eli Sofer. “22-05-0098-00-0000_STM-Runcom_PHY-MAC_Outline”, Technical proposal submitted to IEEE 802.22 WG

[9] Liwen Chu, Wendong Hu, George Vlantis, James Gross, Murad Abusubaih, Daniel Willkomm, Adam Wolisz. “22-06-0113-01-0000 Dynamic Frequency Hopping Community”, Technical proposal submitted to IEEE 802.22 WG

[10] [Online] Available: http://datasheets.maxim-ic.com/en/ds/MAX2820-MAX2821A.pdf

[11] ILOG CPLEX Division. CPLEX 9.0 Reference Manual, 2003.