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ENABLING COEXISTENCE OF MULTIPLE COGNITIVE NETWORKS IN TV WHITE SPACE

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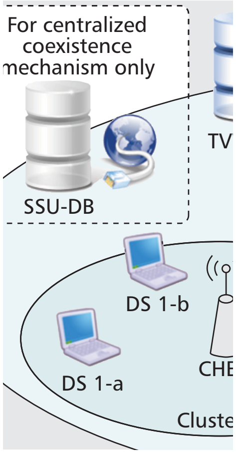

The authors address the problem of coexistence among wireless networks in TV white space. They present a standard independent framework to enable exchange of information relevant for coexistence based on two mechanisms: centralized and distributed.

ABSTRACT

We address the problem of coexistence among wireless networks in TV white space. We present a standard independent framework to enable exchange of information relevant for coexistence based on two mechanisms: centralized and distributed. Both mechanisms introduce the use of multiradio cluster-head equipment (CHE) as a physical entity that acquires relevant information, identifies coexistence opportunities, and implements autonomous coexistence decisions. The major conceptual difference between them lies in the fact that the centralized mechanism utilizes coexistence database(s) as a repository for coexistence related information, where CHEs need to access before making coexistence decisions. On the other hand, the distributed mechanism utilizes a broadcast channel to distribute beacons and directly convey coexistence information between CHEs. Furthermore, we give a concise overview of the current activities in international standardization bodies toward the realization of communications in TVWS along with measures taken to provide coexistence between secondary cognitive networks.

INTRODUCTION

The relative efficiency of coexistence mechanisms in the unlicensed industrial, scientific, and medical (ISM) band, and recent measurements [1] revealing the inefficiency inherent in the fixed spectrum allocation of the licensed regimen have motivated authorities to reconsider traditional spectrum management policies. The Federal Communications Commission (FCC)in the United States and the Office of Communications (Ofcom) in the United Kingdom responded by investigating the feasibility of having cognitive radios (CRs) as opportunistic secondary users (SUs) of the licensed spectrum. This is a bold but crucial step toward efficient spectrum utilization.

Although CRs are envisioned to populate the whole frequency spectrum in the future, as of today, the aforementioned regulatory agencies have considered their utilization only in the unused TV bands, in part due to the desirable propagation characteristics of VHF-UHF bands and their spatio-temporal predictability. This unused broadcast TV spectrum between 54–698 MHz, hereafter referred to as TV white space (TVWS), creates the bandwidth expansion necessary to provide users with an alternative to the current 2.4 GHz and 5 GHz wireless access.

In November 2008, the FCC issued a report and order (R&O) [2] regulating the unlicensed access to TVWS by SUs, also referred to as TV band devices (TVBDs). Ofcom followed the initiative and issued its consultation document [3] in February 2009, outlining several key points for cognitive devices to access the TVWS. Other regulatory bodies, such as the European Conference of Postal and Telecommunications Administrations (CEPT) and the Japanese Ministry of Internal Affairs and Communications (MIC), are following the same path and also considering TVWS utilization.

The commercial importance and benefits brought by TVWS communications are, however, as big as the challenge and controversy underlying this promising application of CR technology. On one hand, there is efficient VHF-UHF spectrum utilization, introducing new wireless services without setting aside new frequency bands. This attractive characteristic of TVWS communications has motivated overwhelming activity toward its standardization, which was manifested by the creation of the IEEE 802.22 Working Group (WG) and IEEE 802.11af Task Group (TG), respectively, in 2004 and 2009. Activities in European Computer Manufacturers Association (ECMA) Technical Committee 48 Task Group 1 (TC48-TG1) toward the creation of physical (PHY) and medium access control (MAC) layer standards for operation in TVWS also followed in 2009. On the other hand, the opposition from TV broadcasters to sharing with TVBDs the spectrum dedicated to primary users (PUs), also referred to as incumbents, is, as expected, strong. Furthermore, the FCC requirements to allow TVBDs opportunistic spectrum access are quite stringent, thus contributing to making the realization of TVWS communications even more challenging. Although the FCC removed the spectrum sensing requirement in September 2010, the implementation of a TVWS

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database, out-of-band emission limitations, as well as specification on accessible channels are mandatory in order to offer a high degree of incumbent protection.

A more recent challenge, however, is the prevention of harmful interference between multiple secondary networks formed by TVBDs upon the availability of TVWS. This problem has drawn so much attention that the IEEE 802.19 Wireless Coexistence WG has created the IEEE 802.19.1 TG, whose aim is to create radio-technology-independent standard methods for coexistence among dissimilar TVBD networks in the TVWS. The IEEE 802.19.1 TG has taken a high-level approach; that is, new PHY and/or MAC design is not considered. Expected outcomes from this TG are coexistence mechanisms providing efficient spectrum sharing, otherwise impossible if TVBD networks are left to *fight* for spectrum.

This article attempts to fill the current lack of methods to coordinate access to the TVWS by introducing a framework based on two distinct mechanisms tailored to enable exchange of information relevant for coexistence of TVDB networks. The proposed mechanisms are conceptually described, and procedures to enable their implementation are provided. Furthermore, some coexistence scenarios of interest are analyzed, illustrating how the proposed framework yields coexistence of TVBD networks.

HOW CROWDED WILL THE TVWS BE?

Insight on how popular wireless access through unoccupied TV channels will be is easily derived from a quick look at the current enormous mobilization from industry stakeholders in international standardization activities. Massive industry participation in standardization is an indicator of future success of a technology, and it should be no different with wireless access in TVWS. As a result of such intense activities, four projects on the creation of MAC and PHY standards for operation in TVWS have been created. The outcomes of these projects are, in order of completeness, ECMA 392 Standard [4], IEEE 802.22 Draft Standard [5], IEEE 802.11af Draft Standard, and SCC41 Committee on WS Radio. With the completion of these standards, one can expect high demand from the market, which will exploit the TVWS in the form of various services including low-data-rate smart grids [6], rural wireless access [7], and broadband home wireless [8]. On the other hand, the available TV spectrum is limited, and such limitation varies according to country regulations.

In order to predict how crowded will be the TVWS, we performed an analysis considering statistical information, such as household density, Internet penetration, WS radio access point (AP) penetration, and number of available TV channels composing the TVWS. The analysis consists of evaluating the spectral availability, which is defined to be the ratio between non-overlapped spectrum and total generated spectrum, of cities with population density ranging from sparse to highly dense. Tokyo is the upper limit used in our analysis, with household density of $2800/\text{km}^2$. We assumed Internet penetration of 90 percent, which is already common in some developed countries and soon will be a common figure in many countries due to the fast paced technological revolution ongoing worldwide. As for AP penetration, we considered 10 , 50, and 90 percent in order to evaluate spectral availability under scenarios where WS radio market success is low, medium, and high. The number of available TV channels composing the TVWS is considered to be two, four, and seven in our analysis.

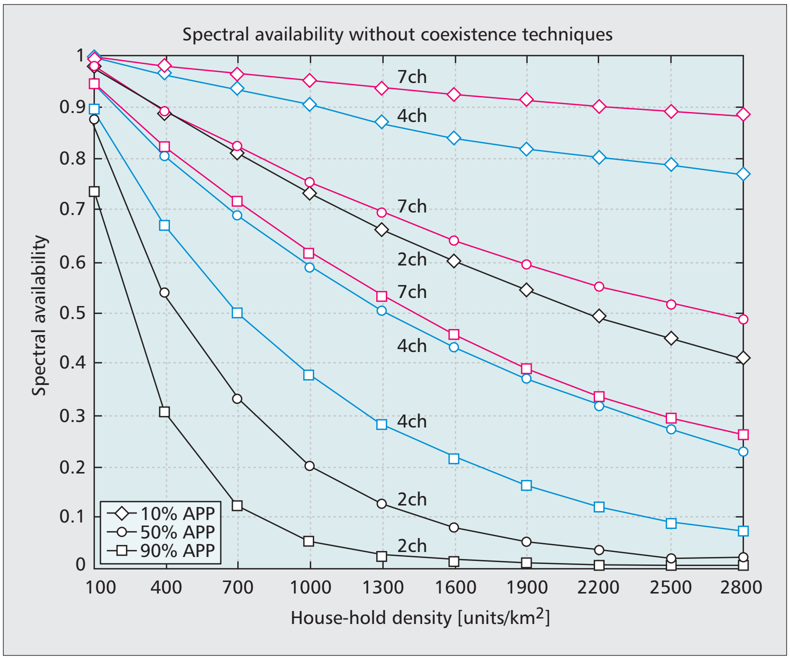

Figure 1. *Spectral availability of cities with different household densities, APs penetrations (10, 50, and 90 percent), and available TV channels (two, four, and seven). Internet penetration is considered to be 90 percent.*

Figure 1 allow us to infer that TVWS will be congested in cities, justifying the efforts by IEEE 802.19.1 TG to ensure coexistence between systems based on different standards. For example, the spectral availability of Rio de Janeiro, Brazil, with household density of $1600/\text{km}^2$, would be about 8 percent if WS radio AP penetration is 50 percent and TVWS is composed of two channels. That is to say, 92 percent of the generated spectrum is overlapped by neighboring networks, thus requiring the utilization of coexistence techniques to coordinate network access.

COEXISTENCE IN TV WHITE SPACE

With the release of the FCC R&O [2], coexistence of wireless secondary networks became a twofold problem. Different from coexistence in the unlicensed ISM band, coexistence in TVWS requires that TVBD networks be able to identify the presence/absence of licensed incumbent TV networks and coexist with other dissimilar TVBD networks. It is within the scope of the latter problem (i.e., coexistence between TVBD networks) that the IEEE 802.19.1 TG created the project IEEE P802.19.1, aiming to provide standard coexistence mechanisms allowing for industry-wise compatible coexistence solutions.

A natural consequence of multiple TVBD networks uncoordinated access to TVWS is uncontrollable interference resulting in inability to coexist. Lack of effective coexistence would prevent full exploitation of TVWS and significantly reduce its utility.

THE IEEE 802.19.1 TG APPROACH TO COEXISTENCE IN TVWS

Since January 2010 a great deal of effort has been put into the creation of standardized coexistence mechanisms for TVBD networks in TVWS. The IEEE 802.19.1 TG published a system design document (SDD) to assist the standardization process, which contains the necessary items to cover (e.g., architecture, requirements, logical entities) in order for a system to be called IEEE 802.19.1 compliant.

A brief description of the logical entities of an IEEE 802.19.1 system is given below.

The coexistence manager (CM) can be regarded as the *brain* of IEEE 802.19.1 compliant systems. Its functional roles are discovering other CMs and making coexistence decisions in order to solve coexistence problems between TVBD networks they serve. They should support interfaces to the coexistence discovery and information server (CDIS), TVWS database (TVWS-DB), and operator management entity (OME). CMs also provide coexistence commands and control information to coexistence enablers (CEs).

The CE acts as the interface between the CM and the TVBD network. Its functional roles are translating reconfiguration commands received from the CM into TVBD-specific reconfiguration commands and sending them to the TVBD network so that the latter can reconfigure itself.

The CDIS is the logical entity responsible for structuring the information (e.g., sensing and spectrum occupancy information) to be contained in a repository (server) deployed over the Internet. Its functional role is to support discovery of CMs by making information relevant to coexistence accessible.

The TVWS-DB is the repository containing information regarding the TVWS available, that is, information on available TV channels in a specific area and time, which will be deployed over the Internet. The CMs will check the TVWS-DB in order to ensure coexistence between the TVBD networks they serve with incumbent TV networks. The OME is responsible for providing the CMs with TVBD network operator/provider related information, such as spectrum policy/limitations concerning various operator networks. Both the TVWS-DB and OME are outside of the IEEE P802.19.1 scope.

In the next section, we introduce two coexistence mechanisms together with their physical entities. The brain of both mechanisms is called cluster-head equipment (CHE), which is the entity responsible for making autonomous cognitive coexistence decisions; hence, it is where the CM logical entity would lie. It is also in CHE that the CE logical entity would be deployed because reconfiguration of the TVBD network is also under CHE's responsibility. The CDIS logical entity exists, however, only in the centralized coexistence mechanism and would be deployed in the database called the secondary spectrum utilization database (SSU-DB) managed by a coexistence service provider.

TV WHITE SPACE COEXISTENCE MECHANISMS

A natural consequence of multiple TVBD networks with uncoordinated access to TVWS is uncontrollable interference resulting in inability to coexist. Lack of effective coexistence would prevent full exploitation of TVWS and significantly reduce its utility.

In this section, we present two novel standard independent mechanisms to enable exchange/obtaining of information relevant to coexistence of TVBD networks in TVWS, the distributed and centralized coexistence mechanisms. The fundamental difference between them lies in how to exchange information relevant to coexistence. The former utilizes distributed beacon transmission through a wireless broadcast channel. The latter, a central database, the SSU-DB, which acts as a repository of the aforementioned information and is managed by a coexistence service provider. Consequently, both approaches have different characteristics with the distributed coexistence mechanism having a *plug-and-play* nature, while the centralized coexistence mechanism has a *subscription-based* nature.

As shown in Fig. 2, both proposed mechanisms utilize the concept of the cluster, which is composed of CHE physically connected to the Internet and dependent stations (DSs) under its control. The main function of the CHEs is to provide the DSs with wireless access over TV channels while ensuring a high degree of coexistence between neighboring clusters/networks and coexistence with the incumbent TV network. CHE can be thought of as a physical device that fits into the fixed or type II classifications recently created by the FCC in [2], with TVWS-DB access and geolocation information acquisition as requirements.

In the future, we anticipate a plethora of dissimilar wireless networks that must coexist in TVWS. Without loss of generality, these wireless networks are assumed to fall under one of the following categories: *coexistence mechanism compliant* and *coexistence mechanism non-compliant*. To be regarded as compliant, a network must follow the steps of the mechanisms presented in this section. Based on the above categorization, two coexistence scenarios of interest are analyzed in this section: *coexistence between compliant networks* and *coexistence between compliant and non-compliant networks*.

Before the coexistence mechanisms are introduced, it should be mentioned that coexistence decisions are not the focus of this article. Coexistence decisions are based on one or a combination of PHY layer and MAC sublayer techniques, such as dynamic frequency selection (DFS), transmit power control (TPC), time-division multiple access (TDMA), and code-division multiple access (CDMA). Each technique is of certain efficiency in providing coexistence to TVBD networks operating in TVWS. The focus of this article, however, is on providing a framework that could be followed in order to enable coexistence mechanism compliant networks to exchange the information necessary for preliminary autonomous coexistence decisions, and to

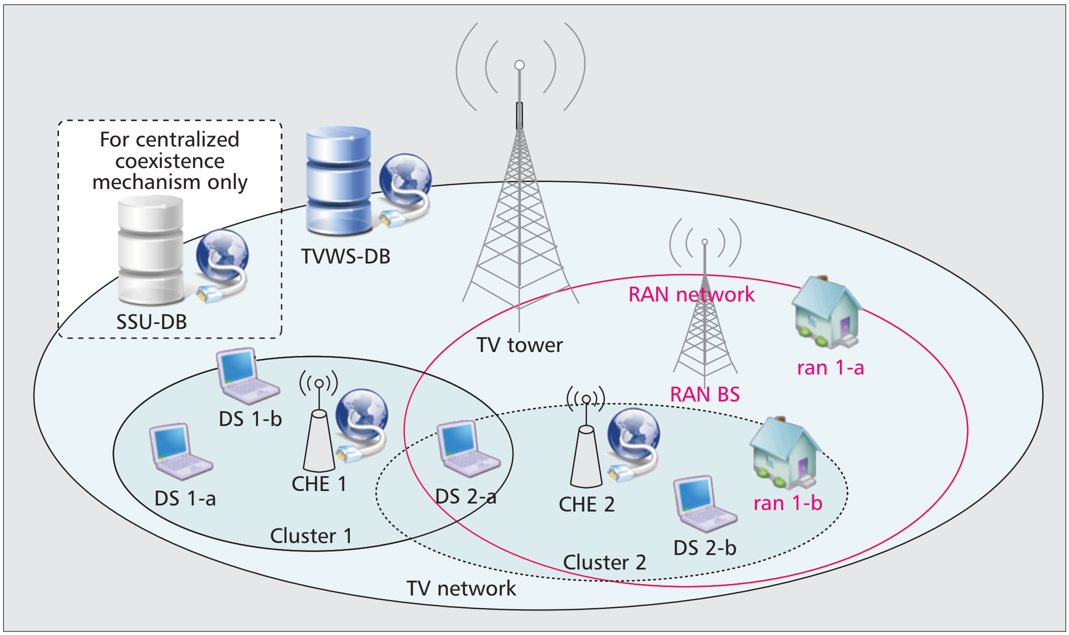

Figure 2. *Coexistence between compliant clusters and non-compliant RAN in TVWS. The distributed mechanism relies on a wireless broadcast channel while the centralized one relies on SSU-DB deployed over the Internet to exchange information between compliant clusters. CHEs multiple-radio feature allows detection of non-compliant RAN users. DSs are provided wireless access in TVWS by CHEs connected to the Internet. TVWS-DB is deployed over the Internet and ensures incumbent TV network protection.*

In future, we anticipate a plethora of dissimilar wireless networks that must coexist in TVWS. Without loss of generality, these wireless networks are assumed to fall under one of the following categories: Coexistence Mechanism Compliant and Coexistence Mechanism Non-compliant networks.

allow coexistence mechanism compliant networks to obtain information from coexistence mechanism non-compliant networks for final autonomous coexistence decisions.

DISTRIBUTED COEXISTENCE MECHANISM

In this subsection we introduce a distributed coexistence mechanism based on distributed beacons. This mechanism relies on a wireless broadcast channel where multiradio CHE units directly exchange beacons in order to convey information relevant for coexistence of the TVBD networks they serve.

In the following, the major steps of the mechanism are introduced together with notes, whenever necessary, to facilitate its understanding. Let us suppose a CHE unit, hereafter called initiating CHE, wants to start a cluster (CHE 2 of Fig. 2) to provide wireless access in TVWS to its DSs:

1) The initiating CHE checks its geolocation and its absolute time (i.e., through GPS).

- Geolocation information is mandatory for fixed and type II category devices, according to [2].

2) The initiating CHE accesses the TVWS-DB to get a list of available TV channel(s) in its location; that is, a list of channels not occupied by incumbents at the specific time and specific location.

- TVWS-DB access prior to utilization of the spectrum is mandatory for fixed devices and devices in the type II category, according to [2].

3) Of all the TV channels listed as available by the TVWS-DB, the initiating CHE must identify which one was selected as the broadcast channel by already operating neighboring CHE. The initiating CHE then switches to the common radio access technology (RAT) and searches for beacons in the available TV channels during the coexistence window.

- The coexistence window is the time dedicated to CHE to broadcast beacons containing information relevant to coexistence. The coexistence window starts and finishes based on absolute GPS time (i.e., every multiple of x seconds and lasting y seconds), so all CHE units are synchronized. Coexistence windows are preceded and followed by communication windows.
- The communication window is the time dedicated to the DSs to utilize the TV channel decided by the CHE, for applications such as wireless Internet (Fig. 3).
- Beacons contain specific information regarding geolocation, spectrum utilization, Tx power, interference tolerance, and so on (Fig. 3).
- Note that common RAT encompass two meanings: networks having the same single RAT and networks with multiple RATs, but with a common one.

4) If the initiating CHE finds beacons in multiple available TV channels, it selects as the broadcast channel the one whose beacons are geographically closer to its location by checking the geo-location field in the beacons.

- The broadcast channel is the channel by which neighboring clusters (i.e., clusters within interference range) exchange information about their own spectrum utilization.
- Initiating CHE is concerned about exchanging information with neighboring clusters, so its decision on which channel to access and how to access it will not result in intercluster interference. Therefore, when selecting a broadcast channel, an initiating CHE should pick the one being utilized by geographically close clusters, rather than the broadcast channel utilized by clusters far away.

Upon knowledge of its geo-location and the absolute time, the initiating CHE 2 will access the TVWS-DB in order to receive a list containing the TV channels not occupied by incumbents at its specific location and time.

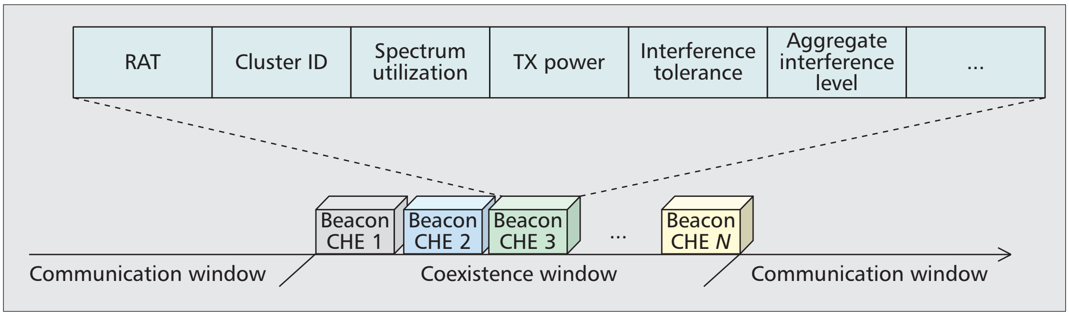

Figure 3. *Beacon sketch, coexistence window and communication window.*

- It should be noted, however, that the selected channel for operation during the communication window (channel provided to its DSs), unlike the broadcast channel, should not be shared by neighboring clusters to avoid interference. This channel could be shared with clusters located far away, where no intercluster interference is expected.

5) Based on the information gathered during the coexistence window, the initiating CHE makes a preliminary autonomous coexistence decision regarding which TV channel to access and how to access it.

- Note that the selected channel must be within the subset of unoccupied channels acquired in step 2.

6) The initiating CHE is now aware of the spectral utilization of its neighboring clusters that are compliant with the distributed coexistence mechanism. However, in order to provide a channel free of (or with minimal) interference to its DSs during the communication window, the initiating CHE must verify if there are users from a possibly non-compliant neighboring network within its coverage area. The initiating CHE switches to the other standardized RATs and detects the presence/absence of users from a non-compliant network by searching for the user identification signature in their packets.

- Upon detection of users from a dissimilar noncompliant network, the initiating CHE becomes aware that the preliminarily selected channel is unavailable within its coverage area. Neither to cause interference nor to be interfered with by these users, the initiating CHE must select another available TV channel. The detection procedure must be repeated.

7) The initiating CHE makes a final autonomous coexistence decision after taking into consideration the information acquired in steps 4 and 6.

- Coexistence decisions may rely on any coexistence techniques (e.g., DFS, TPC, TDMA, CDMA).

8) During the following coexistence window, the initiating CHE broadcasts its updated channel utilization (e.g., selected TV channel, TX power, code) so that other CHE units become aware of its selected operation parameters.

A flow chart illustrating the relationship between the steps of the proposed mechanism is found in Fig. 4.

Now, we illustrate the two scenarios of interest and how the distributed coexistence mechanism yields coexistence between networks accessing the TVWS. It should be noted, however, that in the following two scenarios, association with existing or developing standards is given solely for the sake of illustration. Therefore, any network from the aforementioned standards could be compliant or non-compliant with our proposed mechanisms.

Scenario I: Coexistence between Compliant Networks — Let the clusters (not the radio access network [RAN]) in Fig. 2 represent networks with a standardized common RAT. If these networks are left to fight for spectrum without any coordination, obviously, significant performance degradation will be experienced, resulting in low quality of coexistence. Without the need of any infrastructured beacon network nor subscription to coexistence service providers, the CHE will listen to each other's beacons by utilizing a common RAT in order to make an autonomous coexistence solution.

Upon knowledge of its geolocation and the absolute time, the initiating CHE 2 will access the TVWS-DB in order to receive a list containing the TV channels not occupied by incumbents at its specific location and time. Let the TVWS set of CHE 2 be $\mathcal{S}_2$ = {ch.54, ch.55, ch.61, ch.62}, where $\mathcal{S}_2 \subset$ UHF channels. In order to proceed with the coexistence example in this scenario, it is important to notice the following possible relationships between $\mathcal{S}_2$ and $\mathcal{S}_1$, where the latter is the TVWS set of CHE 1:

- $\mathcal{S}_2 \cap \mathcal{S}_1 = \varnothing$
  - –e.g., $\mathcal{S}_1$ = {ch.43, ch.45, ch.50, ch.51, ch.52}
- $\mathcal{S}_2 = \mathcal{S}_1$
  - –i.e., $\mathcal{S}_1$ = {ch.54, ch.55, ch.61, ch.62}
- $\mathcal{S}_2 \supset \mathcal{S}_1$
  - –e.g., $\mathcal{S}_1$ = {ch.55, ch.61, ch.62}
- $\mathcal{S}_2 \subset \mathcal{S}_1$
  - –e.g., $\mathcal{S}_1$ = {ch.47, ch.54, ch.55, ch.61, ch.62, ch.64}
- $\mathcal{S}_2 \cap \mathcal{S}_1 \neq \varnothing$ & $\mathcal{S}_2$ 6= S1
  - –e.g., $\mathcal{S}_1$ = {ch.47, ch.54, ch.55, ch.64}

In case $\mathcal{S}_2 \cap \mathcal{S}_1 = \varnothing$, the sets of TVWS for both CHE 1 and CHE 2 are disjoint; therefore, cochannel interference is nonexistent. Whenever $\mathcal{S}_2 = \mathcal{S}_1$ or $\mathcal{S}_2 \supset \mathcal{S}_1$, the initiating CHE 2 scans its TVWS set and finds the broadcast channel being used by CHE 1 for beacon transmission, since all channels in $\mathcal{S}_1$ are contained in $\mathcal{S}_2$. Once sharing the same broadcast channel, during a coexistence window, CHE 2 will listen to the beacon from CHE 1 and acquire relevant information in order to make a preliminary autonomous coexis-

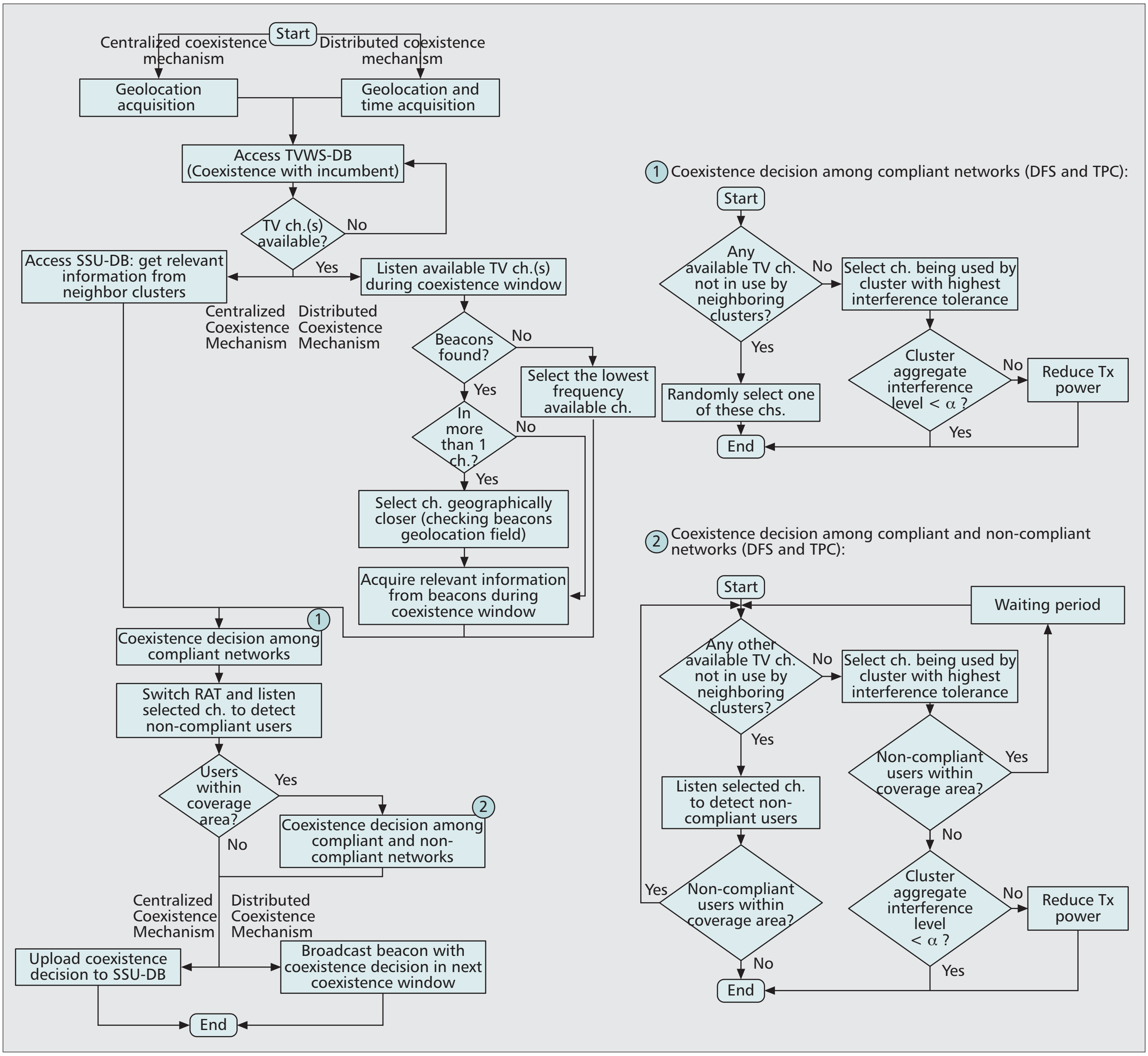

Figure 4. *Flowchart of both distributed and centralized coexistence mechanisms enabling exchange/obtaining of relevant information for coexistence. Illustratively, DFS and TPC coexistence techniques are utilized in the coexistence decisions.*

tence decision. An example of a coexistence decision based on DFS and TPC techniques is provided in Fig. 4.

Before making the final autonomous coexistence decision, CHE 2 must confirm if there are users from a non-compliant network within its coverage area. Since this scenario refers to coexistence within compliant networks only, let us postpone details regarding interaction between compliant and noncompliant networks to the next subsection. Then CHE 2 transmits a beacon containing information about its final autonomous coexistence decision, that is, the selected operation parameters (e.g., the decided spectrum utilization, TX power, code, interference tolerance) during the next coexistence window so that CHE 1 becomes aware of its presence and the details of its operation.

After realization of the distributed coexistence mechanism, CHE 2 informs its DSs, by way of an enabling signal, about its decision on which TV channel to utilize and how to access it, e.g., TX power. Finally, DSs under the cluster served by CHE 2 operate in TVWS during the communication window.

In case $\mathcal{S}_2 \subset \mathcal{S}_1$ or $\mathcal{S}_2 \cap \mathcal{S}_1 \neq \varnothing$ & $\mathcal{S}_2 \neq \mathcal{S}_1$, the broadcast channel being utilized by CHE 1 might not be found at first by the initiating CHE 2. Although the broadcast channel selected by CHE 1 prior to CHE 2 initialization must belong to $\mathcal{S}_1$, it might not be within $\mathcal{S}_2$. In these circumstances, CHE 2 will not find the beacons from CHE 1, so it will select the lowest frequency channel available in $\mathcal{S}_2$ as its broadcast channel, since lower frequency yields wider beacon propagation range. Since CHE 2 did not find any beacons, it *believes* that there are no other clusters nearby. Consequently, CHE 2 might select

It is preferable that small clusters adjust their operation parameters, spectrum utilization, for example, according to RAN rather than the other way around. This could avoid a big chain reaction of neighboring RANs re-adjusting operation parameters and lead to an unstable coexistence equilibrium.

for its DSs the same channel already being used by the DSs served by CHE 1. Interference between these neighboring clusters will occur during the communication window. Obviously, such interference will cause performance degradation in both cluster 1 and cluster 2. Upon noticing severe packet losses in the uplink, CHE 1 and CHE 2 will randomly select a new broadcast channel from, respectively, S1 and S2. When CHE 1 and CHE 2 converge to the same broadcast channel, they will exchange spectrum utilization information and make the appropriate coexistence decision so that interference during the communication window disappears.

Scenario II: Coexistence Between Compliant and Noncompliant Networks — lLet the clusters in Fig. 2 represent compliant networks trying to coexist with a non-compliant network. The inspiration for such a scenario comes from the fact that coexistence between TVBD networks in TVWS is not mandatory. Therefore, there will be standards that do not adopt any mechanism to allow for coordination between its own networks and other dissimilar networks. In this scenario, the non-compliant RAN is oblivious to the existence of a coexistence window, the steps of the coexistence mechanism, and the presence of neighboring compliant clusters.

As previously, CHE 2 wants to serve its DSs with wireless access through TVWS. CHE 2 will go through the steps of the mechanism until it makes a preliminary autonomous coexistence decision based on information from its neighboring compliant clusters. At this point, CHE 2 is aware of the presence of a neighboring cluster served by CHE 1 and the details of its operation. However, this would not guarantee free spectrum ready to be provided to its DSs. The existence or absence of geographically close users from a non-compliant network is necessary information to ensure a reliable final coexistence decision. Therefore, CHE 2 switches to the RAT of the non-compliant RAN, illustrated in Fig. 2, and searches for packets containing the RAN users' signatures in the preliminarily selected channel within its coverage area. If users are detected, CHE 2 becomes aware of that channel's unavailability and must act accordingly. For example, let the coexistence techniques available in CHE 2 be DFS and TPC, as in Fig.4. Based on the information acquired during the coexistence window, CHE 2 utilizes DFS and selects another available TV channel from S_2, which is not in use by the cluster served by CHE 1. Then CHE 2 repeats the search for non-compliant users in this new channel. If necessary, CHE 2 could select a channel from S_2 even though it is in use by the neighboring cluster served by CHE 1; however, the current aggregate interference suffered by the latter cluster must be below a predefined threshold α. Otherwise, TPC must be executed. Once CHE 2 makes its final autonomous coexistence decision, it broadcasts a beacon by using the common RAT, informing its neighboring compliant clusters of its current spectrum utilization.

To adopt a passive coexistence approach, as described in this scenario, seems prudent to the authors since the coverage area of a RAN (e.g., IEEE 802.22) is significantly wider than that of the cluster. It is preferable that small clusters adjust their operation parameters (e.g., spectrum utilization) according to the RAN rather than the other way around. This could avoid a big chain reaction of neighboring RANs readjusting operation parameters, leading to an unstable coexistence equilibrium.

CENTRALIZED COEXISTENCE MECHANISM

In this subsection we introduce the centralized coexistence mechanism based on database access. The database, SSU-DB, is deployed over the Internet and acts as a centralized repository of information relevant to coexistence. SSU-DB is managed and operated by a coexistence service provider. Like the distributed coexistence mechanism, the centralized one utilizes multiradio CHE as the brain, which acquires relevant information, identifies coexistence opportunities, and implements autonomous coexistence decisions. A fundamental difference, however, is that the exchange of information between compliant networks happens through the Internet, by way of SSU-DB access. CHE accesses the SSU-DB in order to update operational information of the cluster it serves and acquire operational information of neighboring clusters. Whenever a CHE wants to start-up a network to provide wireless services to its DSs, it should access the SSU-DB through the Internet. Then the CHE can retrieve from SSU-DB the spectrum utilization information of clusters whose geolocations are in proximity. Next, the CHE makes a reliable autonomous coexistence decision regarding which TV channel to access and how to access it. The CHE must upload to SSU-DB its coexistence decision. Note that information stored in the SSU-DB is the same as information in the beacon utilized by the distributed coexistence mechanism in Fig. 3.

Obviously, the SSU-DB could be divided into small-scale SSU-DBs. Each of them would act as an information repository for smaller areas so as to reduce database access delays. Now, we introduce the centralized coexistence mechanism:

1. The initiating CHE checks its geolocation.
2. The initiating CHE access the TVWS-DB to get a list of available TV channel(s) at its location.
3. Upon availability of TV channel(s), the initiating CHE accesses the SSU-DB in order to acquire operational information from possibly existent neighboring compliant clusters or compliant dissimilar networks (e.g., geolocation, spectrum utilization, Tx power, interference tolerance).
4. Based on the information gathered in the above step, the initiating CHE makes a preliminary autonomous coexistence decision regarding which TV channel to access and how to access it. Note that the selected channel must be within the subset of unoccupied channels acquired.
5. The initiating CHE switches to the preliminary selected channel and to other standardized RATs. It then tries to detect users from a non-compliant network by searching for a user signature in their packets.
6. Initiating CHE makes the final autonomous

decision on which channel to access and how to access it after taking into consideration the information acquired.

7. The initiating CHE uploads its decision (i.e., decided spectrum utilization, TX power, interference tolerance) to the SSU-DB so that other CHEs can access it.

As can be seen in Fig. 4, the centralized and distributed coexistence mechanism share common parts. These are the steps that ensure detection of incumbents, required by the FCC, and those ensuring coexistence between compliant and non-compliant networks. The way the centralized coexistence mechanism handles coexistence between compliant networks only is distinguished by *subscribing* to a coexistence service provider.

ANALYSIS AND SIMULATION

We analyze the expected spectral availability of cities with different house-hold densities under two scenarios. The first scenario is composed by clusters and RANs that are not compliant with our proposed coexistence mechanisms. That is to say, no information exchange happens between the networks. In the second scenario, clusters are compliant, but RANs are not compliant with our mechanisms. The compliance of clusters allow CHE to exchange information, therefore being able to make autonomous coexistence decisions avoiding intercluster interference. Moreover, as described earlier, our mechanisms also enable CHE to search for users of noncompliant networks and make a final autonomous coexistence decision when users are detected within its coverage area.

The analysis consisted of randomly generating clusters over 100 km^2 of city area composed of uniformly distributed households. Each generated cluster represents one household with a WS radio AP. By the Monte Carlo method, we evaluate the spectral availability, which we adopt the same definition as the one from earlier. As can be seen from Fig. 5, spectral availability ranges from 0 to 1, representing fully crowded spectrum and fully empty spectrum, respectively. We assume that the whole city area is covered by RAN spectrum while the range of each cluster is 300 m, which we estimate to be a realistic range considering 100 mW APs. Internet penetration is 90 percent while the WS radio APs penetration is set to 50 percent. The number of available TV channels composing the TVWS is considered to be 3 and 6. Beacons are assumed to be perfectly detected in the broadcast channel and the users from non-compliant networks. Finally, coexistence decisions are based on the DFS coexistence technique.

Figure 5 shows the dependence spectral availability is expected to have on population density and AP penetration. The denser the city is, the lower the spectral availability becomes, resulting in higher needs for coexistence mechanisms. For instance, the spectral availability of Tokyo city, with household density of 2800/km^2, for a TVWS composed of 6 TV channels is about 25 percent bigger if DFS is used as the coexistence technique following information exchange between CHEs. Obviously, if other coexistence techniques are employed (e.g., TDMA, TPC, CDMA), spectral availability will differ.

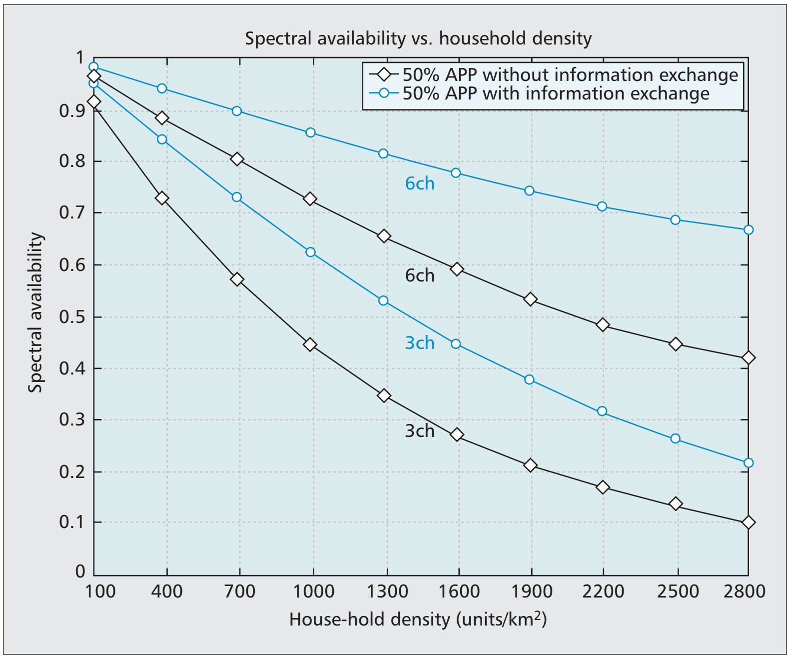

Figure 5. *Spectral availability of two difference scenarios: 1) Information relevant for coexistence is made available by our proposed mechanisms. 2) No information exchange is available. Spectral availability is evaluated for cities with different household densities, Internet penetration of 90 percent, AP penetration of 50 percent for TVWS composed of three and six TV channels. DFS is the employed coexistence technique.*

CONCLUSIONS

We provide two standard independent mechanisms to enable exchange of information relevant for coexistence among radio technology independent (dissimilar) or independently operated TVBD networks. One mechanism is subscription-based and relies on a centralized database approach to enable TVBD networks' coordinated access to TVWS. However, it requires a coexistence service provider to manage and operate the database, which in a real world is likely to create the burden of service fees. The other mechanism provides coexistence in a plug-and-play fashion, utilizing the proximity of interfering networks in a smart way to exchange beacons containing information relevant to coexistence. Both provided mechanisms are capable of obtaining information relevant to coexistence even from networks that do not comply with them.

REFERENCES

[1] FCC, "Spectrum Policy Taskforce Report (rt docket no.02-135)," Nov. 2002.

[2] FCC "Second Report and Order and Memorandum Opinion and Order, in the Matter of Unlicensed Operation in the TV Broadcast Bands Additional Spectrum for Unlicensed Devices Below 900mhz and in the 3 GHz Band (et docket 08-260)," Nov. 2008.

[3] OfCom, "Consultation Doc.: Digital Dividend-Cognitive Access," Feb. 2009.

[4] Std. ECMA-392, MAC and PHY for Operation in TV White Space, 2009.

[5] C. Stevenson *et al.*, "IEEE 802.22: the First Cognitive Radio Wireless Regional Area Network Standard," *IEEE Commun. Mag.*, vol. 47, no. 1, 2009, pp. 130–38.

We provide two standard independent mechanisms to enable exchange of information relevant for coexistence among radio technology independent (dissimilar) or independently operated TVBD networks. Both are capable of obtaining information relevant for coexistence even from networks that do not comply with them.

[6] O. Fatemieh *et al.*, "Low Cost and Secure Smart Meter Communications Using the TV White Spaces," *ISRCS*, June 2010.

[7] Y. C. Liang *et al.*, "Cognitive Radio on TV Bands: A New Approach to Provide Wireless Connectivity for Rural Areas," *IEEE Wireless Commun.*, vol. 15, no. 3, June 2008, pp. 16–22.

[8] F. Martin *et al.*, "Early Opportunities for Commercialization of TVWS in the U.S.," May 2008, pp. 1–5.

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