Comparison of 802.11af and 802.22 standards – physical layer and cognitive functionality

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Abstract – This article discusses two standards operating on principles of cognitive radio in television white space (TV WS) frequencies - 802.22 and 802.11af. The comparative analysis of these systems will be presented and the similarities as well as the differences among these two perspective standards will be discussed from the point of view of physical (PHY), medium access control (MAC) and cognitive layers.

1 Introduction

With the ubiquitous conversion to digital television, the "free" TV WS frequencies appeared for exploitation in television frequencies. Several standards based on the cognitive radio (CR) networks principle such as 802.11af, 802.19, 802.22 and ECMA 392 are prepared to work on this "free" frequencies. All of these standards operate in the TV WS, but each of them has its own characteristics (bandwidth, transmission power, different system architectures, and device types). This paper will consider two from the above mentioned standards - 802.11af (Wi-Fi in WS) and 802.22 (broadband access in WS). The rest of this paper is organized as follows. In Section 2, we introduce the 802.11af and 802.22 standards. Section 3 presents the comparative analysis of the both systems on three layers: PHY, MAC and cognitive. Conclusion is given in Section 4.

2 Description of standards

Prior to the description of the standards, it has to be noted that the standard 802.11af is still under development and expected date of completion this work is 31.12.2013 [16], at that time as a press release of 802.22 standard was published in 2011 [17].

2.1 Standard 802.11af basic architecture

The requirements specification of 802.11af system is formed, the standardization process is not yet finished, but it is known that the standard will use the principles of CR. In another way, this standard is also called "Super Wi-Fi", or "White-Fi", "Super" - because of its cognitive properties, and "White" - due to work in a range of free TV WS frequencies.

802.11af is a modified 802.11 standard, which operate in a range of TV WS using the properties of CR. In this system, cognitive functions are supported using the channel power management (CMP) and mechanisms of dynamic station enablement (DSE), which controls the channel dependent stations (STAs) operating under the control of the enabling STA. In order to describe how the cognitive functions are implemented in this standard, it is necessary to consider the composition of the system. 802.11af includes three different STA types: fixed, enabling, and dependent STA.

Fixed and enabling STAs are registered station that broadcast its registered location. The enabling STA is permitted to enable operation of unregistered STAs, i.e. dependent STAs. The enabling STA gets the available channel information from the TV WS database, and transmits the contact verification signal (CVS). The CVS is used for both establishing that the dependent STAs are still within the range of enabling STAs, as well as for checking the list of available channels.

DSE allows dependent STAs use the available TV channels under the control of the enabling STA. Figure 1 illustrates DSE procedure of processing between enabling STA and dependent STA. In addition channel power management (CPM) is also used to update the list of available channels for work in basic service set (BSS), change a maximum transmission power or change the BSS operation in channel frequency and channel bandwidth, together with a maximum value transmission power [10].

There are two operating scenarios for 802.11af: first is shown on the Figure 1, second is based on the access point (AP) communication to TV WS database through the so-called registered location secure server (RLSS).

Depending on operating conditions, there may be two scenarios for deploying 802.11af standard:
- indoor (<100 m): as in existing WLAN networks 802.11,
- outdoor (<5 km): range of less than worldwide interoperability for microwave access (WiMax)/802.22 and longer than 802.15.4g/4e.

Associated with a number of typical urban models.

Although the 802.22 supports the outdoor mid-range communications, for longer distances the 802.22 standard that will be described below has been developed.

2.2 Standard 802.22 basic architecture

Main purpose of the 802.22 standard creation is to provide a wireless broadband access in rural areas typically 17-30 km (possibly up to 100 km) from the base station (BS)
to the customer premises equipment (CPE). It thus belongs to the category of wireless regional area network (WRAN). The IEEE 802.22 uses cellular topology with a cell consisting from BS and zero or more CPEs associated with and under control of this system. The coverage area of this cell extends up to the point where the signal received from the BS is sufficient to allow CPEs to associate and maintain communication with the BS.

The reference architecture for IEEE 802.22 systems, presented in Figure 2, allocates PHY and MAC levels and the interface station management entity (SME) through PHY and MAC layer management entities (MLMEs), as well as to higher layers such as IP layer. On the PHY level, there are three particularly important features: the main data communications, the spectrum sensing function (SSF), and the geolocation function, the last two of which provide the cognitive properties of the system. PHY and MAC levels interact with each other through the service access points (SAPs), which give modularity to the system, where different components may be partitioned and/or from different vendors. A SME in its turn communicates with PHY level by the PHY layer management entity (PLME) and its SAPs [13].

From the cognitive radio perspective, the key role in the presented architecture has the Spectrum Manager (SM). The SM is responsible for the most important tasks, such as maintaining spectrum availability information, channel selection, channel management, scheduling spectrum sensing operation, access to the database, enforcing IEEE 802.22 and regulatory domain policies, and enabling self-coexistence, etc. (as shown on the Figure 3). The SM is a central part of the WRAN BS, which shall be responsible for ensuring protection of incumbents and efficient spectrum utilization while complying with regulatory policies [8].

It is possible to distinguish the most important functions of SM [8]:

- maintain spectrum availability information,
- channel classification and selection,
- association control,
- channel set management,
- accessing the database service,
- scheduling quiet periods for spectrum sensing,
- enforcing IEEE 802.22 and regulatory domain policies,
- making channel move decisions for one or more CPEs or the entire cell,
- self-coexistence with other WRANs, etc.

After above presented cursory description of two standards, their more detailed comparative analysis will be provided below.
3 Comparison of 802.11af and 802.22 standards

Despite the fact that both standards operate in the TV WS range and that both of them have the properties of CR, in general they are very different. This is what will be discussed in this section.

Comparative analysis of the systems should be conducted in three planes: PHY layer feature, MAC layer feature and Cognitive feature. The results of the comparison are summarized in Tables 1-4.

3.1 Differences on PHY layer

In general, both the two standards use the same technology at PHY layer (Orthogonal Frequency Division Multiplexing (OFDM) modulation and Quadrature Phase-Shift Keying (QPSK), 16-QAM (Quadrature Amplitude Modulation), 64-QAM payload modulation, however Binary Phase-Shift Keying (BPSK) can be used only in 802.11af standard), but there is a difference in the total bandwidth, FFT size and error correcting code.

Table 1: Comparison of parameters of 802.11af and 802.22 standards on PHY layer [7, 8, 11]

<table>
<thead>
<tr>
<th>PHY layer characteristics</th>
<th>802.11af (WLAN)</th>
<th>802.22 (WRAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>Indoor: up to few 100 m</td>
<td>Outdoor: up to few km</td>
</tr>
<tr>
<td></td>
<td>Typ. 17 to 33 km</td>
<td>Max. up to 100 km</td>
</tr>
<tr>
<td>Max Delay spread, µs</td>
<td>&lt; 1</td>
<td>1 to 10</td>
</tr>
<tr>
<td></td>
<td>11 to 25</td>
<td>25 to 60</td>
</tr>
<tr>
<td>FFT (Fast Fourier Transform) size</td>
<td>64, 128, 256; optional 512 and 1024</td>
<td>2048</td>
</tr>
<tr>
<td>Total bandwidth (MHz)</td>
<td>5, 10, 20, 40</td>
<td>6, 7, 8</td>
</tr>
<tr>
<td>Maximum data rate</td>
<td>12 Mbps</td>
<td>22.69 Mbps</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>OFDM</td>
</tr>
<tr>
<td>Payload modulation</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM</td>
<td>QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Error correcting code</td>
<td>Convolutional code; optional: CTC, LDPC, SBTC</td>
<td>Convolutional code</td>
</tr>
</tbody>
</table>

As can be seen from the table 1, the 802.22 optionally employs the duo-binary convolutional turbo code (CTC), low density parity check codes (LDPC) and shortened block turbo codes (SBTC) coding. The most important characteristic of PHY layer is certainly the data rate. Data (or more precisely their example) required for its calculation are in Table 2 [7, 8].

The calculation of data rates for each of the standards defined by formula (1):

$$ R_b = \left( N_D \cdot R_{\text{BPSC}} \right) / T_{\text{SYM}} $$  

(1)

Thereby for 802.11af standard it turns into the following value:

$$ R_b = (48 \cdot 6 \cdot 3/4) / 4 \cdot 10^6 = 54 \text{ Mbps} $$

And for 802.22 standard (the case of maximum available data rate):

$$ R_b = (1440 \cdot 6 \cdot 5/6) / 317.39 \cdot 10^6 = 22.69 \text{ Mbps} $$

Table 2: Selected OFDM symbol parameters of 802.11af and 802.22 standards [7, 8]

<table>
<thead>
<tr>
<th></th>
<th>802.11af (WLAN)</th>
<th>802.22 (WRAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>64-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Coding rate, $R$</td>
<td>3/4</td>
<td>5/6</td>
</tr>
<tr>
<td>Coded bits per subcarrier, $N_{\text{BPSC}}$</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Number of data subcarriers, $N_D$</td>
<td>48</td>
<td>1440</td>
</tr>
<tr>
<td>Symbol duration, including cyclic prefix duration, $T_{\text{SYM}}$ (µs)</td>
<td>317.39</td>
<td>317.39</td>
</tr>
</tbody>
</table>

For the simple users point of view the indicators of most importance are the coverage and the data rate. From this perspective it is preferable to use the 802.11af standard.

3.2 Differences on MAC layer

On MAC layer the 802.22 standard use Time Division Multiplex (TDM)-based access with PHY resources allocated on demand using Orthogonal Frequency Division Multiple Access (OFDMA, while 802.11af will use its Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA)-based protocol (Table 3).

Whereas 802.11af users may back off, when the medium is employed by 802.22 transmissions, the opposite can't be true, since the 802.22 devices do not need to listen before transmitting. The differences in MAC strategy can limit the effectiveness of non-cooperative listen-before-talk mechanism in achieving fairness in TV WS coexistence [9].
3.3 Differences on cognitive layer

In terms of cognitive origins of standards, the most important role is played by their cognitive properties. As seen from Table 4, standard 802.11af has only the interface with the TV WS database, in contrast to standard 802.22 which employs larger set of cognitive properties.

Table 4: Comparison parameters and properties of 802.11af and 802.22 standards on Cognitive layer [3, 7, 8]

<table>
<thead>
<tr>
<th></th>
<th>802.11af (WLAN)</th>
<th>802.22 (WRAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cognitive layer characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface with spectrum sensors</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Interface with geolocation device</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quiet periods for spectrum sensing</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Interface with TV WS database</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

As the most important cognitive properties for CR networks are the geolocation information gathering and the spectrum sensing, the use of these two mechanisms will be described below.

3.3.1 Geolocation information for 802.11af standard

In this standard the enabling STA (or AP) sends the own geolocation information obtained using satellites in order to request for the list of available TV channels from the TV WS database. Moreover, according [1] device may load the channel availability information for selected multiple locations in the vicinity of the current location (a range that includes multiple geo-locations) from the TV WS database. From the information for multiple neighboring locations (so called overlapping channel lists), the device defines the area in which the same TV channels are available and where it thus could operate on the mobile basis. The overlapping channels can be used without querying the TV WS database at most until the 24 hours database access requirement expires. The AP should re-check its position every 60 seconds and if its new location is detected to be outside the stored boundary of the operating geographic area, the AP must contact the database to obtain a valid channel list for the new area.

3.3.1.2 Geolocation information for 802.22 standard

There are two modes of geolocation that can be used with 802.22 standard. A satellite-based geolocation is mandatory, while a terrestrial-based geolocation is optional. The geolocation technology shall detect if any device in the network moves by a distance greater than 50 m. In such case, the BS and CPE shall follow the local regulations and shall obtain the new list of available channels from the database service based on the new location of the device.

In the satellite-based geolocation the BS shall use its satellite-based geolocation capability to determine the latitude and longitude of its transmitting antenna within a radius of 50 m. The BS may also use the altitude information derived from the satellite-based geolocation capability. Similarly each CPE shall use its satellite-based geolocation technology to determine the latitude and longitude of its antenna within a radius of 50 m. Also e the CPE’s may use its altitude above mean sea level. Each CPE shall provide its geolocation coordinates to the BS during the registration process. The satellite-based geolocation antenna shall be co-located (i.e., ≤ 1 m separation) with the transmit and sensing antennas [8].

In addition the support for terrestrial-based geolocation capability has been designed in the 802.22 standard by providing all the necessary PHY and MAC. The terrestrial-based geolocation can be achieved in a two-step process. First, the range between the BS and a number of its CPEs involved in the process is determined with sufficient high accuracy. Second, in order to establish the geolocation of a CPE through triangulation, the precise distances between the CPE to be
geolocated and a number of reference CPEs belonging to the same cell are determined. The goal of this process is to allow an entity called the geolocator to build a precise graphic representation of the geographic location of the CPEs that form a cell under the control of the BS. This is achieved using the capabilities of the coherent multicarrier modulation inherent to the OFDM/OFDMA technique used by 802.22 standard. The BS establishes the precise distance to each of the reference CPEs as well as to the new CPE using the BS-to-CPE ranging process. This multiple “fine” ranging process is conducted in parallel with the CPE-to-CPE ranging process to establish the distance between the new CPE and each reference CPE involved using the ranging process. It is assumed that the terrestrial geolocation process already knows the absolute location of the BS and of the reference CPEs and the BS only needs to gather the information that it has acquired from these various BS-to-CPE and CPE-to-CPE ranging processes. Using all this information, the terrestrial geolocation process computes the location of the new CPE [8].

3.3.2 Spectrum sensing

Another cognitive property in the TV WS standards is the spectrum sensing. This is the process of scanning the radio frequency (RF) spectrum in order to detect the presence of the incumbent signals, usually above a certain sensing threshold, which defines the minimal signal level at which the incumbent signal must be detected. Any methodology used for spectrum sensing is calibrated in terms of two parameters: probability of false alarms ($P_{FA}$) and probability of missed detections ($1 - P_D$). Typically, there is a trade-off between sensing efficiency and the overhead required for sensing (i.e., sensing duration required to achieved a desired ($P_{DB}, P_{FA}$)) [14].

3.3.2.1 Spectrum sensing methods for 802.11af standard

The use of spectrum sensing in 802.11af is still an open question, the possible applications of various spectrum sensing methods has been proposed and evaluated in [4, 6].

In these papers, the application of several sensing methods for 802.11af standard has been evaluated, including the likelihood ratio test (LRT), energy detection (ED) method, matched filtering (MF)-based method and cyclostationary detection method, each of which has different requirements and advantages or disadvantages.

Although the LRT is proven to be optimal, it is very difficult to use, because it requires exact channel information and distributions of the source signal and noise. To use the LRT for detection, it is required to obtain the channel signal and noise distributions first, which is practically intractable.

The MF-based method requires perfect knowledge of the channel responses from the primary user to the receiver and accurate synchronization (otherwise, its performance will be dramatically reduced) [5].

Energy, or power, detector is a simple method that does not depend on properties of a specific signal type. This technique of sensing compares the output of the energy detector to a predefined threshold based on the noise floor. The energy detection sensing can quickly determine if there is a signal in the channel, excepting weak and spread-spectrum signals. Thereby this is a coarse sensing method.

The cyclostationary detection method needs to know the cyclic frequencies of the primary users, which may not be realistic for many spectrum reuse applications. In addition, this method demands excessive analogue-to-digital (A/D) converter requirements and signal processing capabilities [5].

3.3.2.2 Spectrum sensing methods for 802.22 standard

In the 802.22 standard, the spectrum sensing techniques are classified into two main categories: blind sensing and signal specific sensing. There are three blind sensing techniques: the energy detector, the eigenvalue sensing technique and the multiresolution sensing technique (Figure 4).

![Figure 4: Spectrum sensing methods for 802.11af standard in terms of their sensing accuracies and complexities](image)

ED method is the same as for 802.11af standard.

Other blind sensing technique is the eigenvalue sensing that is a coarse sensing method for digital television (DTV) detection but it meets the fine sensing requirements for wireless microphones. In practice, it is very difficult to obtain the accurate information about the noise power. The algorithm based on the eigenvalue sensing technique overcomes this shortage. The maximum and minimum eigenvalue of the sample covariance matrix of the received signal contains the signal and noise information, respectively. Based on random matrix theories (RMT [2]), the information is quantized and then used for signal detection. The threshold and the probability of false alarm are also found by using the RMT. The proposed method overcomes the noise uncertainty difficulty while keeps the advantages of the energy detection. The method can be used without the knowledge about the signal, the channel and noise power [15].

Third blind sensing technique is the multi-resolution sensing. This is a coarse sensing method for DTV. Present sensing technique produces a multi-resolution power spectral density estimate using a tunable wavelet filter that can change its center frequency and its bandwidth [8]. The filter is tuned over a range of frequencies and the power at each frequency is calculated. The power spectral density estimate can be used to test the whiteness level of the spectrum.
A signal specific sensing technique relies upon specific signal features. There are several signal specific sensing techniques, but most important for this standard in Europe is time domain correlation based method (CBM) for **sensing digital video broadcasting - terrestrial** (DVB-T).

This technique can work in two modes: improved cross correlation method and combined feature and energy detection. In detail description algorithms of their work and simulation results are presented in [12].

One DVB-T signal is a super frame that consists of four consecutive frames, with each frame consisting of 68 OFDM symbols (Figure 5).

The DVB-T uses OFDM modulation and is organized in frames. There are two methods for sensing DVB-T: the improved cross correlation (The Proposed_Syn) and the combined signal feature detection and energy detection (The Proposed_Asyn). Detailed algorithms of their work are submitted in [12]. Simulation results for both algorithms and different channels are shown in Table 5.

**Table 5: The sensing time for achieving the sensing goal:** $P_D \geq 0.9$ and $P_{FA} = 0.01$ at $\text{SNR} = -20\text{dB}$ [12]

<table>
<thead>
<tr>
<th>Channel mode</th>
<th>Improved cross correlation ($\Gamma=0.975$)</th>
<th>Improved cross correlation ($\Gamma=1.0$)</th>
<th>Combined feature and energy detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWGN (Additive white Gaussian noise)</td>
<td>1.2 ms</td>
<td>1.2 ms</td>
<td>2.4 ms</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>6.0 ms</td>
<td>2.4 ms</td>
<td>-</td>
</tr>
</tbody>
</table>

Here $\Gamma$ is a metric that is defined to express the time synchronization level [12]. When its value is 1 (perfect synchronization), the minimum sensing time is achieved.

**4 Conclusions**

This paper provides a comparative analysis of two standards, operating on principles of cognitive radio in the TV white space frequencies. After a brief introduction to the standards, a detailed comparative analysis of IEEE 802.22 and IEEE 802.11af standards is carried out in three directions: PHY, MAC, and cognitive layers. For each layer the table that summarizes the main parameters is provided, moreover an example of calculation of one of most important characteristic for users - maximum data rate is provided. As a result of the comparative analysis it reveals that the PHY layer of standards has the same base (OFDM modulation and convolutional coding; QPSK, 16-QAM, 64-QAM payload modulation). The differences in MAC strategy can limit the effectiveness of non-cooperative mechanism in achieving fairness in TV WS coexistence. And by virtue of its cognitive origin both standards have the most important cognitive properties: spectrum sensing, geolocation and communication with the TV WS database. But it should be noted that the standard 802.22 has the most complete set of cognitive properties, by virtue of which is more costly and complicated for a quick introduction to market. As a result, it can be assumed that the standard 802.11af is more promising for the early commissioning as well as the consumer environment "White-Fi" concentrated in cities, where demand for wireless technology is increasing every year. But the demand to introduce of standard 802.22 is also high, because it may serve as a base for "White-Fi" and implement high-speed wireless technology in rural areas.

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References