SIGNAL PROCESSING APPLICATIONS FOR COGNITIVE NETWORKS: STATE OF THE ART

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ABSTRACT

Cognitive radio is one of the most promising techniques of wireless communications, due to its many applications. Cognitive networks have the capability to congregate different cognitive users via cooperative spectrum sensing. Examples of cognitive networks can be found in important and different applications, such as digital television and wireless sensor networks. The objective of this paper is to analyze how signal processing techniques are used to provide reliable performance in such networks. Applications of signal processing in cognitive networks are presented and detailed.

***Index Terms*—** Cognitive Radio, Signal Processing, Spectrum Sensing, Cognitive Networks

1. INTRODUCTION

Cognitive Radio (CR) is an important technology for the evolution of wireless communications worldwide. Cognitive radio enables the modification of the transmission parameters through the interaction with the environment [1]. By monitoring the available frequency bands, cognitive users can opportunistically occupy spectral bands with no harming or interference to primary users [2].

Cognitive networks are emerging as a promising alternative to benefit from the cognitive radio characteristics and the potential new applications in several scenarios. Cognitive radio networks are classified as *Primary* or *Cognitive* Networks. Primary or Licensed Networks are those in which licensed users have the authorization to operate in specific spectrum bands. Due to this priority, cognitive users should not interfere with these users. On the other hand, Cognitive or Secondary networks enable cognitive users to opportunistically occupy vacant bands, as there is no priority for different users to use the available frequencies [1].

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Cooperative spectrum sensing is the tool that enables the monitoring of spectral opportunities by different cognitive radios. This sensing strategy is crucial for the expansion of cognitive networking in different areas.

The objective of this paper is to present the state of the art of signal processing applied to cognitive networks, as well as discuss several applications. The remaining of the paper is organized as follows: Section II highlights the cooperative spectrum sensing, which is a fundamental approach for modern cognitive networks. Section III discusses some major recent applications of those networks and Section IV presents the conclusions of this work.

2. COOPERATIVE SPECTRUM SENSING

Spatial diversity can help to mitigate the hidden terminal problem, decreasing the probability of missed detection of the primary users by employing cooperative secondary terminals [3]. Furthermore, cooperative approaches permit to reduce the multipath fading effects and to increase the sensitivity of the secondary terminals, by exploiting the spatial diversity due to the inherent displacement of the secondary terminals in the environment [4].

In cooperative spectrum sensing, each terminal performs a distinct spectrum sensing task. Then, the local information is exchanged, using a control channel, and collected either in a fusion center, or by other partners, which take the final decision by combining the received data.

In general, cooperative spectrum sensing can be performed as described in the following [5]:

1. N secondary users perform their own local spectrum sensing. This task is usually described as a binary testing problem in which the two hypotheses are denoted by H_0 – *i.e.*, Primary User (PU) absence – and H_1 – *i.e.*, primary user presence – associated with the *a priori* probability P_0 and P_1, respectively;

2. The secondary users forward their decisions to a common receiver, denoted as Fusion Center (FC), which usually is a secondary terminal with enhanced processing capabilities or a Cognitive Base Transceiver Station (CBTS) as suggested by the IEEE 802.22 [6]. For instance, the common receiver could be an Access Point in a wireless Local Area Network (LAN) or a Base Station (BS) in a cellular network [7];
3. The common receiver fuses the secondary users' decisions, $u_i \in \{0, 1\}, i = 1, \ldots N$, and makes a final decision, u_0, to infer the absence or presence of a primary user [4].

The three steps compose the most traditional class of cooperative spectrum sensing: the *centralized cooperative sensing* [8]. The fusion center selects a channel or a frequency band of interest for sensing, and instructs all cooperating cognitive users to individually perform a local sensing. At the local sensing station, all cognitive users are tuned to the selected licensed channel, or frequency bandwidth, which is a physical link between the licensed user transmitter and each cooperating cognitive terminal user for observing the primary signal (sensing channel). At the data reporting point, all secondary users are tuned to a control channel that is a physical link between each cognitive user and the fusion center, to send the measured results (reporting channel). The other two classes of cooperative spectrum sensing are: *distributed and relay-assisted* [9].

Distributed cooperative sensing is not based on a fusion center for making the cooperative decision. By multiple iterations, secondary users interact among themselves and converge to a unified decision on the presence or absence of primary users. Based on a distributed algorithm, each cognitive user sends its own sensing data to other users, combines its data with the received sensing data, and decides whether or not the primary user is present by using a local criterion. If the criterion is not satisfied, cognitive users send their combined results to other users again and repeat this process until the convergence of the algorithm and a decision is reached [9].

The third class of cooperative spectrum sensing is the relay-assisted cooperative sensing [10]. Since both sensing channel and report channel are not perfect, a cognitive user observing a weak sensing channel, but with a strong report channel, and a cognitive user with a strong sensing channel, but a weak report channel, for example, can complement and cooperate with each other to improve the performance of the cooperative sensing. If the sensing results need to be forwarded by multiple hops to reach the intended receive node, all the intermediate hops act as relays. Thus, if both centralized and distributed structures are *one-hop cooperative sensing*, the relay-assisted structure can be considered as *multi-hop cooperative sensing*.

The merit of cooperative spectrum sensing primarily lies in the sensing diversity gain, provided by the multiple cognitive terminals. Even though one cognitive user may fail to detect the signal of the primary user due to a sudden deep fade, there are still many chances for other cognitive users to detect it. With the increase of the number of cooperative CRs, the probability of missed detection for all the users is small. Another merit of cooperative spectrum sensing is the mutual benefit brought forward by communicating with each other to improve the sensing performance [11]. If one CR is far away from the primary user, the received signal may be too weak to be detected. However, by employing a CR that is located nearby the PU as a relay, the signal of the PU can be detected reliably by the far user [5]. Moreover, the cooperation enables the reliable detection of weak primary signal with low cost, low sensitivity CR terminals.

One of the problems of cooperation is to combine the results of various users which may have different sensitivities and sensing times. Some form of weighted combining needs to be performed in order to take this into account. Cooperation also requires a control channel, which can either be implemented as a dedicated frequency channel or as an underlay Ultra-Wideband (UWB) channel. Wideband RF front-end tuners and filters can be shared between the UWB control channel and normal cognitive radio reception and transmission. Furthermore, with multiple cognitive radio groups active simultaneously, the control channel bandwidth needs to be shared. With a dedicated frequency band, a Carrier Sense Multiple Access (CSMA) scheme may be adequate. For a spread spectrum UWB control channel, different spreading sequences could be allocated to different groups of users [12].

Cognitive users in the cooperative spectrum sensing generally fall into two groups. The first group includes busy users, who use the spectrum and continually monitor it to detect the appearance of the primary user. The second group includes idle users, who do not use the spectrum but must perform spectrum sensing to improve the overall sensing performance through cooperation. The massive spectrum sensing power consumption of idle users makes cooperative spectrum sensing a challenger scheme because idle users may use up battery energy before they really require to use the spectrum for communication [13].

Despite the cooperative approach can improve the performance with respect to traditional single antenna CR, various research activities have still to be carried out in this area. There are three main questions regarding cooperative sensing [12]:

1. How much can be gained from cooperation?
2. How can cognitive radios cooperate?
3. What is the overhead associated with cooperation?

In fact, different levels of cooperation can be defined according to the amount of data exchanged among single antenna CR terminals and different fusion rules can be adopted at the fusion center to combine the received local spectrum sensing data, resulting in different performances, required processing capabilities and overhead [4].

2.1. Fusion Rules

In cooperative sensing, data fusion is a process of combining local sensing data for hypothesis testing, which is also an element of cooperative sensing. Depending on the control channel bandwidth requirement, reported sensing results may have different forms, types, and sizes. In general, the sensing results reported to the FC or shared with neighboring users can be combined in three different ways in descending order of demanding control channel bandwidth [9]:

1. **Soft Combining** – CR users can transmit the entire local sensing samples or the complete local test statistics for soft decision. However, if every cognitive radio transmits the real value of its sensing observation, a huge number of bits are required and this results in a large communication bandwidth requirement. That characteristic turns this approach not feasible in the implementation of data fusion;
2. **Quantized Soft Combining** – CR users can quantize the local sensing results and send only the quantized data for soft combining to alleviate control channel communication overhead [14]. Quantization of local observations has attracted much research interest although it introduces additional noise and an Signal to Noise Ratio (SNR) loss at the receiver [15]. Some research has been done on quantization for the signal detection, but most of it is focused on the optimal design of the quantizer [16]. It was shown that a quantization with four or eight levels is adequate, without noticeable loss in the performance [17]. It has been claimed that identical binary quantization, i.e., two-level quantization, performs asymptotically optimal. as the number of users goes to infinity [8].
3. **Hard Combining** – CR users make a local decision and transmit the one bit decision for hard combining. When binary local decisions are reported to the FC, it is convenient to apply linear fusion rules to obtain the cooperative decision. The commonly used fusion rules are `and`, `or`, and majority rules.

In hard combining, the fusion center receives the local decision u_i and apply a fusion rule to combine them [5]

$$T = \sum_{i=1}^{N} u_i = \begin{cases} u_0 = 0 & \text{if } T \leq k \\ u_0 = 1 & \text{otherwise,} \end{cases} \tag{1}$$

in which, $u_0 = 0$ indicates that the primary users are absent, and $u_0 = 1$ indicates that the primary users are present. Note that the fusion rule reported in 1 represents the k out of N fusion rule and indicates that the global decision $u_0 = 1$ if at least k secondary terminals over N decide for the presence of the primary users [5]. The `or` and the `and` fusion rules represent a special case of the k out of N fusion rule. In fact, for $k = 1$ the fusion rule in 1 coincides with the `or` fusion rule, while for $k = N$ it coincides with the `and` fusion rule [4].

The `or` rule is more conservative in the licensed resource utilization than the `and` rule. The `or` rule only allows secondary transmissions if all the terminals of the cognitive network detect the absence of the primary activity. On the other hand, by the use of the `and` rule, if at least one secondary user detects the absence of the primary activity, then the secondary transmission is allowed. The *majority rule* requires at least a half of the CR users to report the presence of a primary user.

3. SIGNAL PROCESSING APPLICATIONS ON COGNITIVE NETWORKING

This section is devoted to the description of some important signal processing applications on cognitive networks.

3.1. TV White Spaces and Regulation

The IEEE 802.22 standard was developed to be used in Wireless Regional Area Networks (WRAN) to exploit the spectral holes available in television broadcasting [18]. This standard is based on the cognitive radio concept to permit the sharing of unused band frequencies in specific geographic areas. The goal is to cover areas subject to precarious TV signal reception (as in rural or low populated areas). These areas are not attractive to TV broadcasters due to infrastructure investment [19].

The IEEE 802.22 standard allows the digital and analog TV signals to operate on the same bands with no interference or meeting some low interfering requirements (to avoid harm concurrent transmissions) [20]. The IEEE 802 work group is completing other regulations and standards, which include the IEEE 802.11, the IEEE 802.22, the IEEE 802.15 and the IEEE 802.19. The IEEE Dyspan Standard Committee released the IEEE 1900.7, 1900.4a and 1900.4.1 standards [18, 21].

3.2. Smart Grids

Smart Grids are the next-generation of the electric power systems. In these systems, every device connected to the electrical grid (such as transformers, voltage regulator, capacitor, circuit breaker, control station, digital meters) has an IP (Internet Protocol) address, making possible a two-way communication between consumers and providers. The smart control centers should monitor and remotely interact with electric devices in real time [22].

The main challenge in a smart grid is to provide a fast, reliable and secure communication network, connecting several different electric devices [23]. However, no existing standardized communication/network infrastructure has been widely adopted to transform the current electrical power grid into a real smart grid [24]. In this context, the usage of a cognitive network infrastructure-based can lead to some advantages as bandwidth, higher coverage areas and reduced costs when compared to traditional cable electrical grid [25].

Smart Utility Networks (SUN) Task Group is developing the IEEE 802.15.4.g standard for infrastructure applications in 700 MHz to 1 GHz and at Industrial, Scientific and Medical (ISM) 2,4 GHz bands. Besides these efforts other workgroups are concentrated on achieving standardizations for the adoption of TV white spaces in smart grid [25].

3.3. Cognitive Wireless Sensor Networks

Wireless Sensor Networks (WSN) can benefit from the cognitive radio and its dynamic capacity to explore new possibilities. Cognitive Radio - Wireless Sensor Networks (CR-WSN) or Cognitive Radio Sensor Networks (CRSN) are defined as a wireless sensor network equipped with cognitive transceivers and sensing circuits. These devices enable the monitoring of an event or environment where the sensor nodes are capable of looking for available channels to propagate the data, which leads to an opportunistic communication between the nodes. The goal is to send the gathered data to the sink node in an efficient and reliable way (in terms of latency and energy consumption) [26].

Wireless sensor networks normally operates in a specific frequency range, which consequences are the reduced coverage of the sensors and the limited data propagation and transmission. Then, the main advantage of a CRSN is the operation of different WSN in the same geographic area. There is no interference between the networks due to the cognitive capacity to look for vacant bands [27, 28].

3.4. Public Safety and Medical Networks

Cognitive networks can be designed to actuate on emergency and public safety and medical networks. Such networks can make the spectrum usage more effective without the exigence of a specific infrastructure. Public prevention of natural disasters (to operate in case of flooding, earthquakes, etc.) would not be affected by temporary or permanent damages in the established network infrastructure [25].

Another possible application would be in the actuation of healthcare and medical emergency teams in hospitals and ambulances. Finally, security forces (as policemen and firemen) could benefit from cognitive networking when in duty or under dangerous situations [27, 28].

3.5. Vehicular Networks

The increase of the automotive market and the continuous evolution of pervasive and embedded systems in all environments lead automakers to focus its efforts in infotainment solutions and new alternatives to drivers and passengers. However, new features and services tend to overload the available spectrum in an automotive environment. Internet access or Bluetooth connections inside cars are already suffering interferences in heavy-traffic roads [29].

Cognitive vehicular networks represent a new tendency in the automotive market. New and future models are being released with pre-installed reconfigurable devices; software defined radio (SDR) offers new possibilities to transmit intra-vehicular commands as well as dynamic access to Wi-Fi and other wireless services using the cognitive capability [30].

In this way, a new tendency in the automotive market is evolving. Cognitive radio for vehicular Ad hoc Networks (CRVs or CR-VANETs) enable cars to monitor the available spectrum bands and to opportunistically operate in such frequencies. The objective is to detect some available spectrum and to access it with no harming to concurrent transmissions (drivers and cars). CR transceivers operate if no other user is using such spectrum or if minimum interference levels are observed in order to not affect other users [29].

The motivation for the establishment of CR-VANETs are the bandwidth scarcity and congestion in vehicular environments; resiliency; spectrum holes when cars travel in highways; SDR flexibility for new in-vehicular applications; as well as the long-term autonomy in terms of energy supply for wireless devices (due to battery and alternator) [30].

4. CONCLUSIONS

Cognitive networks are expanding the possibilities of cognitive radio in the users daily lives. Several areas of modern life have already benefited from the technology. Cognitive users can operate different services and provide applications with minimum harm or interference. Consequently, new opportunities of services are being added and can help improve the area of wireless communications.

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