Physical Communication 9 (2013) 148–170

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

A comparative study of spectrum awareness techniques for cognitive radio oriented wireless networks

Raza Umar [a,b,*], Asrar U.H. Sheikh [a]

[a] Wireless Broadband Communication Research Group, Electrical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia

[b] University of Engineering and Technology, Lahore 54890, Pakistan[1]

ARTICLE INFO

Article history:
Received 29 February 2012
Received in revised form 13 June 2012
Accepted 16 July 2012
Available online 25 August 2012

Keywords:
Cognitive radio
Spectrum sensing
Cooperative detection
Transmitter detection
Blind sensing

ABSTRACT

Spectrum scarcity is impeding practical implementations of emerging wireless multimedia applications requiring significantly more frequency spectrum. Cognitive radio (CR) has emerged as a promising solution to the current spectral congestion problem by imparting intelligence to the conventional software defined radio that allows spectrum sharing through opportunistic spectrum access. The principal objective of CR is to optimize the use of under-utilized spectrum through robust and efficient spectrum sensing (SS). This paper introduces cognitive functionality and provides an in-depth comparative survey of various spectrum awareness techniques in terms of their sensing accuracy and computational complexities along with their merits and demerits. Specifically, key challenges in SS are highlighted and possible solutions are discussed. A classification of SS is presented to address the sensing method selection criterion. Both non-cooperative and cooperative sensing schemes are reviewed and open research problems are highlighted to identify future research directions.

1. Introduction

The emerging wireless multimedia applications are leading to an insatiable demand for radio spectrum. The current fixed frequency allocation strategy worked well in the past as it provided an optimal solution by avoiding interference between active wireless users. However, with steadily growing number of wireless subscribers and operators, fixed assignment of radio spectrum is proving to be a hurdle in the deployment of new wireless services. As a result, several spectrum regulatory authorities around the world carried out studies on current spectrum scarcity with an aim to optimally manage available radio spectrum. Interestingly, these studies revealed that a large portion of assigned spectrum is either not used at all or only sparsely utilized, for significant periods of time. According to Federal Communications Commission (FCC) [1], spectrum utilization varies from 15% to 85% with wide variance in time and space. It was concluded that the root cause of current spectrum scarcity is not the physical shortage of spectrum rather the inefficient fixed spectrum allocation. This finding opened doors to a new communication paradigm of sharing the under-utilized radio spectrum through dynamic and opportunistic spectrum access (DOSA) [2].

The technology that enables un-licensed users to dynamically and opportunistically access the licensed spectrum, without affecting the existing users with legacy rights to that spectrum, is the cognitive radio (CR) technology. The key component of CR technology is the ability to sense and ultimately adapt to the continuously changing radio's operating environment. In CR terminology, the incumbents of a frequency band are called primary users

* Corresponding author at: Wireless Broadband Communication Research Group, Electrical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia.

E-mail addresses: raza.umar@gmail.com, razaumar@kfupm.edu.sa (R. Umar), asrarhaq@kfupm.edu.sa (A.U.H. Sheikh).

1 On study leave.

1874-4907/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.phycom.2012.07.005

(PU) while the term secondary users (SU) is reserved for low-priority un-licensed users equipped with a cognitive capability to exploit this spectrum without affecting the operation of PU. Therefore, the most crucial task of SU (also termed as simply CR in literature) is to reliably identify available frequency bands across multiple dimensions like time, space, frequency, angle and code etc., and efficiently exploit them by dynamically updating its transmission parameters under the stringent requirement of avoiding interference to the licensed users of that spectrum. To accomplish this, the secondary users rely on robust and efficient spectrum sensing (SS) to identify vacant frequency bands under uncertain radio frequency (RF) environment and to detect primary users with high probability of detection, as soon as the incumbents become active in the band of interest [3].

This paper presents an introductory tutorial on spectrum sensing for cognitive radio featuring both non-cooperative and cooperative sensing strategies and provides comparative analysis among various detection techniques in terms of required prior information about the source signal and propagation channel. Section 2 introduces cognitive functionality, identifies its objectives and highlights characteristic features of CR. Fundamental sensing approaches are outlined in Section 3 and a comprehensive classification of these schemes is provided. Section 4 presents a variety of conventional and emerging spectrum sensing techniques based on recent advances in local, non-cooperative detection of spectrum activity at CR and provides their performance comparison. This is followed by a detailed discussion on the limitations associated with single-user centric spectrum sensing, outlined in Section 5. Section 6 explains the cooperative sensing concept and discusses various elements of cooperative sensing including cooperation models, information fusion approaches, control channel and reporting concerns and user selection. An insight into the cooperation overhead as the cost of achievable cooperative gain is presented in Section 7 highlighting the key challenges in cooperative detection. Finally, open research problems and future research directions are provided in Section 8 and our conclusions are drawn in Section 9.

2. Cognitive radio

Cognitive radio is essentially an evolution of software defined radio (SDR) which is formally defined by FCC [4] as

A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

The ultimate objective of CR is to utilize the unused spectrum. In essence, this means that CR introduces intelligence to conventional radio such that it searches for a *spectrum hole* defined as "a licensed frequency band not being used by an incumbent at that time within a selected area". As most of the spectrum is already assigned to PUs with legacy rights, the key task is to share licensed spectrum without producing harmful interference to PUs. Hence the main functionality of CR is to track the spectrum hole [5]. Spectrum usage opportunity is then exploited by CR as long as no spectrum activity is detected. If this band is re-acquired by PU, CR being low-priority secondary user must either vacate the band or adjust its transmission parameters to accommodate the PU or, if available/possible, shift to another spectrum hole.

2.1. Cognitive characteristics

Cognitive functionality described above is achieved by two main characteristics of CR namely, *cognitive capability* and *reconfigurability*. Cognitive capability refers to the ability of radio technology to interact with its radio environment in real time to identify and scavenge "un-occupied" licensed spectrum bands called *spectrum holes* or *white spaces* [6]. The observations published by FCC in [1], categorizes spectrum holes into two groups: temporal spectrum holes and spatial spectrum holes. This gives rise to two secondary communication schemes [7] of exploiting spectrum opportunity in time and space domain which are depicted in Fig. 1(a) and (b) respectively.

A *temporal spectrum hole* occurs when no primary transmission is detected over the scanned frequency band for a reasonable amount of time and hence this frequency band is available for secondary communication in current time slot. A *spatial spectrum hole* is generated when the primary transmissions are confined to a certain area as shown in Fig. 1(b) and hence this frequency band is available for secondary communication (may be in the same time slot) well outside the coverage area of PU to avoid any possible interference with primary communication. The secondary transmission over the spatially available licensed spectrum is allowed if and only if it remains transparent to presumably nearby primary receiver. This puts a stringent requirement on SU to be able to successfully detect PU at any place where secondary communication may cause interference to primary transmission. Therefore, a protection area of PU is defined wherein SU must be able to detect any PU activity to avoid harmful interference with primary receiver $D_{\min}$ apart from SU [8,9]. The cognitive capability is not limited to only monitoring power in some frequency band rather it demands multidimensional spectral awareness [10]. This requires that CR should be able to reconfigure its communication parameters on the fly in order to adapt to its dynamic radio environment, calling for the reconfigurability characteristic of CR.

2.2. Key to cognition: spectrum sensing

The key concept in CR is the provision of opportunistic and dynamic spectrum access of licensed frequency bands to unlicensed users. Hence, the main functionality of CR lies in efficient spectrum sensing so that whenever an opportunity of unused spectrum band is identified, CR may make use of it. This paper aims at exploring various dimensions of spectrum sensing with an aim to review ongoing and emerging trends in SS and compare different SS techniques to identify room for potential research opportunities in this field.