Ad Hoc Networks 36 (2016) 1–20

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Decentralized robust spectrum allocation for cognitive radio wireless mesh networks

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ARTICLE INFO

Article history:
Received 17 December 2014
Revised 26 May 2015
Accepted 27 May 2015
Available online 17 June 2015

Keywords:
Wireless mesh networks
Cognitive radio
Dynamic spectrum allocation

ABSTRACT

During the last decade we have seen an explosive growth in the deployment of wireless networks in unlicensed frequency bands, mainly driven by the great success of the IEEE 802.11 standard. In addition to its traditional last-hop usage, it has also been widely employed for Internet access infrastructure such as wireless mesh networks (WMNs). A problem that is envisioned in the near future is the spectrum scarcity, which could be a serious threat to cope with the ever increasing demand. Regulators are aware about this problem and they have already started to look for more available spectrum. One of the possibilities that has emerged is to allow secondary assignments in licensed bands, based on the recent cognitive radio networks (CRNs) paradigm. In this context, we focus our work in the analysis of optimum spectrum allocation mechanisms for a cognitive wireless multihop mesh network. We introduce a stochastic model to formulate the problem, considering primary users' activity and a periodically scheduled assignment scheme. To solve the problem we propose a novel robust solution, for which we develop a decentralized algorithm implementation. Furthermore, we evaluate our proposal through extensive simulations, showing for instance its superiority compared with an expectation based approach.

1. Introduction

Undoubtedly, the deployment of wireless networks in unlicensed frequency bands has increased significantly during the last years, particularly as Internet access technology for end users. The great success of the IEEE 802.11 standard has been one of the keys to this process. Over the last decade we have also witnessed the highest growth in wireless networks traffic [1] and forecasts indicate that this growth will continue [2]. Moreover, the user density is also increasing, resulting in crowded scenarios where the technology is reaching its limits (e.g. classrooms, large conferences, shopping centers or sport events [3]).

Besides these most common scenarios, where we only have a wireless last hop, requirements also increase for the wireless transport networks we found today, also using 802.11-based technology in unlicensed bands. This is the case of the typical wireless mesh network (WMN) solution, used for example in Plan Ceibal [4] as Internet access for schools located in rural or suburban areas. In that case the problem is not about user density, as we only have point to point or point to multipoint links between a few nodes. Instead, we have higher throughput requirements, because we are talking about the network core. While standards are still evolving, achieving increasingly higher spectral efficiency, we may soon be faced with spectrum scarcity issues to properly cope with traffic demands. Regulators

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http://dx.doi.org/10.1016/j.adhoc.2015.05.021

have taken note about this fact and some proposals already exist to extend the available spectrum [5].

Leaving aside traditional spectrum allocation, a new type of spectrum assignment has emerged some years ago: the so-called cognitive radio paradigm [6]. The main idea is to have two types of users; licensed or primary users (PUs from now on), which have the preferential right to use the band; and unlicensed or secondary users (SUs from now on), which can use the band only in the absence of the PUs. This type of spectrum allocation contributes to a more efficient use compared to traditional static assignments, as testified by some recent FCC rulings [7]. Although adoption is not yet massive, much industrial and academic efforts have been dedicated to this kind of technology. For instance, the IEEE 802.22 standard [8] was approved in 2011, which defines a wireless regional area network (WRAN) based on cognitive radio. Another industrial effort is the 802.11af amendment to enable the operation of WiFi in TV bands, which has been recently published [9].

On the other hand, the development of cognitive radio equipment is still immature, particularly concerning sensing tasks to detect PUs, so the first solutions being deployed are based on databases queries to get the information about the available spectrum [10]. Some major providers such as Google are already authorized in the US to give such spectrum database service [11]. Everything suggests that in the short to medium term dynamic spectrum allocation will expand, and in a few years we will probably have several standards operating under this paradigm. This enables new possibilities for the development of radio communications equipment, which added to the advances in software defined radio (SDR) technologies, may cause a significant change in the world of wireless communications we know so far.

Our work is focused on WMNs [12,13], which have emerged in the last years as a cost-efficient alternative to traditional wired access networks. After many years of research, WMNs are no longer just a promise for the future, but a reality today, thanks mainly to the lower prices of radio cards and the operation in unlicensed frequency bands. In particular, outdoor community mesh networks [14] and rural deployments [15,16] based on IEEE 802.11 have seen tremendous growth in the recent past. An example is Plan Ceibal [17] which provides connectivity to every school in Uruguay, where WMNs are used to reach suburban and rural schools. Lately, even service providers are beginning to use this technology, resulting in an increasing presence of carrier-class equipment in the market [18]. The typical architecture of a WMN is depicted in Fig. 1, which includes one or more Internet gateways and several relay routers. We will concentrate ourselves in the problem of resource allocation for the core of the WMN, that is to say we will only consider the wireless links between the intermediate routers, ignoring then the additional links with the end users (typically in other frequency bands). Moreover, we will develop a decentralized scheme to implement the proposed algorithm, so that the solution properly scales as the size of the WMN grows.

While much research has been recently dedicated to cognitive radio networks and dynamic spectrum allocation, most of the works have mainly focused on the case where there are only licensed bands available [19]. In that case, unlicensed devices can only operate as SUs in the absence of PUs, greatly limiting their possibilities. We believe it is very complex to develop a useful solution in such scenario with high throughput requirements. Several issues arise working only with licensed bands, for example, you need to ensure a control channel to coordinate communication, which is not an easy task without any guaranteed frequency band to use. Moreover, it is possible to have circumstances under which the available spectrum is not sufficient to meet the throughput requirements, as the available capacity strongly depends on the PUs' dynamics. In this paper we work in a mixed licensed and unlicensed scenario, which we believe is more appropriate to support high throughput requirements. This solution has not been deeply explored yet in the literature and we think it is the most suitable model for the equipment and regulations that we may have during the coming years.

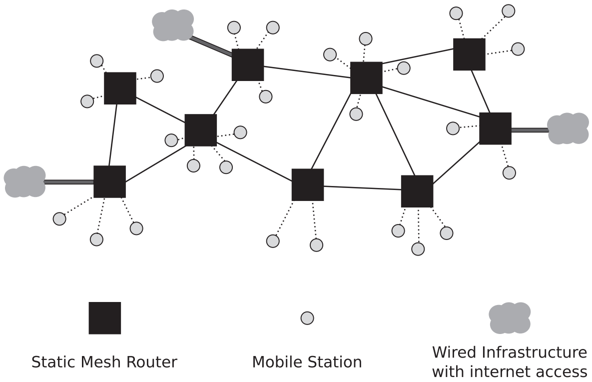

Fig. 1. Wireless mesh network typical architecture.

This paper bears on the dynamic spectrum assignment in a WMN. That is to say, we will study possible methods to decide which frequency bands may be used by the network devices at any given time. It is worth to highlight that such an assignment means that the bands are *available* for the devices, and are not necessarily used. With this in mind, the natural question that arises is to what purpose this assignment should be performed [20]. In our particular context, examples include minimizing the number of licensed bands assigned [21] or maximizing the user's utility (as a function of the mean rate) [22] without exceeding a maximum interference threshold to other networks. However, in the context of a cognitive WMN, we argue that the most natural objective would be to provide a lower bound to the resulting throughput in each link. The purpose of the spectrum allocation should be thus to ensure a certain effective capacity for each link, independently of the channel conditions and the PU's activity.

The other challenge that these systems pose is the timescale at which the assignment should be performed. One possibility is to re-assign (and thus re-optimize) every time a band is used or abandoned by PUs, or if significant changes in channel conditions occur. Although this event-driven solution will lead the system to operate with the optimal allocation all the time, it will typically result in a dramatically high signaling overhead. In this sense, we will assume, as many researchers, a periodic optimization every T time units, which leads us to a better performance tradeoff. However, T may include variations in PUs' activity. This fact implies that a licensed band assigned when the period starts might have to