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CogMAC+: A decentralized MAC protocol for opportunistic spectrum access in cognitive wireless networks

Peng Wang*, Junaid Ansari, Marina Petrova, Petri Mähönen

Institute for Networked Systems, RWTH Aachen University, Kackertstrasse 9, D-52072 Aachen, Germany

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ABSTRACT

The rapidly increasing number of wireless applications are making the wireless spectrum scarcity a serious problem. Cognitive MAC protocols have emerged as a promising solution to address this issue by opportunistically allowing secondary users to utilize unused licensed bands, and enabling spectrum co-existence of multiple secondary networks. In this paper, we present CogMAC+, a decentralized multichannel MAC protocol, which is based on multichannel preamble reservation scheme and CSMA principle. It achieves parallel transmissions for multiple secondary users by enabling them to estimate the duration of channel occupancy of each other. In order to achieve the optimal sensing schedule, it allows secondary users to dynamically access channels according to the channel occupancy of primary users and other secondary networks. Moreover, CogMAC+ uses an adaptive energy detection scheme to dynamically set the energy detection threshold according to the carrier sensing status, the false positive detection ratio and the estimated noise level. CogMAC+ has been verified and evaluated empirically in a software defined radio testbed with realistic spectrum occupancies of licensed users. Our experimental performance evaluation indicates that CogMAC+ is able to carry out reliable parallel communication in multiple channels even in a severely interfered environment.

1. Introduction

Cognitive wireless networks are an attractive solution to increase spectrum utilization efficiency and enable cooperation between different user groups. One of the basic tenets in this concept is that the users are divided into primary users (PU) and secondary users (SU). The primary users have a priority for the spectrum due to a licence or other arrangement, while the secondary users can access spectrum opportunistically. For recent reviews, we refer the reader to [1–3]. One of the key requirements for cognitive communications is to have spectrum aware cognitive Medium Access Control (MAC) protocol. Besides classical cognitive radio operations, enabling efficient spectral co-existence of multiple networks in the ISM band can be also targeted by many cognitive MAC protocols. A number of cognitive MAC protocols have been proposed in recent years [4,5]. In order to carry out secondary transmission while tracking the activity of PU, most of the works include functionalities such as spectrum sensing, PU transmission detection, and coordination among SUs.

One approach to enhance cognitive radio multiple access is to introduce Multichannel Preamble Reservation (MPR) schemes as done in [6]. In this paper we upgrade MPR scheme to a new Multichannel Multiframe Transmission (MMT) scheme and extend such approach by introducing Multichannel Virtual Carrier Sensing (MVCS) scheme with strict time controls, and call this new MAC scheme as CogMAC+. The approach significantly improves performance and allows better control on channel access and energy savings, the properties that can be very important for different Machine-to-Machine (M2M) and Internet of Things (IoT) applications using cognitive radios.

To evaluate CogMAC+ and prove the compatibility of CogMAC and CogMAC+, we have implemented both protocols in a Software Defined Radio (SDR) testbed using LabVIEW [7] and Universal Software Radio Peripheral 2 (USRP2) [8]. In order to verify the validity of LabVIEW-USRP2 testbed and the compatibility of CogMAC protocol, we carry out a number of baseline comparison of CogMAC in the commercially available Wireless Open-Access Research Platform (WARP) [9] and LabVIEW-USRP2 testbeds. Although these two testbeds have different system characteristics, the baseline comparisons indicate that CogMAC follows the same trend on both of the testbeds. In order to provide a comprehensive insight into the new features of CogMAC+, a number of experiments are carried out with respect to a number of key parameters. We use also realistic spectrum models that are statistically characterized from practical measurement campaigns to emulate the behaviors of external transmissions. Experimental results show that CogMAC+ is able to offer reliable data communication services through opportunistic medium access while

* Corresponding author. Tel.: +49 2418020915; fax: +49 24180620900.
E-mail addresses: pwa@inets.rwth-aachen.de, joqoko@hotmail.com (P. Wang), jan@inets.rwth-aachen.de (J. Ansari), mpe@inets.rwth-aachen.de (M. Petrova), pma@inets.rwth-aachen.de (P. Mähönen).

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keeping the interference caused to PU under the permitted level. Especially for unicast and multicast scenarios, CogMAC+ significantly enhances the system performance compared to our earlier CogMAC protocol by enabling the parallel transmission. The rest of this paper is organized as follows. We review related work in Section 2 and describe CogMAC+ in Section 3. Afterward, we briefly introduce the experimental setups in Section 4. The experimental results are analyzed in Section 5. The paper is finally concluded and future work is discussed in Section 6.

2. Related work

A number of cognitive MAC protocols have been proposed in the literature [1–3,10]. In general, two major problems have to be addressed by a cognitive MAC protocol. The first problem is how to gather necessary information of the wireless environment and other users around, and secondly how to utilize the spectrum resources, i.e., determining at what time, in which frequency band, and by what strategy to carry out transmission. The first issue has been widely addressed by adopting different CSMA based schemes [11,12]. The listen-before-talk principle enables the user to verify the absence of other ongoing traffic in the shared frequency band down to the spectrum sensing limit of the devices used, of course. Coordination mechanisms are used to address the hidden node problem. Thus coordination allows users to share their observations and decisions to improve the overall network performance [13]. Park et al. proposed a measurement reporting MAC protocol called as Truncated Time Division Multiple Access (TTDMA) in [14] which enables dynamic control information exchange. The second problem is addressed in centralized protocols [1,3,15] by using a central coordinator. However, the wireless networks often have a decentralized nature in a sense that observation and utilization are all performed individually by distributed terminals. Therefore the environment observation and control information have to be exchanged among central coordinator and users which inevitably causes delay and bandwidth wastage. Distributed protocols, which require no cooperative infrastructure, are widely used in wireless ad hoc networks. In distributed protocols, the major challenge is to coordinate users in a multichannel environment so that different users are able to receive transmission of other users in different channels seamlessly. This is called as rendezvous problem [16–18]. Song and Xie proposed a fully distributed CSMA based broadcast protocol BRACER [19], which addresses the rendezvous problem by downsizing the set of deployed channels and designing the corresponding broadcasting patterns and scheduling algorithm. Relying on the neighboring location information, it achieves high successful broadcast radio with variant broadcast delays.

A number of protocols address rendezvous problem by assuming the existence of a dedicated Common Control Channel (CCC). Intuitively, using dedicated CCC is an effective way to exchange control information for SUs which enables them to coordinate their behaviors. In this category, we can further divide the protocols into two subcategories, licensed CCC based protocol [20–22] and unlicensed CCC based protocols, e.g., C-MAC [23]. However, the assumption of availability of licensed CCC is not always easy to hold for SUs in licensed bands due to spectrum allocation policies. For unlicensed CCC based protocols, the problem is that the commonly available channel may not always simultaneously exist for all SUs which have different locations and channel characteristics. Moreover, how to schedule transmissions in the CCC is another challenge because the CCC may become saturated [4]. Without a dedicated CCC, the rendezvous problem becomes challenging in multichannel scenario where nodes only equipped with a half-duplex radio. RODMAC [24] aims at improving CogMAC through an on-demand-channel hopping scheme to allow simultaneous transmission. However, highly important issue of external transmission is not considered and evaluated in the case of RODMAC. Moreover, the control information in RODMAC is exchanged by BEACON packets from server node to client node in an unlicensed CCC, thus the communication of control information is not necessarily reliable.

Majority of the studies mentioned above are evaluated through simulation and theoretical studies. Numerous studies have shown that simulation and theoretical studies fail to depict the reality of practical wireless communication systems, especially due to inaccurate or non-realistic models of the real wireless channels and physical layer behavior [25–28]. Therefore, it is highly important to evaluate cognitive MAC protocols in actual deployment scenarios. SDR platforms follow the hardware/software co-design architectures which allow them to provide flexibility and reconfigurability to cognitive MAC protocol prototyping. Furthermore, SDR platform provides realistic physical functionalities which enable access to the real wireless channels. Currently, many SDR platforms are available with different architectures and features [29], and an increasing number of cognitive MAC protocols have been verified through them. WARP is an FPGA-based open SDR platform developed by Rice University. Our earlier CogMAC protocol has been implemented on WARP board [6,30]. USRP series platforms [8] aim at prototyping cognitive radio schemes on general purpose CPU architecture, which is able to offer high degree of flexibility and customization.

As mentioned in the introduction, we have proposed and validated earlier a decentralized CSMA-based cognitive MAC protocol CogMAC in [6] that achieves reliable transmission by considering the existence of external transmissions, i.e., PU transmission and other secondary transmissions. CogMAC is designed for wireless nodes equipped with a single half-duplex radio interface, i.e., it can only access one of the available channels for transmission or reception at a particular time. CogMAC uses a MPR scheme to solve the rendezvous problem without a CCC or cooperative infrastructures. It uses the CSMA based principle to avoid interruption of ongoing transmissions. Before attempting to transmit a frame, the transmitting node first needs to sense all the channels to ensure that no other transmission is carrying out. After selecting a channel, it repetitively sends a frame back-to-back for long enough duration so that all receiving nodes in its transmission range can receive it. At the receiving node, the protocol uses multichannel carrier sensing method in which a node sequentially senses all available channels. When a valid transmission is detected, the receiving node stays in the channel until all frames have been received. In this manner, the repetitive frame transmission implicitly synchronizes all receiving nodes. CogMAC has been validated in WARP boards.

3. CogMAC+ design

The new CogMAC+ protocol is a significantly enhanced version of CogMAC. CogMAC+ upgrades the MPR scheme of the previous CogMAC protocol by adopting a stricter timing analysis, and a more accurate carrier sensing scheme. Several frame based bounds are derived in the new scheme which optimize the secondary transmissions while achieve better PU protection. Moreover, its accurate timing control enables idle SUs to estimate the transmission duration of the transmitting SUs. Therefore, parallel transmissions are able to be carried out in different channels according to the meta-data of ongoing transmissions to substantially enhance the overall network performance. Besides, CogMAC+ includes an adaptive noise floor estimation and energy detection mechanism which significantly enhances the stability and portability of its implementation on different SDR platforms. We enhance the channel selection algorithm by using an Exponential Weighted Moving Average (EWMA) scheme. The portability and the synchronization of CogMAC+ is further improved by the new backoff scheme. The new functionalities added into CogMAC+ are shown as the darker shaded blocks in Fig. 1.

The following subsections are organized as follows: we briefly review the principle of MPR scheme and its multichannel carrier