Computer Networks 57 (2013) 2961–2975

Contents lists available at SciVerse ScienceDirect

Computer Networks

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

Media access protocol for a coexisting cognitive femtocell network

Khalim Amjad Meerja [a], Pin-Han Ho [b], Bin Wu [c], Hsiang-Fu Yu [d,*]

[a] Dept. of Computer Science and Engineering, Koneru Lakshmaiah University, India
[b] Dept. of Electrical and Computer Engineering, University of Waterloo, Canada
[c] School of Computer Science and Technology, Tianjin University, PR China
[d] Dept. of Computer Science, National Taipei University of Education, Taiwan

ARTICLE INFO

Article history:
Received 9 January 2013
Received in revised form 15 June 2013
Accepted 27 June 2013
Available online 9 July 2013

Keywords:
Cognitive radio network
Dynamic spectrum access
Femtocell network
Media access control

ABSTRACT

Femtocell networks are widely deployed to extend cellular network coverage into indoor environments such as large office spaces and homes. Cognitive radio functionality can be implemented in femtocell networks based on an overlay mechanism under the assumption of a hierarchical access scenario. This study introduces a novel femtocell network architecture, that is characterized by a completely autonomous femtocell bandwidth access and a distributed media access control protocol for supporting data and real-time traffic. The detailed description of the architecture and media access protocol is presented. Furthermore, in-depth theoretical analysis is performed on the proposed media access protocol using discrete-time Markov chain modeling to validate the effectiveness of the proposed protocol and architecture.

1. Introduction

Because of the exponential growth of data services, telecommunication sectors have experienced the deployment of novel data-oriented mobile wireless systems, such as 3GPP long term evolution (LTE), rather than traditional circuit-switching voice-oriented wireless systems. More than 50% of phone calls and 70% of data services have recently been shown to occur indoors [1], where quality of service (QoS) can be substantially degraded by path loss, shadowing, and multipath fading effects caused by wall penetration. As learned from early experiences in developing macro-cellular networks, it is expensive to support both line-of-sight (LoS) and non-LoS communications in the range of a few tens of kilometers, and it becomes less economically viable to build infrastructure with increasing data rates. Therefore, effectively enhancing low data rates and poor voice quality inside buildings is one of the most critical challenges for wireless service carriers [2].

Recent advances for overcoming indoor communication barriers without taking much infrastructure expenditure is the purpose of femtocells, which can achieve a high data rate and manageable QoS for both users of macrocell and indoor femtocells [3]. A femtocell comprises a small cellular area covering homes or offices, whereas a femtocell base station (FBS) is a low-cost device with low transmit-power (100 mW or less) [4], and a miniature access point BS designed for indoor wireless service coverage of the corresponding macrocell base station (MBS). FBSs can be accessed under various methods such as open access, closed access and hybrid access [5,6], which is related to the deployment of FBSs. With open access, all users can access all services of femtocell networks, in contrast to closed access, which grants services to registered femtocell users. Hybrid access enables the coexistence of both users based on open and closed access.

* Corresponding author. Tel.: +886 2 27321104.
E-mail addresses: kmeerja@kluniversity.in (K.A. Meerja), p4ho@uwaterloo.ca (P.-H. Ho), binwu.tju@gmail.com (B. Wu), yu@tea.ntue.edu.tw (H.-F. Yu).

1389-1286/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.comnet.2013.06.017

Based on the most recent development in the 3GPP LTE/LTE-Advanced standardization progress, femtocells have followed three deployment modes [1]:

- Dedicated channel deployment: The femtocell and the macrocell use radio spectrum orthogonal to each other.
- Co-channel deployment: The femtocell and the macrocell use a common set of radio sub-bands.
- Partial co-channel deployment: Some parts of the radio spectrum used by the femtocell are orthogonal to that of the macrocell, and other parts of the radio spectrum used by the femtocell overlap with that of the macrocell.

Although dedicated channel deployment can avoid cross-tier interferences, the limited bandwidth of both femtocells and macrocells can seriously impair performance. The dedicated channel deployment is particularly unfeasible under the dense deployment of femtocells because each femtocell can only access limited bandwidth. Thus, this study considers co-channel deployment. However, in a co-channel and partial co-channel deployment, a global scheduling scheme is required for channel allocation, otherwise, both the femtocells and the macrocell can cause each other interference. This becomes a major challenge in adopting these schemes. To achieve successful femtocell networking under co-channel deployment, it is critical to reduce the deployment cost and control complexity of these FBSs according to user premises, where a centralized control involving complex frequency planning and global configuration is infeasible [7].

Therefore, people are motivated to implant the concept of cognitive radio (CR) [8] in the design of femtocell networks for co-channel interference mitigation due to analogous operational targets and similar working environments. The fundamental operation principle of CR is that CR users (also referred to as secondary users) can access licensed bands if the bands are free from usage by any primary user. This feature has positioned CR technology as a means of achieving high-efficiency spectrum usage to resolve bandwidth scarcity [9].

The CR technology can be applied to resolve co-channel interferences between a macrocell and the femtocells in its vicinity. This is in line with standardization efforts for co-channel interference avoidance in femtocell networking [3], where dynamic channel measurement of received interference power (RIP) in uplink sub-frames is performed to identify spatiotemporally available channels for supporting femtocell services. Therefore, a two-tier network is formed and the macrocell users have primary access to radio resources and should be free from interferences from unlicensed access, whereas femtocell users can access spatiotemporally available spectrum resources in an opportunistic manner, avoiding any interference with the primary network.

This CR-based femtocell solution is expected to meet the requirements of distributed and autonomous design and is sufficiently scalable and robust for various custom premises. However, because femtocell users are served in a secondary manner, their QoS is highly dependent on primary-user traffic patterns and cannot be guaranteed. This is particularly critical when voice services are provisioned, where a delay of a few tens of milliseconds can cause service outage. Therefore, despite numerous merits and desired features, CR technology and dynamic channel measurement in femtocell networking for co-channel interference mitigation should be enhanced.

Motivated by these observations, this study introduces a novel architecture for CR-based femtocell networking to achieve distributed and autonomous control of resource access. Rather than defining primary and secondary users in a conventional CR environment, the proposed femtocell architecture implements a novel hybrid access approach that considers all legacy mobile phone (LMP) services as being primary and data services are secondary throughout the network. This means that a mobile device can support voice services through LMP in the primary network (i.e., MBS) or can support voice over IP (VOIP) through FBS if the MBS signal is too weak to ensure desired QoS. On the other hand, data services are available for registered femtocell users, where channel availability is identified using dynamic spectrum sensing to prevent interferences to the primary network. This study argues that locations with weak MBS signals should yield a high secondary access opportunity to achieve a better guarantee of the data service quality, which ensures a high quality VOIP service. To resolve a possible contention between adjacent FBS, a distributed media access control (MAC) protocol is developed for secondary spectrum access in supporting efficient data services. The proposed analytical model is extended from that in [10] to make it fit to the proposed MAC protocol.

The rest of the paper is organized as follows. Section 2 introduces a survey on related studies. Section 3 presents the proposed femtocell network architecture. Section 4 contains the proposed CR-based MAC protocol. Section 5 provides a detailed analysis on the proposed MAC protocol using a discrete-time Markov chain model. Section 6 shows numerical results and a discussion on the performance of the MAC protocol. Finally, Section 7 offers a summary of the study and its chief contributions.

2. Related studies

Numerous studies have been reported on femtocell networking and related topics. To achieve the hierarchical access functionality required in femtocell networking, certain studies assume that cooperation (i.e., reliable communication link) exists between macrocells and femtocells [11]. Although effective, this approach subject to extremely high control and hardware complexity. Studies such as [12] assumes that femtocells are autonomous and co-exist with macrocells without any cooperation. Stand-alone channel sensing for each femtocell user plays an important role in the autonomous operations of the femtocell. Cooperative sensing typically provides more reliable channel availability information compared with the stand-alone sensing [13]. The performance of a sensing mechanism is determined by miss-detection probability p_{md} and false-alarm probability p_{fa}.