Cognitive and Cooperative Communications in Wireless Heterogeneous Networks (HetNet): Current Status and Technical Perspectives

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***Abstract*—Cognitive network and cooperative communications are two promising techniques for efficient utilization of scarce radio resources and guaranteeing quality of services (QoS) in wireless heterogeneous networks (*HetNet*). This paper presents an architecture for the integration of cognitive networks and cooperative communications in wireless HetNet. Based on the proposed architecture several techniques related to the integration of cognition and cooperation are evaluated in typical cases and scenarios, for example, cognitive relay network, cognition in two-tier HetNet, geolocation-based cognition, cognitive and cooperative gateway, etc. Simulations and analysis are performed which has shown that the combination of cognition and cooperation can significantly improve the system performance.**

***Keywords*-cognitive; cooperative; heterogeneous; wireless networks**

I. INTRODUCTION

Currently, wireless communications have been severely limited by the heterogeneity of wireless networks (*a.k.a.*, HetNet, Heterogeneous Networks), which causes that the transmission capacity and end-to-end performance for the wireless systems can't be improved fundamentally. In recent years the concept of cognition and cooperation have been studied and discussed extensively from both academia and industrial communities.

Cognitive radio (CR) [1][2] is a promising technology that will enable the next generation intelligent wireless communications. CR technology enables the development of an intelligent and adaptive wireless communication system that are able to work in an environment-aware manner. Different from conventional point-to-point communications, cooperative communications and networking [3][4] allow different users or nodes in a wireless network to share resources to create collaboration through distributed transmission/processing, in which each user's information is sent out not only by the user, but also by cooperating users. Cooperative communications and networking is a new communication paradigm promising significant capacity and multiplexing gain increase in wireless networks.

In summary, although that many works have been done in this fields, the development of wireless heterogeneous networks (HetNet) has been impeded by three major contradictions, i.e., 1) conflicts between the scarcity of radio resources and lower resources utilization; 2) conflicts of independent optimization of resources in an isolated network and convergence requirements of heterogeneous networks; 3) conflicts between non-ideal operation and precise configuration of HetNet. These three contradictions have yet greatly reduced the development of HetNet.

To solve the contradictions fundamentally, two problems must be answered beforehand: 1) "*cognition*" of the complicated heterogeneous environments; and 2) "*cooperation*" of multi-domain radio resources.

Cognitive radio and cooperative communication networks need to be integrated together and work jointly in heterogeneous wireless networks. It represents a new paradigm which involves the innovations in both smart radio transmission and distributed signal processing techniques, promising a significant increase of overall capacity in futuristic wireless networks.

In this paper, based on our previous works [5][6][8] we propose an architecture for the integration of cognitive and cooperative communications in wireless heterogeneous networks (HetNet). Based on the architecture, the multi-domain radio resource cognition and cooperation cycle is described and discussed. Several techniques related to the integration of cognition and cooperation are proposed and evaluated, i.e., cognitive relay network, cognition in two-tier HetNet, geolocation-based cognition, cognitive and cooperative gateway.

The remainder of this paper is organized as follows, in Section II, the architecture of cognitive and cooperative communications for HetNet is proposed and studied. The techniques about the combination of cognition and cooperation in typical cases are proposed and evaluated in Section III. Conclusions are drawn in Section IV.

II. ARCHITECTURE OF COGNITIVE AND COOPERATIVE COMMUNICATIONS IN HETNET

The architecture of cognitive and cooperative communications for HetNet is shown in Fig.1, which consists of three layers, namely, *cognitive and cooperative PHY layer*, *multi-domain radio resource cognitive layer*, and *cognitive&cooperative decision layer*. For the first layer, cognitive and cooperative PHY layer is composed of reconfigurable

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entities which can perform sensing and cognition. This layer can obtain corresponding information from various domains such as wireless environments, networks and user/traffics, and at the same time execute decisions from higher layers.

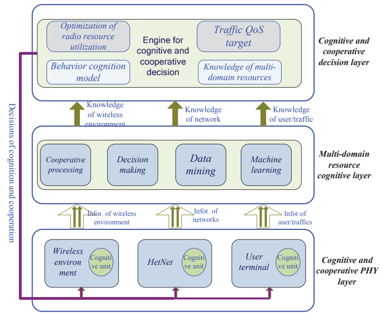

Figure 1. Architecture of cognitive and cooperative communications in HetNet

In the first layer though information can be obtained from the sensing nodes, while knowledge from different domains should be furthermore obtained. The second layer - multi-domain radio resource cognitive layer mainly obtains knowledge of different domains of radio environment, heterogeneous networks and user/traffics, whose major functions are to transfer information to knowledge.

For the cognitive & cooperative decision layer, the main functions are to make decisions through learning, data mining, cooperative processing based on the obtained multi-domain knowledge from the second layer. The decisions should obtain the optimization of multi-domain radio resources and guaranteeing of end-to-end quality of service (QoS). Decisions of this layer will be feedback to the cognitive and cooperative PHY layer which will perform the execution.

III. KEY TECHNIQUES RELATED TO COGNITIVE AND COOPERATIVE COMMUNICATIONS

A. Outage performance in cognitive relay networks

Cognitive radio technology can effectively improve the spectrum utilization efficiency through allowing cognitive (secondary) users to access the licensed spectrum. On the other hand, relay-assisted cooperative communication can effectively combat channel fading through spatial diversity. Inspired by cognitive radio and relay assisted cooperative communication, the authors in [7] proposed the cognitive relay network which combines cognitive radio technique and relay assisted cooperative communication technology. The spectral efficiency and transmission performance can be improved simultaneously in cognitive relay networks.

In this part, we investigate the outage performance of the cognitive relay network, by considering the scenario as shown in Fig. 2.

In Fig.2, there are a primary user receiver (*PR*) and a secondary system which can be represented as a relay-assisted cooperative communication system. The secondary system

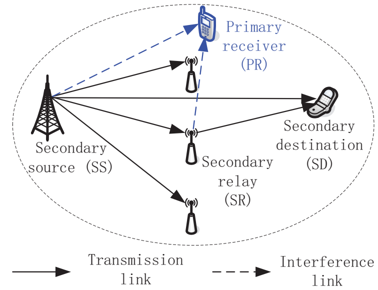

Figure 2. Cognitive relay network.

consists of one source (*SS*), multiple relays (*SR*) and one destination (*SD*). Time division multiple access (TDMA) based *SDF* (Selective Decode-and-Forward) cooperative protocol is utilized in secondary system. The secondary transmitters are with maximum transmit power limits. The primary user and the secondary system share the licensed spectrum using the underlay approach. Hence, the transmission of secondary system may interfere with the PR. In order to protect the *PR*, the interference from secondary transmitters to the *PR* should not be greater than the maximum tolerated interference Q. Thus, the transmit power of secondary transmitter is constrained by the interference power constraint. This is the important difference compared with the conventional relay assisted relay cooperative network.

Fig.3 shows that both the maximum transmit power limit and the interference power constraint cause the outage saturation phenomenon, and more relays (N is the number of relays) can provide better outage performance [6].

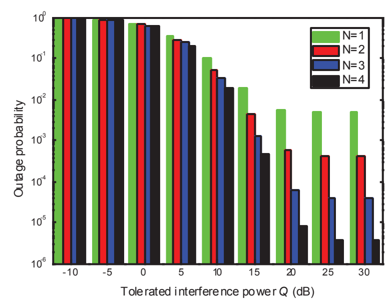

Figure 3. Outage probability vs. tolerated interference power.

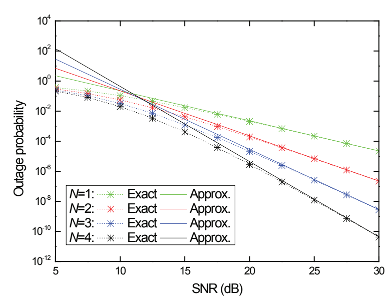

Figure 4. Outage probability vs. SNR

Fig. 4 reveals that the diversity order is $N + 1$ for the cognitive relay network with SDF cooperative protocol. It is indicated that the interference power constraint does not affect the diversity order, and the same diversity order can be achieved in both conventional relay cooperative networks and cognitive relay networks.

B. Cognition in two-tier HetNet

One of the characteristics of next generation wireless network LTE/LTE-Advanced is heterogeneous network (HetNet). HetNet is a kind of multi-tier networks, and each tier has different transmit power, coverage area, backhaul link, etc. There are some challenges in HetNet, for example, interference coordination, handover optimization, backhaul link selection. Among these challenges, the interference is the major challenge. While there are Femtocells in HetNet, the challenge of interference becomes more serious. As the result of random deployment and closed access for femtocells, the conventional network planning scheme cannot tackle the interference. Moreover, due to lack of X2 interface, the inter-cell interference coordination (ICIC) schemes which are defined in 3GPP Release 8 also cannot solve the problem of interference.

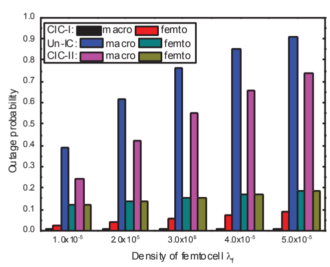

Figure 5. Outage probability vs. density of fetmocells.

The advantages of cognitive radio enable us to propose the cognitive interference coordination (CIC) schemes which are based on the integration of cognitive radio and cooperative communications. In this scheme, the femtocell base station has cognitive capability, which can utilize the information from cognition to realize interference coordination. According to the cognitive content, the cognitive interference coordination can be classified into two categories. One is the cognitive interference coordination based on conventional cognitive radio (CIC-I), and cognitive content is the information of spectrum holes. While the Femtocell base station gets the information of spectrum holes, it can transmit just on the spectrum holes. Hence, the interference between macro cell and Femtocells can be mitigated. The other is the cognitive interference coordination based on broad sense cognitive radio (CIC-II), and the cognitive content is macrocell's scheduling information and macro users' location information. While the Femtocell base station gets the information, it can reuse the resources which are utilized by the remote users with a certain distance separation. Thus, the inter-tier interference between macrocell and Femtocell can also be mitigated under this situation.

Fig. 5 demonstrates that the cognitive radio based cognitive interference coordination can improve the performance for HetNets under different density of femtocell base stations.

C. Cognition and Cooperation for Energy-Efficient Communications

In recent years green communications have attracted more and more attentions from operators, governments, equipment manufactures, academia, etc. As we know, traditional communications protocol design and development in wireless networks is on the purpose of maximization of the performance observed by the end-users, in terms of perceived throughput, delay, Quality of Service (QoS), etc. However, this trend does not consider the power consumed by wireless devices and networks (especially the radio access network which is the major source of energy consumed) which creates a gap between the energy a wireless network needs to operate and the battery capacity of the wireless devices. Hence, the requirement of Energy-Efficiency [9][10] appears as an extremely important property of new protocols for wireless networks with battery-powered mobile nodes. In wireless networks, as shown in Fig.2, through the multi-domain resource cognition and cooperation cycle, environment cognition and cooperative acting can be together utilized for the optimization target - energy-efficiency for a given QoS and throughput requirements. Specifically, for cognition and cooperation for energy-efficient communications, the following topics will be further studied: 1) Green cognitive radio; 2)Green spectrum usage and spectrum access; 3) Decision making (game theory, reinforcement learning) to promote energy efficiency and sustainability; 4) cognitive relay for energy saving; 5) cooperative cognition for energy efficient transmissions, etc.

D. Geolocation-based cognition

The TV and other ISM bands White Space are vastly unused in most of time, especially a large portion of vacant spectrum in UHF/VHF bands that are created during the Digital Switchover (DSO) for the higher spectrum efficiency of Digital TV. In a given location there are some vacant channels from guard bands and locally unused TV channels in TV band. These channels could be utilized by low power devices on the basis that not causing interference to TV service. These white spaces are identified by the Geolocation sensing method, and can be fed into the operative and cognitive network to further migrate the cross tier interference.

In Fig.6, it can be seen that when the Geolocation based TV White Space scheme is applied, the cross-tier interference suffered by Macro users reduced by about 50% compared to that in the tranditional network scheme. This is because the potential interfering Femtocells in the proposed scheme are allocated with the available TVWS from Macro BS rather than the same frequency band as Macro Users. Femto-BSs have no access to RBs that assigned to Macro users, thus cross-tier interference from Femto-BSs to Macro users is significantly mitigated.

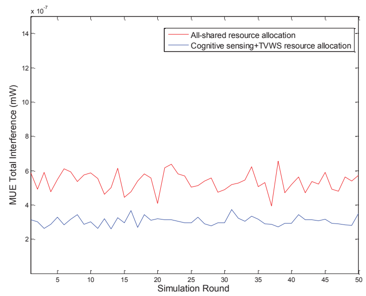

Figure 6. Interference Comparisons of Two Schemes

E. Cognitive and Cooperative Gateway (C^2G)

To better utilize the wireless heterogeneous networks and better guarantee the quality of service for various kinds of terminals with different radio access technologies (RAT), a Cognitive and Cooperative Gateway (C^2G) is proposed which makes full use of cognition and cooperation, as shown in Fig.7. C^2G serves as the entity of multi-domain radio resource cognitive layer, cognitive&cooperative decision layer in Fig.1. The C^2G gathers collects information of radio spectrum and network environment from the distributed sensing nodes; on the other hand, based on the users' different QoS demands, it performs resource allocation and coordinates the heterogeneous network within its coverage area. To counter this, it must have multiple interfaces, such as Ethernet, WiFi, Bluetooth and Zigbee, as shown in Fig.7, in which we assume that all the terminals are multi-mode.

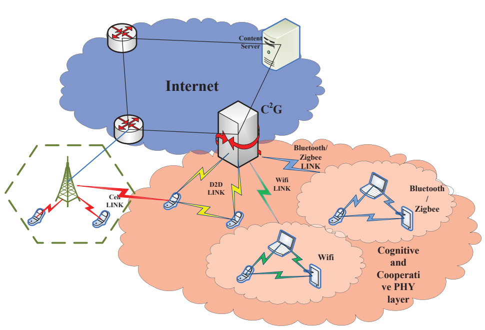

Figure 7. Architecture of Cognitive and Cooperative Gateway (C^2G)

IV. Conclusion

Cognition network and cooperative communications are two promising techniques for better utilization of radio resources and guaranteeing quality of services (QoS) in wireless heterogeneous networks (HetNet). This paper proposes an architecture for the integration of cognitive networks and cooperative communications in wireless HetNet. Then based on the proposed architecture some techniques related to the integration of cognition and cooperation are given and evaluated for some typical cases and scenarios. It is shown that integration of cognition and cooperation can greatly improve the system performance.

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