Relay Selection and Resource Allocation in LTE-Advanced Cognitive Relay Networks

Ardalan Alizadeh, Seyed Mohammad-Sajad Sadough, Seyed Ali Ghorashi

Abstract – In this work, we consider the problem of joint relay selection and resource allocation in Long Term Evolution-Advanced (LTE-A) systems which provides both cognitive radio and relaying scheme capabilities. We assume that the total network is deployed in an overlay scheme where the primary user communicates via a relay assisted LTE-A network, some of the secondary users play the relaying role and the remained nodes are communicate by centralized network model in the licensed spectrum. In the first step of the proposed procedure, the cognitive radio base station (CBS) selects the higher gain component carrier (CC) channels and allocates one CC to each secondary terminal which is denoted as customer premise equipment (CPE). The power updating algorithm is provided in the second step of the proposed scheme which gives the maximum SINR in the secondary CPEs while keeping the minimum SINR threshold at the primary receiver. In the third step of the proposed algorithm, CCs are re-allocated to cognitive radio CPEs. Simulation results are provided to compare the performance of our proposed relay selection and resource allocation algorithms with random relay selection and uniform power allocation respectively. Copyright © 2011 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Cognitive Radio Networks, Dynamic Power Allocation, LTE-Advanced, Relay Selection

I. Introduction

Cognitive radio (CR) is a new design paradigm to combat the problem of scarce and expensive spectrum resources in wireless communications [1]. The basic idea of CR is to allow a secondary (unlicensed) user to utilize a frequency band already allocated to primary (licensed) users.

Recently, various approaches are suggested to mitigate the effects of secondary users on licensed networks [2], [3]. In the opportunistic or so-called interweave approach [2], the secondary user has to sense the spectrum constantly in order to detect the spectral holes or white spaces before transmitting its own signal. Obviously, the cognitive radio users should give back the spectrum once the presence of the primary user is detected in order to minimize their harmful interference to licensed users. Rather than detecting white spaces, in underlay and overlay approaches, cognitive secondary users and primary user(s) transmit simultaneously, while secondary users use their cognitive capabilities to control the amount of interference upon the primary user(s). The underlay approach is similar to ultra wideband (UWB) systems which enforce the spectral mask for secondary users to hold the imposed interference below a predefined threshold. In the overlay approach, the secondary user shares part of its power resources with the primary user to provide a relay-assisted transmission.
Therefore, the secondary network compensates the imposed interference by increasing the signal-to-interference-plus-noise ratio (SINR) of primary receivers. Then, the basic idea of overlay approach is to allocate power and channel resources to whole network, while utilizing the requirements of primary user(s) concurrently. In this technique, channel state information (CSI) should be known in two networks. In such overlay relaying schemes, the power efficiency is a critical issue for common relay nodes which serve single or multiple user pairs to communicate.

Some relay power allocation strategies as well as other resource allocation algorithms are currently proposed in the literature [4]-[7] for relay-assisted communications. Also, using the cognitive radio capabilities in uni-directional relaying networks has been studied for different applications [8]-[10]. In [11], [12], different relay selection algorithms are proposed which are based on SNR maximization of the primary network. In [13], the model is introduced in which the cognitive radio network shares its mobile devices with the primary network to increase the probability of licensed spectrum holes usage by opportunistic approach.

In this paper, the model is based on the overlay approach in which selected secondary users assist (relay) the primary network in order to utilize the licensed spectrum and the remained secondary users are communicating with a cognitive base station (CBS). In such overlay schemes, unlike the opportunistic ones, cognitive radio users (denoted as customer premise equipments (CPE)) can communicate with their base station while they are not imposing harmful interference on the primary relay network. It is assumed that a central controller (i.e., CBS) can obtain SINR measurement results and knows CSI among all CR nodes through dedicated control channels. As a case study, the proposed algorithms are applied in a long term evolution-Advanced (LTE-A) based model. LTE-A is an emerging technology provided by the third Generation Partnership Project (3GPP) in which new features such as relaying scheme [14], [15] and cognitive radio [16] have been considered for the future this next generation system.

The main contributions of this paper are as follows:
1- A novel application for cognitive relaying in LTE-Advanced systems is introduced. This new scenario improves spectrum utilization and increases the SINR of the secondary network, while allowing the primary pairs to communicate via a uni-directional relaying mechanism.

2- A new resource management scheme is proposed for the above mentioned scenario, in order to optimize the utilization of relaying scheme between LTE-A transmitter and receiver. This scheme consists of three main stages as shown in Fig. 1: relay selection for each component carrier (selected CPEs are denoted by RE-CPE), power allocation for primary and secondary users, and finally channel allocation for those CR nodes that are not participating in relaying (the remained CPEs are denoted by CR-CPEs), in order to maximize the throughput of the secondary network.

The rest of this paper is organized as follows. In Section II, we describe the system model of proposed network. In Section III, joint channel and relay selection, as well as resource allocation algorithms are explained, respectively. The power updating approach and channel allocation schemes are provided in Sections IV and V. Simulation results and discussions are presented in Section V, and finally, Section VI concludes the paper.

II. System Model

The 100 MHz LTE-A bandwidth consists of five component carriers (CC), each one have a bandwidth of 20 MHz [17] (Fig. 2).

The features of each CC are in coherence with LTE Release 8. The total bandwidth of the LTE-Advanced can be considered less than 100 MHz, and therefore may consist of up to five component carriers. The frequency band and spectrum allocation expressed via the number of component carriers and their bandwidths are configurable and known a priori by primary base station (hereafter denoted by eNB according to the 3GPP terminology) and by CBS. By using carrier aggregation, an LTE-Advanced mobile terminal (user equipment (UE)) can be jointly scheduled on multiple component carriers providing higher data rates than conventional LTE systems, as shown in Fig. 2. We consider a two-step amplify-and-forward (AF) relaying for all component carriers of the LTE-Advanced network.

We also assume that there is no direct link between eNB and UE as shown in Fig. 3. In the first step of the AF relaying, eNB transmits single or multiple component carriers to the M CPEs, simultaneously.

In the second step, each CPE is able to amplify its received signal and broadcasts it to the UE as well as to the CBS. Since the bandwidth of each component carrier and the required power for relaying are usually large, we assume that each CPE can only use one component carrier for relaying.

![Fig. 1. Proposed resource management procedures](image-url)
By this approach, part of CPEs work as relay nodes (according to the maximum number of CCs, the number of relays will be less than five) and the remained nodes form a separate secondary network for intra-secondary network communications.

Fig. 3 shows the block diagram of the considered model for the c-th component carrier channel (1 ≤ c ≤ 5). In this Figure, $f_{c,j}$ denotes the channel gain between the eNB and the j-th CPE on channel c, where $0 ≤ i ≤ M$, and $f_{c,0}$ is the channel gain between eNB, and CBS. Similarly, $g_{c,j}$ denotes the channel gain between the UE and the i-th CPE on component carrier c, where $0 ≤ i ≤ M$, and $g_{c,0}$ is the channel gain between UE and CBS.

Also, $h_{c,i,j}$ denotes the channel gain between the i-th and the j-th CPE on channel c, where $0 ≤ i, j ≤ M$, and $h_{c,0}$ is the channel gain between CBS and the i-th CPE.

In this Figure, $P_e^{eNB}$ denotes the transmit power of eNB on channel c, and $P_e^{UE}$ denotes the transmit power of UE on channel c. $P_{c,j}^{tr}$ denotes the transmit power of the CBS on c-th channel.

II.1. Problem Formulation

In the first step, the eNB sends information symbols $s_1$ to CPEs. The received signal at the i-th RE-CPE and channel c which is determined by relay selection algorithm is calculated as:

$$r_{c,j} = \sqrt{P_e^{eNB}}f_{c,j}h_{c,0} + \nu_i$$  

where $\nu_i$ is the noise at the i-th relay. We consider a stationary fading where the channel stays constant during resource allocation stages. As mentioned, the cognitive radio network shares N of its fixed-location CPEs as relay nodes with the primary network (RE-CPEs). Also, the cognitive relay network uses a base station to control and support CR-CPEs and provide a point-to-multipoint cognitive radio network. In the second step, N CPEs are selected to transmit via N CCs while each RE-CPE sends in one CC. We assume that the j-th relay is selected and this relay amplifies the received signal and forwards it to primary receiver. Therefore, the j-th relay sends $t_j = \alpha_jf_{c,j}$ where $\alpha_j$ is the amplify weighting of the j-th relay. We assume constant uniform weightings for all relays. The received signal at the second step in UE is:
where \( n \) is the additive noise in the second step of relaying.

We assume that all noises are i.i.d complex Gaussian random variables with zero means and unit variances. We also assume that the primary and secondary networks can cooperate via a common control channel. In this model, two networks can operate simultaneously while the cognitive network does not impose the interference temperature above a predefined threshold. Therefore, the required SINR of primary receiver remains above a threshold level. The objective is joint power and channel allocation for secondary users in order to maximize the total throughputs of the secondary users, while maintaining the required SINR level for the primary receiver. We assume a constant uniform transmit power for primary network.

We consider \( M (M \geq 5) \) fixed CPEs, which are randomly distributed between primary transmitter and receiver. In this model, \( N \) of CPEs are chosen as RE-CPE by the proposed relay selection algorithm where \( N \) is the number of component carriers for UE that is considered by eNB. Note that each of the \( K \) remained CPEs (CR-CPEs, \( K = M - N \)) can reuse only one of \( N \) component carriers, while the SINR of primary receiver and all CPEs are held above a predefined threshold. In this paper, only the downlink scheme (from CBS to CR-CPEs and eNB to UE) has been considered.

### II.2. SINR at Receivers

After the relay selection approach, two subsets of nodes are divided from the initial set of CPEs, i.e., RE-CPEs and CR-CPEs for the secondary network. Consider the downlink scenario in the cognitive radio network for each channel \( c \), let \( \gamma_{c,j}^{CR-CPE(1)} \) denoting the SINR experienced by CR-CPEs at first step of relaying as:

\[
\gamma_{c,j}^{CR-CPE(1)} = \frac{P_s^{c,h_{c,j,0}}}{N_0 + P^{c,BS} f_{c,j}}
\]

and \( \gamma_{c,j}^{CR-CPE(2)} \) denotes the SINR experienced by CR-CPEs at second step of relaying as:

\[
\gamma_{c,j}^{CR-CPE(2)} = \frac{P_s^{c,h_{c,j,0}}}{N_0 + \alpha f_{c,j} h_{c,j,0} P^{c,BS}}
\]

where the \( j \)-th CPE (RE-CPE) is selected for channel \( c \) during the relay selection procedure. Also, we can write the SINR at UE as:

\[
\gamma_{UE}^{c,j} = \frac{P^{c,BS} \alpha_f g_{c,j} s_{c,j}}{N_0 + P_s^{c,h_{c,j,0}} g_{c,j} + P^{c,BS} h_{c,j,0} \alpha_f g_{c,j}}
\]

Two interferences are imposed to UE receiver during relaying steps. The term \( P_s^{c,h_{c,j,0}} g_{c,j} \) is the effect of CBS in the second step and term \( P_s^{c,h_{c,j,0}} h_{c,j,0} \alpha_f g_{c,j} \) is due to the first step of relaying which is amplified and forwarded to the primary receiver.

For satisfying a minimum performance requirement at the primary network, we assume that the received SINR at the UE must be above a predefined value, \( \gamma_p \). In particular, when the cognitive radio network operates in the downlink scenario, we must have \( \gamma_{UE}^{c,j} \geq \gamma_p \).

Finally, we can write the objective of our proposed resource management scheme as the following optimization problem:

\[
\begin{align*}
\arg \max & \sum_{s=1}^{K} \sum_{i=1}^{N} \lambda_i \gamma_{c,i}^{CR-CPE(s)} \\
\text{subject to} & \gamma_{UE}^{c,j} \geq \gamma_p \quad \text{for} \ j = 1, \ldots, N \\
& P_s^{c,h_{c,j,0}} \leq P_{max} \\
& P^{c,BS} = P^{BS}
\end{align*}
\]

In this problem, \( \lambda_i \) equal to 0 or 1 shows the \( i \)-th CR-CPE selection approach in the final stage of the resource allocation, which is applied by bipartite matching.

### III. Joint Relay Selection and Channel Allocation

We consider a relay selection scheme in the first step of resource allocation operation. The objective of this stage is to select the relays and to assign the best channels for selected RE-CPEs. As mentioned, since the bandwidth of each component carrier is large and each relay requires high transmit power for multi-carrier transmission, we assume that each cognitive relay can only amplify-and-forward via one component carrier. For this purpose, we propose a comparative heuristic relay selection algorithm that finds the best total gain for considered order of maximum gain. After that, the primary network can use selected CPEs as CR-CPEs where channel assignment is jointly considered. Also, the remained nodes are used as CR-CPEs for the secondary network. Note that relay selection algorithm is processed in CBS.

Fig. 4 illustrates the flowchart of the proposed relay selection algorithm. In this algorithm, the CBS allocates CCs to the \( r \)-th CPE as follows: The iteration number, \( r \), and CPE index, \( j \), are initially set to 1. In the \( r \)-th iteration \((r = 1, \ldots, R)\), the \( i \)-th CPE, to which no component carrier has allocated yet, compares the \( r \)-th maximum channel gain to the \( j \)-th CPE, \( j = 1, \ldots, M \). If a given channel has the \( r \)-th best gain \((\text{Max}_i \{ f_{c,i}^{r} \times g_{c,j} \})\) for exactly one CPE (except the \( i \)-th CPE), this channel is allocated to that CPE and the next iteration starts.
Fig. 4. Comparative heuristic relay selection algorithm to select CPEs as relays and CC assignment. If all channels are not assigned yet, the algorithm is repeated by remained channels and CPEs.

If an available component carrier has the $r$-th best gain for several CPEs, the channel is allocated to the CPE with the largest gain and next iteration starts. The channel allocation procedure continues until a channel has been allocated to $N$ out of $M$ CPEs. If the number of selected CPEs is not equal to $N$, the algorithm should be applied for remained CPEs and CCs. After joint relay selection and channel allocation procedures, the rest of the CPEs that do not act as relays, communicate to each other as a secondary network (CR-CPEs). A graphical interpretation of this CPE division is shown in Fig. 5. In the next section, we will explain how the power and channels have to be allocated to each of these CPEs, in order to maximize the secondary network throughputs.

IV. Power Updating for Cognitive Relay Network

In this section, we consider the problem of power control to maximize the downlink throughput of the cognitive radio network while protecting primary receivers. We propose a power updating mechanism that tries to maximize the coverage and throughput of the secondary network while guaranteeing the SINR constraint of the primary receiver. Note that the power updating process is applied to one channel at a time. For the $c$-th channel, $1 \leq c \leq N$, the following actions are carried out:

Initialization:

CBS which operates on channel $c$, initiates the power updating process by broadcasting some special tones. Therefore, the CBS sets its transmit powers to the initial values of $P_{c,0}^P(0)$, while the primary transmitted power $P_{c}^{PB}$ is kept constant.

Power Updating:

At $k$-th iteration, the CBS updates the transmit power as follows:

$$P_{c,k}(k+1) = P_{c,k}(k) \delta$$

Here, $\delta$ is a power scaling factor, which is slightly greater than one.

Termination:

The process will be terminated if at least one of the following conditions is true:

- The SINR experienced by UE ($\gamma_{UE}$) goes below the threshold.
- The transmit power of the CBS goes above its maximum transmit power constraint ($P_{CBS,max}$).

A RE-CPE node can terminate the power updating process by broadcasting some special tones (control messages).

Fig. 5. A graphical interpretation of proposed network model. After applying joint relay selection and channel allocation algorithms, the number of remain cognitive radio CPEs ($K$) is $4 (M=8, N=4$ and $K=4$)

V. Channel Assignment by Bipartite Matching

After the power updating process for each channel $c$, the CBS has a maximum transmit power and CR-CPEs have different SINRs for the two steps of relaying. The problem is how to assign $K$ channels to different CR-CPEs so that the total downlink throughput is maximized during the relaying process. This is achieved by first transforming the problem into a weighted bipartite matching and then, finding a maximal weighted match.

We obtain a maximal weighted matching of a bipartite graph by the following procedure. Note that the sum of
the throughput in two steps is considered as the weighted matching parameter.

**Maximal Weighted Bipartite Matching Procedure:**

**Step 1:** Start with empty match graph which edges are not selected.

**Step 2:** Find a maximum augmenting path for the current match. The augmenting path is a path with edges alternating between matched and unmatched while the score of path is maximized. The score of an augmenting path is equal to the sum of weights (rates) of unmatched edges subtracted by the sum of weights of matched edges. While the score of the maximum augmenting path is positive, then go to Step 3. Otherwise, finish the procedure since the current match is maximum.

**Step 3:** Flip the maximum augmenting path obtained in Step 2. Unmatched edges of the path are changed to matched edges and the matched edges of the path are changed to unmatched ones. Go back to Step 2 to find another maximum augmenting path and continue.

By using this method, the total throughput of the secondary network is maximized and one channel is assigned to each CR-CPE.

**VI. Simulation Results**

We consider a square service area equal to $1,000 \times 1,000$ m in which the distance separating eNB and UE is equal to $1,000$ m and a cognitive radio network is deployed between eNB and UE. A CBS is considered in the CR cell to serve a set of CR-CPEs as well as all CPEs. The total number of CPEs is $M = 15$. The number of component carriers is set to 5. All CPEs are randomly deployed across the entire service area with a uniform distribution. A sample network, with 8 CPEs which four of them work as RE-CPE, is given in Fig. 5. Each component carrier is regarded as one channel in our joint power and channel allocation scheme. The fading channel is represented by a Rayleigh distribution channel, with three non-LOS paths.

The path loss exponent is set to 3. The maximum order of relay selection algorithm is set to 2.

The noise power density at each receiver is $N_0 = -100$ dBm. The required SINR for UE is assumed to be between 6 and 20 dB. The maximum transmit power on each channel for CBS and eNB are 60 dBm and initial value of power updating is 20 dBm. The scaling factor used in the power updating process is $\delta = 1.259 \sim 1$ dB. The central carrier frequency of the primary network is considered 3500 MHz which is recommended by 3GPP in Rel.10. We assume that the transmission rate of the primary and secondary networks can be considered as a function of SINR.

This function depends on various factors such as the available coding/modulation schemes and bit error rate requirement. According to [17], we use the approximation $f(\gamma) = \left(\frac{\gamma}{0.6}\right)^{1/3}$ for the rate function.

Our simulations are based on a comparison between the proposed resource allocation scheme and simple models. In Fig. 7, we simulate the random relay selection approach to compare with the performance of our proposed model. In this Figure, only the relay selection stage (see Fig. 1) is contrasted.

Then, Fig. 7 shows the effect of minimum required SINR of the primary receiver in the whole network. The throughput of the secondary network, similarly, received SINR at CR-CPEs is decreased when the minimum SINR for the receiver of LTE-A system (UE) is increased while our proposed relay selection algorithm improves both parameters.

Figures 8, 9 and 10 illustrate a comparison between our proposed algorithm and uniform power allocation in the second stage of our resource allocation scheme.

Fig. 8 shows a comparison between the throughput achieved by using our proposed algorithm and uniform power allocation schemes.
power allocation scheme cannot adjust the interference imposed to the primary network and the SINR of the primary network will be less than that obtained with the power updating approach.

VII. Conclusion

In this paper, we proposed a resource allocation algorithm for LTE-A systems which utilizes the cognitive relaying scheme. We utilize carrier aggregation technology from LTE-A systems which allows the multiple component carriers (CC) transmission over a frequency bandwidth up to 100 MHz. The resource allocation algorithm consists of three main stages. In the first stage, the heuristic relay selection algorithm was proposed to assign higher gain cognitive relay links to the LTE-A network, and to divide the CPE into the relaying nodes and the cognitive radio network. After the relay selection, the power updating method was introduced to maximize the transmit power of CR-CPE while keeping the SINR above a predefined threshold at the primary receiver. This procedure was completed by utilizing the bipartite matching algorithm to allocate the best component carrier to each CR-CPE and to maximize the total throughput of the CR network. Simulation results showed that the throughput of the whole network is increased by using the proposed algorithm in comparison with conventional random relay selection and uniform power allocation methods.

References


**Authors' Information**

Cognitive Telecommunication Research Group, Department of Electrical and Computer Engineering, Shahid Beheshti University G.C., Evin 1983963113, Tehran, Iran.

E-mails: ar.alizadeh@mail.sbu.ac.ir  
ssadough@sbu.ac.ir  
a_ghorashi@sbu.ac.ir

A. Alizadeh was born in Rasht, Iran in 1984. He received his B.Sc. degree in Electrical Engineering (electronics) from Amirkabir University of Technology, Tehran, Iran in 2008. He is currently pursuing his M.Sc. degree in Electrical Engineering (telecommunication) at Shahid Beheshti University, G.C., Tehran, Iran. Since May 2010, he has been with the Cognitive Radio Research Group of Shahid Beheshti University, Tehran, Iran. His current research interests include cognitive radio, two-way relay networks, resource allocation algorithms and convex optimization problems.

S. M. S. Sadough was born in Paris in 1979. He received his B.Sc. degree in Electrical Engineering (electronics) from Shahid Beheshti University, Tehran, I.R. Iran in 2002 and the M.Sc. and his Ph.D. degrees in Electrical Engineering (telecommunication) from Paris-Sud 11 University, Orsay, France, in 2004 and 2008, respectively. From 2004 to 2007, he held a joint appointment with the National Engineering School in Advanced Techniques (ENSTA), Paris, France, and the Laboratory of Signals and Systems (LSS), at Supélec, Gif-sur-Yvette, France. He was a lecturer in the Department of Electronics and Computer Engineering (UEI), ENSTA, where his research activities were focused on improved reception schemes for ultra-wideband communication systems. From December 2007 to September 2008, he was a postdoctoral researcher with the LSS, Supélec-CNRS, where he was involved in the European research project TVMSL with Alcatel-Lucent France. Since October 2008, he has been a member of the Faculty of Electrical & Computer Engineering, Shahid Beheshti University, where he is currently an Assistant Professor in the Department of Telecommunication. Dr. Sadough's areas of research include signal processing, communication theory, and digital communication.

S. A. Ghorashi received his B.Sc. and M.Sc. degrees in Electrical Eng. from the University of Tehran, Iran, in 1992 and 1995, respectively. Then, he joined SANA Pro Inc., where he worked on modelling and simulation of OFDM based wireless LAN systems and interference cancellation methods in W-CDMA systems. Since 2000, he worked as a research associate at King’s College London on “capacity enhancement methods in multi-layer W-CDMA systems” sponsored by Mobile VCE. In 2003 He received his PhD at King’s College and since then he worked at Kings College as a research fellow. In 2006 he joined Samsung Electronics (UK) Ltd as a senior researcher and now he is a faculty member of Cognitive Telecommunication Research Group, Department of Electrical Engineering, Shahid Beheshti University G.C., at Tehran, Iran, working on wireless communications.