Carrier Aggregation for Underlay Cognitive Radio Wireless Mesh Networks

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***Abstract*—Cognitive radio (CR) has emerged as a promising technology to solve the tremendous spectrum scarcity problem. Although CR has shown very interesting results, it is still dealing with some drawbacks such as blocking or forced termination events in opportunistic mode and capacity limitation in underlay mode. In this paper carrier aggregation is proposed for wireless mesh networks to enhance the network throughput in underlay CR condition. In the proposed scenario, the primary user uses traditional channels whereas the secondary user aggregates carriers in PU's channels for its transmission. An analytical performance study is carried out which shows the effectiveness of our proposal. With relatively few aggregated carriers per channel, carrier aggregation outperforms single channel and channel aggregation due to its higher detection probability. These results can be used to extend the already well known properties of wireless mesh networks and their applications.**

***Keywords*—** Cognitive radio network, wireless mesh network, carrier aggregation, detection probability, underlay, overlay.

I. Introduction

Cognitive Radio (CR) or Dynamic Spectrum Access (DSA) is one key solution to spectrum scarcity in wireless communications [1], [2] and [3]. According to [4] and [5] CR is a radio that adapts its transmitter parameters using interactions with its environment.

Two main users are named when talking about CR, the primary user (PU) and the secondary user (SU). The PU is a spectrum license owner and usually does not need to perform CR. The SU is the one who implements CR to make profit of the spectrum without owning any spectrum license.

There are mainly two paradigms in CR technology [6].The opportunistic usage of the spectrum holes, with or without the PU's cooperation, which is called overlay mode, and the underlay mode which allows the SU to share the spectrum with the PU without harming the PU. According to [6], the Underlay paradigm is more efficient in spectrum utilization.

There exist some interesting prior work in this context. Carrier Aggregation has been investigated in [7]–[11]. The main goal of those studies is bandwidth or capacity improvement. In [7] CA is used to provide substantial improvement to LTE-Advanced by allowing up to 100MHz of bandwidth increase after carrier aggregation. In [8] carrier aggregation is associated to ralaying to enhance the capacity of LTE-A networks. [7] and [8] do not consider CR technology neither wireless mesh networks networks (WMNs). [9], [10] and [11] consider CR technology and carrier aggregation in different manners. [9] considers cooperation between PU and SU in underlay CR fashion while [10] investigates power allocation for joint overlay CR and underlay CR scheme. [11] investigates relay selection and carrier aggregation to improve throughput in underlay CR technology. CR WMNs have been investigated in [12]–[14]. Also a fair scheduling scheme for subcarriers and power allocation to mesh routers (MRs) and mesh clients is presented in [15]. An orthogonal frequency division multiple access WMN is investigated but without considering CR.

In all the above mentioned works on CR, CR is applied either on channels or carriers for both PU and SU. For those studies underlay CR means PU and SU sharing directly the same spectrum segment. We consider a different strategy where PU and SU share the spectrum by using different spectrum segment. The PU uses channels while the SU uses carriers or component carriers (CCs) of those channels.Then the SU aggregates the carriers to reach sufficient capacity for transmission.

The main contribution of this work is an increase in SU's detection probability which in turn increases SU's capacity inside the spectrum segment dedicated to PU. In addition, a WMN is considered for Carrier aggregation in underlay cognitive Radio. We conducted numerical analysis to show the effectiveness of our proposal.The results show that carrier aggregation outperforms traditional underlay CR and channel aggregation in terms of throughput, due to its higher signal detection probability.

Wireless Mesh Networks (WMNs) are known to have very interesting properties [15], [16] and can be used as backhaul for internet connectivity [17] in either rural or urban area. One interesting property of WMNs is their cost-effectiveness, which means they do not require high cost for deployment. By applying CA (proposed model) to WMNs in low frequency, we will be able to build more robust and more cost-effective WMNs.

The remainder of this paper is organized as follows. In Section II, we introduce CR technology and the problem caused by its overlay and underlay paradigms. In Section III, we describe our method for solving the capacity limitation problem and increasing the network throughput in an underlay CR WMN. After that, we assess the performance of our proposed method by numerical analysis in Section IV. Finally, the conclusion is drawn in Section V.

II. Problem in CR and WMN

In CR technology, many drawbacks affect the network performance.

Overlay CR uses sensing technique to opportunistically access idle channels or frequency holes [1]. The use of sensing has an impact on the network throughput. Before transmitting data, the network node needs to perform sensing. If T_{DATA} is the time for sending data, T_S the sensing time and C the link capacity, the throughput can be computed as $C(T_{DATA} - T_S)$ for only one link instead of CT_{DATA} as usual. In case of many channels, the throughput becomes $C(T_{DATA} - LT_S)$ [18], where L is the number of channels for which sensing was performed.

Besides the sensing drawback in overlay CR are the blocking and forced termination events which occur at anytime on SU [19]. The blockade of SU occurs when an SU wants to access a channel while no idle channel is available. That SU will be denied access to the spectrum. The forced termination of SU occurs when a PU wants to access the spectrum while no idle channel is available. In that case, the PU forces the SU to leave the channel. The blocking and forced termination probabilities associated to the above-mentioned events impact on data transmission in the network and reduce the overall network throughput when overlay CR is implemented.

The situation is quite different in underlay scenario. PU and SU use the same frequency band at the same time with some restrictions to the SU. SU's transmit power is set so that the interference to PU should never exceed a threshold called Interference Temperature Limit [20]. This limitation in SU's transmit power reduces drastically SU's link capacity, resulting in a very limited throughput in SU network.

Channel or Carrier Assignment is among the most important tasks to perform in order to achieve considerable network service quality in WMNs [21]. Channel assignment ensures an effective utilization of bandwidth to avoid retransmissions in the network [21]. A high number of retransmissions introduce delay in successful end-to-end transmission, which in turn reduces network throughput. The network delay depends also on other factors such as queuing delay, channel switching delay [22] etc.

III. System Model

This section describes the proposed CA to overcome the capacity limitation in underlay CR. The SU uses carriers instead of channels for data transmission whereas the PU uses channels. Channel is a segment of spectrum resource with given bandwidth B. A carrier is a smaller segment of spectrum resource with bandwidth Δf so that a channel can contain K carriers. Carriers have to be created inside each channel and used by the SU. As carrier capacity is not sufficient for reliable data transmission, the system needs to use many carriers to gain enough capacity for data transmission. The carriers aggregated by one SU node can be contiguous or non-contiguous, from one channel or different channels. At this stage, we do not include the additional requirements of non-contiguous carriers in this study. We only focus on the effect of carriers on SU's capacity. Thus, we do not make difference between contiguous carriers and non-contiguous carriers.

In the proposed model, the first step is carrier (or channel) estimation. We assume a perfect CSI between SU nodes.

The second step is carrier aggregation. The SU node searches for available carriers for a given link. After obtaining a sufficient number of carriers for transmission, those carriers are assigned to the designated link.

A. System overview

The system is composed of a PU network and a SU network. The PU network can be a TV broadcast station and its TV receivers or a mobile network base station and its mobile users as our target is the licensed low frequency band. The SU network is a Multi-radio WMN, which means each Mesh Router is equipped with R wireless network interfaces, $R > 1$. The whole SU network is in the transmission range of a PU Access Point as shown in Fig. 1. In these conditions, the SU network has necessarily to perform CR in order to be able to transmit. We assume a situation where only underlay CR is possible, no spectrum holes nor TV white space are available. As underlay CR is already known for its efficiency in spectrum utilization [6], the main goal of this study is to improve underlay CR technique.

In the described model, the existing PU uses channels such as Wifi channels or VHF/UHF channels. The SU creates carriers inside those channels in order to perform Underlay CR as illustrated in Fig.2. The bandwidth of the carriers has to be chosen so as to obtain enough carriers for the desired improvement. The carriers can be contiguous to each other or not, from the same channel or from different channels. We do not include the additional requirements of non-contiguousness of carriers at this stage. We only focus on the effect of component carriers (CCs) on SU's capacity. The SU makes use of CCs inside PU's channel in underlay fashion. As each CC has a very limited capacity, each MR has to aggregate many CCs in order to gain sufficient capacity for data transmission. The aggregated carriers are assigned to the active link bound to one interface of the MR. There are K component carriers in the frequency band indexed by $k = 1, 2, .., K$. In order to achieve higher rates, each MR aggregates α available CCs from the frequency band for its active links as shown in Fig. 2.

B. Carrier Estimation phase

For the proposed model, full CSI is required only among SU nodes, similar to the channel estimation model in [9]. The sending node i sends pilot symbols to the receiving node j. Node j estimates the channel coefficients h_{ij} for the current CC. After estimation node j transmits the CSI values to node i using a feedback link. CSI is not required from the PU network because we do not assume any cooperation between PU and SU. We assume a constant path loss between SU network and PU network h_{sp} or h_{ps}.

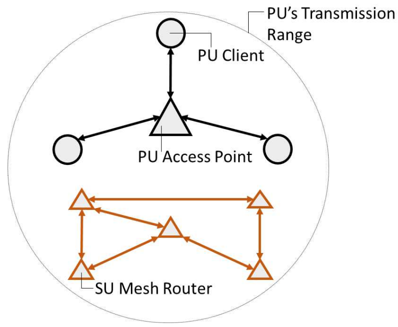

Fig. 1. Underlay CR model.

C. Carrier Aggregation

According to [9] and [11], the received signal y_{ij} from node i at node j can be written as

$$y_{ij} = \sqrt{P_{ij}[k]}h_{ij}[k]x[k] + \sqrt{P_{ps}[k]}h_{ps}[k]z[k] + n_j[k] \quad (1)$$

Where P_{ij}, h_{ij}, x are respectively the transmit power, the channel state information (CSI) of an SU node's signal on CC k; P_{ps}, h_{ps} and z are respectively the transmit power, the CSI of PU node's signal on CC k. n_j is the noise received at node j on carrier k. The CSI includes the path loss for each carrier. We assume perfect CSI between SU nodes. The SU network does not receive CSI from PU network as there is no cooperation between them. The h_{ps} in PU's signal indicates the path loss. For a given active link l, the MR looks for available carriers in the designated channel with bandwidth B, by computing the signal-to-noise-plus-interference (SINR) value of each CC as shown in (2). Δf is the CC bandwidth such as $\Delta f = \frac{B}{K}$.

$$\gamma_{ij} = \frac{P_{ij[k]|h_{ij}[k]|^2}}{P_p[k]|h_{ps}[k]|^2 + \sum_{m\neq i} P_{mj}[k]|h_{mj}|^2 + \sigma_j^2[k]} \quad (2)$$

σ_j^2 is the noise variance. Carrier capacity is computed as follows, using Shannon's law

$$C_{ij}[k] = \Delta f \log_2(1 + \gamma_{ij}[k]) \quad (3)$$

We consider the outage probability of SU due to PU's traffic. According to [23] the throughput can be written as

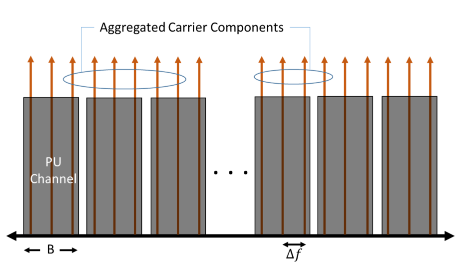

Fig. 2. Underlay CR Carrier Components.

$$\phi = \frac{1}{L}\log_2(1 + \gamma_{ij}[k])P_d \quad (4)$$

where L is the link population in the subnet and $P_d = P_r\{SINR \geq \xi\}$ is the probability of SU's signal detection and ξ is the SINR threshold. Furthermore, we consider $P_d = 1 - P_{out}^{su}$ where P_{out}^{su} is the outage probability of SU due to PU. SU's packet is detected when there is no outage of SU. We consider the interference range as the target subnet because those nodes in the interference range need necessarily to use different CCs to avoid interference. Thus the interference comes only from the PU network. SU's SINR in this condition is computed as

$$\gamma_{su}[k] = \frac{P_{ss}[k]|h_{ss}[k]|^2}{P_{ps}[k]|h_{ps}[k]|^2 + \sigma_{ss}^2[k]} \quad (5)$$

If R_0 is the desired data rate for SU, the corresponding value of SINR threshold is

$$\hat{\gamma}_{su}[k] = 2^{2R_0} - 1 \quad (6)$$

Then the outage probability is given as

$$P_{out}^{su}[k] = P_r\{SINR \leq \hat{\gamma}_{su}[k]\} \quad (7)$$

Similarly to [9] and [24] the outage probability of a CC from SU side is given as

$$P_{out}^{su}[k] = 1 - \frac{\sigma_{ss}^2[k]\exp(-\frac{\hat{\gamma}_{su}[k]}{\sigma_{ss}^2[k]})}{\sigma_{ps}^2[k]\hat{\gamma}_{su}[k] + \sigma_{ss}^2[k]} \quad (8)$$

Where σ_{ps}^2 and σ_{ss}^2 are respectively the variance of h_{ss} ($h_{ss} = h_{ij}$) and h_{ps}. The details of the above equation are provided in [24]. The throughput of a single CC is given as follows

$$\phi_{su}[k] = \frac{1}{L}\log_2(1 + \gamma_{ij}[k])\frac{\sigma_{ij}^2[k]\exp(-\frac{\hat{\gamma}_{su}[k]}{\sigma_{ij}^2[k]})}{\sigma_{ps}^2[k]\hat{\gamma}_{su}[k] + \sigma_{ij}^2[k]} \quad (9)$$

Then as independent events, the outage probability of the SU node aggregating α CCs becomes

$$\begin{aligned} P_{out}^{su} &= \prod_{k=1}^{\alpha} P_{out}^{su}[k] \\ &= \prod_{k=1}^{\alpha}\left(1 - \frac{\sigma_{ss}^2[k]\exp(-\frac{\hat{\gamma}_{su}[k]}{\sigma_{ss}^2[k]})}{\sigma_{ps}^2[k]\hat{\gamma}_{su}[k] + \sigma_{ss}^2[k]}\right) \end{aligned} \quad (10)$$

$$P_d = 1 - \prod_{k=1}^{\alpha}\left(1 - \frac{\sigma_{ss}^2[k]\exp(-\frac{\hat{\gamma}_{su}[k]}{\sigma_{ss}^2[k]})}{\sigma_{ps}^2[k]\hat{\gamma}_{su}[k] + \sigma_{ss}^2[k]}\right) \quad (11)$$

The link capacity after carrier aggregation becomes

$$C = \sum_{k=1}^{\alpha} C[k] = \Delta f \sum_{k=1}^{\alpha}\log_2(1 + \gamma_{ij}[k]) \quad (12)$$

The throughput of an SU link can be written as

$$
\begin{aligned}
\phi_{su} &= \frac{1}{L}\sum_{k=1}^{\alpha} C[k] \times \left(1 - P_{out}^{su}\right) \\
&= \frac{\Delta f}{L}\sum_{k=1}^{\alpha} \log_2(1+\gamma_{ij}[k]) \times \\
&\left(1 - \prod_{k=1}^{\alpha}\left(1 - \frac{\sigma_{ss}^2[k]\exp(-\frac{\hat{\gamma}_{su}[k]}{\sigma_{ss}^2[k]})}{\sigma_{ps}^2[k]\hat{\gamma}_{su}[k] + \sigma_{ss}^2[k]}\right)\right)
\end{aligned} \tag{13}
$$

IV. Numerical Evaluation

In this section, numerical results are presented. We compare the performances of carrier aggregation, single channel (No aggregation) and channel aggregation to each other according to our mathematical analysis in section III-C. Without loss of generality, let $R_0 = 1bit/s/Hz$ for any link between two SU nodes and $L = 6$ the number of links in the WMN interference range. We assume that the channel parameters are $\sigma_{ss}^2 = 2dB$, $\sigma_{ps}^2 = 4dB$, $B = 20MHz$, $\Delta f = 2MHz$. Thus, the channel between two nodes is assume to be Rayleigh fading. In addition we consider all the carriers and channels to have the same detection probability.

To numerically assess our proposed model, we first evaluate its performance inside one channel. It is extremely important to know the gain in capacity of CA compared to traditional underlay CR in the same channel Fig.3, Fig.4 and Fig.5. A logical way to increase the capacity of underlay CR is to allow one SU to share many channels with different PUs. We called it Channel Aggregation. We also compared the performance of Carrier Aggregation to Channel Aggregation, Fig.6 and Fig.7, to show the effectiveness of our method, to clearly make the difference between the two solutions and also to show that the SU can use carriers from different channels.

As shown in Fig.3, the detection probability of carriers inside a channel is higher than that of the channel itself in underlay CR. Meaning that the signal has more chance to be detected when using many carriers instead of one channel, even though the channel has larger bandwidth than the aggregated carriers. According to Fig.4 carrier aggregation shows interesting results,in terms of throughput, with only four carriers ($\alpha = 4$). Figure 5 confirms the effectiveness of carrier aggregation according to the SINR value of the signal. CA clearly outperforms traditional underlay CR with four aggregated carriers as shown in Fig.5.

A similar behavior is observed in Fig.6 and Fig.7 when many channels are considered. According to the SINR value, CA shows better performance than Channel Aggregation when only four ($\alpha = 4$) carriers are used, Fig.6. and Fig.7. Two channels are aggregated while four carriers are aggregated per channel. As a result, we obtain for one link, $2 \times 20MHz = 40MHz$ with channels and $4 \times 2MHz \times 2 = 16MHz$ with carriers. We saw that $16MHz$ outperformed $40MHz$. Knowing that the transmission power is proportional to the bandwidth, the only remaining factor explaining this result is the high probability of carrier aggregation.

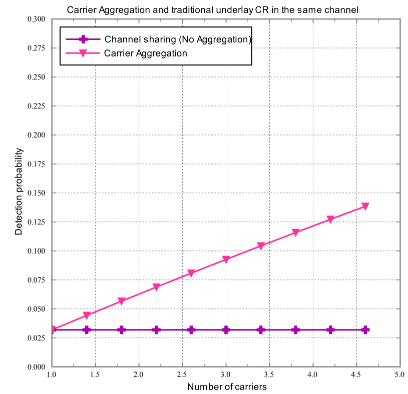

Fig. 3. Detection probability versus number of Carriers in one channel for CA and Channel sharing

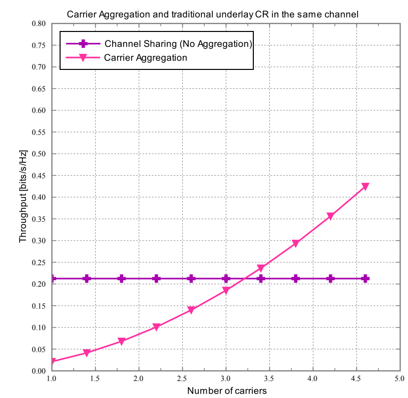

Fig. 4. Throughput versus number of carriers in one channel for CA and Channel sharing.

V. Conclusion

In this study, Carrier Aggregation for underlay CR wireless mesh networks is presented. Mathematical formulation and numerical analysis have been conducted. The results show that Carrier Aggregation outperforms traditional underlay CR (single channel sharing) and channel aggregation in underlay CR scenario. This work is based on the fact that PU and SU use different spectrum segment (channel Vs Carriers) to perform Underlay CR for data transmission.

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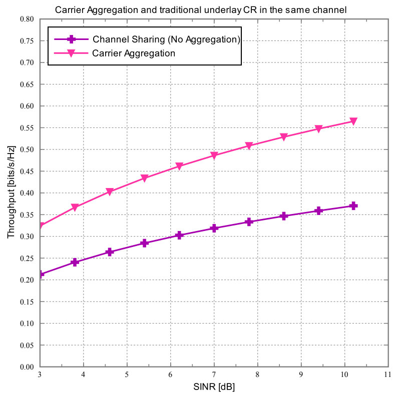

Fig. 5. Throughput versus SINR in one channel for CA aggregating 4 carriers and Channel sharing.

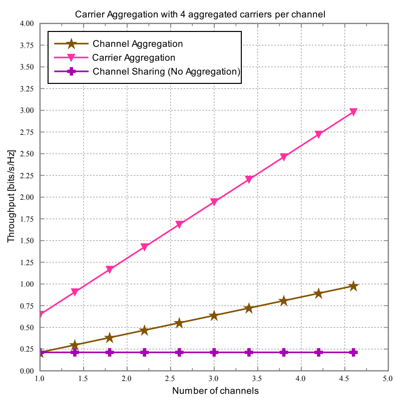

Fig. 6. Throughput versus Number of channels/carriers while aggregating 2 channels and 4 carriers per channel.

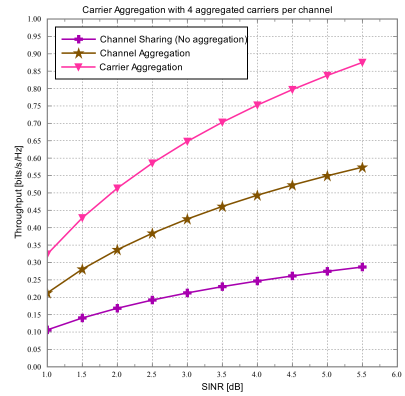

Fig. 7. Throughput versus SINR while aggregating 2 channels and 4 carriers per channel.

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