Dynamic spectrum access based on cognitive radio within cellular networks

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Dynamic Spectrum Access based on Cognitive Radio within Cellular Networks

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***Abstract*—Overlay transmissions in *cognitive radio* (CR) permit a secondary system to use spectrum concomitantly with a primary system, though adopting this spectrum sharing strategy presents a number of challenges, such as the requirement for a secondary user to have *a priori* knowledge as side information about the primary user. In this paper, a cognitive cellular network is proposed which uses an overlay approach to dynamically share its radio resource by incorporating cognition, leading to enhanced cell capacity. To compensate for the interference caused by the overlay, cognitive base stations use robust *dirty-paper coding* in combination with variable transmission powers, which are set depending upon the location of the mobile stations. A detailed performance analysis is presented to corroborate the improved spectrum utilization achieved using this technique.**

Keywords: Cognitive radio, dynamic spectrum access, spectrum sharing, overlay approach, dirty-paper coding (DPC).

I. INTRODUCTION

The radio spectrum is a precious and finite natural resource, with demand for wireless communications inexorably increasing in order to support high data-rate multimedia services and applications. The International Telecommunication Union (ITU) [1] estimates the total spectrum demand for mobile communications by the year 2020 will range from 1280 to 1720 MHz, while there is currently around 230-430 MHz of spectrum either occupied or recommended for mobile communication depending on the geographic region. It is clear this large spectrum demand cannot be sustained by existing, inefficient static spectrum allocation schemes. Moreover, studies undertaken by various international regulatory bodies including FCC (USA) and Ofcom (UK), confirm that most of the licensed spectrum is underutilised [2-4], and as a consequence, innovative techniques which allow opportunistic utilisation and exploitation of the available spectrum are required. *Cognitive Radio* (CR) is a technology which provides the capacity for a wireless device to both recognize its dynamic communication environment and adapt to its operating parameters, based on the awareness of its surroundings, without interfering with other wireless users [5].

Dynamic spectrum access (DSA) is an integral facet of CR technology [6] as it allows the CR to operate in the best available channel. DSA can occur in a variety of ways [6]: *i)* between a licensed primary system and a license-exempt secondary system, *ii)* between two primary systems and *iii)* within the same primary system. In this paper, the third DSA category is considered with the cellular network being deemed the primary system. This is a less disruptive application domain because there is no need to either act as a spectrum scavenger or cooperate with other systems.

Three alternative DSA models have been analysed in [7]: *underlay*, *overlay* and *interweave*. In the overlay approach, a cognitive user can simultaneously communicate with a non-cognitive user, with the interference to the non-cognitive user offset by using part of the cognitive user's power to relay non-cognitive user messages [7], [8]. The assumption in the overlay model is that the cognitive transmitter knows the non-cognitive user message before it starts transmitting. This strategy is adopted in this paper for simultaneous transmission between the *base station* (BS) and *mobile stations* (MS). Its basis is the cognitive cellular paradigm proposed in [8], where the cellular system concurrently uses the TV UHF band. This model however, has a number of constraints due to the spectrum sharing arrangement between the TV and cellular systems. For instance, it assumes non-cognitive user messages are known in advance at the cognitive transmitter, which interrupts non-cognitive user communications because the cognitive and non-cognitive transmitters are not in the same location, thereby introducing extra latency. The location of the TV receivers is also unknown to the BS, so accurately estimating the channel gains is an essential design prerequisite in order to determine the correct relay power. Furthermore, the cellular network is the only secondary user permitted to share the TV UHF band. No other secondary users are allowed despite the TV UHF band being targeted for other feasible cognitive applications [2] and [3]. Finally, the cellular system must have the necessary digital TV (DTV) data stream distribution and management capability, as well as a formal agreement with the TV system provider. Collectively this imposes significant extra overheads upon the cellular system provider, aside also from having to sacrifice the vast proportion of its power (up to 93% in [8]) to relay the DTV signal.

This paper presents a cognitive cellular network model that uses an overlay strategy and importantly, relaxes some of the system constraints of [8]. For instance, since it is a single CR model, it does not introduce any latency to other systems and there is no need to incorporate additional functionality to interact with the other systems. *Dirty-paper coding* (DPC) [9] is applied to the data in the CR channel to compensate for the interference at the secondary receiver generated by the primary transmission, with a high interference gain regime case i.e., the interference-to-noise ratio is much greater than the *signal to noise ratio* (SNR) [10], [11]. Using DPC enables the effect of interference to be cancelled subject to the interference being known at the transmitter [9], [12], [13]. To implement DPC requires knowledge of the channel gains at the transmitter [12], though since the same system cognitive model is used, relevant *a priori* information relating to the primary users codebook, its message and the respective channel gains will be available. This means when only the downlink is considered, the proposed cognitive cellular model permits the BS to dynamically share its radio spectrum based on the location of MS to improve the *cell spectral efficiency* (CSE). In this proposed approach, the BS is assumed to be cognitive as it knows in advance both the MS messages and their locations.

The rest of the paper is organized as follows. Section II describes both the proposed cognitive cellular network and channel model. Section III presents a quantitative analysis of the system's performance before Section IV provides some concluding comments.

II. NETWORK AND CHANNEL MODEL

In the proposed cognitive cellular model, *cognitive base stations* (CBS) treat a number of its MS as *cognitive* or *secondary mobile stations* (SMS), while others are classed as non-cognitive or *primary mobile stations* (PMS). In the overlay approach, the CBS share the same radio channels to simultaneously communicate between pairs of SMS and PMS. Classifying a MS as either a PMS or a SMS depends on its location within a macrocell as conceptualised in Figure 1. Each cell is partitioned into three zones: opportunistic or cognitive (A), protected (B) and regular or primary (C). An MS inside zone A behaves as a secondary receiver i.e., SMS, whereas a MS inside either zone B or C behaves as a normal mobile receiver while a MS in zone C is considered solely as a PMS. The protected zone B allows the signal transmitted to SMS to attenuate below the acceptable signal level received at PMS in zone C.

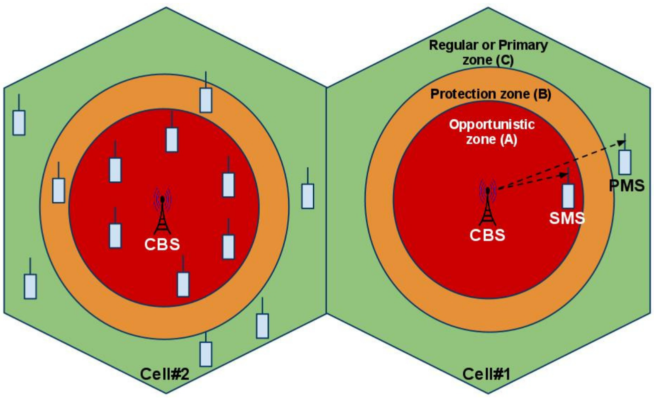

Figure 1: Conceptual diagram of the *cognitive cellular network*.

Figure 1 represents a common scenario where a BS wishes to transmit signals to two MS at the same time in a cell, one of them located in zone A (SMS) and the other in zone C (PMS). The CBS concomitantly transmits messages to PMS and SMS at the same frequency, but at different powers P_p and P_s respectively, where $P_s = \alpha . P_p$ with $0 \le \alpha < 1$. The value of α is selected depending upon both the PMS threshold received SNR and path losses. Since the CBS shares the same frequency band as PMS and SMS, the PMS signal interferes with SMS. In these circumstances, the SMS transmitted power is chosen sufficiently low that the SMS transmission does not affect PMS due to path losses. In addition, the CBS applies DPC to the SMS signal, with the PMS message as known interference, to eliminate the interference at the SMS caused by the PMS signal.

To design an overlay system using DPC at the CBS, *side information* (SI) including the MS location, channel gains, codebooks and messages for PMS must be employed. As only the downlink is considered, the CBS is a common transmitter so MS messages are always available at the CBS. Moreover, as there is feedback provision in the cellular network by means of a pilot signal, the CBS is able to estimate all channel gains, which means gathering SI in this system is a straightforward process.

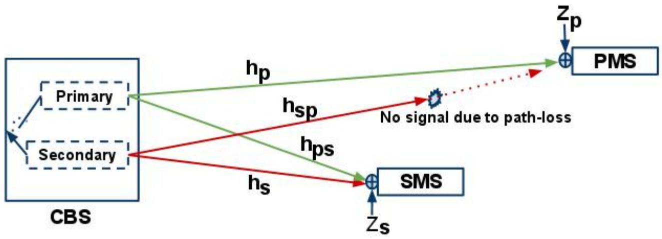

Figure 2: Cognitive cellular radio channel.

A. Cognitive Cellular Radio Channel

The overlay cognitive radio channel model is illustrated in Figure 2. The general input-output relationship of the two-user cognitive radio channel model is given by:

$$Y_p = h_p X_p + h_{sp} X_s + Z_p \qquad (1)$$

$$Y_s = h_{ps} X_p + h_s X_s + Z_s \qquad (2)$$

Where X_p and X_s are the respective channel inputs for non-cognitive and cognitive users; Y_p and Y_s are the corresponding channel outputs; and $Z_p \sim \mathcal{N}(0, N_p)$ and $Z_s \sim \mathcal{N}(0, N_s)$ are additive white Gaussian noise (AWGN). Complex-valued channel gains are denoted as h_p, h_s, h_{sp} and h_{ps}. The transmitted signal powers are respectively constrained by P_p and P_s so:

$$\|X_p\|^2 \le P_p \qquad \|X_s\|^2 \le P_s$$

Using DPC, the CBS encodes the SMS message which is transmitted at power $P_s = \alpha . P_p$, while X_p is treated as *a priori* known interference at the CBS which affects the SMS in the presence of $\mathcal{N}(0, N_s)$ noise. In this case, it can be assumed $h_{ps} \approx h_s$ and $h_{sp} \approx h_p$ since the BS is common to both SMS and PMS, so (1) and (2) can be expressed as:

$$Y_p = h_p X_p + h_p . \sqrt{\alpha} . \hat{X}_s + Z_p \tag{3}$$

$$Y_s = h_s . \sqrt{\alpha} . \hat{X}_s + h_s X_p + Z_s \tag{4}$$

Where $\hat{X}_s$ is the DPC output. The respective interference components in (3) and (4) now need to be compensated, as will be described in the following sections.

B. Protection of PMS from SMS Transmissions

The received *signal-to-interference plus noise ratio* (SINR) at the PMS is:

$$SINR_p = \frac{|h_p|^2 P_p}{|h_p|^2 \alpha . P_p + N_p} \tag{5}$$

So to protect the PMS from cognitive transmissions, α must uphold the following:

$$SINR_{p(th)} < \frac{|h_p|^2 P_p}{|h_p|^2 \alpha . P_p + N_p} \tag{6}$$

Where $SINR_{p(th)}$ is the threshold received SINR at the PMS. Rewriting (6) gives:

$$\alpha < \frac{|h_p|^2 . P_p - N_p . SINR_{p(th)}}{SINR_{p(th)} . |h_p|^2 . P_p} \tag{7}$$

C. Protection of SMS from PMS Transmissions

When DPC is not used, the received SINR at the secondary receiver (SMS) can be expressed as:

$$SINR_s = \frac{|h_s|^2 \alpha . P_p}{|h_s|^2 . P_p + N_s}$$

So the SINR at the SMS is very low due to severe interference caused by the PMS transmissions. When DPC is now applied however, the corresponding interference term is cancelled at the SMS, so the received SINR becomes:

$$SINR_s = \frac{|h_s|^2 \alpha . P_p}{N_s} \tag{8}$$

Thus, the SINR at the SMS is higher due to DPC compensating for the interference introduced by the PMS transmission.

D. Cell Spectral Efficiency Analysis

In the proposed cognitive cellular network, the CBS simultaneously shares spectrum between MS depending upon their location, with the objective of increasing the overall spectrum utilization. This is measured by the CSE η which is defined as the achievable throughput per unit bandwidth per cell area, measured in bps/Hz/macrocell area.

If the allocated bandwidth of a macrocell is BW_{tot}, then the achievable throughput of this cell can be estimated by the classical Shannon relationship:

$$C_m = BW_{tot} . \log_2(1 + SINR_{rx})$$

where C_m is the achievable throughput and $SINR_{rx}$ is the received SINR.

A portion $\sum_{i=1}^{N_o/2} BW_{oi}$ of this allocated bandwidth is used twice in the proposed system since the CBS uses the same frequency for both SMS and PMS transmissions. The achievable throughput for the opportunistic use of the spectrum is:

$$C_o = \sum_{i=1}^{N_o/2} BW_{oi} . \log_2(1 + SINR_{orx}) \tag{9}$$

where $SINR_{orx}$ is the received SINR at the SMS and N_o is the number of MS simultaneously sharing the bandwidth $\sum_{i=1}^{N_o/2} BW_{oi}$. The maximum value of N_o is found from:

$$N_{o(\max)} = 2 \times \min\{N_{SMS}, N_{PMS}\} \tag{10}$$

where N_{SMS} and N_{PMS} are the number of MS in zones A and C respectively.

The total joint capacity of the macrocell is thus:

$$C = C_m + C_o \quad \text{(bps/Hz)}$$

So the CSE η of the cognitive cellular network is:

$$\eta = \frac{C}{BW_{tot}} = \frac{C_m + C_o}{BW_{tot}} \tag{11}$$

Thus the CSE with cognitive use of the spectrum will always be greater than the corresponding CSE $\eta' = \frac{C_m}{BW_{tot}}$ when cognition is not applied provided $C_o \neq 0$, and the only situation where this condition is not upheld is when there is neither a primary nor secondary MS available for the CBS to simultaneously communicate with (see Figure 1).

III. PERFORMANCE EVALUATION

The performance of the proposed cognitive cellular network has been evaluated in a test environment developed using Matlab® 7.10.0 (R2010a). Table I displays all the simulation environment parameters, which are congruent with the 3GPP LTE specification [14]. An AWGN channel model is assumed with noise power 10^{-15}W and the hexagonal macrocell has a radius of 500m. The 5MHz bandwidth has 300 occupied subcarriers, which are allocated equally to 50 active MS randomly located within the macrocell. Since the size of zones A, B and C is fixed, the power scaling factor α is constant for each simulation run.

TABLE I. SIMULATION ENVIRONMENT PARAMETERS

Parameters		Value
Bandwidth		5 MHz
Modulation scheme		BPSK
BS transmit power		46 dBm
Noise power		10^{-15} W
α (Power scaling factor)		0.33
Full traffic load		50 users
BS antenna gain		14 dBi
MS antenna gain		0 dBi
Cell size	Cognitive zone (A)	250 m
	Protected zone (B)	300 m
	Regular zone (C)	500 m
Path loss, dB		128.1 + 37.6log10 (d) ; d in km
Lognormal shadowing		8 dB

The first series of experiments analysed the achievable downlink throughput of the macrocell when the proposed cognitive overlay strategy was used together with DPC. The corresponding results plotted in Figure 3 also include the cell throughput when no cognition has been applied. The CBS allocated more bandwidth to the 50 MS depending upon the number of SMS and PMS, and it was assumed between 30% and 60% (1.5MHz to 3MHz) of the total macrocell bandwidth was shared by the proposed overlay cognitive system. The various graphs reveal the overall throughput commensurately increased with the bandwidth percentage being shared. For example, at an SNR of 10dB and with 60% of the cell bandwidth shared, the achievable throughput improved by approximately 10Mbps compared to when no spectral sharing was employed. Similar improvements can be observed across the SNR range, with those at low values being especially noteworthy, i.e. even for SNR of 2dB and 30% CR bandwidth sharing, an increase in throughput of more than 2Mbps has been realised.

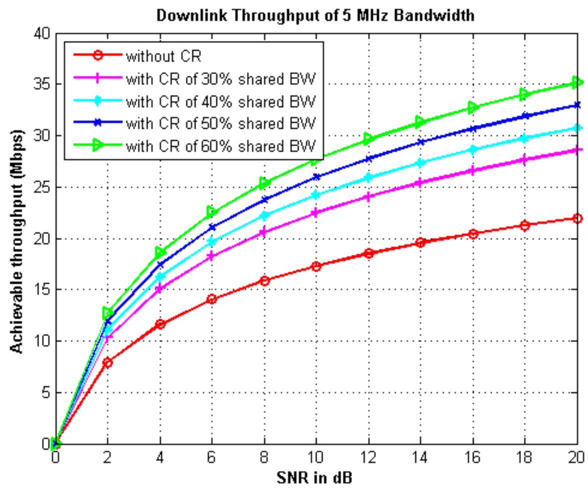

Figure 3: Downlink throughput for a single 5 MHz macrocell and 50 MS users. Note: since interference at the SMS is eliminated using DPC and the use of a protection zone (B) means propagation path losses lead to negligible interference at the PMS, the x-axis plots SNR in preference to SINR.

In terms of the CSE performance of the proposed spectrum sharing scheme, the corresponding results are displayed in Figure 4 with respect to the number of opportunities created within a macrocell. This reflects the additional active MS able to be supported alongside existing active MS served by the CBS. In these simulations, a fixed received SNR of 12dB was assumed, with 50 active MS being located in zone A (SMS). Up to 50 extra active MS were thus able to be supported in zone C (PMS) when the CBS employed the overlay strategy. The maximum number of additional supported MS with this proposed approach is achieved when all MS are located in zones A and C, and the number of SMS and PMS is the same. From (10), the overlay model can thus be generalised so a CBS can support up to $\min\{N_{SMS}, N_{PMS}\}$ additional MS, where N_{SMS} and N_{PMS} are the number of active MS in zones A and C respectively. Figure 4 shows that with the cognitive model, the CSE η increased linearly with the number of opportunities created. In this case, all MS were allocated the same bandwidth as the 50 active users would have been assigned if no cognition has been applied, so effectively doubling η. The results also show the CSE does not degrade when the CBS is unable to find a MS simultaneously located in zones A and C to communicate. This underscores the pivotal compensating role DPC performs in cancelling PMS interference at the transmitter to enable more active MS to be supported.

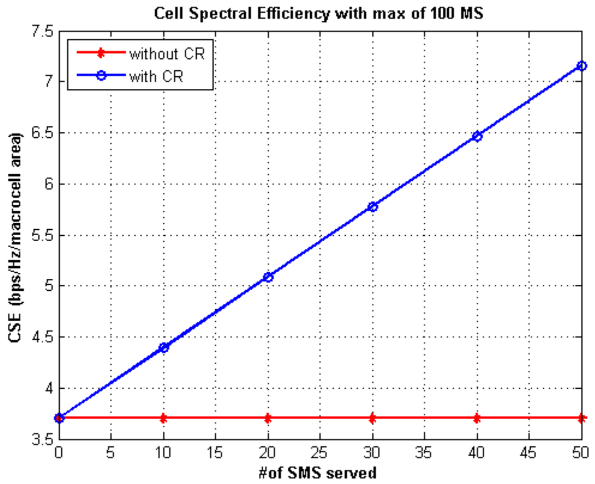

Figure 4: *Cell spectral efficiency* η of a macrocell in a cellular network.

Finally, an important point to stress in introducing this overlay strategy into a cellular network is the negligible latency cost incurred by the proposed cognitive model. Furthermore, in designing the overlay strategy to share spectrum between two systems, the secondary system would usually expend its power on primary transmission if interference free communications were to be achieved. This is not the case in this proposed overlay strategy where the cognitive cellular network does not need to disburse its own power on other users' transmissions.

IV. CONCLUSION

This paper proposes a cognitive cellular network model to improve spectrum utilization. An overlay approach has been introduced into the cellular network framework by partitioning the macrocell coverage area and designating some users as secondary receivers and others as primary receivers so they can share the same frequency without interfering with each other. Since this is a single cognitive radio system, there is no need for cooperation with other systems to exploit available *side information* (SI) which may incur added latency. Due to the availability of SI, *dirty-paper coding* (DPC) also adds more value in terms of compensating interference. We have presented scenarios showing how a base station can share the same channel to communicate to two mobile stations (MS) in a macrocell to provide more capacity, where cognitive overlay strategy is used in combination of DPC with variable transmission powers. Although this proposed model is dependent on the location of active MS, the paradigm can successfully assist cellular operators in a variety of situations where MS density and spectrum demand is high. In the current work, only the downlink of the network has been considered, with dynamic spectrum access for the uplink being a current research focus.

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