Smart Dynamic Pricing in Cognitive Radio Systems

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Abstract Smart Dynamic Pricing has been introduced to address the under-utilised network resources problem in mobile telecommunications systems. In this paper, we investigate the applicability of Smart Dynamic Pricing and its signalling models into Cognitive Radio Systems. Cognitive Radio System is defined as one in which cognitive radios are employed to access shared spectrum and/or dynamically allocated spectrum. Network elements, protocols, traffic and control channels, and system architecture are proposed for the implementation of Smart Dynamic Pricing in Cognitive Radio System. It is found that Smart Dynamic Pricing and its signalling models can be applied to Cognitive Radio Systems.

Key Words : Dynamic pricing, cognitive radio, software defined radio, software radio, HSDPA, HSPA+, LTE.

1. Introduction

Smart Dynamic Pricing, also known as Smart Pricing (SP), has been introduced in [1]. It is a dynamic pricing scheme that varies prices according to the current users' responses to rising load. SP is a proposed solution to the under-utilised network resources problem. Treatment for the SP signalling in WCDMA systems is detailed in [1] and [2], and for the High Speed Downlink Packet Access (HSDPA), High Speed Downlink Packet Access Evolution (HSDPA+) and Long Term Evolution (LTE) systems in [3].

Network capacity of these networks is dictated by the amount of spectrum a network operator is assigned under its licence. For WCDMA, HSDPA and HSPA+ systems, the amount of bandwidth needed for operation is fixed at 5 MHz, whereas for LTE, it varies between 1.4 and 20 MHz.

Spectrum is a scarce resource and shared between many services. It is said to be one of the most tightly regulated resources of all time [4]. A form of spectrum assignment is through issuing spectrum licenses. Such a licence authorises a licensee to use a particular frequency band within a particular geographical area for a fixed period (e.g. 15 years). For some frequency bands, the demand exceeds supply and in those situations, spectrum licenses are generally offered at auction [5]. Hence, it could be very costly to obtain a spectrum licence. Nonetheless, not all allocated spectrum is effectively utilised, for instance in the 50-950 MHz band as shown in [6] or the 2-6 GHz band in [7] where many parts of frequencies are not used at all or are very lightly used in certain periods of a day. Contradictively, some underutilized spectrum is eagerly sought after by other users. An example of this can be found at the 2.5 GHz band in [8] whereby the mobile telecommunication industry supports the government's plan to make frequencies in part of the band available for their use. The support is a result of a foreseeable significant

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spectrum deficit to meet the industry forecasted demand which is growing substantially every year. Even if certain under-utilised spectrum is not sought after by a strong industry like mobile telecommunications, it still makes sense for the spectrum to be shared, at least with opportunistic users. Allowing that to happen will see spectrum efficiency improve, which is consistent with principles of scare resource management.

As such, spectrum sharing and dynamic spectrum allocation are clearly options for addressing the problem of under-utilised spectrum and for improving spectrum efficiency. Sharing of spectrum is also an option for addressing shortages of frequency allocations for some services. Sharing a frequency band, instead of assigning to one exclusive licensee, will allow access by multiple licensees using techniques like time division, separation of geographical area or orthogonal codes. Inherently this problem is similar to the problem of under-utilised network resources in mobile telecommunications that SP has addressed for the four 3rd Generation Partnership Project (3GPP) systems mentioned above. In this paper, we report the first steps of our research into extending SP and the Monte Carlo Simulation (MCS) and State Space Analysis (SSA) signalling models proposed in [1] and [2] to address the spectrum sharing and/or dynamic spectrum allocation problems.

Spectrum bands not in use are called white spaces and could be exploited by the Cognitive Radio (CR) approach [6]. For spectrum to be shared or dynamically allocated, CRs need to be employed. We define a CR System is one in which CRs are employed to access shared spectrum and/or dynamically allocated spectrum.

Section 2 discusses characteristics of CRs and capacity of CR Systems, Section 3 discusses the applicability of SP in CR Systems and Section 4 provides a summary of this study and identify future work.

2. Cognitive Radio

2.1 Software defined radio and software radio

CR is said to be a particular extension of software radio (SR) [9], A Software Defined Radio (SDR) is a radio in which digitization is done after the antenna stage. A SDR can handle concurrently multi-bands (e.g. 900, 1800 and 2100 MHz) and multimode (e.g. TDMA and WCDMA). A SDR is said to be a practical version of a SR [10].

A SR is a SDR in which the software control processing engine is placed at the antenna and all the processing is performed by software [11]. SRs are seen as an essential component of Fourth-Generation (4G) mobile communication systems [12]. As SRs can be configured, necessary intelligence of SP can be encoded in the SR software for SP use.

2.2 Characteristics of Cognitive Radio

CR enables a frequency band to be shared by sensing for parts of the band that are in use and use the other parts. For spectrum to be shared, secondary users i.e. those who are allowed to use the band (or parts of it) in fixed periods, dynamically or opportunistically, must not cause harmful interference to the primary users i.e. those who own the license. In addition, secondary users must not interfere with each other beyond certain thresholds. Primary users do not need to use a CR but secondary users do. For simplicity, hereafter, we call secondary users who use CRs simply CRs.

Where primary users of a frequency band do not constantly use their licensed spectrum, they can share with CRs with or without charging them a fee. Spectrum available for sharing can be from a singular licensed spectrum, or from a combination of a licensed spectrum. The latter is termed spectrum pooling in [9].

By nature, in order to operate, a CR needs information about the radio environment it is in. That information can be acquired autonomously by the CR through sensing or it could be provided to the CR through pre-installed software or updates over the air interface.

When issued, a spectrum licence is associated with a rich set of conditions with which they need to be complied. These conditions include limits on the license frequency band, latitude and longitude coordinates, radiated power and spurious emission limits. A full list of such conditions can be found in [5]. If licensed frequencies are shared, those conditions must be informed to the CRs and the CRs must comply with the conditions the same way as the primary users do. In addition, as owners of the bands, primary users may set additional conditions for CRs.

A CR must know its location, has spectrum awareness and controls its transmit power [13].

As mentioned in Section 1, a spectrum licence may authorise a licensee to use a particular frequency band only within a particular geographical area. Thus, without knowing its coordinates, CRs will not able to operate. Another reason why a CR needs to know its location is that if it realises it is on top of a hill and has a line-of-sight signal propagation with its receiver, it can use a higher order modulation scheme plus a higher coding rate. That combination results in an increase in the received bit rate.

Many CRs close to each other in a small geographical area may sense the same yet-to-be-occupied parts of the shared spectrum, thus a mechanism must be put in place to regulate these potential contentions. If two such CRs transmit at the same time on the same frequency, both of their respective receivers most certainly will not be able to successfully receive the data sent because of the interference they caused to each other.

A main factor that determines the magnitude of the interference is the transmit power. If a CR transmits with unnecessarily high power, not only does it cause co-channel interference but also adjacent channel interference. That means primary users of spectrum that are not shared by the CR will be interfered with as well. The use of directional antennas, small beamwidths and high elevation angles can help reduce CR transmission power.

2.3 Challenges

Shared frequency bands for CRs can come from many sources. It could, for example, be bands allocated by an administration for use primarily for Electronic News Gathering (ENG) or Aeronautical Mobile Telemetry (AMT) services. For ENG in Australia, the band is so-called the 2.5 GHz band with the frequency range of 2.5-2.69 GHz and a Television Outside Broadcast Network (TVOB) licence is required for a broadcaster to use this band. For AMT in Australia, the band is 2.2-2.3 GHz and is used for operations lasting short durations on a limited number of days a year. Clearly, the two radiocommunications services only use allocated frequency bands intermittently. The problem is that the events are not known in advance. If the bands are not shared, it is wasteful; however, if they are shared, CRs must stop transmitting when the ENG and AMT radios are in use, otherwise the interference could have serious impacts. In such cases, times and durations when these services are in use must be informed to the CRs with short notices in the order of possibly seconds. Therefore, the policy module [6] in the CRs must be developed robustly enough to accommodate such rapid regulatory changes.

If the shared spectrum is frequency band pooled from with different licensees in adjacent jurisdictions or countries, the policy module must also adapt quickly enough when CRs change geographical areas, particularly when movements are with high speeds.

In order for frequency bands to be shared, licensing frameworks may need to be changed. For example, the Australian Government is in the process of making necessary changes to their spectrum regulatory frameworks. This reflects in [14].

Spectrum for sharing can be spectrum commons or with property rights. QoS cannot be guaranteed under spectrum commons approach but can be specified under a property rights approach spectrum of which CRs are allowed to access opportunistically [15]. In Australia, spectrum commons are a limited set of common frequencies which people can use if they comply with the conditions specified by the Government, specifically the Australian Communication and Media Authority, in the relevant class licences free of charge [16]. Radios operating under a class licence are not protected from interference from their peers who share the frequency band with them. In contrast, spectrum with property rights are equivalent to spectrum authorised for use under spectrum licences in Australia. Holder of a spectrum licence is required to register their devices which enable the devices to be protected from interference [17]. If a spectrum licence holder shares its band with CRs but the licence holder does not register the CRs, the CRs will not be protected from interference. This is against the spectrum licence policy. Therefore, some form of protection must be developed to protect the CRs. A result of this may require that the Radiocommunications Act, as in [18], be modified. This is a great challenge and will require tremendous effort.

If primary users cannot be protected from interfering power from CRs, licensed spectrum may not be shared. Cyclic scanning or filter bank proposed in [13] can be employed so that CRs are able to detect what channels are being used by primary users to avoid. Once detected, information about unused channels can then be stored in a centralized or de-centralised spectrum database for access by all CRs in the same cohort. Such a database may require updating [19]. To ensure primary users can access the shared spectrum wherever a need arises, the Polite Backoff protocol can be used [9].

The well known hidden node problem of CR can be made less severe by improving sensitivity of CR monitoring instead of deploying more CR nodes [19].

2.4 Capacity of CR Systems

Capacity of a CR System depends on the size of the shared spectrum. The spectrum can come from a frequency band of only one licensee or multiple frequency bands of multiple licensees. Frequency bands in the spectrum pool do not have to be adjacent to each other. OFDM is found to be the best physical layer for CR System because it allows the use of discontinuous and arbitrary-sized frequency bands [20].

Apart from the size of the spectrum pool, how significant interfering power in a wireless channel and whether CRs have knowledge of the primary users′ transmissions also affect the capacity of a CR System. Capacity under strong interference powers is discussed in [21].

3. Applicability of SP in CR Systems

In making the first steps to extend SP and the MCS and SSA models to CR Systems, we limit ourselves to consider CRs which are yet to have their full potentials. These CRs can still autonomously observe the radio environment, infer context and assess alternatives. They can then propose plans to use, but must not yet use the radio resources. The plans are then signalled to the CR System operator. Upon receipt of these plans, the CR System operator can approve, adjust or reject the plans after taking into consideration the instantaneous policy at that moment and/or any strategic decisions. Resting such final decisions on the CR System operator is believed to only enhance the spectrum efficiency due to the following reasons:

- the CR System operator has an overall view of the radio resource usage and the number of spectrum users in the system. Further, if scheduling is used, efficiency will increase;
- in unexpected events (e.g. CRs unwillingly ceasing contention for a certain channel), intervention is necessary; and
- CRs will have to make less intensive decisions which may reduce the amount of information needed by CRs. This could potentially help reduce CRs' power consumption.

The idea behind the above choice is to keep the admission and resource allocation control at the CR System operator. As SP aims to reserve certain capacity for high willingness to pay users as well as to give guaranteed spectrum units, even in the event of graceful degradation, a CR System operator needs to have such a control to meet SP's objectives. Without such control power, guaranteed QoS may not be achieved.

The dynamic spectrum leasing and interruptible spectrum leasing models in [21] and the spectrum with property rights model in [15] are deemed suitable for SP. This is because these models facilitate a mechanism in which the CR System operator controls admission to the system and the allocation of frequencies and bandwidth within the spectrum pool.

If OFDM and time-sharing techniques are chosen, the maximum capacity of a CR System, η_M, can be calculated in a similar manner to that with the LTE system as detailed in [3]. That is the shared spectrum is divided into spectrum units, each with a nominal value of 15 kHz in the frequency domain and 0.5 ms in the time domain. The low load threshold factor, η_T, can also calculated. The user's maximum and minimum spectral rates, $R_{SP,max}$ and $R_{SP,min}$, respectively can also be determined based on relevant ratios relative to the η_M specified by the CR System operator.

We propose that:

a. a network element called the Cognitive Radio Gateway (CRW) to host the policy database from which the CR's policy module obtains update. The CRW hosts the spectrum database from which CRs obtain master information about unused frequencies that CRs could use. The CRW is also responsible for making decisions in response to plans to use the spectrum pool proposed by the CRs and on admission and resource allocation. Finally, the CRW is responsible for reporting load of the CR System to the Dynamic Pricing Engine (DPE)[1];
b. the DPE is responsible for not only receiving congestion information of the CR System from the CRW, but also for setting prices depending on levels of congestion in the CR System. With the latter, in effect, it means the Tariff Setting System (TSS)[2] is now incorporated into the DPE;
c. four channels, 15 kHz each, are set aside from the spectrum pool for the purposes of CR System signalling. We adopt the idea of having these channels from 3GPP systems, which has resulted in proven success. The effectiveness of having these four channels is a focus of our further research. The proposed four channels are:

   - the CR Random Access Channel (CR-RACH) is an uplink control channel for transmit CRs to signal their intention to communicate with the CRW about their plans using the spectrum pool;
   - the CR Uplink Control Channel (CR-UCCH) is for direct communications negotiating spectrum pool access plan between the transmit CRs and the CRW;
   - the CR Downlink Control Channel (CR-DCCH) is for receive CRs to send feedback of

1) See [1] for details
2) See [1] for details

channel quality to the CRW. Like the HSDPA, HSPA+ and LTE systems, adaptive modulation and coding necessitates this channel. The idea of having a channel for feedback is also flagged in [13]; and

- the CR Broadcast Channel (CR-BCH) is for the DPE in conjunction with the CRW to notify CRs to take advantage of periods the CR System is underutilised. Understandably, prices during these periods are significantly low. The idea of having a broadcast channel is also flagged in [13], however, there the broadcast channel is for use in the case of a non-licensed frequency band, which is different from what being proposed here as spectrum pools are from licensed bands.

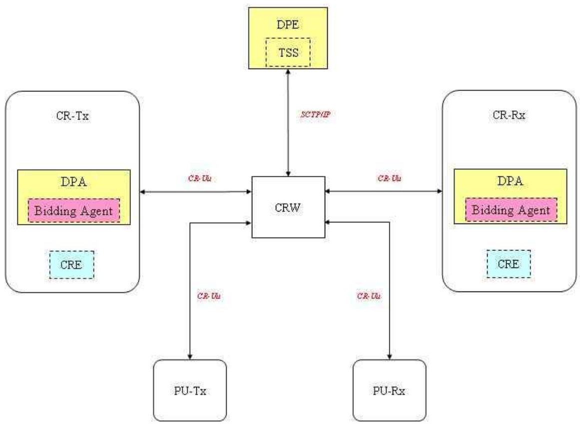
d. CRs contain the CR Engine (CRE) proposed in [22]. The CRE accepts input parameters of three types: transmission, environment and QoS. In addition, the CRs must host the Dynamic Pricing Adaptor (DPA), a designated network element assisting a CR to interact with the DPE (e.g. bidding); and
e. the protocols used in the links from CRs and primary users (PUs) to the CRW is CR-Uu, and between the CRW and DPE is proposed to be Stream Control Transmission Protocol/ Internet Protocol (SCTP/IP). Details of the former protocol are a subject of our future research.

Taking the above elements into account, a proposed SP system diagram for CR System is given in Figure 1. In the diagram, the CR-Tx and PU-Tx are the transmit CR and transmit PU stations, respectively. The CR-Rx and PU-Rx are the receive CR and receive PU stations, respectively. The PU-Tx and PU-Rx are included only to show the complete CR System, these two stations are not involved in SP signalling. The reason is that they are primary users and should have exclusive access to the spectrum pool whenever they need.

For the signalling components, the following modifications to [1] should be made:

- CR-Tx replacing MS;
- CRW replacing RNC and MSC; and
- setting the numbers of signalling components between the TSS and DPE to 0 as the TSS is now collocated with the DPE.

As we have addressed the required five pieces of information mentioned in [3], it can be concluded that SP and the MCS and SSA models can be applied to CR Systems. Once results from further research on Section 2.4 are available, the signalling requirements for SP in CR Systems can be determined.



<Figure 1> System diagram of SP for CR Systems

4. Conclusions

In this paper, we report on the first steps of our researching into extending SP and the MCS and SSA signalling models to CR Systems. We investigate characteristics and challenges of CR, consider aspects of capacity of CR System and propose system architecture for the implementation of SP in CR System. It is found that SP and the MCS and SSA signalling models can be applied to CR Systems to address the problem of spectrum sharing and/or dynamic spectrum allocation. Further research on the proposed channels and protocols and on CR System capacity is being undertaken. Results of that work together with the signalling traffics required for SP in CR Systems will be published in near future.

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