Dynamic Spectrum Access in Cognitive Radio

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Abstract - *In recent years, demand for wireless communication services has grown far beyond earlier predictions, raising serious concerns about future radio spectrum shortages. Current spectrum management policy is characterised by static spectrum allocation where radio spectrum is allocated on a long term for large geographical regions on exclusive basis. This is an effective way to prevent interference, but it leads to highly inefficient use of radio spectrum. This paper investigates possibilities of policy change towards dynamic spectrum access. Cognitive radio technology is proposed as a key technology enabling this policy change, but ensuring compatibility with legacy wireless systems. Based on hierarchical overlay model of co-existence between primary licensed users and secondary cognitive users interference avoidance constraints are presented.*

Keywords - *Spectrum Management Policy, Cognitive Radio, Dynamic Spectrum Access, Interference Constraints*

1. INTRODUCTION

Radio spectrum is a valuable commodity, and a unique natural resource shared by various types of services. Unlike other natural resources, it can be repeatedly re-used, provided certain technical conditions are met. In practice though, it is finite, radio spectrum can accommodate a limited number of simultaneous users and requires careful planning and management to maximise its value for all services. In recent years, demand for wireless communication services has grown far beyond earlier predictions, raising serious concerns about future radio spectrum shortages. Nevertheless, related surveys have proved that most of the allocated spectrum is under utilized [1, 2].

This paradox indicates that spectrum shortages result from the outdated spectrum management policy rather than the physical scarcity of usable frequencies. The current spectrum regulatory framework is based on static spectrum access (SSA) and assignment policy. Currently, radio spectrum is allocated to the radio services on the primary or secondary basis. This is reflected in the Radio Regulations published by the International Telecommunication Union (ITU), which contains definitions of these services and a table defining their allocations for each of ITU regions. Additionally, government agencies assign radio spectrum to licence holders on a long term for large geographical regions on exclusive basis. This is an effective way to prevent interference, but it leads to highly inefficient use of radio spectrum.

In order to satisfy future market demand for mobile and broadband services, we can envisage deployment of next generation mobile networks and services which will need rapid and more flexible access to the radio spectrum. The general trend towards more flexible spectrum management is driven by the ever-growing market pressure for more commercial applications, and the continuous development of new technologies.

To deal with increasing conflict of spectrum congestion and spectrum under utilization, cognitive radio (CR) technique has been proposed as a flexible method which allows secondary users to opportunistically utilize already licensed bands [3, 4]. Dynamic spectrum access (DSA) has the possibility to improve spectrum utilization and in perspective allowing next generation mobile networks access to the attractive radio spectrum bands. In line with that, the spectrum management policy has to face major change in order to reflect future radio spectrum needs and technological advances.

In this paper we present new spectrum management policy applicable for flexible access to the radio spectrum. We give overview of three basic models which can be used for dynamic spectrum access. Cognitive radio functionalities for opportunistic radio spectrum access are presented and analysed. Main objectives of CR considered in this paper are: achieving highly reliable communication whenever and wherever needed and efficient utilisation of radio spectrum. Based on assumption of hierarchical co-existence of primary licensed and secondary overlay CR system, interference avoidance constraints are presented.

The outline of the paper is as follows. Section 2 describes dynamic spectrum access models used by CR system, its characteristics and possible implementations. In section 3 CR functionalities used for dynamic spectrum access in hierarchical primary and secondary sharing scenario are considered. CR transmitter related and receiver related interference avoidance constraints are presented in section 4. Conclusions are given in Section 5.

2. DYNAMIC SPECTRUM ACCESS MODELS

Current spectrum management policy is based on an outdated static spectrum access practice which results in obvious spectrum shortages. Opposite to static spectrum access currently used is dynamic spectrum access which has broad connotations that encompass various approaches and applications. Dynamic spectrum access strategies can be categorised by three basic models: dynamic exclusive use model, spectrum commons model and hierarchical access model [5, 6].

Dynamic exclusive use model: This model maintains the basic structure of the current spectrum regulation policy where spectrum bands are licensed to services for exclusive use. In order to improve spectrum efficiency some level of flexibility is introduced. Flexibility helps licensees to put spectrum to its most valuable use with the most effective technology, without waiting for a regulator's permission. Two approaches have been proposed under this model: spectrum property rights and dynamic spectrum allocation [6]. Users having spectrum property rights can have various levels of flexibility. They can use assigned radio spectrum however they wish, or they could be restricted to specific service applications. Licence is assigned for temporary basis with long duration or for permanent usage. This approach allows licensees to sell, lease and trade assigned radio spectrum and to freely choose technology and services. Economy and market forces will therefore play an important role in driving toward the most profitable and efficient use of this limited resource. The second approach, dynamic spectrum allocation aims to improve spectrum efficiency exploiting the spatial and temporal traffic statistics of different services. Based on observed traffic statistics, spectrum is shared between different services. In a given region and at the given time, spectrum is assigned to services on exclusive use, but this allocation varies at a much faster scale than the static policy. Dynamic spectrum allocation can take advantage of daily user's migration from residential to business areas, or day and night variations of usage statistics. Furthermore, governmental and emergency applications have exclusive access to large portions of radio spectrum which are rarely used. This radio spectrum can be also used for some commercial application under dynamic spectrum allocation model.

Spectrum commons model: This model employs open sharing among peer users as the basis for managing radio spectrum. Spectrum commons model [6] requires radio spectrum sharing without priority allocation to service or class of users. Similar model is used with success in unlicensed industrial, scientific and medical (ISM) frequency band. In a shared radio spectrum band, devices might cooperate or merely co-exist. When devices cooperatively share radio spectrum band they have to use common inter-networking protocol and communicate with each other. Cooperative approach is more technologically demanding, but most of the possible time and spectrum collisions can be avoided.

Hierarchical access model: This model adopts a hierarchical radio spectrum access structure with primary and secondary users. Licensed spectrum is consequently opened to secondary users, while limiting the interference observed by primary users. Interference constraints for secondary users have to be defined carefully in order to allow primary users to operate without noticeable reduction of service quality. Two approaches to spectrum sharing between primary and secondary users have been considered: spectrum underlay and spectrum overlay [5]. The underlay approach imposes constraints on the transmission power of secondary users. They operate below the noise floor of primary users. By spreading transmitted power over a wide frequency band (UWB), secondary users can achieve high data rate on short distances. This approach is based on worst case assumption of interference potential of secondary users to primary users. Spectrum overlay approach targets at spatial and temporal unused radio spectrum called white space by allowing secondary users to identify and exploit local and instantaneous spectrum availability in non-intrusive manner.

3. CR FUNCTIONALITIES

CR technology is the key technology for dynamic spectrum access using spectrum overlay approach. CR is an intelligent wireless communication system that is aware of its surrounding environment and uses the methodology of understanding by building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters in real time, with two primary objectives: highly reliable communications whenever and wherever needed and efficient utilisation of radio spectrum [4]. In order to achieve these objectives, CR is required to adaptively modify its characteristics and to share radio spectrum without interfering with the primary licensed users. Cognitive cycle of CR operation as secondary radio system is shown in Fig. 1. Steps of the cognitive cycle are: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility [7].

Spectrum sensing: A CR monitors its radio environment, detect usage statistics of other users and determine possible white spaces. Spectrum sensing can be done by one CR or by multiple terminals exchanging information in a cooperative way.

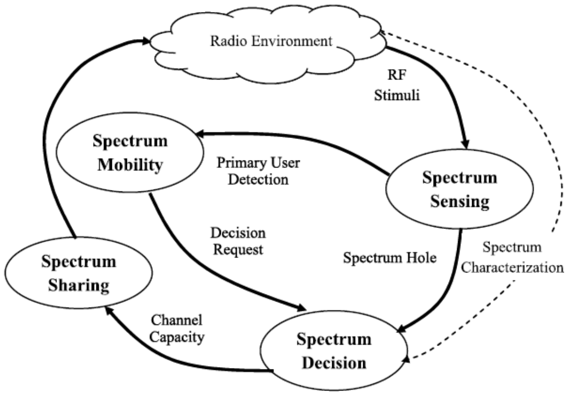

Fig. 1. Cognitive cycle of CR - [7]

Spectrum decision: Based on spectrum sensing information CR selects when to start its operation, operating frequency and its corresponding technical parameters. CR primary objective is to transfer as much as possible information without causing excessive interference to the primary users. Additionally, CR may use data from regulatory database and policy database in order to improve its operation and outage statistics.

Spectrum sharing: Since there is number of secondary users participating in usage of available white spaces, CR has to achieve balance between its self goal of transferring information in efficient way and altruistic goal to share the available resources with other cognitive and non-cognitive users. This is done with policy rules determining CR behaviour in radio environment.

Spectrum mobility: If primary user starts to operate, CR has to stop its operation or to vacate currently used radio spectrum and change radio frequency. In order to avoid interference to primary licensed user this function has to be performed in real time.

4. CR INTERFERENCE AVOIDANCE

There are different compatibility cases to take into account when establishing technical conditions for dynamic spectrum access.

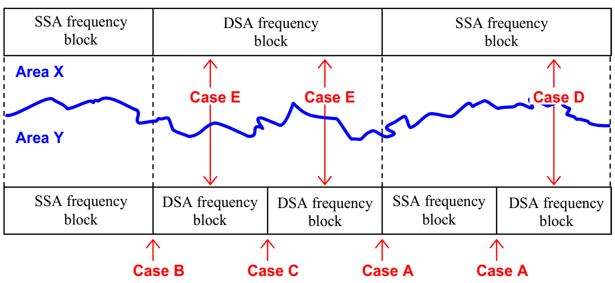

Fig. 2. Illustration of compatibility cases - [8]

Fig. 2 shows relevant compatibility cases for co-channel (cases D and E) and adjacent channel (cases A, B and C) dynamic spectrum access for CR. In Fig. 2, there is a geographical separation between Area X and Area Y, which could be two countries if the geographical separation is a country border. Different spectrum usage rights (SUR) can be used to define interference avoidance rules for CR secondary users. SUR can be transmitter or receiver focused [8].

4.1. Block Edge Mask approach to define SUR

This model [8] was used, for example, for point-to-multipoint systems in the band 3.4-3.8 GHz addressing the situation where no decision is taken beforehand regarding the technology anticipated. It provides flexibility and freedom for operators to choose how to make best use of the radio spectrum. Block edge mask (BEM) controls interference between radio systems by defining a power/frequency envelope within which radio transmitter emissions must remain. This is done by specifying a maximum in-block transmission power in addition to out of block or out of band powers. A spectrum mask is usually defined as a maximum permitted power spectral density within a given bandwidth.

In determining BEM, assumptions have to be made about the type of systems that are most likely to be deployed. In addition some knowledge of the system to be protected is required. The BEM is derived under typical assumptions for the adjacent system's receiver characteristics such as antenna gain, sensitivity and selectivity. If the BEM is defined in terms of total output power it may also include the typical transmitter's antenna characteristics. BEM can be defined in various ways, but two common types are transmitting power mask and EIRP mask [8]. They are outwardly very similar, but the transmit power mask defines an absolute limit for a given transmitter's total output power at a certain distance from the edge of the block, whereas the EIRP mask defines that limit as if a power were radiated equally in all directions.

Type 1 - Tx power BEM: Transmit power mask set a boundary upper limit on emissions that arise from any single transmitter. Provided that Tx power BEM has been derived under appropriate assumptions for the transmitting antenna system it tend to self limit the probability of interference. Unless an associated maximum antenna gain is jointly defined, Tx power BEM does not control the maximum worst-case interference level. Transmit power mask permits greater flexibility than EIRP mask, but specific determination of the expected interference requires detailed information about transmitting and receiving antenna systems.

Type 2 - EIRP BEM: EIRP BEM can be based on Tx power BEM levels including peak gain of the antenna system. In principle, once an EIRP BEM is determined for a given transmitter, any technology that fits within the mask should cause no more interference than the system used as a reference. However, if a new technology will use a mix of output power and antenna gain quite different for the original assumptions made in the study leading to the BEM definition, the occurrence probability of interference cases might significantly change. EIRP BEMs set a boundary upper limit on emissions that a co-channel or an adjacent channel user can expect to see from a single transmitter - even if detailed knowledge about that system is unknown. As the EIRP BEM does not consider the particular deployment details for the transmitting technology, it is effectively technology neutral, but not necessarily application or service neutral.

4.2. Aggregate PFD approach to define SUR

The aggregate Power Flux Density (PFD) SUR method [8] aims to offer certainty by specifying directly the levels of interference that a licensee may generate to the neighbours. The main difference compared with the BEM approach is that regulation is given on the expected aggregate received power on the victim, rather than on the emission power from a single interferer. This approach gives the certainty in understanding the levels of interference expected at the primary user receiver, whilst still allowing the CR flexibility in spectrum usage, since any change of use or technology is allowed as long as it does not increase these levels of interference.

The aggregate PFD method allows a clear mean by which neighbouring (both spectral and geographical) parties can consider a change in licence terms between themselves through commercial negotiation and seek regulatory approval for it. The in-band and out-of-band interference are controlled by placing restrictions on the aggregate PFD that a licensee may generate in an area as follows: the average PFD at a height H m above ground level should not exceed X dBW/m^2/MHz at more than Y % of locations in any area A km^2. Geographical interference is controlled by placing restrictions on the aggregate in-band power flux density at a boundary, as is currently used in cross border agreements between neighbouring countries. The average PFD at or beyond a geographical boundary at a height H m above ground level should not exceed X dBW/m^2/MHz.

This approach allows flexibility both in the deployment density of transmitters and in the individual transmitter powers in the deployment. This is bounded however by the aggregate interference levels that can be generated in any area. For example, a higher density network could be rolled out by an operator, but only if the power of transmitters in any area of the network were reduced enough to meet the aggregate limits on interference. Conversely, if a network of higher power transmitters is desired, this can be achieved with an appropriate reduction in density of transmitters across any given area or other mitigation techniques.

5. CONCLUSION

This paper gives an overview of dynamic spectrum access models which could replace outdated spectrum management policies resulting in spectrum shortages. Under this new policy change, CR functionalities for hierarchical overlay radio spectrum access model are investigated. In order to protect primary and other concurrent secondary users, CR has to apply appropriate interference constraints. These SUR constraints have to be general and simple in nature in order to give CR necessary flexibility for network implementation on service and technology neutral way. This paper presents two possibilities of defining SUR. BEM approach is simpler to define and easier to implement, but it does not take into account possible interference aggregation at victim receiver. Aggregate PFD approach is more convenient for protecting legacy users, but is harder to control and implement.

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