Towards a Cognitive Radio based Distributed Spectrum Management

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ABSTRACT

The under-use of spectrum offers new perspective for a secondary usage of the spectrum. The flexibility provided by reconfigurable transceivers (terminals and base stations) allows exploiting this additional spectrum to enhance capacity and QoS of the networks. However, this can be achieved at the expense of a tight spectrum sharing control and management between the different involved parties (operators and users). Firstly, this paper looks at two approaches for a brokerage based spectrum sharing including the bidding and pricing incentives. Secondly, the paper looks at the achievable capacity gains and the underlying spectrum sharing coordination processes to manage the interference. For both of the economic and technical aspects, concepts and related simulations results are presented. The followed approaches pave the way for a cognitive radio based distributed spectrum management.

I. INTRODUCTION

Some studies have shown that spectrum is not scarce but is rather under-used or not appropriately used by the radio access technologies (RATs), creating new opportunities for an additional spectrum usage. Some substantial temporal traffic patterns variations have been observed for cellular voice service ([2]-[3]) and TV broadcast [4] systems. Some other measurements have outlined the existence of "white spaces" into spectrum at lower temporal resolutions (milliseconds to minutes) [5]. These observations are all the more interesting when considering these observations into a business context. Indeed, the revenue for an operator is highly connected with the amount of time that the communications channels are being occupied, raising high interest in a secondary spectrum usage.

As such, secondary spectrum usage is a joint economic and technical problem. However, the technical feasibility of flexible spectrum sharing is a prior condition to any economic (business model) consideration. Regardless of the spectrum ownership, the technical problem aims at assigning spectrum flexibly between different operators and/or different RATs with the necessary interference control and management. On the other side, the economic aspects looks at how spectrum sharing access and use contention issues can be dealt between primary and secondary operators on a secondary market.

Both of these issues are addressed in "The End-to-End Reconfigurability" (E^2R) research project [1]. This paper presents the work that is ongoing in both the above economic and technical aspects. The paper approaches the spectrum sharing problem with a distributed control and management solution perspective. The results presented in this paper provide first insights on the potential of a cognitive radio based flexible spectrum management.

The first section presents two different secondary markets models enabling spectrum sharing. The first of which considers the spectrum retailing between different operators (see subsection A), while the second approach allows retailing to (and between) end users (subsection B).

Regardless of the negotiation outputs between the primary and secondary systems, the second section presents the capacity gain that can be achieved for FDMA and CDMA based systems in case negotiation is always successful.

II. SECONDARY MARKET MODELS FOR SPECTRUM SHARING

E^2R considers two basic models to establish secondary markets for spectrum usage. The first of which considers the spectrum retailing between different operators (see subsection A), while the second approach allows retailing to (and between) end users (subsection B).

A. Inter-operator spectrum brokerage

The aim of Dynamic Spectrum Allocation (DSA) mechanisms is to exploit temporal and spatial variations to the traffic (and demand) loads in different RANs. [6] outlines the main problems and initial approaches and technologies for a DSA scheme. E^2R extends and furthers this work by (1) considering data and video traffic, by (2) considering interference and power as limiters and finally by (3) developing an auctioning mechanism that implements recurrent auctions to constantly re-distribute the available spectrum between the various bidders (who in this case are two – or more- operators). The defining mechanisms for the negotiation and dynamic allocation of spectrum are based on game theory and microeconomic approaches [7]. Real time spectrum sharing in secondary markets has already been initially discussed in [8] and the auctioning mechanisms that are considered have been documented in [9]. The auctioning mechanisms chosen treat spectrum (and radio resources in general) as economic good and the approach considers the impact of the SIR and power rather than only the pure availability of spectrum.

To facilitate spectrum sharing between different operators, a different business model may need to be envisaged. The principle is based on a pool of spectrum that can be auctioned, for defined periods of time, to the highest bidder. To achieve biggest flexibility for the dynamic allocation, it would be ideal if all available wireless operators would provide their spectrum to this pool and would participate in the bidding process to temporally lease the spectrum back from the 'broker' who controls the spectrum pool and performs the auctions (on behalf of the spectrum owners, i.e. the operators could actually own this broker).

The spectrum (or parts thereof) would be repetitively auctioned to the highest bidder and after a (also pre-defined) time the awarded spectrum usage rights would cease and the spectrum would be available for re-auctioning.

The principle of sharing this pool of spectrum is not too complex, yet there are some intrinsic issues that need to be tackled: this includes the matter of motivation (maximized profits, fairness, etc), type of auctions to be used (sealed bid, ascending, etc), recurrence rate of auctions, bidding strategies (depending on business target and auction type used), and pricing policies.

In case the operators own the spectrum 'broker', the principle of maximized profits may be applied. For the auction design, an approach like the one documented in [9] (i.e. a bidder's share of the spectrum will have the size of $dB = b_i/B$ (with b_i is the bid, while B is the sum of all bids). This basic allocation rule is not in all cases "optimal", but it satisfies "weighted proportional fairness", as introduced in [10]. Furthermore, it can be assumed that the optimal recurrence rate of auctions will depend on the rate at which the traffic demands change.

Finally bidding and pricing policies will depend on the scenario applied. Considering a single DSA area that is shared by two differentially loaded operators who bid for the available spectrum, the bidding and pricing strategies should be determined by each of the operators.

Each operator must perform a valuation of a share of the spectrum, therefore they must consider the immediate demand for services by their active customers. The customers do not necessarily demand a share of the spectrum directly, but may require a certain service instead. This services' requirements are then converted into an optimal amount of spectrum, and finally into an 'optimised' bid (i.e. bidding exactly for the spectrum that is required). However, the customers' demand will depend on the pricing policies of the operator and therefore the bid and pricing must be chosen simultaneously. The aim hereby is profit maximization through efficient use of spectrum and network resources.

Already while a bid is being negotiated (the auction takes place), the operator should plan ahead and estimate future demand and plan upcoming auctions.

A detailed analytical investigation of the problem and solution approach is described in [12].

B. Brokerage as a medium access control

Spectrum considered goods will be dynamically allocated to users. The combination of more complex market, signaling and cognitive radio concepts [13] offers a new relationship between customers and operators. The resource spectrum will be periodically auctioned every view milliseconds using a multi-unit sealed-bid auction [14]. This special type of auction possesses a very short signaling which is linear in the number of customer participating and is suitable for the capacity and time constraint in communications systems. In contrast, the signaling effort of other auction types like open or sequential auction cannot be determined because of the unpredictable iteration of bid submissions.

Clearly, a customer cannot manage an Auction Sequence (AS) in which an auction occurs every few milliseconds, therefore a Spectrum Allocation Agent (SAA) will assist in bidding for spectrum. The SAA is located in the MAC-layer and mapping the customer's needs and wishes as good as possible to the bidding sequence by a parameter set in order to fulfill the QoS constraints which are mainly delay and data rate with respect to reduced costs.

On the other side, an Auctioneer Agent (AA) leads the auctions sequence. The main goal is to increase the spectrum usage efficiency and the auctioneer's revenue. It can mainly influence the auction by varying the Reserve Price (RP).

The signaling of on auction cycle can be described as following:

1. After a duration T an AA proclaims an auction by broadcasting an announcement including RP and the bandwidth available.
2. The SAAs compute their bid vectors.
3. After waiting a duration, an SAA needs for this computation, the AA requests for the bid vectors individually. Hence, the whole request process takes the number of participating customers times a request-answer-duration.
4. Having received all bids the AA assigns the spectrum according to a special mechanism, e.g. in a standard auction the highest bids get the goods.
5. Finally the AA broadcasts the allocation vector including who has won how much spectrum.
6. After the duration T a new auction starts.

In order to compare the established Fixed Pricing (FP) in communications systems with auction sequence, assume that the auctioneer (operator) proclaims the fixed price per Bandwidth Piece (BP) and the RP. The operator offers N BP available at an auction. Only bids are allowed which exceeding the RP. The consideration of the well-known multi-unit sealed-bid uniform-price auction which is a standard auction will show the behavior and the advantages in comparison to fixed pricing.

Its Market Clearing Price (MPC) is the maximum of the highest loosing bid and the RP. Therefore the selling price is not fixed. The higher the number of bidder is, the higher is the probability for the MPC to get higher.

Furthermore the lower the RP is, the higher is the probability that more than N bids are higher than RP. So both a low RP and high number of bidders will lead to a higher operator's gain in comparison to fixed pricing assuming the same customer's needs, the same purchasing power and the same spectrum usage efficiency. Thus, the difference between the sum of MCP per BP and the sum of RP per BP is the operator's gain.

A following simulation will show the behavior of these two market models. As described above, 50 BPs are offered to customers which arrives in the cell according to the arrival rate λ_1=2/T and λ_2=1/T. The fixed costs per BP are equal to the RP and the RP is normalized to the highest possible bid. In case of fixed pricing the gain is assumed as 0.3 times the fixed costs as usually determined in practice.

Figure 1 shows the averaged operator's gain for the different market models and for different average numbers of customers. The lower the arrival rate is, the less users participate to the auction sequence, the lower is the averaged gain. But the lower the fixed costs are relative to the highest possible bid, the higher the auctioneer's gain becomes. In contrast to this, the operator's gain will get less by reducing the fixed costs for fixed pricing models. For high fixed costs there exists only a small RP interval for which the fixed pricing models lead to a higher gain. Finally, the auction sequence leads to a higher operator's gain for a low relative RP and a high number of customers.

This underlines market model for future communications systems reminding the faster reaction to the market and to customers' needs and the greater customers' freedom influencing the price based on their budget, their demands and their QoS levels.

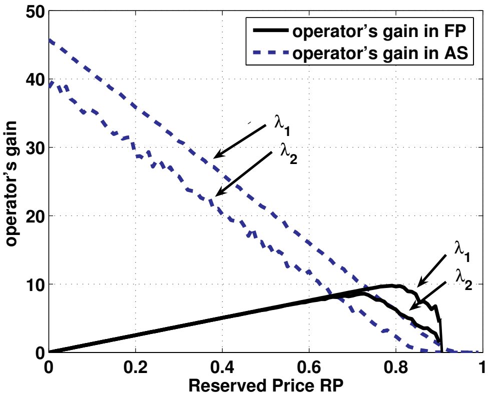

Figure 1: Comparison of the two market models Auction Sequence (AS) and Fixed Pricing (FP) in communications systems

III. ACHIEVABLE CAPACITY GAIN WITH SPECTRUM SHARING

Regardless of the negotiation outputs between the primary and secondary systems, this section presents the capacity gain that can be achieved in case negotiation is always successful. FDMA and CDMA use cases are considered.

A. Distributed licensed open spectrum coordination

"Cognitive Radio" [13] is foreseen as one of the key enabling technologies allowing the implementation of spectrum sharing to improve spectrum access and use. In particular, the FCC [15] has identified cognitive radio as an enabler for facilitating a real time secondary market based frequency sharing coordination between overlaid (homogeneous or heterogeneous) radio access technologies (RAT) operated by different operators. Real time spectrum sharing can be approached by pooling frequencies of the different RATs owned by different operators. Resulting trunking gain can be expected at the expense of a tight coordination of the frequency assignment between the base stations (BS). The coordination solution followed in this section is to allow each reconfigurable BS to be assigned on a real time fashion with the only required amount of spectrum in fully compliance with the number of active users within the cell. This distributed (i.e. on a cell by cell fashion) approach provides the capability to adapt dynamically the real time temporal and spatial traffic (i.e. spectrum usage) variations. This proposed approach falls under the dynamic channel assignment (DCA) application field. DCA has been initially extensively developed [16] to coordinate frequency assignment in the case of a single RAT. This section extends this initial DCA paradigm to several RATs (namely eDCA for extended DCA). As a preliminary step towards a cognitive radio based solution level, a non SIR based traffic adaptive eDCA is generalized from [17].

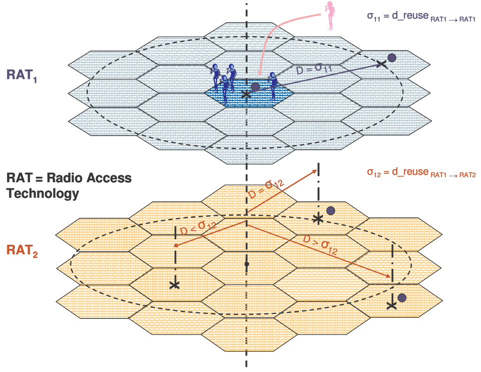

Figure - 2 : eDCA principle between two co-located and overlaid RATs

With respect to this, the eDCA principle is: (1) The frequency carriers of the overlaid RATs are pooled; (2) When admitting a new call, the pool of spectrum can be accessed by any of the RAT provided that the co-channel intra and inter RATs reuse distance constraints are not violated. This is illustrated in of Figure - 2 in case of two RATs. The intra-RAT frequency reuse constraint is depicted in the upper side of Figure - 2 for RAT$_1$. A given frequency (denoted here by a sphere in the cell of the middle) is reusable between two BSs operating RAT$_1$ if they are separated at least by the spatial reuse distance σ_{11}. Consequently, the new arriving user operating RAT$_1$ (his arrival is depicted by the narrow) can be served with this frequency provided that the σ_{11} constraint is not violated. The inter-RAT frequency reuse constraint is depicted in the lower side of Figure - 2 between RAT$_1$

and RAT_2. In addition to the intra-RAT interference, the new arriving RAT_1 user (his arrival is still depicted by the narrow in the upper side) can be served with the frequency (still denoted by the sphere in the cell of the middle) already operated by a BS of RAT_2 provided that the distance between the BS operating RAT_1 and the BS operating RAT_2 are at least separated by a distance σ_{12} to ensure the inter-RAT reuse constraint is not violated; (3) In each cell (BS are reconfigurable), the distributed approach allows each RAT to share on a cell by cell and on a call by call basis the spectrum with the neighboring cells (not limited to the first ring); (4) A set of eligible frequencies is assessed for each new call. A channel is eligible if the intra and inter reuse constraints are both satisfied. In case eligible channels exist, a channel is selected randomly among the eligible channels and the user is served (otherwise, the user is blocked).

In case of two equally loaded FDMA based systems with normalised $\sigma_{11} = \sigma_{22} = 3$ and $\sigma_{12} = \sigma_{21} = 6$, eDCA trunking efficiency is compared to single RAT based systems performance in Figure -3.

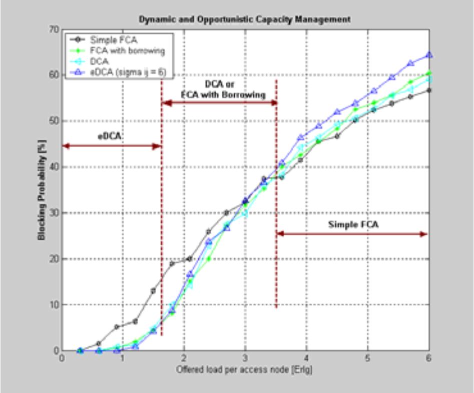

Figure -3 : Opportunistic and dynamic capacity management

Results show that : (1) for 95% satisfied users, eDCA can provide up to 144% capacity gain compared to simple fixed channel allocation, (FCA), and up to 46% compared to FCA with channel borrowing or single RAT based DCA; (2) pooling the spectrum between several RATs can « kill » the trunking gain efficiency if the inter-RAT co-channel reuse distances (i.e. σ_{12}) are not approapriately managed; (3) eDCA does not outperform for all the traffic ranges. The appropriate capacity management relies on the activation of the right strategy in the right traffic loads window. Further information on the results analysis and on the simulation approach can be found in [11].

B. Dynamic inter-operator spectrum sharing with shared networks

The concept and additional investigations pursued in this section are extensions to the concepts and results that can be found in [18] and [19]. Here, operators providing multiple services (i.e speech and video on demand (VoD)) are considered.

For a single operator providing multiple circuit switched type services, queuing theory can be used to model this system assuming a variable amount (due to soft blocking in CDMA systems) of total finite capacity of C units, where each unit of resource is viewed as a server. Let's assume for generality that we have k service class types, where k is finite but arbitrary. We assume each service class $i, i = \{1, 2, ..., k\}$ arrival according to a Poisson process which requires b_i units of resource (i.e. servers) to be served. Further we assume the service times are exponentially distributed. The state description in the multidimensional Markov model can be written as $\underset{\sim}{n} = (n_1, ..., n_k)$ where n_i denotes the number of type i services actively using the resource. The maximum number of supportable services of a particular type N_i, which depends on the number of other service types currently being served and their associated number of resource units required:

$$N_i(\underset{\sim}{n}, \underset{\sim}{b}) = {}^{C}\!/\!{}_{b_i} - \sum_{\substack{j=1 \\ j \neq i}}^{k} \left\lceil \frac{n_j b_j}{b_i} \right\rceil .$$

When considering such a mix of services, several combinations of both services and operating states can be considered, presenting a multi-dimensional system. It is evident that even for the inter-operator spectrum sharing (SS) for the two service case, to consider/simulate all states requires much effort. Therefore, bearing in mind that the minimum capacity gain of spectrum sharing is of interest, we only consider for simulation the worst case spectrum sharing scenario, i.e. when both operators have equal capacity demands, hence requiring fair resource allocation in the shared band.

For a fair resource allocation, it's evident that the threshold values used for both operators in the shared band must be equal. Therefore the simulation goal here is to show the capacity gain obtainable through spectrum sharing in the ideal case (operators fully cooperate and jointly perform admission control) which will be referred to as "Sce2-Ref" and in the case of equal thresholds which we denote as "Sce2-Th". In the simulations conducted here, we pursued an approach, where an average amount of speech users are expected to be served by the network of each operator at each simulation step. The VoD users are to be governed by Poisson distributed arrival processes with exponential distributed service duration. Users of both service types for each operator are uniformly distributed in the network. Further details of the simulation parameters and the algorithm for SS can be found in [19].

Observing the results of Sce2-Th, it shows that Algorithm 2 seems to perform better than Algorithm 1. Additional downlink (DL) transmission power thresholds for an operator compared to the RANs limit is obviously too stringent, especially considering services requiring high DL power per channel i.e. VoD, leading to a reduced capacity. However, it seems that Algorithm 2 is giving results similar to the ideal case (Sce2-Ref). This is because, the simple approach used to dimension the *Energy Threshold* $E_{th|T}$ as an initial step revealed to be an over dimensioned value. That generally led the system to operate identical to Sce2-Ref. A proper dimensioning of energy thresholds, $E_{th|T}$ is important as it would give room for new operators to dynamically request capacity from the shared band and also help save cost if there is an associated cost to the assigned $E_{th|T}$. More research is required to develop means for dimensioning energy thresholds based on the relative operator capacity demands. Furthermore sustained guarantee of QoS is of concern. All these seem to suggest that SS is more suitable for low power services and data services with less time constraints. Possible means for improving the algorithm have been suggested in [20].

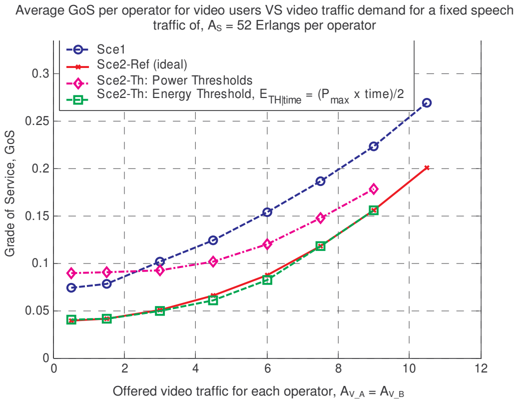

Figure 4: Comparison of the VoD service GoS in Sce1, Sce2-Ref and Sce2-Th employing power and energy based thresholds

IV. CONCLUSIONS

The paper has provided material towards a cognitive radio based distributed spectrum management. Both the economic and technical aspects enabling a secondary usage of spectrum on a market basis have been addressed. The first part of the paper has presented two brokerage based spectrum sharing schemes. The first one allows the spectrum retailing between different operators while the second approach allows retailing to (and between) end users. The second part of the paper has presented distributed based spectrum sharing schemes enabling respectively spectrum sharing between FDMA and CDMA based radio access technologies.

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