Cloud-Assisted Real-Time Spectrum Trading and Auctioning System

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***Abstract*—During the past twenty years lots of new technologies and applications in the wireless communications domain were developed. That led to huge data explosion and accordingly significant wireless spectrum usage rates that degraded the quality of services that should be offered to end-users. Hence, there has been a need for new systems that deal with the wireless spectrum in an efficient way to get the maximum benefit of this scarce resource. In this paper we propose a system that simulates the dynamic spectrum allocation in the context of an auction-based spectrum trading system. This system utilizes cloud technologies and infrastructure to fulfill spectrum requests on real-time basis. This spectrum trading system is providing an efficient way to utilize spectrum resources. This patented system is illustrated in terms of algorithms and proof of concept supported with examples to show the dynamics of allocation and de-allocation of spectrum. Python and Matlab were used to develop the concept and illustrate the graphs and results.**

***Index Terms*—dynamic spectrum allocation DSA, cloud spectrum services, spectrum trading, spectrum auctions**

I. Introduction

Radio spectrum is an essential and precious resource for current and future wireless communication. The development of various radio communication systems and the rapid growth of number of users resulted in congestion and inefficient use of radio spectrum. As a result, it became limited and scarce. The lack of spectrum resource leads to lowering the system performance and users' satisfaction.

Nowadays, spectrum regulations allocate spectrum to operators in a fixed/static allocation. Each operator is given a long-term contract to have the exclusive rights to use certain bands of spectrum. The current scheme of fixed allocation leads to underutilized situation of the radio spectrum resources, and this also causes a useless fragmentation of the licensed/unlicensed spectrum.

To realize an efficient usage and optimum allocation for the radio spectrum, we should migrate from the static spectrum allocation to the flexible and Dynamic Spectrum Allocation (DSA). The DSA can be achieved by enabling the concept of spectrum sharing between different types of users or systems. A primary user is the one who has the exclusive right to use the spectrum. When the primary user (PU) isn't using this spectrum for short or long periods, another user (secondary) can have a chance to use it until the PU wants it back. This procedure of transferring the usage rights between primary and secondary users can be regulated through an auction-based system.

Here we introduce a dynamic algorithm that performs the auction procedure in a cloud-based network. In this algorithm, a mediator/broker entity is designed to handle the auctioning stage. This entity transfers the rights of using a particular spectrum bands from a spectrum holder (e.g. Emergency Systems) to mobile network operators (MNO) upon a predefined service level agreements.

This broker consists of two components: the controller and the auctioning agent. Generally the auctioning process can be done on any commodity server, but applying this auctioning process on a unique and real-time sensitive commodity like spectrum is a challenge. Fig. 1 depicts our spectrum auctioning system architecture that was verified by a PoC explained later in section V. architecture is shown in Fig. 1.

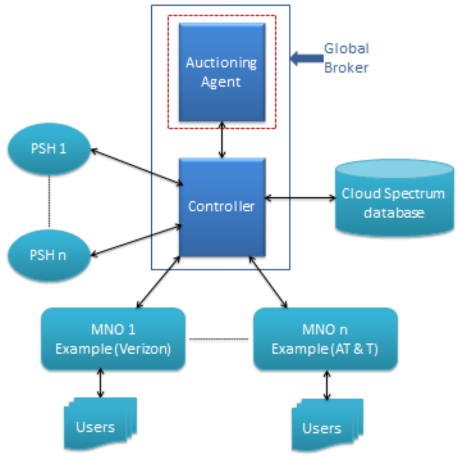

Figure 1. PoC system architecture with auctioning agent. Finally we'll show different scenarios that we faced during the simulation and the experimental results in section VI.

In the following sections we discuss the system flow, components in more details and the auctioning algorithm that basically tends to increase the usage efficiency of the wireless spectrum and the total revenue for the spectrum owners. Related work to our algorithm is analyzed in section II. In section III we describe in details the main entities in the cloud system architecture that contribute in the auctioning process and the flow of interactions between these entities. In section IV steps of the working

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algorithm will be elaborated. Our novel and main contributions are discussed in section V.

II. Preliminaries and Related Work

Radio spectrum can be considered a scarce commodity that can be traded and leased by dividing it into small chunks to be transferred from an exclusive spectrum owner to a secondary spectrum user. Spectrum trading applies pricing-based incentives to stimulate users to rent and lease under-utilized spectrum. The concept of 'Spectrum Trading' refers to two complementary policies [1]:

- *Trading process:* The transfer of spectrum usage rights between parties in a secondary market in many forms as sale, lease or options.
- *Liberalisation (for rights):* The relaxation of restrictions on services and technologies associated with spectrum usage rights.

This means that with spectrum trading many users can benefit from the same spectrum bands with different usage priority levels, exploitation periods, locations and various services. Spectrum trading improves the efficiency and economy by allocating spectrum fairly. It is also more responsive to the dynamics of changing spectrum needs over time.

Before signing an agreement between any two parties, there are some obligations and rights that should be predefined in the scope of the given spectrum license. The dimensions of rights and obligations in a spectrum license include [2]:

- The band which is available for use;
- The geographical area in which it can be used;
- The period for which the license will last;
- The services/applications that will use the spectrum;
- The licensee's degree of protection from other users;

Generally sellers use auctions to improve their revenue by dynamically changing the prices of their goods based on the buyers' demands. Also buyers benefit as they get the resources they value most. Multi-unit auctions have two types [3]:

- *Uniform pricing:* where auctioneer determine a fixed per unit price and applies it to all the winning bidders. The main drawback of this algorithm is the difficulty of calculating the optimum price for maximizing the auctioneer's revenue we use this model in our proposed algorithm.
- *Discriminatory pricing (Non-uniform):* where the auctioneer charges different prices to different bidders. This may be less fair to the bidders however it produces high financial revenue.

According to [4], [5], in the spectrum market the competition or the interaction that takes place between spectrum provider and operators is termed as upstream competition. The competition between users and operators is termed as downstream competition. This hierarchal business model shows the interdependency between the different stakeholders in the network as shown in Fig. 2. The operator's spectrum demands depend on the service demands pattern from underlying users. That may differ based on different times and geographical locations. The service demands also influence the operator's valuation for the spectrum. On the other hand, prices and quality of the offered services by the operator has an impact on the user demand and also on the operator's spectrum demand. That has direct impact on the auctioneer and operator's revenue.

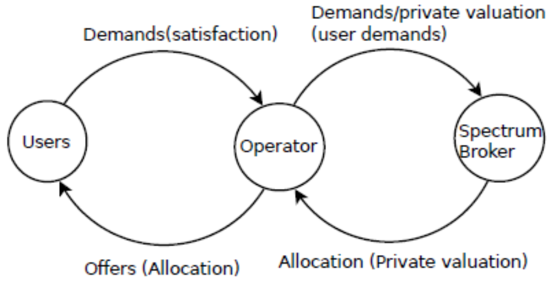

Figure 2. Interdependency between different stakeholders at spectrum market. [4]

One could ask, what is the dimension of the spectrum unit that the operator will bid for? In Fig. 3 [6], a concept named "The Micro-Trading Pixilation Model" was introduced. It divides the spectrum into many pixels. Each pixel has three dimensional domains: Micro-spatial, Micro-frequency and Micro-temporal domains as shown in Fig. 3. By considering these domains we can identify each spectrum unit based on its coverage location boundaries, frequency band and its availability period.

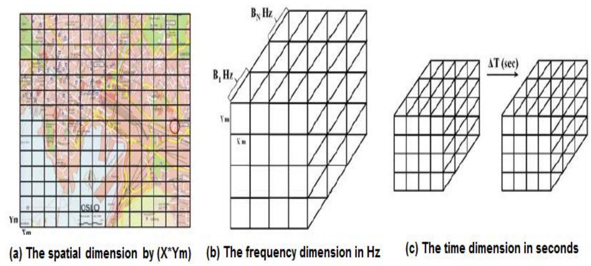

Figure 3. Micro trading pixilation model [6].

In spectrum micro trading the minimum tradable unit is a pixel. A broker (auctioneer) offers a certain quantity of pixels for the operators (bidders) to bid on them at a spectrum auction. In our algorithm a Time-Frequency Unit is the minimum tradable unit.

III. System Components and Flow

As mentioned before, the broker in a cloud-based network consists of two parts; the controller and the auctioning agent. When a new auctioning session starts, the Spectrum Owner announces to all the MNOs that there is a portion of its spectrum available for renting. MNOs submit their spectrum demand to the controller on per needs basis and based on their users' traffic needs.

The auctioning agent has two interfaces to interact with the controller of the system. After the controller gathers all requests from Mobile Network Operators (MNOs), it sends them to the auctioning agent with all the needed information about the available spectrum from the spectrum holders.

Inside the auctioning agent, the following operations are executed:

- Check location operation.
- Auctioning operation.
- Allocation process.
- Customization process

After the execution of these operations & processes, the auctioning agent sends back the auction's results and the winners' info to the controller to inform all the MNOs with the results of their requests and bids. This is shown in Fig. 4.

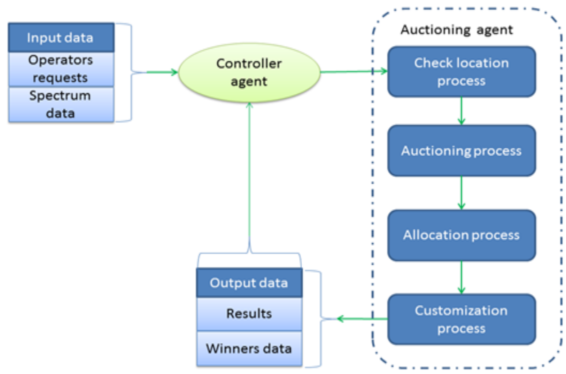

Figure 4. Interaction between controller and auctioning agents.

IV. Working Algorithm and Functionality

The steps of the algorithm and its functionality are described below:

1. The auctioning agent receives the MNOs spectrum requests from the controller agent.
2. It also gets the overall spectrum capacity offered by the spectrum holders from the controller.
3. It gets the location of each operator and locations of all available time-frequency units in terms of x, y and z coordinates along with the coverage radius.
4. Check Locations operation:
   From the MNOs requests, the auctioning agent checks the location of each operator with the locations of all available time-frequency units.
   If there is no matching location for a certain operator, this operator is rejected from entering the auctioning stage.
   Note that each operator's request contains info like Operator name, Security key, Location, Total aggregated demands in time-frequency units, Radio access technology (RAT) and Biding price per time frequency unit.
5. Requests of all the operators with matching locations will be processed into the auction operation.
6. Auction operation:
   Here the requests will be ordered in a descending order w.r.t the bid prices.
7. Allocation process:
   Now and after the bids are sorted and modified based on the demands and the matched time-frequency units, we can distribute the available capacity among the operators. As shown in the Fig. 5.

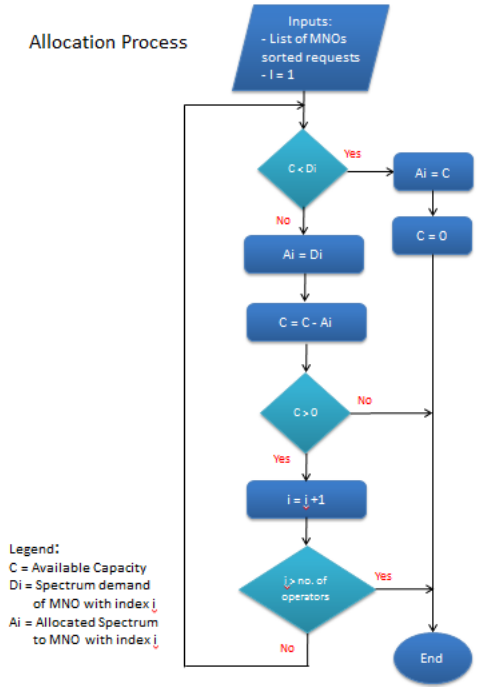

Figure 5. Allocation process.

8. Customization process:
   In this stage, we calculate the utilization function. This function gives an indication about the satisfaction of the MNOs by the end of the allocation stage; the auctioning engine should be able to define the stop out price that all the winner operators should pay per each time-frequency unit. This price will be the bid price of the last winner.

The utilization equation:

$$U = \sum_{i=0}^{no\ of\ operators} \left(1 - \frac{D_i - A_i}{D_i}\right) \times 100 \times P$$

where:

- Di: Actual demand of operator (i)
- Ai: Allocated spectrum to operator (i).
- P: Stop out price.

This function will calculate utility of an auctioneer based on the satisfaction percentage of each operator and the price per each time-frequency unit. This equation doesn't consider the cost that the auctioneer affords to offer this spectrum to the MNOs.

The auctioneer can take commission as a broker/mediator between the spectrum holders and MNOs. It will be a predefined percentage of the total revenue. This percentage has an effect on the auctioneer utility.

The utilization equation with cost factor:

$$U = \sum_{i=0}^{no\ of\ operators} \left(1 - \frac{D_i - A_i}{D_i}\right) \times 100 \times P \times C$$

where: C: The percentage that the auctioneer takes as a commission.

9. The auctioning agent will list the winners and the stop out price. Then it sends this information to the controller to announce the winners.

The flow of our overall algorithm is illustrated in Fig. 6.

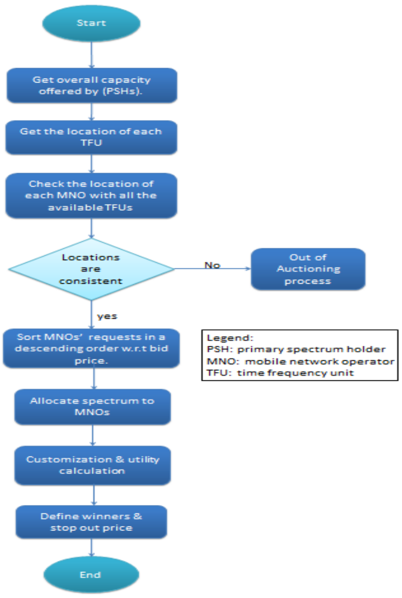

Figure 6. The algorithm flow of the auctioning agent.

V. Contribution

Our main contributions in this wireless spectrum auction algorithm are:

- The procedure of checking the location of each MNO with all the available time-frequency units for trading. As in this procedure, some of the MNOs' requests could be rejected because of unmatched location conditions with time-frequency units' availability. This decreases the computational power needed to perform the auctioning stage, as only those operators who matches time-frequency units will be processed.
- After "Check Locations operation," number of accepted time-frequency units for a certain MNO may be less than its spectrum demand due to not having enough matched time-frequency units in the MNO location. At the end of the auctioning process, if this MNO becomes a winner, it will be allocated only the amount of accepted time-frequency units even if it is less than its demands. This MNO will be kept in an "On-serving queue" to record its unallocated demands. A MNO will be deleted from this list if its agreement time expires - i.e. the agreement is valid as long as a MNO is still using some of the rented spectrum -. When a new spectrum is offered for renting by a primary holder, we'll look at the unallocated spectrum of the MNOs in the "On-serving queue". If there are any time-frequency units in the same location, these MNOs will have the priority to be served after any new auctioning session.
- Finally, the utility equation which gives a practical indication of the satisfaction rate of all the winning MNOs in any allocation scheme, it also gets the total utility of the auctioneer based on the sum of all the satisfaction rates of each MNO.

VI. Scenarios and Simulation Results

In this section we will show some detailed scenarios with figures to illustrate the entire algorithm:

Example: If bids are in pairs as [Di, Bi] where:

- i, operator number in this auctioning session.
- Di, the aggregated demands in time-frequency units for operator number (i).
- Bi, the bid price per time-frequency units.

Let's assume we have this bids list: [25, 5], [30, 4], [19, 5], [67, 3].submitted by operator number (i).

At Auction process: In the case of having two or more requests with the same bid prices there are two different scenarios.

Scenario 1: when sorting requests at the allocation stage, it is being sorted in a descending order w.r.t the bid price in each request. When having 2 or more requests with the same price, the request with the higher spectrum demand is ordered first.

Scenario 2: requests are being sorted in a descending order w.r.t the bid price in each request. When having 2 or more requests with the same price, the request with the lower spectrum demand is ordered first.

At the first scenario we will sort the bids as follows: [25, 5], [19, 5], [30, 4], [67, 3].

And at the second scenario we will sort the bids as follow: [19, 5], [25, 5], [30, 4], [67, 3].

At allocation process: If the available capacity for this auctioning session = 60 time-frequency units.

In scenario 1, spectrum allocation will be [25], [19], [16], [0] time-frequency units respectively. This means that operator 1 and 2 will be allocated with all their demands, operator 3 will take part of each its demands and operator 4 will not acquire any time-frequency units, and that means that the first three operators are winners and the last one is a loser.

In scenario 2, spectrum allocation will be [19], [25], [16], [0] time-frequency units respectively. This gives the same result as scenario 1. That may differ if we have another set of bids.

The stop out price in the two scenarios will be (4).

In Fig. 7, it is shown how the auctioning agent can handle these two different scenarios.

We created a Proof of Concept demo (PoC) in which we compared the performance of the two scenarios, and we had calculated the utilization function with and without the cost factor in both cases. 9.

Utility1 (in red), Utility2 (in green) refers to the utilization calculated in Scenario 1, Scenario 2 respectively.

First we investigate the utility without the cost factor. It was noticed that in most of the run times Utility 1 & 2 are equal. At the rest of the run times only scenario 1 wins. So, scenario 2 never wins. When fixing number of available time-frequency units form the Spectrum Holders and increasing number of operators, we find that the winning percentage of scenario 1 increases in a high rate. See Fig. 8.

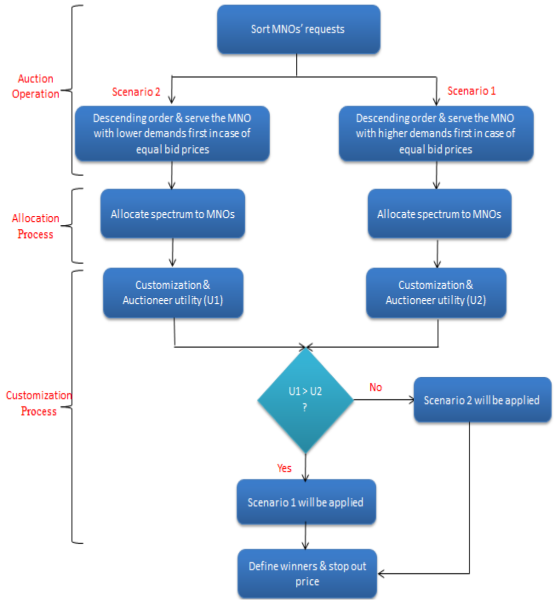

Figure 7. How the auctioning agent deals with different scenarios

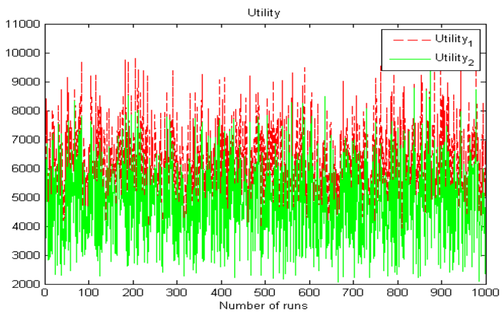

Figure 8. Utility test without cost factor.

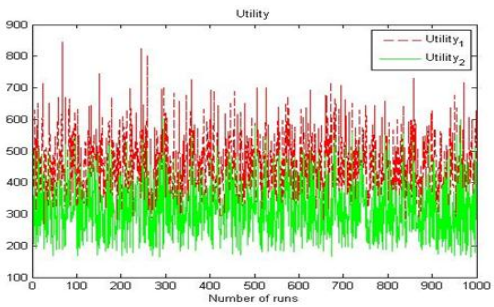

Figure 9. Utility test with cost factor.

When testing the utilization equation with the cost factor = 0.1, we found that scenario 2 also never wins. The winning percentage of scenario 1 increases by increasing number of operators and fixing amount of available time-frequency units. See Fig. 9.

From these results we can say that we will always apply scenario 1 and serve first the operator with the higher demands at the case of equal bid pricing as it will give the best utilization for the auctioneer.

VII. Conclusion

In this paper we proposed a practical spectrum trading auction-based that can be executed over a scalable cloud based infrastructure. In this system, the auctioning agent tends to achieve the most efficient spectrum utilization in addition to increase the revenue. We illustrated the flow of the algorithm from the time when the controller receives the MNOs requests passing by the four operations inside the auctioning agent, till having the final results out of the auction. We used the uniform pricing auction to preserve fairness among all the MNOs. We considered all the necessary parameters as locations, available capacity, bidding price to reach efficient spectrum allocation scheme. We made a proof of concept to test our algorithm. We investigated different scenarios and compared between the performances of the algorithm in both of them. In the future, we are planning to provide a cloud hosting environment for this system along with cloud based analytics to support large scale auction system.

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2. Computational and Data Grids: Principles, Designs, and Applications (IGI Publishing, 2011).

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