Enhanced Auction-Assisted LSA

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Abstract—Virtual Network Operators (VNOs) that construct networks from a pool of shared resources provide flexibility in how services are offered to the end-user. They also enable dynamic use and release of resources according to the demand. This paper investigates sharing of spectrum and infrastructure by VNOs using Licensed Shared Access (LSA) as a basis. LSA is a European spectrum-sharing framework that enables mobile network operators to share spectrum with the primary spectrum users on an exclusive basis, preserving thus Quality of Service (QoS) for all the licensed users of spectrum. In our work, an auction-based approach to the LSA framework is proposed, with VNOs that share not only spectrum but also infrastructure, i.e. antennas. In that, we avail of massive-MIMO and virtualisation and identify key architectural aspects to enhance the LSA framework. Further, we investigate how our approach performs in terms of the number of VNOs that can be served by the available spectrum, and the proposed auction-based approach to the LSA framework is optimal in terms of the particular price of infrastructure (antennas), the proposed mechanism to allocate resources to the VNOs in the context of the LSA framework. Accordingly, the spectrum resources are orthogonally assigned to maintain service quality. Regarding the infrastructure, we consider a cloud-based massive-MIMO system, where multiple VNOs can share all the antennas1. Antennas are connected to the centralised processing units that reside in the cloud and create a baseband pool. The cloud and fronthaul physical resources are logically separated and shared between VNOs, creating virtual base stations [3]. In this way, each VNO has a virtual slice comprised of infrastructure and radio resources, enabling them to provide distinct services to their users. This paper presents the case when all VNOs offer the same service to their users, evaluated through average user rate. The infrastructure provider may be third-party, or may be a public network provider [4]. This approach to spectrum and infrastructure management is in line with the radio access network (RAN) sharing scenario proposed by 3GPP in [5], where the participating operators share RAN by utilising orthogonal portions of the licensed spectrum.

A. Related work & main contributions

LSA has been a topic of interest for standardisation bodies, cellular operators and academic community. For an overview of regulation and standardisation activities, the reader can refer to [6] and [7]. State-of-the-art and challenges associated with the deployment scenarios and implementation of LSA can be found in [8] and [9].

Other works focus on specific aspects of LSA. For example, in [11], a two-tier evolutionary game for dynamic allocation of LSA spectrum resources is proposed, where the use of a proposed payoff function offers fairness for the LSA licensees and coexistence with the incumbents. The authors in [10], on the other hand, propose Cloud-RAN and massive-MIMO as a platform for LSA, evaluating the trade-offs between spectrum and antennas while maximising cost efficiency. In [12], a distributed antenna system (DAS) architecture in a network virtualisation context using fractional frequency reuse is considered. The paper compares the capacity of cell-edge users between two cases. One is the case when LSA spectrum can be used in combination with Single-User MIMO with a joint transmission. In the other case, the LSA spectrum is not available, but all users can avail of Multi-User MIMO transmission with coordinated beamforming. The authors in [13] consider a cellular operator in Finland and compare LSA and MIMO in terms of cost, spectral efficiency and throughput.

Recently, an auction-based approach to spectrum sharing in LSA has been proposed in [14]. There, the authors present a mechanism to allocate the LSA incumbents’ idle spectrum

1In this paper, the term antenna denotes a Remote Radio Head with collocated or integrated antenna, transmitting signals at different frequencies.
to a number of LSA licensees. The proposed mechanisms - LSA Auction (LSAA) combines independent set selection by bidding and a group bid to tackle interference between competing base stations. The goal is a policy aiming for revenue maximisation and market regularity. Different from [14], our auction is situated in Cloud-RAN massive-MIMO scenario and takes into account not only spectrum, but also infrastructure. Furthermore, bidders i.e. VNOs also need to provide minimum rate requirements for their users while minimising their cost.

An auction-based approach for the combined allocation of spectrum and infrastructure is proposed in [15]. There, the authors design a hierarchical combinatorial auction mechanism, based on Vickrey - Clarke - Groves (VCG) auction and consider the infrastructure providers and mobile VNOs. The authors evaluate the allocation with three degrees of freedom i.e. frequency, power, and antennas, and propose computationally tractable solution. Different to [15], our work is set within an LSA context and also considers antennas as a shared resource among all VNOs. Furthermore, we identify key architectural aspects related to situating the proposed auction into the LSA framework. As in [15], we also compare our auction-based solution to a static fixed sharing scheme where the VNOs are preassigned a fixed subset of resources in different domains. In [16], the authors propose a clock auction, which is performed by a third party auctioneer for the combined acquisition of spectrum and antennas. Compared to the current paper, [16] is not LSA specific and focuses on continuous spectrum allocation. In this paper, we discuss both - the architectural implications for the LSA framework and the effects of 5MHz channelisation, as defined by LSA. Moreover, as compared to [16], we incorporate more expressive bidding options into the auction process, whereby the VNOs can now XOR different package bids to minimise the required spectrum by incrementing the number of antennas.

The main contributions of our work can be summarised as follows:

- In our work, for the first time, we propose an auction-based enhanced LSA framework, encompassing not only spectrum but also infrastructure i.e. antennas. Our approach takes full advantage of massive-MIMO and virtualisation.
- We investigate how our auction-based approach fares as compared to a benchmark, that is the fixed allocation of spectrum and antennas, or of spectrum alone.
- We identify key architectural aspects that extend the LSA framework to incorporate the auction mechanism and infrastructure sharing.

The rest of the paper is structured as follows. Section II describes the enhanced LSA architecture that supports infrastructure and spectrum sharing. The proposed auction-based spectrum allocation algorithm is discussed in Section III. Numerical results are presented in Section IV, while Section V concludes the paper.

II. ENHANCED AUCTION-ASSISTED LSA ARCHITECTURE

The proposed enhanced LSA architecture is depicted in Fig. 1. It consists of three main building blocks: the LSA architecture, auctioneer and infrastructure provider for a given area. The enhanced LSA architecture extends the conventional one, where the key actors include National Regulatory Authority (NRA), incumbents and LSA licensees i.e. the cellular operators. NRA is responsible for establishing the conditions of the spectrum sharing agreement and the licensing process. It can perform the LSA system administrator role, or it can employ a third-party to conduct it. It should be noted that the role of NRA may vary from country to country. The incumbents are the current holders of the right to use the spectrum. In 2.3-2.4 GHz band, typical incumbents include Programme Making and Special Events (PMSE) applications, telemetry and other governmental use [17]. The incumbent specifies the terms of the sharing agreement regarding the current and future spectrum requirements, including aspects such as utilisation of frequencies in a geographical area, pre-defined time of use, and pre-emption conditions in the case of an emergency. The LSA licensees i.e. cellular operators are authorised to share spectrum with the incumbent using time or spatial separation [18]. In the event of an emergency, they also need to be able to release spectrum, according to the specified conditions. The main functional entities in the LSA architecture are the LSA Repository, LSA Controller and Operations & Maintenance System (O&M). The LSA Repository contains all the required information about the spectrum and its use by the incumbent in time, frequency and space. Based on the sharing arrangement and information provided by the LSA Repository, the LSA Controller, which is a part of the LSA licensee domain, computes spectrum availability in temporal, frequency and spatial domains [18]. Accordingly, it instructs the network O&M to manage the spectrum.

In this paper, an enhanced LSA architecture is envisaged - incorporating Cloud-RAN, virtualisation and software defined radio/network concepts [19]. Cloud-RAN envisages cloud-based baseband processing, where baseband resources are pooled and shared among different remote radios. Virtualisation can be considered as a next stage in the evolution of Cloud-RAN [3], allowing multiple operators to share common infrastructure (baseband, transport and access) resources, as well as spectrum resources. Software radio/networking enhances virtualisation, enabling direct programmability of the network. In the context of this paper, virtualisation envisages providing distinct wireless network resources - antennas, baseband, fronthaul and spectrum to different VNOs. The resources i.e. slices are logically separated, enabling each VNO to manage their resource allocation policy. Here, the spectrum is a public resource, whereas infrastructure may be provided by a third-party (i.e. an infrastructure provider), or may be a part of a public (cellular) network. If present, an infrastructure provider is responsible for defining the terms of infrastructure sharing. Should the infrastructure be a part of
a public network, the NRA role would need to be extended to set the terms of infrastructure sharing. Furthermore, the new LSA licensees are virtual cellular operators, which now do not own infrastructure. We also envisage that the sharing arrangements involve the auction mechanism, where a third party i.e. the auctioneer is introduced on behalf of NRA and infrastructure provider to manage both - spectrum and infrastructure sharing. The auction mechanism follows the LSA spectrum sharing rules, where the temporal allocation of spectrum follows the statistics of the incumbent(s) in the band, as explained in the following section. Concerning the infrastructure sharing, we consider cloud-based massive-MIMO antennas as a resource that multiple VNOs can share at the same time. Based on the input from the auctioneer and the LSA Repository, the Wireless Resource Controller assigns spectrum and infrastructure resources to each VNO i.e. the appropriate channels, the number of antennas and the required cloud and fronthaul resources. The Wireless Resource Controller instructs the Resource Manager to manage the assigned resources. Considering that resources may belong to different entities, Wireless Resource Controller and Resource Manager may consist of separate logical units that each control/manage spectrum or infrastructure. It should also be noted that, in general, independent providers may provide different resources i.e. antennas, cloud and fronthaul. In this paper, a single infrastructure provider is responsible for all the resources.

III. AUCTION PROCEDURE

In our auction, the bidders i.e. VNOs bid for spectrum and infrastructure resources. Each VNO serves the same number of (its own) users. To comply with the LSA framework and according to the LTE standard, the available spectrum is channelised into blocks of 5 MHz. Thanks to the merits of massive-MIMO, users of the same VNO can reuse the same spectrum. However, the LSA framework stipulates the orthogonal use of spectrum by VNOs. It should be noted that allocation of resources is valid for the time period determined by the type of incumbent and their usage of spectrum. In the case of appearance of an incumbent in a given band, there are a few options as to how the resources can be reassigned: i) the residual spectrum from the current auction can be reassigned to the VNOs that are affected by the appearance of an incumbent, ii) the auction can be repeated over the updated available spectrum, iii) the affected VNOs will be left without LSA spectrum, waiting for the incumbent to evacuate the band.

We consider $N$ VNOs, $K$ users to be served by each VNO, and $M$ distributed antennas. In our model, VNOs lease antennas at a fixed price and acquire access to spectrum via an auction mechanism. It should be noted that when referring to the antenna price, here, we refer also to the required cloud and fronthaul resources. The fixed price associated to the usage of each antenna affects the spectrum utilisation. Since spectrum and antennas are partially interchangeable resources [16], the demand for spectrum will vary with the cost of antennas. As a case in point, if the cost of antennas is too high, the remaining budget might not be sufficient to acquire the spectral resources necessary for delivering a given rate. In this paper, we have adopted a clock auction for the assignment of resources to the VNOs. The clock auction operates in two phases - namely, the price discovery (clock) phase and the final assignment phase. The price of spectrum monotonically increases in each round and VNOs indicate the packages of spectrum and antennas they are willing to buy at a given price. In particular, if the auctioneer detects excess demand for the spectrum after a round of bidding has closed, it increases the posted spectrum price and opens another round of bidding. In our model, in each round each VNO can XOR
2 package bids. A VNO computes the first package bid as the number of antennas and 5 MHz blocks that minimise its cost within its budget constraint, whilst providing its users a minimum rate. The cost is a linear combination of the number of antennas and spectrum at the prices indicated by the auctioneer. With the exception of spectrum channelisation, this is the same model discussed in [16]. However, since the price of spectrum increases at each round, we also consider a second bidding strategy which models a less aggressive price of spectrum increases at each round, we also consider this is the same model discussed in [16]. However, since the auction ends when all excess demand is removed from the market. In the ideal situation, both supply and demand completely match. However, this is unlikely to happen in complex multi-item-unit, multi-item-type auctions. Consequently, the approach that is used in this part of the auction may result in the oversupply of spectrum. This will happen if the bidders’ private valuation of the minimum required rate is lower than the corresponding cost to acquire spectrum and antennas at the requested price. If this situation arises, the bids are assigned using a revenue maximising approach, i.e. using a winner determination algorithm. This algorithm determines which combination of the bids that stood at the last clock price which caused excess demand will maximise the auctioneer’s revenue. The winner determination problem can be formulated as follows.

\begin{aligned}
\text{maximise } & \sum_{i=1}^{N} \sum_{j=1}^{2} (c_a a_{ij} + c_b b_{ij}) y_{ij} \\
\text{subject to } & \sum_{i=1}^{N} \sum_{j=1}^{2} y_{ij} \leq B, \\
& y_{ij} \in \{0, 1\}, \forall i \in \{1, 2, \ldots, N\}, \forall j \in \{1, 2\}. \\
\end{aligned}

where \( y_{ij} \) = 1 if package \( j \) of bidder \( i \) is accepted, otherwise \( y_{ij} = 0 \). \( c_a \) and \( c_b \) are the costs per antenna and spectrum block, respectively. Finally, \( B \) is the total available bandwidth.

### IV. Numerical Analysis

The simulated scenario is based on the auctioning strategy explained earlier. The scenario includes 15 VNOs competing in a bid to acquire spectrum and infrastructure to meet their requested minimum rate. The minimum requested rate is the same for all the operators. We consider 10 users per VNO that are randomly distributed in a given area. A total of 64 antennas are available for sharing between the VNOs. The total available spectrum is 50 MHz, where each VNO can acquire spectrum in blocks of 5 MHz, according to the LSA rules. The budget of each operator is proportional to the rate required by its users. The results of the simulated scenario are depicted in Fig.3 and Fig.2. Fig.3 illustrates two directly related aspects - the required bandwidth and number of VNOs that can be served. Fig. 2 depicts the number of required antennas, again as a function of the minimum rate and antenna price. To understand the trends, these figures should be considered together.

Looking along the x-axis in both figures, we can see that for the lowest considered user rate, the same number of antennas and spectrum are required, regardless of the antenna price. In this case, spectrum is abundant as VNOs cannot lease less than 5 MHz of spectrum, or less than 10 antennas. This spectrum is therefore sufficient to provide the required rate, with the minimum number of antennas. In total, 10 VNOs are served. As the minimum considered user rate increases (looking along the y-axis), the number of antennas increases up to the highest possible number. The VNOs can still serve its users with 5 MHz of spectrum, but with the increasing number of antennas. This is the case until maximum number of antennas is reached and as long as the antenna price is less than a certain value (approximately 250 % of the budget per kbps). For higher antenna prices, it is more cost-effective for VNOs to buy more spectrum than to further increase the number of antennas. The spectrum requirement therefore jumps to the region of 10 MHz, when 5 VNOs can be served. This trend repeats itself with 10 and 15 MHz of spectrum, serving 5 and 3 VNOs, respectively. It should be noted that this periodicity with the number of antennas is observed only in the case when discrete spectrum is considered, which is one of the

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**Algorithm 1: THE SECOND BIDDING MECHANISM**

**Input:** First package bid of bidder \( i \), i.e. \( \{a_{i1}, b_{i1}\} \)

**Output:** The second package bid of bidder \( i \), i.e. \( \{a_{i2}, b_{i2}\} \)

1. **Initialisation:** \( a_{i2} = a_{i1}^{(0)} = a_{i1}, \) \( b_{i2} = b_{i1}^{(0)} = b_{i1}, \) \( \ell = 0 \)
2. \( b_{\text{Min}} \leftarrow \text{Rate}(b, a_{\text{Max}}) = \text{Rate}_{\text{Min},i} \)
3. **while** \( (a_{i2}^{(\ell)} \leq a_{\text{Max}}) \) and \( b_{i2}^{(\ell)} \neq b_{\text{Min}} \)** **do**
   4. \( \ell = \ell + 1 \)
   5. \( a_{i2}^{(\ell)} = a_{i2}^{(\ell-1)} + 1 \)
   6. \( b_{i2}^{(\ell)} \leftarrow \text{Rate}(b, a_{i2}^{(\ell)}) = \text{Rate}_{\text{Min},i} \)
   7. **if** \( (c_a a_{i2}^{(\ell)} + c_b b_{i2}^{(\ell)}) \leq \beta_i \) **then**
   8. \( a_{i2} \leftarrow a_{i2}^{(\ell)}, \) \( b_{i2} \leftarrow b_{i2}^{(\ell)} \)
9. **return** \( \{a_{i2}, b_{i2}\} \)
main differences between this and the case when continuous spectrum is considered.

A. Comparison with Fixed Sharing

In this subsection, we compare the results of auction-based sharing with fixed-based allocation of resources. In that, we consider two approaches - one with orthogonal and equal allocation of both spectrum and antennas, and the other with equal allocation of spectrum, where all VNOs can utilise all the antennas. Figure 4 depicts the number of served VNOs versus the rate requirement for the considered approaches. It should be noted that two different antenna price values are evaluated for the auction-based sharing. The case of fixed sharing with equal and orthogonal allocation of spectrum where all the antennas are shared can be considered as a benchmark in terms of system efficiency, but excluding the cost of infrastructure. Namely, as in our study all VNOs have the same rate requirements, under the assumption of orthogonal spectrum allocation, using all antennas and equally dividing the spectrum among the VNOs is the optimal solution in terms of system efficiency.

The fixed sharing case with orthogonal usage of antennas serves the lowest number of VNOs, regardless of the rate. This degradation in the number of VNOs that can be served is due to the fact that virtualisation is not exploited i.e. each VNO uses smaller number of antennas. As it is shown in Fig. 4, the auction-based approach for two different antenna prices under consideration outperform the fixed sharing case with orthogonal utilisation of antennas. Furthermore, with a cost of antennas that is less than approximately 250% of the budget, we can always achieve the optimal performance through the auction-based approach.

V. CONCLUSIONS

This paper proposes an enhanced, auction-assisted LSA framework, which encompasses not only spectrum, but also infrastructure, i.e. cloud-based massive-MIMO antennas. The approach takes full advantage of massive-MIMO and virtualisation and identifies the key architectural aspects that are required to enhance the LSA framework to avail of these technologies. In our numerical evaluation, we observe periodic patterns in the antenna allocations to VNOs when considering a range of minimum rate requirements and antenna prices. This
is the consequence of the discretisation of spectrum allocation, which was not present in the continuous case. Furthermore, we prove that our auction based approach outperforms fixed static sharing with orthogonal use of spectrum and antennas. Finally, we show that for cases when the cost of antennas is below a certain percentage of the budget (per kbps), we can achieve optimal performance in terms of the number of VNOs being served.

ACKNOWLEDGEMENT

The project ADEL acknowledges the financial support of the Seventh Framework Programme for Research of the European Commission under grant number: 619647. We also acknowledge support from the Science Foundation Ireland under grants No. 13/RC/2077 and No. 10/CE/i853.

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