Efficient Spectrum Allocation: A Simultaneous Multi Round Auction Approach

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***Abstract*—A new era of communication is about to begin with the arrival of 6G technology, which promises previously unheard-of speeds and bandwidth capacities. To fully realize the promise of 6G networks, effective spectrum resource trade and allocation are still essential. In this work, we put forth a unique strategy for spectrum trading that makes use of concurrent multi-round auctions designed especially for the 6G environment. We create a framework that tackles the particular difficulties presented by 6G spectrum allocation, such as dynamic spectrum sharing and varied user demands, by drawing on ideas from game theory and auction design. We show the effectiveness and scalability of our suggested strategy in promoting effective spectrum usage and improving overall network performance through simulation tests and analytical modeling.**

***Index Terms*—6G, Spectrum Trading, Simultaneous Multi-Round Auctions, Auction Design, Game Theory, Spectrum Allocation, Network Performance**

I. Introduction

Some aspects of 5G networks that are unheard of, such as an unparalleled data-carrying capacity coupled with reduced time delays, are, however, targeted by 6G technology to enhance them beyond previous limits and explore new frontiers in wireless communication. In the future, 6G networks are estimated to provide data speeds in the range of several tens of gigabits per second and delay times of a few microseconds. These advances might enable live interactions via holographic technology, immersive augmented reality experiences, or even the integration of artificial intelligence into routine activities [6].

The Virtual Spectrum Providers (VSPs) and Mobile Network Operators (MNOs) interrelation will have a significant impact on the dynamics of spectrum allocation and usage in the 6G network ecology. In particular, these barriers include costs associated with spectrum licensing, as well as obligations linked to spectrum bands used by mobile broadband services, which create issues for market newcomers, also known as vertical markets [12].

New possibilities have emerged as a result of the recent progress in 5G networks and the establishment of local small cells, which is particularly interesting for players involved in vertical industries. Likewise, there are also value-added service providers such as VSPs who operate individual private networks to cater to specific end-users.

The landscape of wireless communication is changing at a fast pace, and the significance of Vertical Sector Players (VSPs) within the spectrum ecosystem becomes more pronounced with time. By doing this, VSPs make sure the bands are maximally used making them maximize on the worthiness of their spectrum assets. They have an indispensable role to play in terms of dynamically allocating spectra resources due to demand variation and network situation which needs to be dealt with in a prompt manner. To maintain service levels amidst dynamic market conditions, MNOs must rely on adaptable licensing models, innovative auction strategies, and collaborative spectrum sharing agreements that permit rapid adaptation to changing market conditions.

The efficient allocation and management of spectrum resources becomes important as the telecommunications industry transitions to 6G networks. The conventional ways of allocating spectrum characterized by rigid licensing frameworks and static allocation policies do not meet the changing needs of advanced 6G applications and services. This is why early approaches in trading and assigning spectrum are necessary for meeting emerging demands of 6G network. In addition, these methods should enable distribution of spectrum on one hand, competition among firms on the other hand, innovation in telecommunication, as well as attraction of investments in this sector [3].

In the micro-licensing paradigm where MNOs and VSPs coexist, VSPs function as active participants who utilize Paul Milgrom's Spectrum Auction Algorithm (SAA) that is an iterative procedure. Spectral blocks serve as the main points of attention in auctioning. The maximum dedicated bandwidth

(B) for MNO is constant and will be shared between MNO and VSP; this bandwidth is divided into equal spectrum blocks with uniform bandwidth w. Additionally, the available bandwidth of the MNO in each frame is denoted by BW_f and calculated such that $J_f = BW_f/w$, where J_f is a number of spectrum blocks within a frame. This advanced approach ensures optimal usage and fair division of spectrum resources according to requirements of both VSPs and MNOs [10]. This paper presents a new methodology for 6G networks spectrum trading based on simultaneous multi-round auctions (SMRAs) as a technique for allocating spectrums. We designed a comprehensive framework based on game theory, auction design to address issues related to 6G spectrum allocation which include dynamic spectrum sharing, heterogeneous user demands ,and regulatory constraints [4].

By way of simulations and analytical models, this study seeks to determine how well the proposed SMRA system performs in terms of spectrum efficiency, revenue collection, justice and right resource allocation. We also investigate how our suggested mechanism affects network dynamics; user satisfaction and regulatory policy; which lay a foundation for the development of strong, adaptable and scalable spectrum trading systems that can meet 6G application requirements and drive wireless communication to next decade as well as beyond.

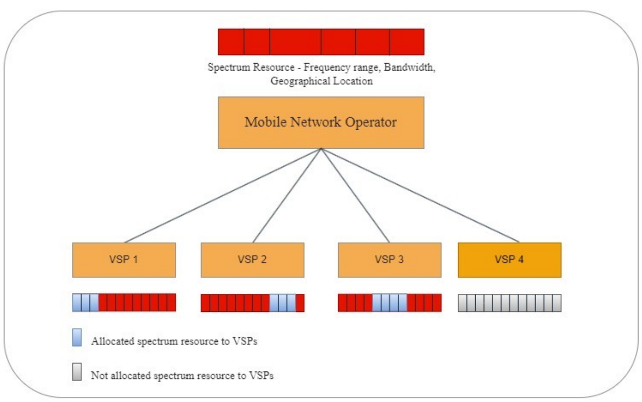

Fig. 1: MNO and VSP resource distribution

II. Literature Review

Regulators are guided by two principles: efficient use of a scarce natural resource and fairness among competing stakeholders in the radio frequency spectrum while making decisions on how to manage the spectrum. In case of different needs when there are different stakeholders, spectrum management involves choosing optimal mobile bands. However, the latter is full of conflicting interests as the majority of bands that can be used for mobile communications have already been assigned to other wireless services [1]. Nowadays it is getting harder to define regulations and conditions regarding spectrum usage that are supposed to be followed by everybody. Mobile communication has successfully acquired new blocks of frequencies during past decades which resulted in global 2G, 3G and 4G networks . This procedure takes place at the highest international level through WRC's organized by ITU-R. There were several instances where this sector made significant dedications for mobile services with specific designations as IMT bands (such as in 2007, 2012, 2015 and most recently in 2019) [5]. The development of mobile communication services among other factors, has brought about the need for new approaches and designs in managing smart spectrum sharing. In their role as regulators, national governments usually determine which companies are allowed to deploy and operate cellular mobile communication networks and provide telecommunications services using spectra. In many countries around the world, 5G spectrum awards have recently been made and this year they plan to launch the first 5G networks. This is also a story of how, frequency control methods that were unimaginable in previous generations are now coming into place with 5G [7]. These traditional nation-wide long-term licenses are supplemented by local ones for 5G and unrestricted access to it, which constitutes a major paradigm shift in spectrum management for wireless systems. Announcements have been made about 5G deployments while at the same time, research on 6G networks has since started with the release of world's first 6G White Paper in 2019 [11]. The research vision for 6G presented in is targeted to a society that shall be data-driven by the year 2030 and supported through near-immediate wireless access. As in any other previous mobile communication network, spectrum will remain a critical element of future communication systems [9]. At the same time, spectrum management requirements for 6G are becoming increasingly intricate due to wider range of possible frequency bands as well as ways of using them, and pre-existing deployment scenarios with occupied spectrum. Efficient utilization of scarce national resource is the main goal of spectrum management which has been evolving over time. Overall, approaches towards spectrum management can be further divided into three distinct categories – administrative allocation [8], market-based mechanisms, and unlicensed commons approach [2].

III. System Model

Consider a dynamic spectrum allocation system where Vertical Sector Players (VSPs) and Mobile Network Operators (MNOs) participate in a simultaneous multi-round auction for the allocation of spectrum resources in a 6G network. Several iterations are performed by Paul Milgrom's Spectrum Auction Algorithm (SAA) auction mechanism. Each of the bidders presents their bids indicating that they value certain bands of the spectrum.

Let N be the total number of bidders participating in this auction and $m$representing the total number of available spectrum bands under consideration. The set $S = \{s_1, s_2, \ldots, s_m\}$ denotes all available spectrum bands with their attributes such as bandwidth, frequency range and quality of service parameters.

The process of auctioning involves R rounds whereby bidders simultaneously submit their sealed bids for the spectrum bands they wish to purchase. In each round r, bidder i submits bids denoted by $B_{ij}^{(r)}$ for spectrum band s_j.

After every round, the auctioneer assesses all the tenders and using predefined principles and standards makes decisions concerning who will be awarded with spectrum bands. The allocation outcome is represented by an allocation matrix $A^{(r)}$, where $A_{ij}^{(r)} = 1$ indicates that bidder i is allocated spectrum band s_j in round r, and $A_{ij}^{(r)} = 0$ otherwise.

The auctioneer applies the pricing mechanism to establish clearing prices for each spectrum band basing on the bids submitted. Let $p_j^{(r)}$ denote the clearing price for spectrum band s_j in round r.

Bidders aim at maximizing utility by acquiring spectrum bands at lower prices than their valuations. The utility $U_i^{(r)}$ of bidder i in round r is calculated as:

$$U_i^{(r)} = \sum_{j=1}^{m} (v_{ij}^{(r)} - p_j^{(r)}) \cdot A_{ij}^{(r)}$$

where $v_{ij}^{(r)}$ represents the valuation of bidder i for spectrum band s_j.

For R rounds, this auction process continues whereas the clearing prices are adjusted according to bids received in each round by an auctioneer. Bidders can revise their bids in future rounds based on bidding war and outcomes from previous rounds.

The aim of simultaneous multiple rounds auction is to give spectrum bands to bidders in such a way that serves social welfare at maximum level, encourages efficient use of spectrum and makes sure that resources are allocated fairly as well as transparently.

This system model offers a systematic approach for assessing the effectiveness and efficiency of the simultaneous multi-round auction mechanism for spectrum trading in 6G networks. It includes major aspects like bidding, allocation, pricing and utility computation mechanisms which help one to understand how the auction works in a holistic manner.

TABLE I: Parameter Description

Symbol	Description
N	Total number of bidders participating in the auction
m	Total number of spectrum bands available for auction
R	Number of auction rounds
S	Set of spectrum bands
$B_{ij}^{(r)}$	Bid of bidder i for spectrum band s_j in round r
$A^{(r)}$	Allocation matrix indicating bidder-band allocations in round r
$p_j^{(r)}$	Clearing price for spectrum band s_j in round r
$U_i^{(r)}$	Utility of bidder i in round r
$v_{ij}^{(r)}$	Valuation of bidder i for spectrum band s_j in round r

Algorithm 1 Adjust Bids

function ADJUST_BIDS(P, S)
  for each participant p_i in P **do**
    Display p_i's name and remaining budget
    Display existing bids for p_i
    for each resource s_j in S **do**
      if s_j is in p_i's bids **then**
        Prompt user for new bid price $B_{ij}^{(r)}$ for s_j
        if $B_{ij}^{(r)}$ is valid **then**
          place_bid(p_i, s_j, $B_{ij}^{(r)}$)
        end if
      else
        Prompt user for bid price $B_{ij}^{(r)}$ for s_j
        if $B_{ij}^{(r)}$ is valid **then**
          place_bid(p_i, s_j, $B_{ij}^{(r)}$)
        end if
      end if
    end for
  end for
end function=0

IV. Proposed Mechanism

DSASMRA, a proposed mechanism, is referred to as Dynamic Spectrum Allocation with Simultaneous Multi-Round Auction. In the context of 6G networks, it offers a holistic approach to spectrum allocation. Starting at initialization phase wherein major parameters including total bidders (N), spectrum bands (m) and auction rounds (R) are set. Furthermore, a subset S of bands for which each has attributes such as bandwidth, frequency range and quality of service parameters is built. Participants, including Vertical Sector Players and Mobile Network Operators, are initialized along with the spectrum resources.

A. Detailing of DSASMRA

The Adjust Bids algorithm is used to manage bid adjustments for each participant based upon spectrum resource availability. This is done by iterating through the participant set P and allowing bid adjustments over all available spectrum resources, S. The algorithm then displays the names of participants, p_i (remaining budget), and previous bids. For each spectrum resource s_j, it checks if there was a prior bid made by the participant. If so, they are asked to submit new bid prices $B_{ij}^{(r)}$. The `place_bid` function updates valid bids if any, else prompts a bidding process for any resource with no bids. This iterative process allows participants to carefully review their respective bidding tactics across available resources and hence improve these auction strategies.

The algorithm assesses whether participants have converged by comparing their previous bids with their present ones. It verifies that the number of participants in the last bid matches the current one and scrutinizes individual names along with their earlier bidding data. Current bidding information is then compared with previous bids for each participant. Any discrepancies suggesting bid changes indicate a lack of convergence. However, if all participants place similar prices on their commodities, indicating mutual agreement, the algorithm returns True.

The Allocation Algorithm for Resources organizes the distribution of spectrum resources based on participant bids. It

Algorithm 2 Checking Convergence

function CHECK_CONVERGENCE($prev\_bids, curr\_bids$)
  if length of $prev\_bids$ is not equal to length of $curr\_bids$ **then**
    return False
  end if
  for each participant name $participant\_name$ and previous bid data $prev\_bid\_data$ in $prev\_bids$ **do**
    curr_bid_data ← $curr\_bids$ for $participant\_name$
    if curr_bid_data is None or $prev\_bid\_data$ is not equal to $curr\_bid\_data$ **then**
      return False
    end if
  end for
  return True
end function=0

Algorithm 3 Allocate Resources

function ALLOCATE_RESOURCES($participants, resources$)
  for each resource s_j in $resources$ **do**
    winner ← None
    winning_bid ← None
    for each participant p_i in $participants$ **do**
      if s_j is in p_i's bids **then**
        total_bid ← p_i's bid for s_j
        if winning_bid is None or total_bid > winning_bid **then**
          winner ← p_i
          winning_bid ← total_bid
        end if
      end if
    end for
    if winner is not None **then**
      Display resource s_j
      Display winner's name
      Display winning bid price
    end if
  end for
end function=0

Algorithm 4 Main Function

function MAIN
  Initialize resources S
  Initialize participants P
  Display base prices for each resource
  for each participant p_i in P **do**
    Prompt user for participant p_i's name and budget
    for each resource s_j in S **do**
      Prompt user for bid price $B_{ij}^{(r)}$ for resource s_j
      if $B_{ij}^{(r)}$ is valid **then**
        PLACE_BID(p_i, s_j, $B_{ij}^{(r)}$)
      end if
    end for
  end for
  Initialize R to 0
  while not converged **do**
    $R \leftarrow R + 1$
    Adjust bids P, S
    Allocate resources P, S
    if convergence reached **then**
      Stop iterations
    end if
  end while
end function=0

iterates through each resource in set S and assigns a winner to each. For every s_j, it initializes variables to track the winning participant and their bid price. Then, it examines each participant in P to determine if they have bid for this resource. A new winner emerges if a bidder has submitted a higher bid than the current highest one. Once all participants are evaluated for a resource, the algorithm presents the winning participant's name alongside the resource's name and value. This methodical approach ensures efficiency and fairness in allocating spectrum resources, catering to participants' preferences.

Initially, it sets up the resources at hand and participants themselves. These are required to input their names and budgets, relevant along with bidding prices on each resource. This makes sure that the system starts with the initial data needed to move forward.

After that, an algorithm is employed to make multiple auctions until they come to a stop. In each round, bids have been changed and then resources allocated. Also, adjusting bids allows participants to change their strategies when auction dynamics keep changing. At the same time, resource allocation seeks for maximum utilization of available spectrum bands taking into account both bids and preferences of participants.

B. Time Complexity

The auction mechanism's time complexity analysis involves three primary functions: adjusting bids, checking convergence, and allocating resources.

When adjusting bids, the function iterates over participants and resources. This involves nested loops, with each participant prompted to adjust their bids for each resource. Consequently, the time complexity is $O(P \times R)$, where P is the number of participants and R is the number of resources.

In the check_convergence function, the bids of each participant are compared, requiring a linear iteration over the participants. Thus, the time complexity is $O(P)$, directly proportional to the number of participants (P).

The allocate_resources function iterates over each resource, checking bids from participants to determine the winner. In the worst-case scenario, each participant bids for every resource, resulting in a time complexity of $O(P \times R)$, where P is the number of participants and R is the number of resources.

Overall, considering the dominant factor of adjusting bids, the time complexity of the auction mechanism is $O(P \times R)$, reflecting the primary operations involved in adjusting bids, checking convergence, and allocating resources.

V. Simulation

To prepare the environment for running the DSASMRA algorithm code, start by confirming the presence of Python on your system. Install required Python libraries like ‘random‘ and ‘matplotlib‘ using pip. Select a suitable code editor or IDE, and consider Google Colab for a cloud-based alternative. Organize input data, including spectrum band features and participant information. Following these steps enables smooth execution of the DSASMRA algorithm code and facilitates simulation of spectrum allocation in a 6G network.

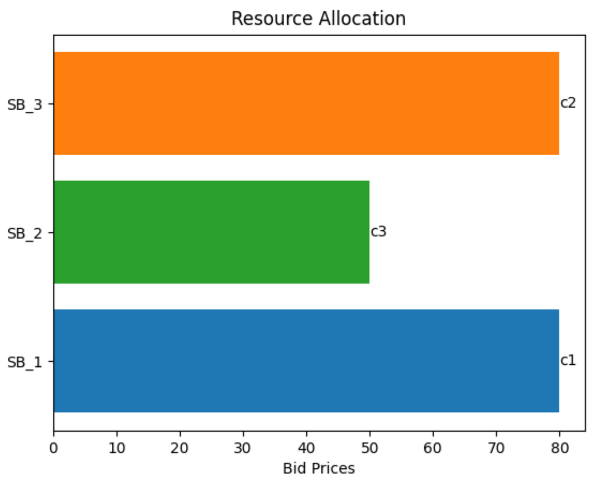

Fig. 2: Resource Allocation

A. Resource Allocation of VSPs

In the spectrum allocation process, MNOs distribute resources among Vertical Sector Players (VSPs) through competitive auctions. VSPs submit bids reflecting their valuation for spectrum bands, and the highest bidder secures the allocation. This iterative process ensures efficient resource utilization and equitable competition among VSPs, as determined by the equation:

$$\text{Winner} = \underset{i}{\text{argmax}} \left(\sum_{j=1}^{m} B_{ij}^{(r)} \right)$$

where $B_{ij}^{(r)}$ denotes the bid of VSP i for spectrum band j in round r, and m represents the total number of spectrum bands available for allocation.

B. Spectrum Utilization

This depicts the cumulative bids placed by participants across various frequency ranges within the spectrum band. Each bar represents the total bid amount for a specific frequency range, providing insights into the overall demand for spectrum resources across different frequency bands.

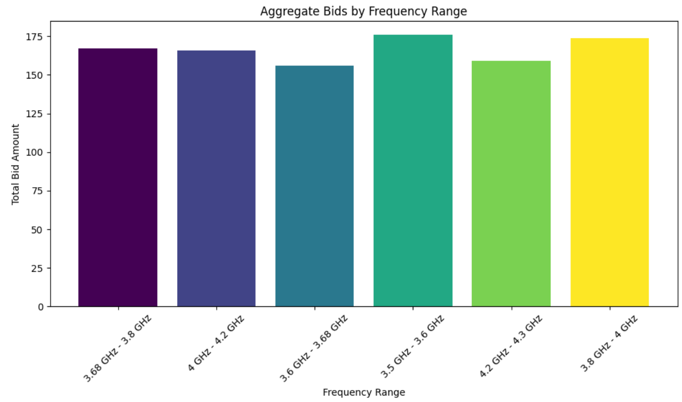

Fig. 3: Aggregate Bids by Frequency Range

In the simulated scenario, participants with assigned budgets have placed bids for different sub-bands based on their valuation of the spectrum resources and budget constraints. Through iterative bid adjustments, convergence is achieved, leading to the final allocation results.

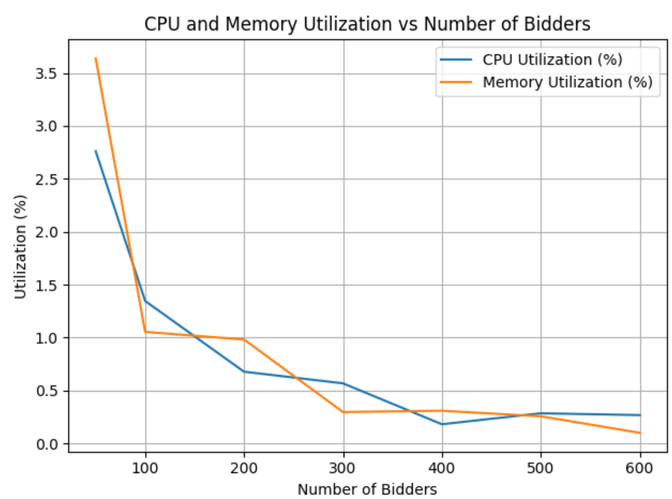

Fig. 4: Utilization by No. of Bidders

C. CPU and Memory Utilization

The Simultaneous Multiple Round Auction (SMRA) impacts CPU usage with increasing bid processing complexity over multiple rounds. Memory utilization is essential for storing bid matrices, allocation data, and bidder utility values. Effective resource management strategies are crucial for optimizing both CPU and memory usage. SMRA principles, inspired by auction theory, guide bid evaluation and allocation determination. As more bidders and spectrum bands join, CPU demands may escalate, necessitating efficient computational handling. Transparency and fairness in spectrum allocation rely on well-managed memory structures. Paul Milgrom’s auction theory contributions influence SMRA’s design and implementation. Balancing CPU and memory utilization is key to maintaining auction efficiency. Optimal resource management ensures equitable outcomes amidst increasing auction complexity. Fairness and transparency are upheld through efficient CPU and memory handling in the SMRA mechanism.

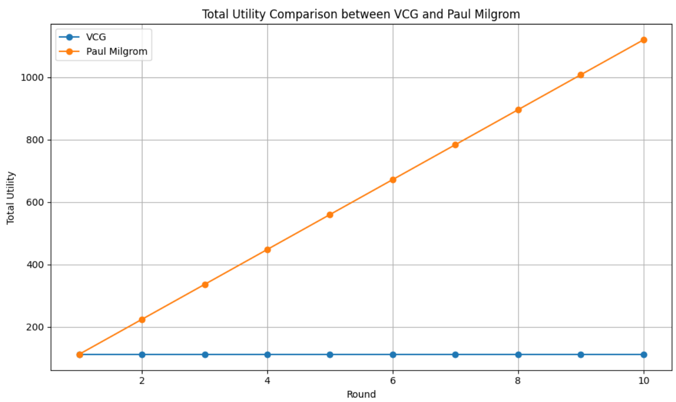

Fig. 5: Utilization by No. of Bidders

D. Comparison of Utility Calculation

In both the VCG mechanism and Paul Milgrom's auction theory, bidder utility is calculated by subtracting the clearing price from their valuation for each allocated spectrum band. This reflects the difference between the perceived value of the spectrum and the price paid. In the VCG mechanism, this utility calculation captures the bidder's influence on final prices through their bids, expressed as:

$$U_i^{(r)} = \sum_{j=1}^{m} (v_{ij}^{(r)} - p_j^{(r)}) \cdot A_{ij}^{(r)}$$

Similarly, Paul Milgrom's auction theory employs a comparable formula for bidder utility. However, Milgrom's iterative approach allows for utility calculations across multiple auction rounds, accommodating changes in valuations and prices over time. This iterative process empowers bidders to adjust strategies based on past outcomes, potentially affecting their utility in subsequent rounds. Thus, while both mechanisms aim to optimize bidder utility through efficient spectrum allocation, Milgrom's iterative approach introduces dynamic adjustments that can influence bidder utility over successive rounds.

VI. Conclusion

In this work, we have proposed a new model for spectrum trade in 6G networks through use of simultaneous multi-round bidding (SMRAs) to allocate the spectrum resources efficiently. Our method tackles the unique challenges imposed by 6G spectrum assignment, including dynamic sharing of radio resource, heterogeneous user demands and regulatory constraints.

We have shown that our developed SMRA framework is effective in enhancing spectrum efficiency; it generates revenue, ensures fairness and enforces proper resource allocation through systematic analysis and evaluation. The proposed approach utilizes concepts from game theory, spectrum management and auction design to develop a robust mechanism capable of accommodating needs of different 6G applications effectively.

Simulation studies and an analytical modeling done in this study give important implications related to network dynamics, user satisfaction and regulatory policy about the consequences of our proposed mechanism. Consequently, our findings provide the basis for scalable; adaptive; efficient systems for trading spectrums that can drive wireless communication through the next decade towards more advanced years.

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