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T-BLAST: Token-Based Leveraging of Autonomous Spectrum Trading

Maninder Pal Singh*, William Bjorndahl*, Gagangeet Singh Aujla†, and Joseph Camp*
*Electrical and Computer Engineering Department, Southern Methodist University, Dallas, USA
†Department of Computer Science, Durham University, United Kingdom
Email: {maninderpals, wbjorndahl, camp}@smu.edu, gagangeet.s.aujla@durham.ac.uk

***Abstract*—In the era of continuously increasing demand for bandwidth and revolutionary wireless technologies, efficient spectrum management is essential. This paper proposes a novel multi-tier tokenization approach for dynamic spectrum management. Leveraging the concept of heterogeneous tokenization of spectrum bands, we develop a decentralized framework based on blockchain technology that enables the sharing of spectrum among users. The spectrum space is represented by multi-planes, the first plane consists of unique spectrum bands converted into NFTs for long-term allocations, while the second plane involves subdividing these NFT spectrum bands for short-term usage by retail users through fungible tokens. The fungible tokens are dynamically traded and mapped using particle swarm optimization (PSO) to manage demand and supply. The paper presents formal models of the involved entities and algorithms for creating multi-tier tokens, dynamic token trading and demand-supply mapping using PSO. To enhance privacy, a zero-knowledge proof (ZKP) based approach is employed for user authentication. The proposed framework offers a secure, transparent, and scalable solution for spectrum management, addressing the limitations of traditional centralized approaches. Simulation results demonstrate the effectiveness of the framework in dynamic spectrum access, while providing privacy-aware and scalable solutions suitable for future wireless networks, including 6G.**

***Index Terms*—Tokens, Smart Contracts, Blockchain, NFT, Spectrum.**

I. Introduction

SPECTRUM is a vital and finite resource for modern wireless communication systems, and its demand has been growing rapidly due to the proliferation of mobile devices, the Internet of Things (IoT), and emerging technologies such as artificial intelligence (AI). As the demand for bandwidth continues to increase, traditional spectrum management approaches, which are largely static and inflexible, are proving to be inadequate in addressing the dynamic nature of spectrum allocation and usage. The static nature of current allocation systems often results in an underutilized spectrum and inefficiencies, especially in high-demand environments, such as dense urban areas. The need for a more agile, efficient, and scalable solution for spectrum management has become more pressing than ever, particularly as we look toward the next generation of wireless networks, including 5G and the upcoming 6G technologies.

Traditional spectrum management mechanisms involve allocating fixed spectrum blocks to licensed users, often on a long-term basis [1]. These rigid approaches fail to accommodate the growing and rapidly shifting demand for spectrum [2]. A significant challenge lies in balancing the allocation of spectrum between commercial, governmental, and private entities, particularly when dealing with diverse and competitive usage patterns [3]. Moreover, the lack of transparency, trust, and coordination among stakeholders further complicates the process, making it difficult to ensure efficient and fair spectrum usage.

To address these issues, this paper introduces a Token-Based Leveraging of Autonomous Spectrum Trading (T-BLAST), a novel, blockchain-based framework for dynamic spectrum management. By leveraging the power of tokenization, T-BLAST facilitates the efficient and flexible sharing of spectrum resources among users, while ensuring transparency, security, and scalability. The T-BLAST framework incorporates two key types of tokens: Non-Fungible Tokens (NFTs) and Fungible Tokens (FTs). NFTs are used to represent unique spectrum bands that can be traded for long-term allocations, while fungible tokens enable the dynamic, short-term trading of spectrum rights. This multi-tier tokenization approach enables both macro-level and micro-level management of spectrum resources, offering a solution that adapts to varying user demands, regulatory requirements, and technological constraints.

T-BLAST operates on a decentralized blockchain platform, ensuring trust, security, and transparency in all transactions. The framework leverages Particle Swarm Optimization (PSO), a metaheuristic algorithm, for dynamically managing the supply and demand of spectrum resources, optimizing resource allocation, and minimizing inefficiencies. Additionally, to preserve user privacy and enhance the integrity of the system, a Zero-Knowledge Proof (ZKP) mechanism is employed for authenticating spectrum users without revealing sensitive information. This approach ensures that the framework remains adaptable to future wireless networks, including the anticipated 6G networks, which are expected to operate in highly dynamic, heterogeneous, and resource-constrained environments.

The primary contributions of this paper are as follows:

- **T-BLAST Framework**: A multi-tier tokenization model for dynamic spectrum management, using both NFTs and FTs for efficient allocation.
- **Blockchain Integration**: Utilization of blockchain to enable secure, transparent, and decentralized spectrum trading.

- **PSO for Demand-Supply Mapping**: Application of Particle Swarm Optimization for dynamic spectrum allocation, improving the scalability and flexibility of spectrum trading.
- **ZKP-based Authentication**: Implementation of Zero-Knowledge Proofs to ensure privacy and enhance the trustworthiness of the system.
- **Scalable Simulation Results**: Validation of the framework's performance through simulations in MATLAB, showing its effectiveness in managing spectrum resources at scale.

The paper is organized as follows: In Section III, we present the system model that underpins the T-BLAST framework, including the tokenization approach and the blockchain-based architecture. Section IV outlines the proposed techniques for dynamic spectrum trading, token creation, and optimization using PSO. In Section V, we describe the experimental validation of the framework, showcasing its scalability and real-time performance. Finally, in Section VI, we conclude the paper and discuss potential future work in the field of tokenized spectrum management.

As wireless technologies continue to evolve, the importance of flexible, scalable, and efficient spectrum management will only increase. The T-BLAST framework provides a robust solution to these challenges, paving the way for a new era of dynamic, blockchain-powered spectrum management that is both privacy-preserving and adaptable to the needs of next-generation wireless networks.

II. Related Work

Integrating blockchain technology into spectrum management can address some limitations of traditional spectrum allocation systems. Traditionally, spectrum management has relied on centralized regulatory bodies that assign fixed frequency bands to specific users or services, leading to inefficient utilization as some bands remain underused while others face congestion. However, blockchain technology enables dynamic spectrum sharing through smart contracts, automated compliance verification, and real-time trading between users, creating a more efficient and transparent marketplace for spectrum resources. The development of blockchain-based solutions for spectrum management has been explored by many researchers through various approaches [4]–[6]. Work in [7] explores the benefits and limitations of a blockchain approach to radio spectrum management in four cases: primary cooperative sharing, secondary cooperative sharing, secondary non-cooperative sharing, and primary non-cooperative sharing.

Digital tokens, both fungible and non-fungible [8], present novel mechanisms for spectrum trading and management. Work completed in [9] uses NFTs to authenticate ownership of spectrum bands and employs permission tokens for granular sharing among primary and secondary users. This framework addresses challenges such as fraudulent activities and inefficient resource utilization. In [10], a spectrum securitization model for dynamic spectrum sharing in 6G networks, which

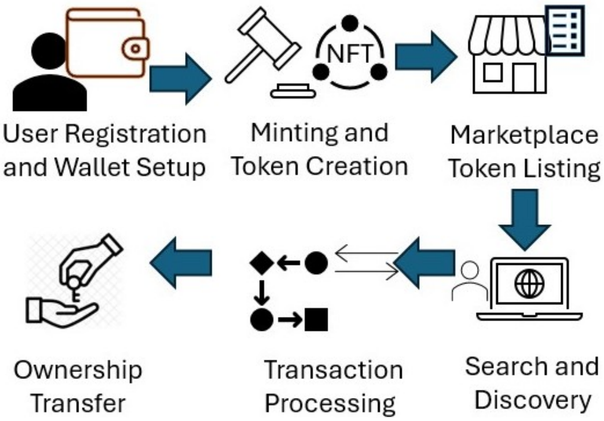

Fig. 1. Spectrum trading using tokens

leverages NFTs and FTs based on the ERC-404 and ERC-4907 standards, is introduced. By integrating FTs for fractional ownership and NFTs for representing specific spectrum resources, the model enhances spectrum liquidity, incentivizes primary users to share spectrum, and enables temporary usage rights through a transparent leasing mechanism. While some approaches [11] have explored multichain architecture for spectrum trading, micro-management at the sub-block level is still an area to be further investigated.

FTs have properties of being identical, interchangeable, and of equal face value, and they have the capability of being subdivided (e.g., Bitcoin) [12]. In contrast, NFTs have unique individual characteristics and attributes but cannot be subdivided. While a few works [13]–[15] have used NFTs for spectrum management, the application of both FTs and NFTs in a unified framework to overcome their individual limitations remains relatively unexplored.

The conceptualization of using tokens for spectrum trading is visualized in Fig. 1. Motivated by the idea of using a token-based system to efficiently manage spectrum allocation, this paper explores the possible ways in which the blockchain can be used to deal with the issues of the current system.

Integrating NFTs and FTs for spectrum management presents several key challenges that need to be addressed before such a framework can be deployed:

Implementation Complexity: Developing sophisticated smart contracts and blockchain infrastructure for seamless interaction between NFT and FT tokens [16].

Security & Resilience: Ensuring system security and protection against misuse, particularly with regard to oracle vulnerabilities in blockchain-based frameworks.

Governance: Establishing the rights and rules for controlling and managing the framework through appropriate models.

Legacy Integration: Integrating new capabilities with existing spectrum licensing systems, as an immediate and complete transition is not feasible.

Market Balance: Finding a balance between revenue generation through auctions and ensuring unbiased service access.

Based on the literature study and identified gaps, a multi-tier tokenization-based approach for dynamic spectrum management emerges as a promising direction for research. Our proposed T-BLAST framework offers multiple advancements over existing approaches. While prior works such as [9], [10] have explored the use of NFTs or a combination of NFTs and FTs, T-BLAST introduces a multi-tier tokenization approach that addresses both macro- and micro-level spectrum management. Furthermore, unlike existing solutions that focus on ownership verification [13] or trading mechanisms [15], our proposed framework integrates a particle swarm optimization (PSO) based dynamic allocation with a zero-knowledge proof authentication to create a more efficient and privacy-preserving ecosystem. While multichain architectures such as [11] have addressed spectrum trading at a high level, T-BLAST provides a dual-marketplace structure that enables both long-term spectrum rights management through NFTs and dynamic, short-term spectrum allocation through FTs. This multi-token approach combined with PSO for demand-supply mapping and ZKP for user authentication presents a comprehensive solution for the current challenges of spectrum management compared to other blockchain-based approaches.

III. Spectrum Space Tokenization Model: A Multi-Tier Approach

The proposed multi-tier tokenization framework is visualized in Fig. 2 where the spectrum space is considered as a multi-plane system. As depicted, NFTs represent the individual spectrum blocks that are purchased by telecommunications companies and the plane for fungible tokens represents the subdivision of bandwidth among different users in that range. To better describe the framework, the formal model of involved entities is presented as follows.

Regulatory Authority ($\mathcal{R}a$) is the entity responsible for setting the rules and guidelines for spectrum allocation and management. In this framework, the $\mathcal{R}a$ generates NFTs for the various spectrum blocks. The terms and conditions along with validity and other legal policies are implemented in the form of a smart contract that ensures the buyer adheres to the regulations. $\mathcal{R}a$ is represented in (1).

$$\mathcal{R}a = f(P, C, M, A) \tag{1}$$

where the policies (P) are the rules and guidelines established by $\mathcal{R}a$, and they are represented by (2). The process of the regulatory authority is represented by the function g.

$$P = g(L, T, E, S) \tag{2}$$

where, L represents legal requirements, T technical standards, E economic standards, and S is the social impact of policies like accessibility and public welfare. In this work, g is defined as the weighted sum of L, T, E, S for their relative importance, as presented as in (3)

$$g(L, T, E, S) = w_L \cdot L + w_T \cdot T + w_E \cdot E + w_S \cdot S \tag{3}$$

Further, C in (1) represents compliance, which is defined using function h in (4).

$$C = h(V, R, I, P) \tag{4}$$

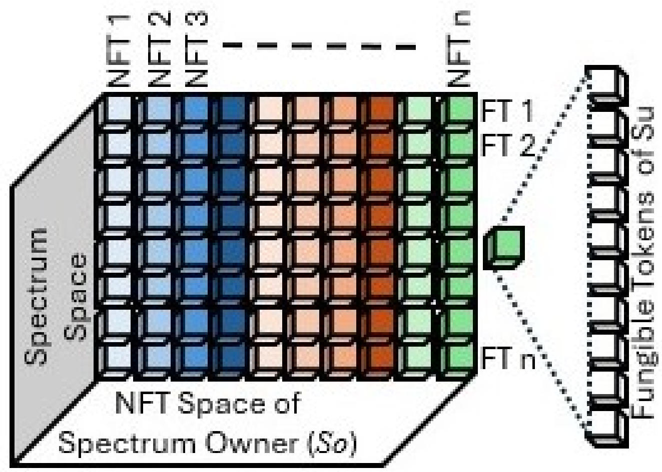

Fig. 2. Multi-tier tokenization of spectrum space

where, V represents verification processes, R represents reporting mechanisms, I represents inspections and audits, and P represents penalties and enforcement actions. These mechanisms are enforced through smart contracts for better transparency. Function h is defined as weighted sums as in (5) for the relative importance of mechanisms.

$$h(V, R, I, P) = w_V \cdot V + w_R \cdot R + w_I \cdot I + w_P \cdot P \tag{5}$$

Moreover, in (1), M is for monitoring the actions and is defined as in (6) using function k.

$$M = k(D, A, F, R) \tag{6}$$

where D represents data collection, A represents analysis, F represents the frequency of monitoring, and R represents reporting and feedback. The k is defined as a function that integrates these factors as a weighted sum presented in (7).

$$k(D, A, F, R) = w_D \cdot D + w_A \cdot A + w_F \cdot F + w_R \cdot R \tag{7}$$

The final parameter in the definition of $\mathcal{R}a$ in (1) is the approval process (A) defined as in (8).

$$A = m(R, E, C, T) \tag{8}$$

where, R is regulatory compliance, which ensures that the spectrum allocation or transaction adheres to all relevant laws and regulations. E represents economic viability, used for assessing the economic benefits and sustainability of the allocation or transaction. C represents capacity and technical feasibility based on the evaluation of whether the technical requirements and capacity needs are met. T is timeliness prioritized timing and urgency of the approval process. The function m is defined in (9) as weighted sums.

$$m(R, E, C, T) = w_R \cdot R + w_E \cdot E + w_C \cdot C + w_T \cdot T \tag{9}$$

These weights determine the relative importance of each factor in the approval process. The sum of the weights should ideally be 1 i.e., ($w_R + w_E + w_C + w_T = 1$) to ensure a balanced approach.

Spectrum Owner ($\mathcal{S}o$) are the entities like telecoms companies, broadcasters that hold the rights to specific spectrum bands through the spectrum band NFT they got from $\mathcal{R}a$. They tokenize their band using fungible tokens to further allocate and sublease the spectrum band. $\mathcal{S}o$ has three functional modules, *ownership rights* ($\mathfrak{R}$) (rights to specific spectrum bands), *tokenization process*($\mathfrak{T}$) (process of converting spectrum rights into fungible tokens) and *value of spectrum* ($\mathfrak{V}$) (economic value of the spectrum bands). Mathematically it can be defined as a in (10).

$$S_o = n(\mathfrak{R}, \mathfrak{T}, \mathfrak{V}) \tag{10}$$

Spectrum Users ($\mathcal{S}u$) purchases or leases spectrum from $\mathcal{S}o$ using fungible tokens. $\mathcal{S}u$ is represented in (11).

$$\mathcal{S}u = p(d, t, u) \tag{11}$$

The key aspects of spectrum user are demand (d) for fungible tokens (bandwidth required by user), transaction (t) is the purchase parameter of fungible tokens for completion of d, and usage (u) is the parameter specifying the quantified period of extent for completion of d.

Tokenomics Marketplace One of the fundamental components of this framework is the functionality related to tokenomics. In the system two different levels of tokenization are used, hence, the marketplace has two other parts to represent the logistics required by each case. As the two have their individual functionalities in terms of how the fungible tokens and non-fungible tokens differ from one another, they have some similarities/commonalities as discussed in table I:

NFT marketplace is the level 1 marketplace, where we have the tokenomics activities between the $\mathcal{R}a$ and $\mathcal{S}o$. The activities are:

- NFT creation ($\mathfrak{C}$): is the process that involves the minting and creation of the NFT. $\mathcal{R}a$ does the NFt creation as in (12)

$$\mathfrak{C}(\mathcal{R}a, S_b) = NFT(\mathcal{R}a, S_b, \mathfrak{M}) \tag{12}$$

  where S_b is the spectrum block (bandwidth, frequency range), and $\mathfrak{M}$ is related metadata.
- Listing ($\mathfrak{L}$): The NFT created through $\mathfrak{C}$ are listed for auction and bidding processes.

TABLE I
DIFFERENCES BETWEEN LEVEL 1 NFT MARKETPLACE AND LEVEL 2 FT MARKETPLACE

Feature	Level 1 NFT Marketplace	Level 2 FT Marketplace
Token Type	NFTs for unique spectrum rights	FTs for divisible and interchangeable spectrum rights
Transaction Mechanism	Unique NFTs	Fungible tokens
Market Dynamics	Scarcity and uniqueness	Utility and liquidity
Order Matching	Direct sales/ auctions	Bulk trading fungible tokens
User Interaction	Unique listings and bids on individual NFTs	Order books and trade fungible tokens in bulk

- NFT Transactions ($\mathfrak{T}x$): The $\mathfrak{T}x$ comprise of the operations for validation of transactions including transfer, payment verification as in 13.

$$\mathfrak{T}(\mathcal{S}o, NFT) = \begin{cases} \text{Transfer} & \text{If verified} \\ \text{Revert} & \text{Not Verified} \end{cases} \tag{13}$$

- Ownership Transfers ($\mathfrak{O}t$): Once the transactions are verified, the final step that the marketplace needs to ensure in completing $\mathfrak{T}$ is $\mathfrak{O}t$

$$\mathfrak{O}t(\text{NFT}, \mathcal{S}o) = \mathfrak{B}c(\text{Update}\mathfrak{O}) \tag{14}$$

  where (NFT) is the spectrum NFT, $\mathfrak{O}$ is the new owner, and $\mathfrak{B}c$ is the blockchain.

Fungible token marketplace is the level 2 marketplace that is operational for $\mathcal{S}o$ and $\mathcal{S}u$. The key components of this marketplace are identical in nomenclature to level 1 NFT marketplace but have different functionalities as follows:

- Fungible Token Creation ($\mathfrak{c}$): $\mathfrak{c}$ are created by the $\mathcal{S}o$ along with the bandwidth (b_i) such that $\mathfrak{c}(\mathcal{S}o, b_i) = \sum_{k=1}^{m} \tau_k$ where τ_k represents the fungible token.
- Listing ($\mathfrak{l}$): The output of $\mathfrak{c}$ is the τ_k fungible tokens that are listed on level 2 marketplace as, $\mathfrak{l}\tau_k \rightarrow \text{Marketplace}\tau_k$
- Transactions Validation ($\mathfrak{t}x$): Once the listing proceeded with the auction and bidding the transaction is processed for validation as in 15.

$$\mathfrak{t}x(\mathcal{S}u, \tau_k) = \begin{cases} \text{Transfer} & \text{if payment is verified} \\ \text{Revert} & \text{if payment not verified} \end{cases} \tag{15}$$

  This status is used for ownership transfer as discussed in the next step.
- Ownership Transfer ($\mathfrak{o}$): Once the $\mathfrak{t}x$ ends in status *Transfer* the $\mathfrak{o}$ is initiated on the $\mathfrak{B}c$ as $\mathfrak{o}(\tau_k, \mathcal{S}o) = \mathfrak{B}c(\text{Update} \rightarrow \mathfrak{o})$

Based on this system model, the framework has been designed as discussed in the following section.

IV. OPTIMIZING SPECTRUM UTILIZATION WITH NFTS AND DYNAMIC TOKENIZATION

The proposed ecosystem outlines a novel method for managing the spectrum using non-fungible tokens (NFTs) and fungible tokens. By allocating spectrum blocks to the highest bidder on a long-term basis through NFTs, and subsequently creating sub-blocks within each spectrum block using fungible tokens, we aim to optimize spectrum utilization and streamline the allocation process.

Non-Fungible Tokens for Spectrum Block Allocation: Non-fungible tokens (NFTs) will be employed to represent unique spectrum blocks. Each NFT can encapsulate specific details about the spectrum block, including its frequency range, geographic area, and usage rights. These NFTs can be auctioned to the highest bidders, ensuring that spectrum is allocated efficiently and transparently to those who value it most. The long-term nature of these allocations provides stability and encourages investment in infrastructure and technology. In this work the ERC-721 [17] NFT standard is used for the creation and management of the NFT.

Fungible Tokens for Sub-Block Spectrum Management: Within each NFT-represented spectrum block, the ecosystem introduces fungible tokens to create and manage sub-blocks. These fungible tokens represent divisible units of spectrum within the larger block, allowing for flexible and dynamic allocation. This approach enables spectrum holders to lease, trade, or subdivide their spectrum holdings efficiently, fostering a more dynamic and responsive spectrum marketplace. This process is a sequence of actions that must be performed to establish. Each token produced has a unique identity and is system-wide uniquely distinguishable using the tokenId field which is a uint256 data type.

Creating NFT for Spectrum Blocks: When a specific frequency range is allocated to a spectrum holder through NFT bidding and allocation mechanism implemented through the smart contract for the necessary regulatory procedures for this block, it is subdivided and auctioned further as identical tokens. The ERC-721 NFT as discussed in the above section, is used for minting of tokens for the spectrum block sold by $\mathfrak{R}a$ to So.

Algorithm 1 Smart Contract for Spectrum NFTs

Initialize Contract
$O \leftarrow msg.sender$
$T_s \leftarrow 0$
$mint\_Spectrum\_NFT(F_r,\ G_a,\ O_n)$
if $msg.sender \neq O$ **then**
  throw ”Not Authorized to Mint”
end if
$T_s \leftarrow T_s + 1$
$S_b \leftarrow S_b(T_s, F_r, G_a, O_n)$
$S_b[T_s] \leftarrow S_b$
emit Minted(T_s, O_n, F_r, G_a)
$transfer\_Ownership(id,\ O_n)$
if $S_b[id].O \neq msg.sender$ **then**
  throw ”Not Authorized to Transfer”
end if
$S_b[id].O \leftarrow O_n$
get_$S_b[id]$
return $S_b[id]$

In the algorithm for the minting process and ownership transfer for user rights, notations used are as follows: frequency range (F_r), geographic area (G_a), new owner (O_n), owner (O), total supply (T_s) and spectrum block (S_b).

Dynamic Spectrum Allocation: Optimization of spectrum usage is achieved through various techniques at various levels like dynamic spectrum allocation (DSA), spectrum sensing and cognitive radio, spectrum sharing, etc. DSA is of particular interest for this work as DSA-related functionalities can be implemented and achieved efficiently using smart contracts. For DSA the key entities at the level of fungible tokens are $\mathcal{S}o$, $\mathcal{S}u$, and DSA. Where $\mathcal{S}o$, $\mathcal{S}u$ are defined in the system model, and DSA is the mechanism that allows the spectrum to be allocated dynamically based on real-time conditions. The interaction flow with DSA includes the following steps:

- *Tokenization by Spectrum Owners:* The So tokenize their spectrum holdings into spectrum holdings and these are offered to the users through a web3 marketplace for tokens.
- *Demand and Usage by Spectrum Users:* Su expresses d for spectrum and engage in t to acquire the necessary tokens. Once the tokens are acquired, Su utilizes the spectrum u based on needs.
- *Dynamic Allocation Mechanism:* The DSA system continuously monitors spectrum usage and availability and reallocates spectrum dynamically to ensure optimal utilization. It can be defined as in (16), where A represents the allocation algorithm that dynamically reallocates spectrum based on real-time data and is presented in algorithm 2.

$$DSA = f(S_o, S_u, A) \tag{16}$$

Algorithm 2 Fungible Token Based Dynamic Spectrum Allocation Algorithm

Input: Su, d, p, A_v
Output: Allocation of Su
for $i = 1$ **to** n **do**
  Sort user priorities
  $\forall u \in Su,\ p \in P$
  $Su = u_1, u_2, \ldots, u_n \& P = p_1, p_2, \ldots, p_n$
  $Su' = u_i \mid p_i \geq p_j$ for all $j \neq i$
end for
for u_i in Su' **do**
  if $d_i \in A_v$ **then**
    Allocate: $d_i \mapsto u_i$
    Call: Algorithm 3
    Update: $A_v = A_v - d_i$
  else
    Allocate partial available spectrum to u_i
    $d_i' = \min(d_i, A_v)$
    Mark $u_i \to Starving - List$
    Update A_v: $A_v = A_v - d_i'$
  end if
  Record: $d_i \mapsto u_i \in A_v$
end for
for $u_i \in Starving - List$ **do**
  if $t \to u_i \in Starving - List \leq th_t$ **then**
    Set: $p = p_{top}$
  else
    Starvation Alert
  end if
end for

where A_v is the list of available spectrum band fungible tokens, Su' is the sorted list of spectrum users where (u_i) has the highest priority (p_i), followed by the next highest. th_t is the threshold time that is the acceptable time to maintain QoS. After the th_t the user will experience compromised QoS.

This algorithm for token-based dynamic spectrum allocation further uses a metaheuristic approach known as particle swarm optimization (PSO) for optimizing the allocations. In computational science, the PSO is used to iteratively optimize the solution known as the candidate solution also referred to as particles. The search space is explored by particles based on their position (x_i) and velocity (v_i). The algorithm is presented as in algorithm 3.

In this algorithm position of each particle ($\mathbf{x}_i$) represents the allocation of spectrum tokens to Su. If there are (n) Su and (m) spectrum bands (fungible tokens), the position vector length is n, such that each element (x_{ij}) represents the number of fungible tokens allocated to Su (i) from band (j). The fitness function ($f(\mathbf{x}i)$) is designed to balance objectives as $f(\mathbf{x}_i) = \alpha \cdot \frac{\sum j=1^n xij}{A_v} - \beta \cdot \sum_{k\neq i} \sum_{j=1}^{n} \text{overlap}(x_{ij}, x_{kj}) + \gamma \cdot \frac{\left(\sum_{j=1}^{n} x_{ij}\right)^2}{n \cdot \sum_{j=1}^{n} x_{ij}^2}$. Where, α is the utilization weight for the effectiveness of the used spectrum, β is the interference weight to measure the level of interference between users and γ is the measure of how fairly the spectrum is distributed among Su. By optimizing this fitness function, the algorithm aims to achieve an efficient, interference-free, and fair allocation of spectrum resources. Also to measure and minimize interference between users *overlap* is designed with negative weights so that the algorithm is penalized if its allocation causes interference. Global best (gb) is the current value of an optimized function, gb' is the change in global best, thr for change in gb', and particles prt.

Algorithm 3 Fungible Token Mapping using Particle Swarm Optimization

Initialize swarm: $\mathbf{x}_i = random(x_i) \& \mathbf{v}_i = random(v_i)$
Evaluate: $f(\mathbf{x}_i) \forall prt$
while ($itr \leq max\_itr$) & ($gb' > thr$) **do**
  for $prt_i \in 1 \rightarrow prt_{max}$ **do**
    $\mathbf{v}_i \leftarrow \omega \mathbf{v}_i + c_1 r_1 (\mathbf{p}_i - \mathbf{x}_i) + c_2 r_2 (\mathbf{g} - \mathbf{x}_i)$
    $\mathbf{x}_i \leftarrow \mathbf{x}_i + \mathbf{v}_i$
    $\lceil \mathbf{x}_i \rceil$
    Evaluate fitness $f(\mathbf{x}_i)$
    if $f(\mathbf{x}_i) > f(\mathbf{p}_i)$ **then**
      $\mathbf{p}_i \leftarrow \mathbf{x}_i$
    end if
  end for
  Update: $\mathbf{gb}$, if $p_i \mapsto x_i > \mathbf{gb}$
  Update gb'
end while

Zero Knowledge Proof (ZKP) User Authentication: The spectrum users in the framework at the level 2 marketplace are retail users and many. Hence, authenticating them into the ecosystem is important and challenging as the confidentiality of their personal information has to be ensured. Further as suggested in [18] the ZKP-based authentication scheme can prevent possibilities of denial of service attacks. Hence, a knowledge-based approach is used in this work where a derivative of Schnorr Protocol [19] is used to enable the ZKP-based authentication scheme used in the level 2 marketplace as in Fig. 3. It begins with choosing two large prime numbers p and g using these a secret (S) is generated in the range of [1,p-1]. Further, a public key (P) is generated as $P = g^S mod p$. After that, the session is created with a maximum attempts threshold and authentication window. The prover who is a spectrum user, in this case, generates r in the range of 1 o p-2 and computes $A = g^r mod p$. This A is transmitted to the verifier which is level 2 marketplace in this case, generates a challenge (c) by using A as input to a hashing function such that $c \neq 0$. On receiving this c the prover, computes a response (R) as $R = (r + c * S) mod (p-1)$. On receiving this R the verifier computes $A' = g^R * P^(- c)) mod p$ and checks if $A' = A$ is true in which case the authentication is true otherwise the process is halted.

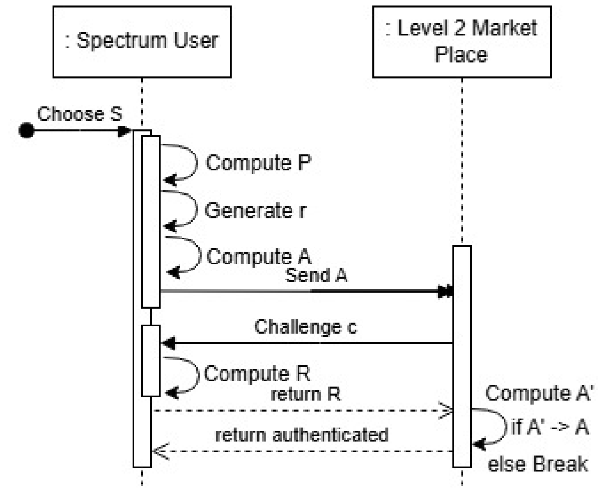

Fig. 3. ZKP Sequence for Level 2 Marketplace Spectrum User Authentication

V. Framework Validation: Performance, Scalability, and Verification

The framework comprises various tools and technologies for the verification and validation of the concepts. To begin with the creation of tokens there are many commercial tools available that act as exchanges through which NFTs can be created and transacted. These commercial platforms have their fee to do the processing related to the creation of NFTs and other related functionalities. One such tool is the Reservoir [20] platform that offers limited capabilities access well suited for testing the deployability of NFTs without incurring additional costs. [20] offers API for easy integration of bidding and auctioning mechanisms needed for the framework to be developed. The scalability testing of the work is performed to test the effect of varying loads on the system. To accomplish this simulations are designed in MATLAB for level 1 and level 2 marketplaces covering, transaction initialization, validation and verification, blockchain simulation and smart contract execution (using Truffle and Ganache), ownership updates, and user notifications of ownership changes. For verification and validation purposes the blockchain and smart contracts are deployed through Truffle [21] and Ganache [22] on a system running Ubuntu as a host operating system. To interact with the Ganache-based Ethereum blockchain with MATLAB marketplace simulation a python script is used as a pipeline component. Further, smart contracts for creating and minting NFTs are developed to facilitate the targeted functionality, along with smart contracts for bidding and auction in the Solidity programming language. Simulation findings for level 1 and level 2 marketplaces for the above-listed combined functions are presented in Fig. 4 and Fig. 5 respectively. The results suggest the framework can scale in real time and show the capabilities of keeping the transaction timings checked. For keeping the cost of deployment in check strategies for developing efficient contracts were used as suggested in [23]. In terms of evaluation with other similar works, in [13] authors have considered the rentable NFTs for spectrum trading using ERC4907 standard for NFT minting. Their work evaluation presents the interfaces for bidding, auction along minting. The auction considers a case of three primary and

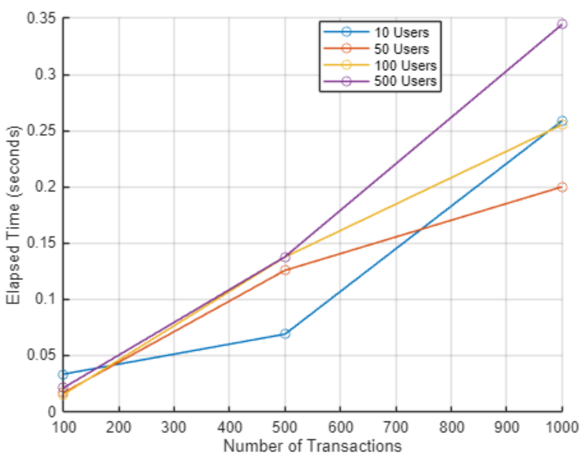

Fig. 4. Level 1 Marketplace Performance Evaluation

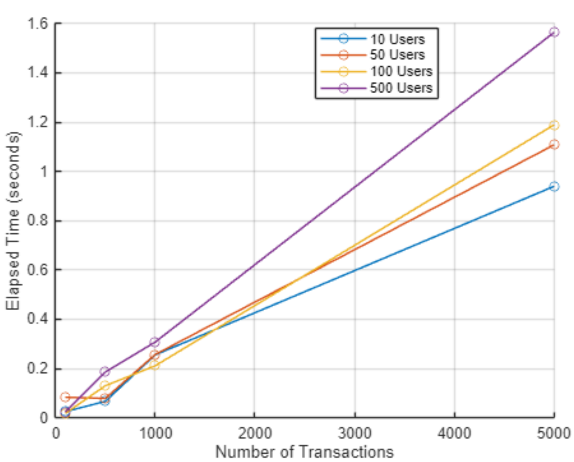

Fig. 5. Level 2 Marketplace Performance Evaluation

secondary users to show the input and output of the interfaces. Meanwhile, in T-BLAST, the evaluation is performed for the scalability of the overall system comparatively at a larger scale. Further, the optimized allocation of fungible spectrum tokens to users is performed through metaheuristic algorithms due to the scalability, flexibility, and efficiency offered by them. In this work, PSO and Genetic algorithm (GA) that belong to the metaheuristic family of algorithms are compared for suitability in the framework. For testing the scalability, flexibility, and efficiency, the convergence of these is observed in the tokenization-based spectrum allocation approach. The findings of the comparison are presented in Fig. 6 where the best fitness value is plotted against the iteration/generation parameter. The experimentation is further analyzed for trends in convergence with respect to the varying particles (ptr) and dimensions (dim) values where ptr $\in$ $[30, 60, 90]$ and dim $\in$ $[2, 5, 10]$. The presented results indicate that PSO outperforms GA and converges better in this case where it is used for the optimization of tokenized spectrum allocations. Another contribution of the work is to ensure the confidentiality of spectrum users for which a ZKP-based approach is designed. On testing the approach for deployability and scalability performance, the findings are presented in Fig. 7. The plot depicts the scale of time complexity of the mechanism based on various starting point values along with scaling for simultaneous requests. The starting point values of p and g are important for the time-bound completion of steps between beginning and completion. The results show the mechanism is integrable with the framework if we consider the amount of overhead in computational time vs the benefits of preserving user privacy.

VI. Conclusion

To conclude, the proposed multi-tier tokenization framework for dynamic spectrum management presents advance-

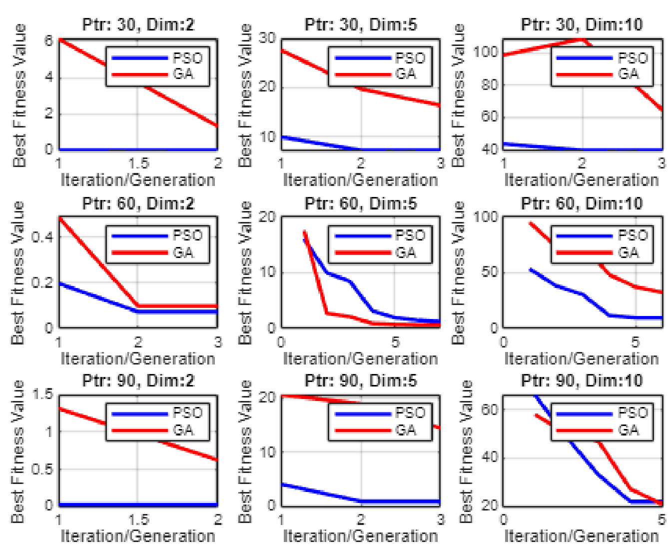

Fig. 6. Convergence of PSO vs GA for Tokenized Spectrum Allocation

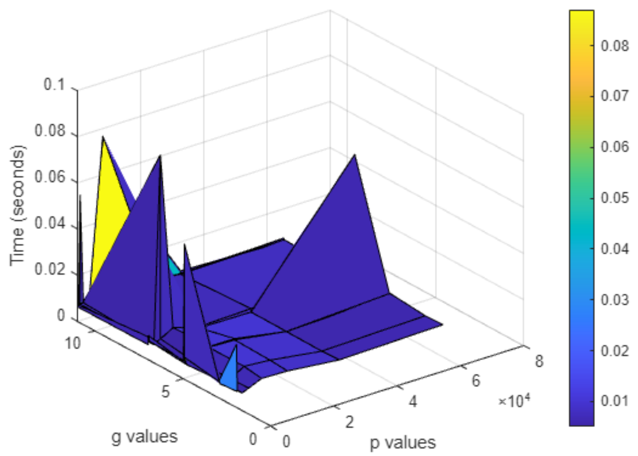

Fig. 7. Scalability Evaluation of ZKP Based Authentication

ment in addressing the challenges of efficient spectrum utilization. Through blockchain and heterogeneous tokenization, the system offers secure and transparent spectrum sharing among spectrum users. The dual-plane approach, involving NFTs for long-term allocations and fungible tokens for short-term usage, ensures flexibility and adaptability in spectrum management. The integration of particle swarm optimization for dynamic trading and zero-knowledge proofs for user authentication further enhances the system's efficiency and privacy. Simulation results validate the framework's effectiveness in optimizing spectrum access and managing demand-supply dynamics. Although the framework shows effectiveness through a test environment, the impact of the underlying blockchain network's transaction throughput has a proportionate impact on the system's performance. Hence, a high transaction throughput blockchain is important for such a solution to be viable.

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