Smart Land Registration in BD: A Blockchain-Based Architecture for Decentralized Land Governance and Secure Registration

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Thesis (CSE 400) submitted in partial fulfillment of the requirements for the degree of

Bachelor of Science in Computer Science and Engineering

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FALL 2025

DECLARATION

Title	Smart Land Registration in BD: A Blockchain Based Architecture for Decentralized Land Governance and Secure Registration
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We declare that this thesis entitled *Smart Land Registration in BD: A Blockchain-Based Architecture for Decentralized Land Governance and Secure Registration* is the result of my own work except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ACKNOWLEDGMENTS

We would like to express our honest thanks to the **Chairman of the Department of Computer Sciences and Engineering** for continuous support and visionary leadership and our educational journey.

Our deepest thanks to all the respected faculty members of the department. His dedication to teaching and mentorship has contributed significantly to the development of our knowledge, skills and professional approaches.

We especially thank our research supervisor and co-supervisor, **Ms. Farhana Akter Sunny** madam and **Mr. Mozdaher Abdul Quader** sir for granting us the opportunity to work under their invaluable guidance. Their insight, inspiration, and continuous encouragement have been instrumental at every stage of this research. It has been a great privilege and honor to work under their supervision.

We are always grateful to **our parents** for our unconditional love, prayer, and unbreakable support. Their victims have provided the basis for our education and personal development.

We also want to acknowledge the contribution of our colleagues from our **research team**, whose collaboration, dedication, and teamwork made the journey smooth and more fun.

Special thanks to our friends and well-wishers for their continuous support, courage, and companionship throughout this research journey. Finally, We extend our heartfelt gratitude to everyone who supported us directly or indirectly in successfully completing this research.

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Dedicated to Almighty Allah-for his endless marcy. Dedicated with love and gratitude to our mothers—our first teachers, quiet strength, and constant inspiration. This work stands as a reflection of everything you gave us.

– *Khondokar Saim*

Dedicated to our loving teachers, whose guidance, patience, and encouragement shaped our learning and inspired this work.

– *Hasnat Zamil Sayad*

With sincere gratitude to our respected teachers and mentors, whose mentorship and dedication inspired us to pursue excellence.

– *Ibrahim Al Rifat*

ABSTRACT

The land administration in Bangladesh is still susceptible to institutional fragmentation, forged documentation, sluggish processing, and ineffective transparency. These problems become more acute in such extensive projects as Purbachal New Town where a paper-based workflow and centralized digital registries cannot necessarily secure, scalable, and accountable governance of the land. This study suggests a decentralized land registration system to be used on the administrative and infrastructural setting in Bangladesh.Its architecture has a hybrid blockchain design: the institutional participation will be permissioned and publicly audited to maintain accountability, and the off-chain storage of documents with the help of the InterPlanetary File System (IPFS). District and sub-registry offices are validator nodes in a peer-to-peer network which forms a single point of failure, enhances the institutional traceability. Online portal that is based on workflow help buyers, sellers and officials in the registry start, verify and process transfers using formalized digital processes. Authentication and non-repudiation are ensured by cryptographic signatures and multi-stage administrative validation whereas immutable blockchain references connect to title document hosted at IPFS to ensure integrity and trackability.One of the key contributions is the Territorial Proof of Authority Consensus Protocol (TPACP), in which the criterion of eligibility of the validators is based on jurisdiction and long-term performance instead of computational power or financial interest. The outcomes of the simulation show that the overhead of message-exchange is lowered by 56.8 percent in comparison with Proof of work. TPACP process transaction times of 132.9 seconds (100 nodes), 433.7 seconds (500 nodes) and 629.0 seconds (1000 nodes) and is faster than PoW and other permissioned baselines such as DPoS, RLSCA and TNCA. In an effort to determine the level of practical deployment cost, the research paper evaluates the Ethereum gas usage in the operations of the core system. The initial deployment cost of smart contracts will have to be 2,930,431 gas units. The latter transactions incur much less gas, and khatian registration, ownership mutation and user identity registration take 818,432, 474, 367, and 204,868 gas units each. These values are converted to cost units between 4,097,360 to 58,608,620 in the gas price of 20 Gwei, which means that the operations can be run at a cost-effective level in spite of the increased overhead cost of initializing the operations.

Keywords: Territorial Proof of Authority, Transaction Processing Velocity, InterPlanetary File System (IPFS), Permissioned Blockchain,Territorial Communication Efficiency, Gas Consumption in Blockchain.

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1. Introduction

1.1 Background of the Study

Land administration systems have been paper-based for centuries. These traditional methods kept a record of property on file in actual registries that were in charge of government offices. The process was slow and prone to errors. Multiple parties had to check each transaction manually [1]. Digital transformation began in the 1980s and also 1990s when computer systems began to substitute paper ledgers. The centralized databases provided faster access to records [2]. They saved physical storage requirements. The move from paper to digital was a very important step in land management evolution. Introduction of the distributed ledger technology in 2009 by Satoshi Nakamoto through Bitcoin introduced a new paradigm [3]. This invention was a demonstration of how transactions could be recorded without the central authorities. The system had cryptographic methods to ensure security [4]. Each transaction was subject to and linked to previously transacted transactions via a chain of blocks. With this breakthrough, options beyond digital currencies were opened up. Blockchain technology was initially developed as a result of the architecture of Bitcoin. This offered a decentralized system in which several parties could keep synchronized records. The technology was based on the use of consensus mechanisms for validating transactions. Cryptographic hashing was based on protecting data from tampering. These features made blockchain appropriate for use in applications that require high trust and transparency of transactions. Early adopters saw the potential of land registry systems [5] for blockchain. Georgia launched a successful test for land titling based on Blockchain in 2016. The system helped in automating the process of transferring properties using smart contracts. It eliminated bureaucratic hurdles and transaction times [6]. The Netherlands Land Registry started a blockchain trial in 2018. Results showed 50% reduction of land transfer processing time. Sweden cut the title registration related to property from four months to a few days using blockchain. Dubai entered a broad initiative of blockchain to modernize the governance of the city. Bangladesh initiated the process of digitization through the Digital Land Management System [7] from 2011 to 2017. The initiative was to convert paper records into electronic formats. It was to reduce the problem of forgery and administrative delays. The Land Management

Automation Project was launched in 2020 to help increase digital services across the nation. These projects brought online applications for mutation and property check. They were steps towards e-governance in the area of land administration.

1.1.1 State of the Art in the Modern Context

Blockchain-based land registry systems are now incorporating many advanced technologies [8]. Smart contracts are used to automate property transactions by following certain rules when certain conditions are met [9]. These self-executing programs eliminate the act of manually verifying. They help to shorten the time of processing from weeks to hours [10]. The InterPlanetary File System is used to store large documents off-chain while storing references on the blockchain. This is an approach that balances the efficiency of storage with the integrity of the data [11]. A hybrid blockchain is a combination of the benefits of the public and private blockchain. Private layers are used to process sensitive information about the transaction. Public layers allow for transparency to verify on. This structure enables organizations to exercise this control without losing accountability [12]. Cryptographic hashing algorithms are used to generate unique digital fingerprints of each block. Any modification of data changes the value of the hash. This makes immediately detectable tampering possible [13]. Digital signatures are used to verify the participants in the land transactions. A pair of cryptographic keys is given for every user. The function of the private key is to sign documents. The public key enables other to check the authenticity [13]. This removes the necessity of reliance on physical signatures and notary. Real-time verifying systems allow for systems to actually check ownership in real time. Buyers and sellers get to know the up-to-date status of the properties through web portal. Government offices are able to validate transactions in minutes rather than days [10]. Consensus mechanisms have come a long way from the Proof of Work. Proof of Stake is based on allocating validators based on their stake in the network. It requires less energy than computational mining. With Delegated Proof Of Stake, the new path introduced various voting systems that involve the stakeholders electing validators. Practical Byzantine Fault Tolerance is suitable for permissioned networks where participating users are considerably known [10]. Reputation-based consensus mechanisms put the trustworthiness of nodes based on historical behavior. These mechanisms reduce the overhead of messages and improve the transaction throughput [8]. Research indicates there are transaction costs that fall to \$0.01 per operation in hybrid blockchain systems. Processing speed is much faster than in classical method. Security is enabled by protection against 51% attacks. Due to the immutable nature of the blockchain, audit trails are created and remain permanent. Regulators and auditors are able to trace the history of transactions efficiently.In terms of fraud detection, it is easier facilitated when any and all changes are permanently recorded [13, 11]. Current systems have a number of challenges. Bangladesh's digital land infrastructure faces the problem of uneven implementation between ministries. More than 75 percent of the land records of Dhaka are in digital format. Different departments have different databases that do not communicate with each other. There is no standard verification system across the agencies. A considerable data breach happened in 2023 in which 50 million personal information were exposed to the world. This incident exposed flaws in centralized storage systems [10]. Technical limitations continue to exist in many parts of the world. Overlapping of boundary data and inconsistency of property identifier leads to confusion. Limited Internet connectivity in rural areas limits access to the system. The officials are simply not willing to adopt new digital processes. Low levels of digital literacy among citizens makes the system less effective. Such issues make it difficult to realize the benefits of digitization [14].

1.1.2 Importance and Relevance of the Topic

Land ownership forms the foundation of economic activity in developing nations. Bangladesh's agricultural sector contributes 12% to national GDP [15]. Millions of families depend on land for their livelihoods. Secure property rights enable individuals to use land as collateral for loans.Clear ownership records facilitate business investments. Economic growth requires reliable systems for property transactions [16]. Fraud and corruption undermine trust in land administration.Over four million land-related cases await resolution in Bangladesh courts.Most disputes involve ownership conflicts and forged documents. Research by Transparency International found 97% of households paid bribes for land registration in Bangladesh. Another 85% paid bribes for ownership mutation processes. These unofficial payments range from 1,000 to 500,000 BDT [17] per transaction. Corruption increases costs for property owners. It delays legitimate transactions.Small landowners face the greatest burdens [18]. Multiple jurisdictions experience similar problems.Kenya's land registries rank among the most corruption-prone government offices. Average bribes reached $65 in 2011. Nearly 58% of people [19]seeking land services received requests for illegal payments. One-third complied with these demands. Such widespread corruption creates high informal costs. It discourages property registration. Unregistered land cannot serve as loan collateral [20]. This limits economic opportunities for owners. Double allocation of land parcels occurs when registration offices lack coordination. The same property gets sold to multiple buyers. Legal battles ensue that last years. Document forgery remains common where verification systems are weak [21]. Fraudulent papers appear authentic without blockchain-based validation. Opaque procedures enable officials to abuse discretionary power. Insider information allows connected parties to acquire valuable properties illegally. Blockchain technology addresses these governance failures through several mechanisms. Immutable ledgers prevent alteration of recorded transactions. Once data enters the blockchain, no single party modifies it [3, 4]. All network participants maintain copies of the complete transaction history. Attempts to change records require consensus from the majority. This makes unauthorized modifications nearly impossible. Transparency increases when transaction details are visible to authorized participants. Buyers verify ownership before transferring funds. Sellers prove legitimate possession through blockchain records.Government agencies access complete property histories. This visibility reduces opportunities for fraud [6]. Trust improves when all parties view the same information. Intermediaries become unnecessary in blockchain systems. Smart contracts execute ownership transfers automatically. Payments trigger title updates without manual intervention. Processing times decrease from months to minutes [22, 23]. Administrative costs drop significantly. The Netherlands reduced land registration expenses by implementing blockchain. Transaction fees fell to minimal levels. Rural clinics and mobile applications benefit from blockchain land registries. Remote areas with limited government presence access verification services online. Farmers confirm property ownership without traveling to district offices. Microfinance institutions validate collateral through blockchain queries.This expands credit access for small landowners. Urban property markets gain efficiency through faster transaction settlement.High-value commercial properties change hands with reduced legal complexity. Purbachal New Town represents a critical test case. This planned community covers 6,213 acres in Dhaka's northeast corridor. It includes 26,000 residential plots and 62,000 housing units [24]. The Anti-Corruption Commission filed six cases regarding plot allocation irregularities. Accused officials bypassed proper procedures. Some applicants received plots despite ineligibility. The scandal damaged public confidence in large-scale urban projects. A blockchain-based system for Purbachal would prevent such abuses. Every plot allocation would be recorded transparently. Eligibility verification would occur automatically through smart contracts. Review committees would access complete application histories. Citizens could monitor allocations in real-time. This accountability discourages corrupt practices. It protects legitimate buyers from fraudulent schemes.

1.2 Research Problem and Its Context

Traditional land registry systems in Bangladesh suffer from fragmentation across multiple agencies. The Directorate of Land Records and Survey maintains property maps. Local registrar offices handle transaction registration. Revenue departments collect land taxes.These entities operate independent databases. Information rarely synchronizes between systems.Property records at district offices differ from those at subdivision levels. Physical documents stored in different locations create inconsistencies. Paper-based processes enable document forgery.Deed writers produce counterfeit property papers. Registry office workers demand extra payments for legitimate services. Verification requires visiting multiple offices. Each step introduces delays and opportunities for manipulation.Digital systems were introduced to reduce these problems. More than 75% of Dhaka's land records now exist electronically.Different ministries implemented separate digitization projects. The lack of uniform standards created new fragmentation. Ministry websites showed security vulnerabilities including SQL injection risks. A 2023 data breach exposed 50 million citizens' personal information. Purbachal New Town exemplifies these systemic issues. After 26 years of development, land distribution remains problematic. Bribes ranging from 1,000 to 500,000 BDT accompany each registration. Plot owners struggle to obtain legal property records. RAJUK announced it would transfer ownership information directly to the Land Record and Survey Department[24]. This change aimed to speed processing. It raised concerns about data accuracy and user ability to verify records.Unofficial payments remained common throughout the registration process. Existing blockchain solutions face limitations in computational efficiency and scalability. Proof of Work consensus requires extensive energy consumption. Processing times increase as network size grows.Message exchange overhead becomes prohibitive in large networks. Proof of Stake reduces energy requirements. It introduces centralization risks when wealthy participants dominate validation. Traditional Byzantine Fault Tolerance algorithms need multiple communication rounds. This consumes network resources and limits throughput. Land registry applications demand consensus mechanisms optimized for permissioned networks. Registry offices and authorized validators form a defined participant group. Trust levels differ among participants based on performance history. High-reputation offices should receive greater influence in validation. Low-reputation actors need monitoring to prevent malicious behavior. Existing consensus algorithms do not adequately incorporate reputation metrics. This research addresses the gap by developing a Territorial Proof of Authority consensus mechanism. The algorithm selects validators based on territorial performance. It reduces message exchange requirements compared to Proof of Work. Execution time decreases relative to Proof of Work,Delegated Proof of Stake, Reputation-Based Leader Selection and Trusted Node Consensus. The system maintains security while improving efficiency. It suits the specific requirements of Bangladesh's land administration context.

1.3 Motivation

Several factors led to the selection of the research topic. The social impact of land dispute is affecting millions of families in Bangladesh. Court system is still overwhelmed by property cases. Individuals lose productive assets in fraud. Economic development is retarded if property rights are not secure. Technical solutions reducing corruption are a direct improvement of lives. Blockchain technology has the power of transformation for developing countries. These countries tend to have poor institutional frameworks. Corruption flourishes in weakly supervised environments. Immutable ledgers establish accountability in where there is neither in traditional system. Distributed architectures are fault tolerant. The technology is in line with goals of modernization to the governments of digitizing governance. As a result of its scale, Purbachal New Town is an ideal target for implementation. The project consists of 6213 acres and 26,000 plots. Transaction volume is going to grow as development continues. Traditional systems can not be able to carry this load efficiently. Blockchain based infrastructure scales to cope up with rising demand. Success in Purbachal would prove the point of possibility for nationwide deployment. The optimization of the consensus mechanism is one of the major technical challenges. Existed algorithm is designed for crypto-currency applications. Land registries have highly varied requirements. Transactions finality is more important than throughput. Energy efficiency issues always top the priority list for government deployments. Solving these problems helps to advance both the practical implementation and the academic knowledge. Personal interest in understanding the issue of local governance motivated the research direction. The problems of land administration in Bangladesh are well recorded. Citizens feel frustrated with the procedures that are opaque. Technology professionals have skills to bring solutions. Combining blockchain knowledge and local context provides the opportunity for the meaningful impact to occur. The research contributes to many objectives. Early identification of fraud can save property owners money by preventing a financial loss. For improved market liquidity, transaction times are reduced. Lower costs enable registration access to small landowners. Government offices are put on the path of hassle-free workflows. Transparency in operations helps to build public trust The work reveals the ways that new technologies provide solutions for ongoing problems in governance in developing countries.

1.4 Applications and Practical Use Cases

Block chain-based land registry systems are used by various stakeholder groups. Urban property market has a quicker transaction settlement. Buyers and sellers make transfers of ownership within days rather than months. Title searches become instant searches that are made against blockchain records. Legal disputes are reduced by having own histories that are transparent and tamper proof. Real estate developers for project planning have access to verified information of the land. Banks have quick validation on collateral for mortgages. Rural areas are brought into the formal systems of property. Land registration done by farmers in remoted locations used mobile interfaces. Local offices are validation nodes in blockchain network. Small landowners demonstrate ownership without much documentation. This allows an entry into agricultural credit programs. Microfinance institutions are a type of financial ID verification that does asset verification electronically.

Land-based lending opens up to previous populations Government agencies makes administration more efficient. Registry offices handle applications through automatic work processes. Smart contracts enforce the procedural requirements. Documents are cryptographically verified instantly. Staff are concerned with the exceptions and not the routine validations. Audit trails make it easy to monitor compliance. Property transfers are tracked by revenue departments for the purpose of taxing the property. Survey offices are involved in coordinating the boundary information against the transactions. Legal systems have the advantage of the blockchain evidence.

Courts have access to complete ownership chains in case of a lawsuit. Judges resolve disputes between conflicting claims against permanent records. Forgery is made provable by performing cryptographic analysis. Resolution times of cases decrease. Backlog reduction creates judicial resources for other issues. Law enforcement is used to trace fraudulent transactions across multiple properties. Urban planning applications are combined with blockchain property data. City administrators use ownership patterns to analyze the need for infrastructure development. Zoning enforcement checks the compliance of the land use regulations. Environmental agencies monitor restricted area transaction.

Property owners are identified by disaster response teams to assist with the evacuation. Census operations combine the housing data and demographic data. International investment is enhanced when property rights are secure. Foreign buyers have faith in Blockchain verified ownership. Diasporas remit money for land acquisition with less fraud. Real estate investment trusts have access to reliable information on assets. Market transparency is an attraction for institutional capital. Property values rise as transaction friction reduces.

Purbachal New Town implementation would show the example of multiple use cases at the same time. Plot allocations would be carried out using open blockchain processes. Eligibility verification would be done automatically. Between origin and safety, Review committees would validate the applications based on the blockchain records. The status of the allocations would be monitored in real-time by citizens. Transactions in the secondary market would be processed efficiently. Handover of infrastructure to

plot owners would be used to trigger updates on the blockchain.
The system would be the reference implementation for other planned communities. Integration with existing systems in the government needs to be planned carefully. The blockchain layer would be connected to digital land databases. Smart contracts would take cadastral survey data into account. E-stamp certification would have links with blockchain transactions. National identification systems would be used to authenticate parties. Banking interfaces would ease the processing of payments. Mobile applications would result in citizen access to services.

1.5 Research Objectives

- To design a secure and tamper-proof land registration system aligned with the administrative structure.
- To develop an Property Transaction Process via Digital Portal to handle stamp obtaining and stamp duty payment digitally.
- To develop an Digital Verification Protocols for Title Transfers to manage ownership transfer transactions between buyers and sellers.
- To design a Network Structure for the System to support structured and transparent transaction flow.
- To propose and apply a Territorial Proof of Authority Consensus Protocol (TPACP) consensus algorithm to ensure secure and successful transaction validation.
- In this study, the investigators are going to identify the security and transparency of a blockchain-based land registration system but also its computational and economic efficiency through the gas consumption and the cost of conducting transactions core-operations. In particular, the investigation aims at measuring the gas consumption of smart contract deployment, the initial registration of khatians, their ownership mutation, and the registration of user identity, and at examining whether the resulting cost of transactions is feasible to use in the real world repeatedly in the context of administration.

1.6 Research Methodology (Overview)

This study is based on the idea of blockchain technology land registration to solve the problem of transparency, security, and efficiency of the current land management in Bangladesh. A literature review is done to study existing solutions of blockchain and set clear research objectives after identifying some of the major problems.A system architecture that is aligned to administrative boundaries is developed and a new consensus mechanism, Territorial Proof of Authority Consensus Protocol (TPACP), is created to minimize the overhead of transactions and processing time. The proposed system is ultimately analysed in terms of its performance against the current consensus algorithms and shows better efficiency and efficiency in the condition of large scale land registry. On the other hand the study design a simulation-based gas usage and cost analysis implementation in an environment compatible with Ethereum. The transactions of smart contracts were also made under controlled conditions, and the values of gas consumption were taken directly out of the blockchain runtime. These values were turned into transaction costs based on a fixed gas price to enable an objective comparison of the various land registration operations.

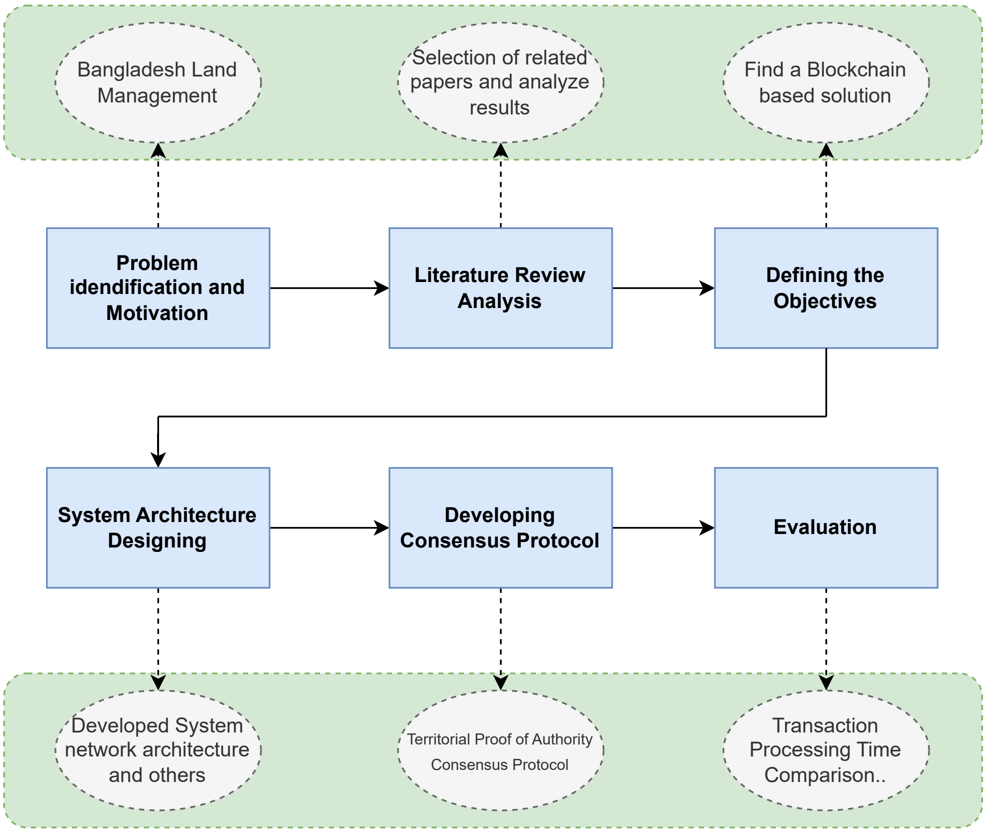

Figure 1.1: Block Diagram of Research Methodology Overview.

1.7 Organization of the Dissertation

This dissertation has been divided into 5 chapters covering different parts of the research.

Chapter 2: Literature Review examines derived theories, models, and studies of blockchain technology, distributed ledger systems, consensus, cryptographic security, and decentralized architecture of storage. The chapter provides the comparative analysis of the previous land registry methods and outlines the most important research gaps, which drive the proposed solution.

Chapter 3: Proposed Methodology explains the proposal of the blockchain-based land registration system by providing the design and implementation of the system. It describes the network structure, workflow of transaction, digital verification, document storage systems and Territorial Proof of Authority Consensus Protocol (TPACP) development. Also, engineering, ethical, and societal factors are discussed.

Chapter 4: Results and Discussion expresses the evaluative analysis of the experimental work with the offered system. Efficiency, scalability, and applicability to the application of land governance Performance measures, results of a simulation, and an alternative comparison with current consensus mechanisms are examined.

Chapter 5: Conclusion recounts the findings of the research in general, identifies the primary contribution, addresses limitations, and provides possible directions for further work. The chapter is also complemented by the recommendations of how blockchain-based land governance systems should be technically implemented and adopted at the policy level.

2. Literature Review

2.1 Introduction

In this review research, the author examines blockchain land record systems and digital property registries. It remains centered on permissioned and decentralized blockchains, cryptographic validation, IPFS storage and large and database-focused consensus models [25, 26]. The work has the reflection of the land management situation in Bangladesh with much emphasis on Purbachal New Town. Disparity of data, paper based processes and bribery slows down ownership and erosion of people trust [27]. The review discusses the research of the last decade, which is in line with the development of blockchain applications and registries. These sources consist of journal articles, conference papers, and some of the public reports that were selected concerning land records and digital governance in Bangladesh.

This review has three goals. The first objective interconnects between blockchain land registry, digital title system research to demonstrate how distributed ledgers enhance the integrity of the data, audit trail, and speed of title transfer [26, 28, 29]. The second objective is to compare the consensus models, like Proof of Work, Proof of Stake, Delegated Proof of Stake, Pbft based system and round robin scheme to use in land record network [30]. These models have an impact on cost, delay, and trust between registry offices. The third objective is limited by existing systems, where a focus on the volume of messages, slow validation, and weak scaling are of low priority [9, 27]. Such limits cover major urbanization ventures like the Purbachal New Town. It is these gaps that inform the design of both the proposed e registry system and the RwPOA consensus model.

The search of the study was performed in a fixed manner. These were found within the Scopus, IEEE Xplore and Web of Science. The keyword list comprised of blockchain land registry, e registry, permissioned blockchain, IPFS land records, and blockchain consensus. The review retained research about blockchain systems of land or property data or analysis of consensus models of shared ledgers. The review eliminated the papers lacking land focus, lacking system data, and lacking technical testing. The procedure eliminated duplicates and filtered titles and abstracts before proceeding to full text screenings. This is how a relevant and narrow source set could be obtained.

The review has a theme based arrangement. The initial section describes blockchain to ensure safe storage of records [31]. The second section is a review of blockchain land registry and e registry systems, and it highlights the system design and outcome [26, 28]. The following section will make comparison of the consensus models through speed, scale, and security in land transactions [30]. The last section enumerates work limitations in the past. The limits assist the design of the blockchain e registry system and the model of TPACP of Purbachal New Town [27].

2.2 Theoretical Background / Existing Models

This section provides a summary of the theoretical background that will be used to design and implement a blockchain-based system to digitize land registration in Bangladesh. The study relies on various fields: distributed computing, cryptography security, consensus mechanism, and decentralized storage systems. Each framework presented below provides certain ideas and technical aspects that, combined with each other, allow securing, transparent, and resistant to manipulation property transactions control [32].

2.2.1 Framework of Distributed Ledger Technology

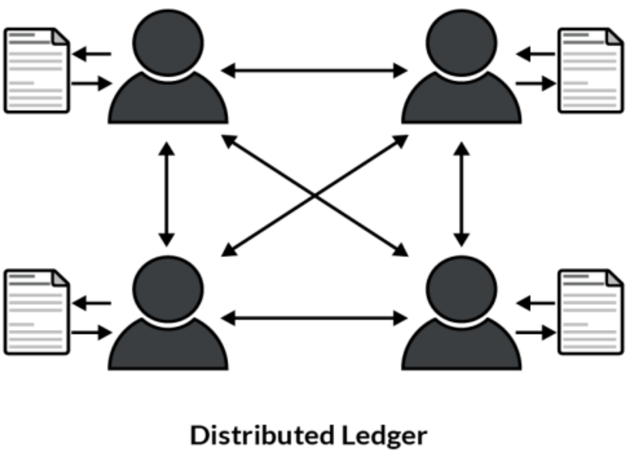

Figure 2.1: Diagram of Distributed Ledger Technology DLT.

Distributed Ledger Technology (DLT) is a transitional step to change centralized record-keeping to a decentralized data architecture. Various players maintain congruent records of transaction information and all this without having a central repository. DLT emerged as a result of the necessity to resolve Byzantine Generals Problem that poses a question of how distributed nodes can reach a truth with malicious actors. The significance of DLT to land registration is that it will remove single points of failure and have clear audit trails. All this is centralized through the registry databases which place vulnerability in a central location and enables the privileged administrators to manipulate the data. Conversely, as the number of validation nodes keeps growing with the use of DLT, fraudulent alterations will have to be present in the majority of the network instead of in a single administrator.DLTs strengths would include:

- **Immutability** - There is cryptographic connection between two transactions once they are registered and begin to be verified, so that, subsequent alteration becomes computationally unfeasible.
- **Transparency**- Transactions can also be verified by authorized users not by intermediaries.
- **Resilience** - the distributed structure is resistant to technical failures and attacks superior to centralized structure. Nonetheless, the models of DLT are based on assumptions, which might not be true in all places. Attackers may gain too much validation power in permissionless networks, making the majority-honest assumption to fail. Coordinating nodes over the long distance may not fit in the real time transaction requirements because of latency. The cost of storage is more expensive in that storage redundancy enhances fault tolerance, yet every validator has a complete copy of the ledger. Poor network connectivity in most districts is also a challenge that Bangladesh land registry is having. These facts demand that hybrid design is needed that can support intermittent connections [33].

2.2.2 Consensus Mechanism Models

The algorithmic basis of distributed networks making it possible to come to a consensus on what is right about the proposed transactions without coordination is the consensus mechanisms. These protocols define which nodes have power to authenticate a transaction, the path in which this authentication decisions are broadcast throughout the network, and the circumstances by which new records attain finality [34].
Proof of Work (PoW): The first form of consensus model, the PoW introduced by Nakamoto in the Bitcoin protocol. PoW is a blockchain system that makes validator nodes (miners) solve computationally-intense cryptographic puzzles to be given the authority to propose new blocks. The main strength of PoW is security against Sybil attacks since, to create false identities, there is no benefit, and it requires the use of computational resources. The high cost of purchasing majority hashing power is the economic incentive to not encourage malicious actors to launch a blockchain reorganization attacks. PoW had however terrible drawbacks in terms of land registry applications. Bitcoin respects networks that consume over 200 terawatt-hours of energy

each year generating the issue of environmental sustainability. Finalization of transactions take between 10 minutes and hours based on block confirmation needs making it not compatible with the expectations of administrative efficiency [35]. Validation power is also centralised in the hands of the participants with access to special hardware which is a factor that reduces the goals of decentralization in the competitive mining structure. In the context of Bangladesh land registry, PoW cannot be used due to it's message exchange overhead and processing time due to the 56.8 percent communication overhead reduction of the proposed Territorial Proof of Authority Consensus Protocol over PoW. The PoS presented an alternative that has become much more energy-efficient, with the ability to be validated as economically important, rather than based on computing power. Validators place cryptocurrency as a collateral and block proposers are chosen in a fair manner by the protocol depending on the stake size. PoS has a better energy consumption with power consumption approximately 99.95 in comparison to PoW, which was witnessed in Ethereum. The throughput achieved in go of the transaction is very high as block time becomes smaller and no delays done by solving puzzles through computations. Economic security is the result of cutting systems that punish bad actors by holding their stake, to incentives involving honest behavior. Such factors as the possibility of centralization can be considered the critical limitations, in the case that the stakeholders who are wealthy will amass unequal validation power. The other problem is the problem of nothing at stake where the cost of supporting various competing blockchain forks is low to the validators. In the case of land registry, maintenance of economic stake-conflict with the governmental administrative frameworks, in which the validation authority is based on the jurisdictional instead of monetary investment. The fact that the legitimacy that validators have long term economic commitment is bad when the registry node operators are government employees with the mandate attained through administrative appointments as opposed to capital investments.

Delegated Proof of Stake (DPoS) [36] proposes democratic election of delegates (or witnesses or block producers as it is also termed) by the token holders, a few of them, responsible of validating transaction and block creation. The formal organization divides the stakeholders into voters and validators: voters are the owners of tokens to give their ballots on the candidates of the delegates, and elected delegates undertake consensus actions. The election process involves nonstop voting and is such that the stakeholders are able to give their voting power to their representatives who may be trusted or the stakeholders can engage in voting themselves in the selection of the delegates. It usually has a range of active delegates between 21 and 101 (depending on the type of network setup) and new voting rounds usually revise this. The delegates are produced in a round-robin manner, where transaction fees and block rewards can be issued; many of which are shared with voters who voted in favor of their election. The performance accountability systems enable the stakeholders to vote out the incompetent or malicious representatives by voting, an economic type of incentive to operate effectively. DPoS has a high level of scalability when compared to PoW and PoS with the finality of transactions in seconds and a throughput of thousands of transactions per second. This is because the restricted set of validators makes communication complexity not O(n2), as in all-to-all systems, but O(n) in which n is the number of active delegates. The amount of energy used significantly reduces since block production uses few computational services relative to the PoW mining. There are some limitations according to critical analysis. Skew risks are encountered when a small set of delegates is granted the power to validate; cartels can conspire to provide transplantation ranking, or restrict individuals. When token holders are major token holders in disproportionate number, i.e. when they are weak centers, then this is the weak center phenomenon and may lead to improper style of democracy governing. Attacks on vote buying are possible on assumptions that the candidates of the delegates give large kickbacks to be elected, and when they are voted, they loot votes by engaging in unethical actions. The assumption that voters are technical knowledgeable enough to assess the competence of delegates is not usually practically true, and elections become corruption by popularity. In the case of land registry, DPoS is a source of basic incompatibilities with governmental administrative systems. The model presupposes a system of voting whereby tokens grant voting rights, whereas governemt registry systems are based on legal regulations and not the ownership of cryptocurrencies. The use of election-based delegate election has added political interference with the ability to maintain stable, which validates jurisdictional requirements, where certain registry offices need to handle transactions as to which they operate jurisdictionally. The constant changes of the delegates with the permanence of local knowledge in checking boundaries of the property, historical records of ownership, as well as with the rule of the locally applicable land regulation go against the problem of the necessity to utilize the long-term and permanent aspect of knowledge.

Reputation-Based Leader selection Consensus Algorithm (RLSCA) is a Consensus Algorithm based on votes, oriented at consortium blockchains. It does not need to run any computational process or an economic interest; rather it chooses its leaders according to node reputation. RLSCA is based on the past performance, time-basis faith, and democratic selection of validators [37]. The algorithm helps lessen the overhead in messages than Proof-of-work systems. Voting is not carried out on the entire network, but in a small set of validators. The reputation will make the nodes responsible; continuous rogue behavior will reduce the score of a node and ultimately it will be out of the candidate list. Voting is dispersed to many nodes instead of the wealth of those possessing more computers or money and this assures that power is distributed. Hyperledger Fabric experiments demonstrate that RLSCA is capable of executing 500 transactions per second with 10 nodes and the latency can be measured in the range of

5Ms, which is superior to most trust-varying and fast-pipeline BFT constructions. In the case of land-Registry systems RLSCA is more performance accountable than pure Proof-of- Authority. It however does not take geographic jurisdiction into consideration. Any highly reputed node can be made a leader though she may be distant to the location of the transaction. Validators might be unfamiliar with the local knowledge on the confirmation of property boundaries, MAP accuracy, or district regulations. The single-leader model of RLSCA redeems all validation responsibilities to a single node whereas land administration requires multiple local professionals, as well as outside control in order to minimize the fraud risk.
Trusted Node Consensus Algorithm (TNCA) employs multi dimensional trust evaluation to form consensus groups which only contain greatly trusted validators. The concept is based on the cognitive trust models which integrate the previous performances, risk-assessment and peer-feedback into an overall score. The key strengths to TNCA are that it examines multiple dimensions of trust rather than only previous transactions and, thus, targeted reputation hack attempts are more difficult. The system can compromise security and get validator availability by modulating the trust threshold. TNCA operates with the current BFT protocols which retain the proven fault tolerance parameter and enhance the quality of validators [38]. The algorithm is based on a number of assumptions. It puts its faith in the honesty of peer about the recommendations; whereby, bad nodes may exaggerate the ratings of their friends and decrease the ratings of the honest nodes. TNCA constructs a Direct Trust Tree which requires close network connectivity to form multi-hop paths; in sparsely connected networks or during early stages deployment it can fail. Values of the weights (w1, w2, w3) which aggregate the trust factors are not done through a formal optimization procedure, rather they are selected by hand. Lastly, TNCA does not manage trust that varies over time; a node which has been compromised despite initially being trustworthy may be considered trustworthy. TNCA works well when used in applications to land registration, as its capability of identifying credible validators has its drawback of geographic blindness like that of RLSCA. Trust is computed no matter the location of where a validator is in connection with a property transaction hence they do not consider local expertise. There is also an assumption about the frequency of interactions between the validators in the feedback system to provide meaningful ratings, which is that in a large scale distribution of district networks, there is a risk that validators have too little shared history. The binary inclusion criterion may be excessively strict the land registries may find a more graduated model in having high-trust validators do initial check-ups and medium-trust checks doing subsequent reviews.

2.2.3 InterPlanetary File Systems Architecture

The InterPlanetary File System (IPFS) is a peer-to-peer decentralized data storage system which builds permanently persistent data datatypes, and is content-addressable.

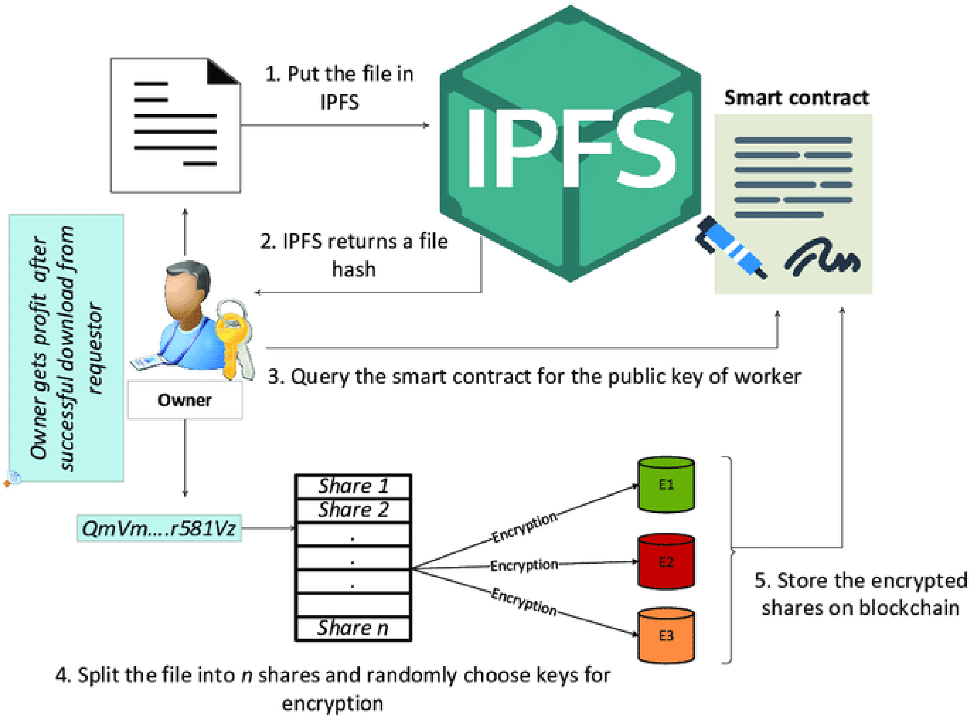

Figure 2.2: Diagram of InterPlanetary File Systems Architecture.

It addresses the issues of the traditional HTTP in which content is recurrent to a particular server and domain existence. IPFS comprises five layers. The identity layer is based on the idea of a public-key cryptography to generate unique node identities using hash functions to provide self-certifying identities as with the Kademlia networks. The network layer handles numerous transport protocols including WebRTC, SCTP and uTP and has multiaddress syntax as it makes addresses protocol-neutral. The layer comprising routing implementation follows a hash table distributed protocol, Under Kademlia which allows peers to locate each other and files without a global index. The exchange layer manages the flow of data by using BitSwap in which nodes offer blocks they desire and offer blocks they have to enhance efficiency in distribution. The object layer stores object data - immutable objects in a Merkle dag such that they can be hierarchical files, have a version history and can have linked data structures. The IPFS has a number of advantages to land registries. The files can be accessed as the hash of the content is used; therefore, they are still accessible even when the server or a domain is modified. Redundancy among nodes on the network creates availability as well as mitigates node failures or intentional attacks. Unauthorized changes are also avoided through cryptographic hashes and this gives evidence of integrity. Limitations exist. Unpinned content can be garbage collector used to release space, thus documents are only pinned in order to remain forever. Firstly, it may take time to access a file that is not requested very often as not many nodes will have it, but popular information will spread all over. DHT routing layer also adds extra overhead to the communication as compared to centralized lookups, but this reduces with size of the network. Lastly, any person can store data on public IPFS networks which is a cause of concern because sensitive documents can be accessed by non-authorized individuals. Governments can also alleviate it by operating their own IPFS network whose nodes are restricted to organizations that have been verified by the government [39].

2.2.4 Models of Cryptographic Security

Authentication, integrity and non -repudiation in the distributed transactions system are all based on cryptographic primitives. Digital signature schemes and cryptographic hash functions are the two fundamental models of security that are implemented in blockchain-based registries. The most common standard of the digital signature in blockchain implementation is the **Elliptic Curve Digital Signature Algorithm (ECDSA)**.It is based on the problem of elliptic-curve elliptic-curve discrete-logarithms so that it is computationally infeasible to compute a private key would you have a public key but still be able to generate a public key efficiently by having a private key. The security of ECDSA is based on the hard elliptic -curve discrete-logarithm problem. It provides equal security as RSA signatures, but smaller keys 256-bit ECDSA is of equal protection as 3072-bit RSA key. This efficiency is important when validation nodes are resource-constrained and can represent transaction data in a compact form, which will minimize the storage requirements and bandwidth requirements. In the deployment of the usage of the ECDSA take note of the nonce-reuse vulnerabilities; nonce-reuse may be classified as the same key value (k this value is used to send more than one message to the destination server) using the common key can provide attackers with the opportunity to extract the all important private domain through algebraic manipulations. The cryptographically secure random-number generators should be implemented and each nonce should be checked to be unique. Scaling Time implementation is required to counter side channel attacks based on time or power consumption differences. As a land registry, ECDSA enables property owners to give consent to any transaction without revealing their private keys. The validators can then validate these authorizations with merely the public keys thus removing the necessity of trusted intermediaries. Cryptographic hash functions are showing one way, collision-resistant non-invertible algorithms, which detail the mapping of inputs of any length to fixed length outputs. A very common is a 256-bit hash (SHA 256) which out of 256 bits generates 256-bit digests that are used in blockchain networks. SHA-256 is based on Merkle-Damgard construction. It divides the messages in 512-bit blocks with 64 rounds. The non-linear functions that are used in each round include majority and choice: In case of distributed ledger applications, it is possible to do fast integrity verification of large-scale data sets with Merkle trees with the help of hash functions. Root hashes only should be stored and each element can be verified. This also improves the integrity of the chain since the hash of the previous block is included in the header of the block hence any alteration on any block in history would require recalculation of the remaining blocks. Document fingerprinting is also supported by hash functions where the registry materials can be compactly represented with on-chain hash values, with the entire documents being stored in the other layers of storage [40].

2.2.5 Gas Consumption and Gas Cost Mechanisms in Blockchain Technology

Gas consumption forms a basic concept in the modern blockchain platforms, especially those that implement programmable smart contracts. Basically, gas is a measurable unit of computing power, which is required to process transactions in a blockchain system. Every operation the invocation of a smart contract function, maintenance of data, or authentication of a transaction all take a fixed number of gas proportionate to the computational complexity of the operation. As a result, computationally intensive operations or those that require permanent storage always require more volumes of gas compared to elementary value-transfer operations. The concept of gas cost refers to the financial cost that is incurred via using gas. Gas is used to measure computational work which is then converted into a user fee through gas cost. This price has been calculated by most means by multiplying the volume of gas used by the price of gas in fine denomination of the indigenous cryptocurrency of the network. Gas price is a current cost of network conditions and demand; this means that a user can choose to suggest a higher price in busy times to ensure that their transaction is completed before others in a congested network, or low prices can be used in times of low activity.Gas cost can be calculated conceptually thus as: **Gas Cost = Gas Used × Gas Price** This price generating mechanism serves several functions in a blockchain. To begin with, it reduces the use of network resources wastefully through economic punishment of stagnant or malicious computations, making unjustified intensive operations prohibitively costly. Second, it suits fair distribution of the computational resources by allowing users to indicate transaction priority by making wise gas price choices. Thirdly, gas charges encourage the validators or miners to execute the transactions hence towards the overall security and stability of the network. Gas consumption and gas cost analysis is of special importance when designing blockchain-based systems. The careful design of smart contracts can significantly reduce the operational costs and increase the scale. In major or publicly funded systems, e.g. land registration or financial record maintenance, a detailed knowledge of gas behaviour is essential to the determination of economic feasibility and long-term viability. Therefore, the analysis of gas usage and the associated expenses are beyond a strictly technical issue, as it turns out to be one of the decisive factors that combine blockchain performance, security, and practicality.

2.3 Related Studies

Alam et al. (2022) suggest the three-phase adoption of blockchain in land registration (commencing with a pilot of a public blockchain, then ridge to a small hybrid, and finally to a full hybrid with government systems) will be more acceptable to countries with low levels of digital skills and slow digitization as a result of the fact with a sudden and risky switch [41]. This work is solid at demonstrating how to slowly deploy blockchain to actual institutions, yet, it lacks a clear description of forming a formal trust or threat model hence critical elements of security such as collusion by validators, key theft, or transactions censorship are not systematically studied. On the other hand, Yadav et al. (2021) concentrate on the optimization of the performance of consensus and propose a variant of Round-Robin Consensus Algorithm (MRRCA) to increase transaction confirmation and minimize message overhead when compared to simple round-robin in the experimental design [42]. Nevertheless, they merely benchmark their modified scheme against standard round-robin (as opposed to other consensus algorithm families), and experiment with small numbers of nodes, which suggests that the scalability and safety of MRRCA at larger and more realistic land record systems is unknown.Shithy et al. (2021) present a permissioned version of blockchain model, as simple and applicable in Bangladesh, and the algorithm is through Hyperledger Fabric that registers land and ownership, in which government offices, land offices and banks are designated as authorized nodes [43]. The idea is to substitute its disjointed and paper-based procedures with a common and inaccessible ledger to minimize fraud and increase coordination between these institutions. The paper, however, fails to provide a clear picture of how governance would take place, onboard new actors into the network, and how conflicts and pre-existing land laws would be managed during and after the transition, but somewhat assumes that all these parties will enter the network and collaborate.

Table 2.1: Literature review summary of blockchain-based Architecture for Decentralized Land Governance and Secure Registration

Author(s) (Year)	Contribution	Limitation
K.M. Alam et al. (2022) [41]	Suggests three stages (public - small hybrid - full hybrid) that fits. poor in digital expertise and pace of digitization.	This paper uses gas consumption but lacks detailed numerical benchmarking of transaction costs of major land registration activities at practical scale, which limits the economics of scalability consideration in Bangladesh.
A.S.Yadav et al. (2021) [42]	Suggests a Modification Round-Robin Consensus Algorithm (MRRCA) to imcommitment of transactions efficiency.	They only modify round robin and compare transaction time, not other consensus algorithms. and they test on just 50 nodes, so scalability is unclear.
S Agrawal et al. (2022) [44]	Introduces a Trusted Nodes Consensus Algorithm (TNCA) based on dynamic trust values instead of Proof-of-Work.	Each node maintains and updates trust tables; at large scale this increases computation and synchronization cost.
Munir Hussain et al (2025) [45]	Proposes a reputation-based, vote-driven leader selection consensus algorithm with rewards and penalties to improve blockchain performance.	Performance gains become marginal as the network size grows large.
Shithy et al. (2021) [43]	Suggests a Fabric-based Hyperledger, authorised blockchain model of. Bangladeshi own- registration and land registration. ership management.	The paper assumes that government, land offices, and banks will join the blockchain, but it does not clearly explain governance, onboarding, or how disputes and existing land laws will be managed.

2.4 Comparative Analysis of Existing Approaches

Table 2.2: Comparative Analysis of Existing Land Registry Approaches

Approach / Representative model	Network type	Consensus / validation idea	Performance & compute cost	Governance & onboarding	Security / privacy risks	Suitability for Bangladesh land registry
Centralized digital land databases (traditional e-gov)	Centralized	Admin-controlled writes	Fast query/write, low compute	Easy to operate, but fragmented across agencies	High breach/tamper risk; insider manipulation	Weak trust + corruption resistance; fragmentation remains
Round-Robin / MRRCA (Yadav et al.)	Permissione	Scheduled validator turns	Low compute; improves confirmation time vs basic RR	Simple membership assumption	Limited attack modeling; benchmark narrow	Useful baseline, but incomplete comparison + unclear scaling
Trust-table model / TNCA (Yadav & Agrawal)	Permissione	Dynamic trust values and trusted nodes	Higher overhead: maintaining trust tables	Requires consistent trust updates across offices	Trust manipulation / update disputes possible	Hard to scale nationally without heavy coordination
Reputation + vote-driven leader selection (Hussain & Mehmood)	Permissione	Reputation, rewards/penalties	Improves performance, but gains reduce as size grows	Requires clear incentive/governance rules	Risk of reputation gaming	Promising concept, but large-scale benefit uncertain
Fabric-based permissioned registry (Shithy et al.)	Permissione consortium	Hyperledger Fabric endorsement	Efficient, controlled access	Governance/onb not clearly described	Policy conflicts with land laws not resolved	Practical stack, but adoption + dispute/legal integration unclear
Our thesis approach: Territorial Proof of Authority Consensus Protocol (TPACP)	Hybrid (permissioned + audit transparency)	Territorial + performance-based validator eligibility	**56.8% lower message overhead vs PoW**; execution time reduced vs PoW/D-PoS/RLSCA/T-NCA	Aligns with admin boundaries; fits gov accountability + confidentiality	Depends on correct identity, reputation integrity, and policy enforcement	High alignment with Bangladesh constraints (intermittent connectivity, fragmentation, audit need)

2.5 Summary of Research Gaps

The comparative analysis synthesis and corresponding table of related-studies indicate that there were a number of unresolved gaps in the literature that directly inform the methodology of Chapter 3.

1. **Gap 1:** The major research gap in current literature of land registration based on blockchain is the lack of analysis on the numerical gas consumption and transaction costs. The vast majority of studies refer to efficiency in a qualitative way without providing the precise values of gas consumption on core activities like contract deployment, registration, or ownership transfer. This exclusion constrains the capacity to determine economic scalability, especially in the developing states such as Bangladesh, where high frequency land deals may increase cumulative expenses. To overcome this gap, it is necessary to measure gas consumption and cost per operation, which is explicitly done in this research.

2. **Gap 2:** Cross-family comparisons not done fully thus narrow benchmarking. Some of the studies only compare a protocol to a lone baseline (such as, a modified round-robin to a conventional round-robin), but do not perform comparisons with larger consensus families (such as Proof-of-Stake or Delegated Proof-of-Stake or Practical Byzantine Fault Tolerance). The empirical meaning of this restriction is that, without benchmarking between families, there are simply no empirical ways of substantiating a consensus decision regarding governmental deployments that are simultaneously required to meet restrictions on speed, cost, trust, and accountability.

3. **Gap 3:** Under-governance, under-onboarding and under-legal-dispute-integration. Hyperledger Fabric-based land registration Hyperledger Fabric-based land registration as a permissioned blockchain proposal often assumes the universal involvement and collaboration of all stakeholders, but does not specify some mechanisms to govern it, onboard actors or how conflicts and compatibility with existing land law can be reconciled during the transition. This exclusion is especially applicable in Bangladesh where land administration is divided into several agencies; without well-defined governance frameworks and procedures in the resolution of disputes, technically sound blockchain solutions can eventually become functionally useless.

4. **Gap 4:** Poor formal threat analysis in trust/reputation models and scale may be expensive. Proposals at hybrid stages generally offer partial threat models that disregard important adversarial behavior like collusion, key theft or censorship. Furthermore, trust -table designs are associated with scalability issues, because computational and synchronization costs increase with the size of the network. There is much at stake when it comes to land registries: any form of adversarial activity (such as collusion or insider trading) or operational limitations undermines trust among citizens, hence a clear, and scaled threat framework needs to be present.

5. **Gap 5:** The threat of persistent privacy and intrusion in centrally digitalized form. The existence of centralized systems and fragmented databases has proved to be susceptible, e.g. the many disclosures of a large personal data and also issues with addressing coherent inter-agency validation. It is these inadequacies that reduce the trust and present a possibility of corruption which are the concerns of the present thesis.

Overall it can be seen that these literature sources show that existing blockchain solutions to land registration either -

- Do not take into account performance optimization in limited environments,
- Do not consider the realistic scaling criteria,
- Lack detailed specification of governance and legal integration that would be required to be relevant to Bangladesh with fragmented institutional environment.

In order to address these shortcomings, the current thesis suggests a hybrid blockchain solution that jointly includes Territorial Proof of Authority and Reputation -Weighted validator selection. This architecture specifically aims at low communication overhead and high processing speed in addition to similar validation authority to administrative jurisdictions and measurable office performance. The methodological decisions developed in Chapter 3, therefore, are inspired directly by this proposal.

3. Proposed Methodology

3.1 Introduction

This chapter provides the methodology of implementing a blockchain-powered system of digital land registration of Bangladesh. The methodology is based on the learning on the literature review. The chapter outlines the network organization, process of property transacting, digital verification, structures of property titles documentation, and Territorial Proof of Authority Consensus Protocol. The method converts the paper-based land registration to a safe online information management system without violation of the administrative jurisdiction of Bangladesh. This approach will tackle corruption weaknesses, forging of documents, and institutional fragmentation that was reported in Chapter 2.

3.2 Network Structure for the System

- The system connects all the registration offices in the administrative regions of Bangladesh. All Sub-Registry and District Registrars have validator nodes which constitute a peer-to-peer network. Registration offices replicate their web servers to satisfy blockchain needs and professional miners with sophisticated hardware supplement the infrastructure of the government. All components are connected with the help of a distributed cloud server which was aleady mentioned in **figure 3.1**

- The system has adopted InterPlanetary File System (IPFS) to store it as content-addressable. All nodes in the IPFS network that are validators have a unique identifier. The approved peers are connected with the help of the nodes to bootstrap server which keeps the active lists of the participants.

- The administrative regions vary on land transaction fees. Verification is a multi step procedure which is administered by the Sub-Registry and District Registry Officers. District validators are networked down the P2P network each of which maintains a complete copy of the blockchain. The framework connects the validators in and across districts via the IPFS net that allows the direct node-to-node communication in the absence of central servers.E-registry documents are generated in the district registry offices.

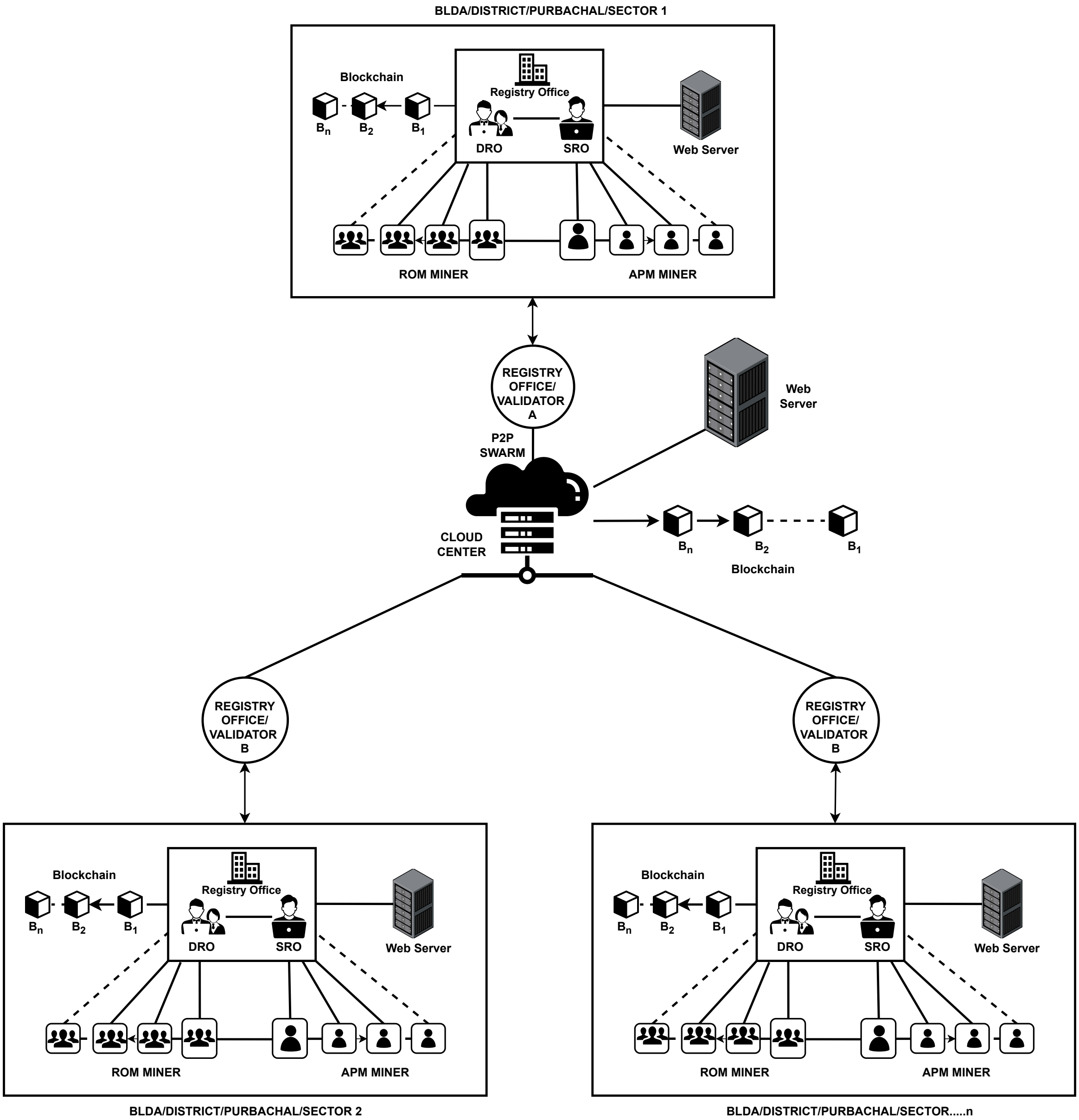

Figure 3.1: Network Structure for the System

- They are also organized into a number of registry offices interlinked to a central web server where land records are stored in each district. These offices have validators in their network, which are under the Territorial Proof of Authority Consensus Protocol. Credit is required based on historical performance scores and geographic jurisdiction and nodes are granted validation credits by the regular, proper and verifying work.

- Professionally elected miner nodes are approved to attend to the territorial validation building. They provide computational power when the volume of transactions is high and obey the same demands in their territories as government validators. This saves the district registry offices the burden of work and still maintains integrity in verification.

- Customers also trigger transactions through the transmission of property information to the network. They are reviewed and put in queue by validators in the transaction pool. The consensus protocol picks a primary validator on the territory of the transaction, whereas secondary ones on the other territories offer control. Once a sufficient number of transactions have been received, then the primary validator forms a block which must be signed by both primary and secondary validators. Before the system adds these block transactions to the blockchain, it verifies these transactions. Validator nodes ensure the chain, accept the transactions and answer calls to verify land. The web servers that are located in district registry offices provide users with the property information.

3.3 Property Transaction Process via Digital Portal

- From the **figure 3.2** it visualized the framework executes an online property transfer portal. The portal allows users of the portal to first calculate the right amount of stamp duty. Some of the payment methods namely can be digital channels, bank deposits, Treasury Challan or automatic payment system.

- Also from the mentioned **figure 3.2** stamp fees are verified by system validators. They issue digital stamp documents and transfer certificates to property buyers. After this, verification of payment of registration fees is given by the users. All the necessary papers are submitted online to the appropriate registration body.

- Each of the documents is reviewed by registration authorities. They review past property sale reports, national identification registration, land ownership, area maps, photographs and other supporting documents.

- Document review by document reviewers results in the creation of digital registry entries by validators. They include the transaction data into the distributed ledger. Final registration is issued to property buyers as soon as this is done. Anytime that transactions are validated, the distributed ledger is automatically updated. Digital stamp certificate is added to new transaction data blocks in every update.

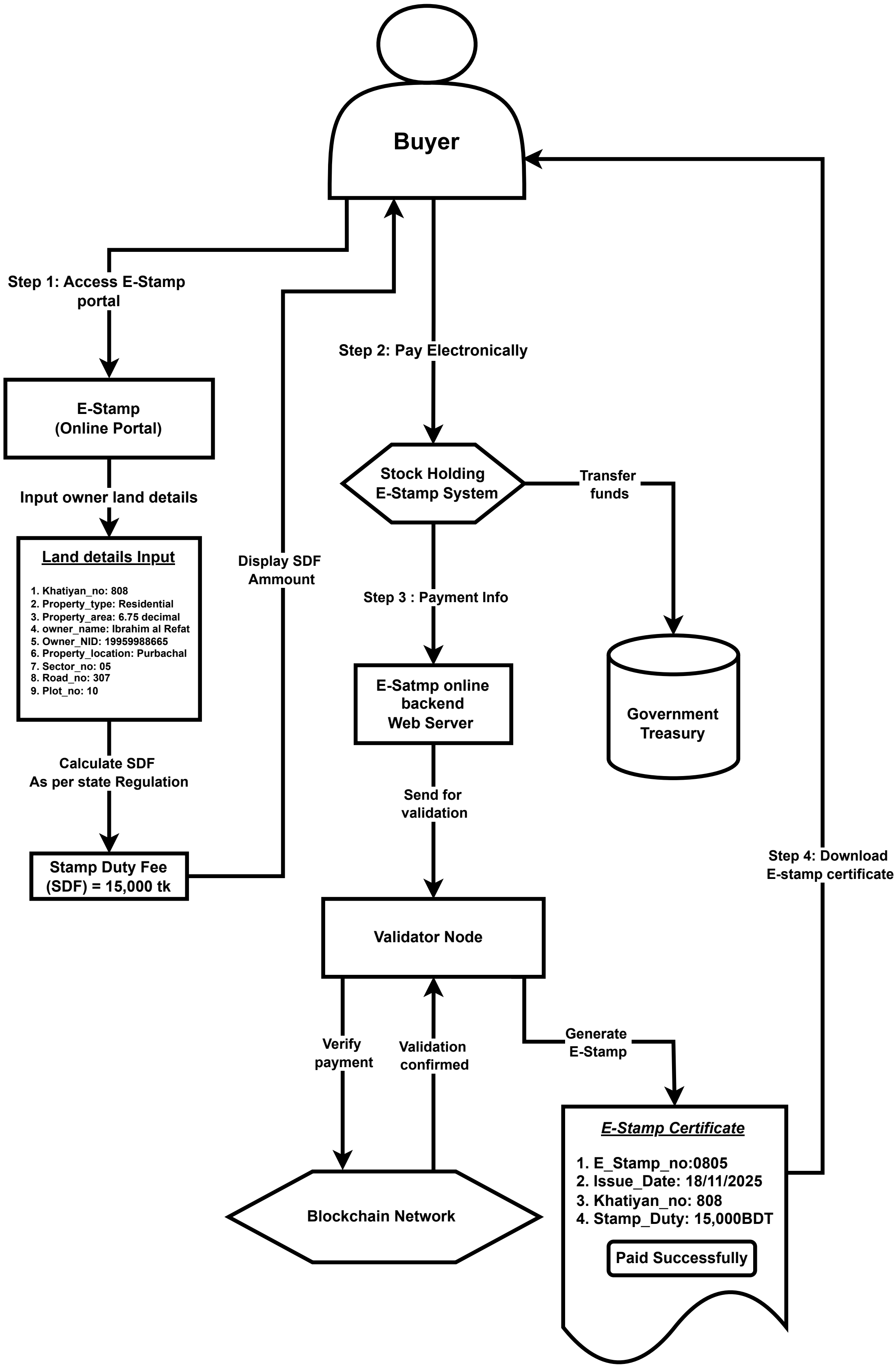

Figure 3.2: Property Transaction Process via Digital Portal

3.4 Digital verification protocols for title transfers

- Safety in property transfer means that there must be verification measures to avoid tampering and illegal alterations. This system of verification is based on distributed ledger infrastructure.

- From the mentioned **figure 3.3** title transfers are made in systematized validation of property records. Registry administrators use cryptographic verification protocols instead of inspections of documents by hand. Both transferring parties need cryptographic authentication prior to the finalization of the transaction. Every participant will have distinct cryptographic keys that create authenticable digital signatures. They are authorized by checking these signatures against registered public credentials and then the process proceeds.

- Also the **figure 3.3** visualizedd when the verification of signature has succeeded, the system gives a particular transaction identifier to each registry record. This ID can be used to track through the further processing stages. Every authenticated transaction is added to a holding queue awaiting the formation of blocks.

- Formation of periodic blocks is done after gathering enough confirmed transactions. Creation of block involves network consensus between authorized validation parties. In this step, transactions are aggregated by registry administrators in authenticated blocks based on distributed ledger protocols.

- Complete transaction processing is achieved once the distributed ledger has verified block incorporated. Registry documents can only be made available through official portals after this integration. Whenever documents are pending, they cannot be accessed to avoid accessing transfers before certification.

- Processing notifications are passed to the administrative unit of the Sub-Registrar following a successful validation. This causes automatic creation of official registry documentation. Registry administrators have constant transaction status supervision. They track future transactions until all validations in the network are done.

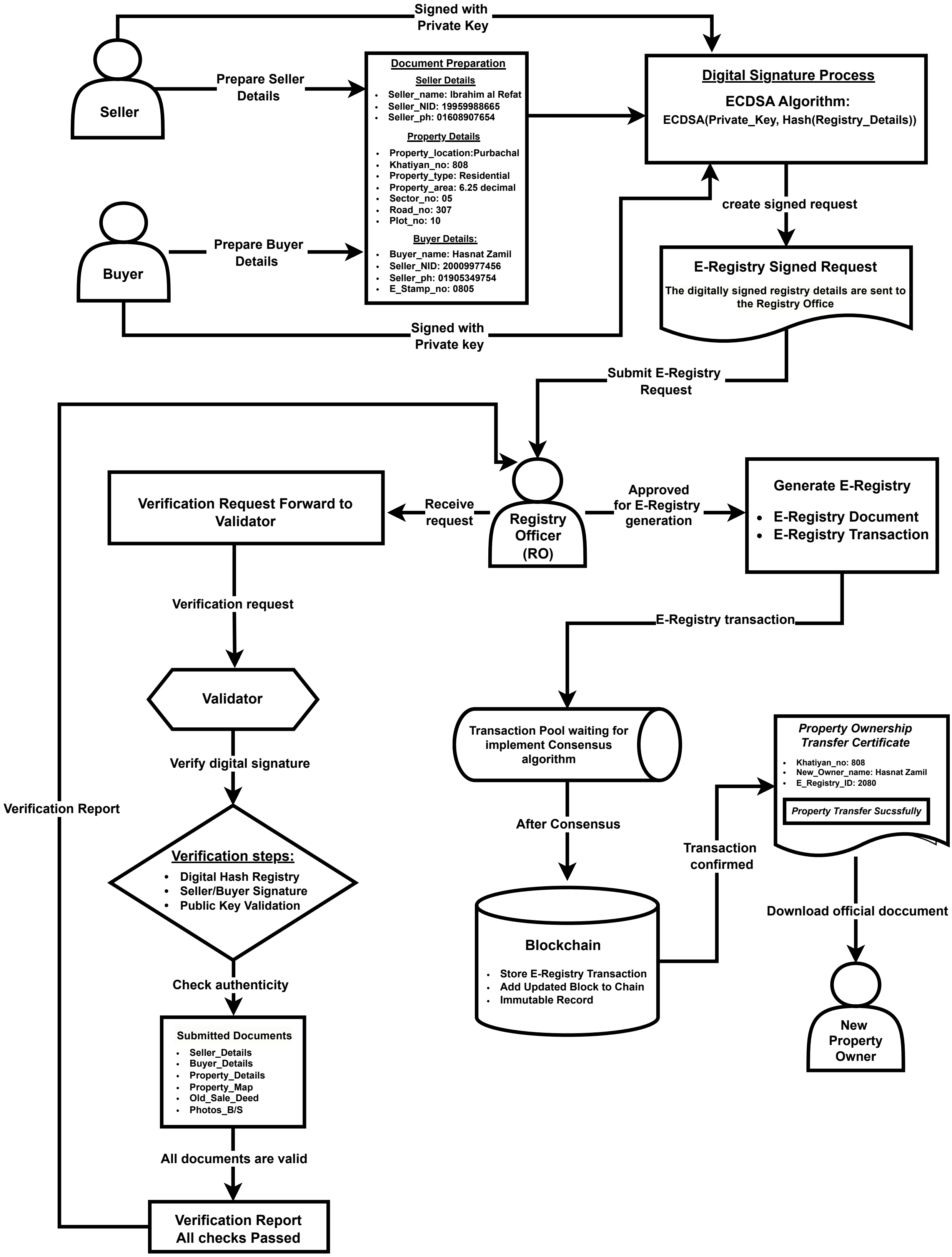

Figure 3.3: Digital Verification Protocols for Title Transfers

3.5 Secure Property Title Documentation Framework

It takes transaction data into the distributed ledger system in the way of a structured verification pipeline. The first step in the documentation procedure consists of citizens filing the property transfer information at the registry offices. Any record of transaction is cryptographically verified before being included in blockchain.

Listing 3.1: Sample E-Registry JSON Record Structure

```
{
  "ER": {
    "previous_block_hash": "0575877b9f485lsjab12",
    "property_record_number": "DHK-2026-001234",
    "property_location": "Purbachal, Sector-20, Plot-45",
    "property_area_decimal": 6.25,
    "e_stamp": {
      "serial_number": "EST-984532",
      "issue_date": "2026-01-13",
      "stamp_duty_amount_bdt": 150000
    },
    "digital_registry_hash": "0983afchjhkjuy9d77",
    "digital_signature_authority": "BLRA Digital Sign",
    "seller": {
      "name": "Ibrahim Al Refat",
      "national_id": "19959988665",
      "father_name": "Md. Sheikh Mujibur Alom",
      "address": "Dhaka, Purbachal Sector 20",
      "contact_number": "+880198774564",
      "signature_hash": "0085afg168753ef56",
      "public_key": "0sd41004b709632cvytq876c2"
    },
    "buyer": {
      "name": "Hasnat Zamil",
      "national_id": "20009977456",
      "father_name": "Md. Tarek Zia",
      "address": "Dhaka, Purbachal Sector 20",
      "contact_number": "+880193482346",
      "signature_hash": "01k65def21kjlkfb78",
      "public_key": "01io831nb86jnmv53204c9yu764n33"
    }
  },
  "hashER": "0x6e3ajnmnc41i9g65v556vy5f90c",
  "digitalSignature": {
    "digitalSignature_Seller": {
      "algorithm": "ECDSA",
      "signedBy": "seller",
      "publicKey": "0iu7504b7jhhe423gd7c2",
      "signature": "MEUCIQD... (base64/DER)"
    },
    "digitalSignature_Buyer": {
      "algorithm": "ECDSA",
```

```
      "signedBy": "buyer",
      "publicKey": "0x04c9hjue421af5333",
      "signature": "MEUCIQD... (base64/DER)"
    }
  },
  "ERegistryDoccumentFile": {
    "fileHash": "0jhu763xc65b2d22ew6q615095dft54xbpijut432aa10"
  },
  "TX": {
    "components": [
      "ER",
      "hashER",
      "digitalSignature",
      "ERegistryDoccumentFile.fileHash"
    ],
    "status": "PENDING_IN_POOL"
  }
}
```


SHA256 hash offers the integrity of the document during registration. Every transaction that transfers property is allocated a distinct cryptographic fingerprint that is permanently stored in the distributed ledger. The model ensures electronic authentication among the parties involved in the transactions. Transaction records are verified by the property seller with the help of own cryptography keys. Buyers also offer authentication based on their digital credentials. These cryptography operations are regulated by the ECDSA standard so that they can provide tamper proof documentation.

Once first verified, the Territorial Proof of Authority Consensus Protocol can choose special nodes on which to process transactions. This protocol selects a base validator within the administrative territory of the property of the transaction. It chooses secondary validators of other territories to create independent control. Primary validators do a local checks and boundary marker checking of the local records. Secondary validators are concerned with technical verification of document hashes and matching of ownership history.

All the chosen validators give strict validation tests prior to offering to include blocks. Primary validator testing is based on a weight of 60% in the decision. Secondary validator assessments have a weighted contribution of 40%. Any transaction will be carried out to block creation when its document scores exceed 75%. Any form of transactions whose score is less than 40% will be rejected. The district registry officers cause a manual review as a result of marginal cases.

Final block acceptance is achieved by this territorial validation framework which is the consensus protocol. The contents in a block are checked by network participants together with the known property records. The approved blocks are permanently stored in the distributed nodes with the different levels of redundancy depending on the property value. Blocks rejected are either reprocessed or removed out of the queue. Electronic documents obtained using finalized property records are immutable. Immediately they are authenticated buyers pay in the blockchain and get copies. The verifiable hash value is stored in the transaction ledger of every registration document. This hash has the property of continuous integrity verification.

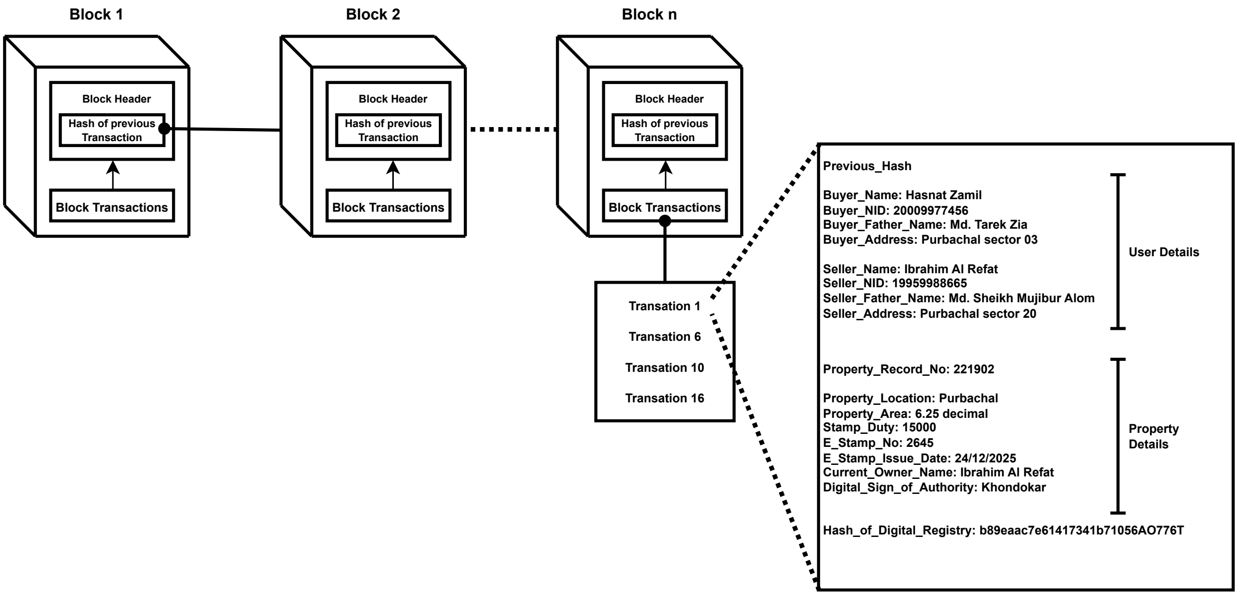

Figure 3.4: Secure Property Title Documentation Framework Block Structure

The transactions that have been completed combine four key factors, including verified registry data, document hash values, cryptographic signatures, and file reference identifiers. These components constitute an entire set of transactions that is conducted by the mining infrastructure. These verified records are summarized in the global transaction pool until block incorporation completes the process of transfer of properties.

3.6 Territorial Proof of Authority Consensus Protocol

An agreement among network participants is required in land registry systems. Such standard consensus mechanisms as Proof of Work and Proof of Stake present issues of land registration in Bangladesh. Verifiable legitimate property is based on administrative boundary and geographical jurisdiction.

This study presents Territorial Proof of Authority Consensus Protocol (TPACP). TPACP is a combination of geographical authority and measures of performance. This architecture minimizes on network overhead. It accelerates agreements in land transactions. TPACP is aware of two land verification requirements. Local expertise matters. Corruption will be mitigated by external control. The protocol constitutes four elements in collaboration. These elements deal with the eligibility of the nodes, selection of territorial validators, document validation, and finalization of records. This structure complies with the administrative frontiers of Bangladesh and also allows cross district checking.

TPACP reconciles both local and independent verification. Validators gain the right of participation by demonstrating performance. The protocol observes the legal regulations on the appropriate administrative delimitation. This method reduces message exchange overhead by 56.8 per cent as opposed to Proof of Work. It has strict checking procedures on land registration in Bangladesh.

3.6.1 Performance-Weighted Node Eligibility

Algorithm 1 Performance-Weighted Eligibility Selection

Require: TransactionPool, NodeHistory
Ensure: QualifiedValidators

```
Initialize performanceScores ← ∅
for each node in NetworkNodes do
    if node.isNew then
        node.baseScore ← 30
    else
        node.baseScore ← node.historicalPerformance ×0.7+ node.responseSpeed ×0.3
    end if
    if node.recentValidations > 0 then
        accuracy ← node.correctValidations / node.recentValidations
        node.adjustedScore ← node.baseScore ×(0.8 + 0.2 × accuracy)
    else
        node.adjustedScore ← node.baseScore
    end if
    performanceScores[node.id] ← node.adjustedScore
end for
avgScore ← calculateAverage(performanceScores)
threshold ← avgScore ×0.85
QualifiedValidators ← {node | performanceScores[node.id] ≥ threshold}
return QualifiedValidators
```

All nodes are not left in equality in TPACP. The protocol provides dynamic scoring to nodes based on historical performance in terms of the accuracy of verification and speed of response. Validators get experience through regular work as the registry offices. New nodes augmented into the network are given a default score of 30. The score of nodes varies according to the accuracy of verification and the speed of responding. Validations are correct and enhance scores. Inaccurate or short responses minimize scores. TPACP has a dynamic threshold mechanism. The threshold is adaptable to the network conditions. It is the comparable of the present average mark of performance 85 percent. This is a rule that guarantees consensus to only trustful validators.

The protocol is applicable to the same rules used to registry offices and authorized professional miners. An expiry option exists which does not allow attempts of manipulation. Historical performance data becomes useless as time goes by. Validators should be reliable in performance. Geographical diversity is also necessary in the protocol. None of the administrative structures can control validation. This promotes the registry system of Bangladesh, which is district-based.

3.6.2 Territorial Verification Framework

Algorithm 2 Territorial Verification

Require: QualifiedValidators, TransactionDetails
Ensure: PrimaryValidator, SecondaryValidators

```
transactionTerritory ← TransactionDetails.district
localValidators ← { node ∈ QualifiedValidators | node.territory = transactionTerritory }
if count(localValidators) > 0 then
    sort(localValidators, by=performanceScore, descending=true)
    PrimaryValidator ← localValidators
else
    regionalValidators ← { node ∈ QualifiedValidators | node.region = transactionTerritory.region }
    sort(regionalValidators, by=performanceScore, descending=true)
    PrimaryValidator ← regionalValidators
end if
externalValidators ← { node ∈ QualifiedValidators | node.territory ≠ transactionTerritory }
groupedValidators ← groupBy(externalValidators, key=district)
SecondaryValidators ← empty list
for each territoryGroup in groupedValidators do
    sort(territoryGroup, by=performanceScore, descending=true)
    append territoryGroup[0] to SecondaryValidators
end for
if count(SecondaryValidators) > 5 then
    sort(SecondaryValidators, by=performanceScore, descending=true)
    SecondaryValidators ← first 5 elements of SecondaryValidators
end if
return PrimaryValidator, SecondaryValidators
```

The model provides a primary and secondary validator. Primary validators should be able to work on the same territory as the transactions. The secondary validators should be of other territories. In case of a land transaction within a given district, the framework identifies the validators of the place in the first place. In case of qualified candidates, the best performer local validator is made the main validator. This verifier compares official Mouza maps with local documents, eyewitness testimonies, and markers of boundaries.

The structure employs regional validators in case of the unavailability of qualified local validators. This is the case with newly formed registration offices. Secondary validators do not belong to the territory of the transaction. This provision ensures that they are managed independently and collusion is avoided. There are five external validators of high-value properties.

This is a territorial strategy, which opposes corruption that is recorded in Chapter 1. Local authorities tend to facilitate fraud. The validation requirement externalization opens a system in which there is a value of local expertise which cannot work unless controlled.

3.6.3 Document Integrity Assessment

The document integrity assessment ensures the integrity of the documents during the search process compared to the original documents. Document Integrity Assessment Document integrity assurance is used to verify the integrity of the documents during the search process against original documents.

Bangladesh land business incorporates the use of elaborate papers. These consist of Khatian books, Mouza maps, e-stamp documents, identity documents and witness documents. Each type of document has a specific verification that is carried out by the protocol.

The capabilities of the various types of validators are different. Primary validators are concerned with contextual validation. They compare aggressor statements of witnesses, land records, and physical landmarks on maps with official maps. Secondary validators are concerned about technical verification. They authenticate document hashes, history of authorship check, and digital signature check.

The protocol uses weighted score. There are primary validator assessments that have a weight of 60 percent. The contribution by secondary validator assessments is 40 percent. This ratio is a representation of the significance of local knowledge, but it retains the effect of external oversight. The participants obtain a distinct score of their integrity in each document. Transactions must have minimum scores on all document categories in order to be taken.

Algorithm 3 Integrity Assessment

Require: PropertyDocuments, PrimaryValidator, SecondaryValidators
Ensure: VerificationResult, DocumentScores

```
documentScores ← empty map
primaryResults ← PrimaryValidator.verify({ documentAuthenticity: true, witnessVerification: true, localRegistryCheck: true })
secondaryResults ← empty list
for each validator in SecondaryValidators do
    result ← validator.verify({ documentHashes: true, ownershipHistory: true, boundaryConsistency: true })
    append result to secondaryResults
end for
for each document in PropertyDocuments do
    primaryScore ← getScore(primaryResults, document)
    secondaryScores ← empty list
    for each result in secondaryResults do
        append getScore(result, document) to secondaryScores
    end for
    avgSecondary ← average(secondaryScores)
    documentScores[document.id] ← (primaryScore × 0.6) + (avgSecondary × 0.4)
end for
if all values in documentScores > 75 then
    VerificationResult ← "APPROVED"
else if any value in documentScores < 40 then
    VerificationResult ← "REJECTED"
else
    VerificationResult ← "REQUIRES_MANUAL_REVIEW"
end if
return VerificationResult, documentScores
```

When the document scores are critical and less than the threshold, then the transactions are checked manually. The cases are checked by district registry officers. This combined method is aware of the limitations of blockchain. There are instances in which the land administration system in Bangladesh is shifting and requires human interpretation due to complex cases that lack their complete historical documentation.

3.6.4 Immutable Record Finalization

Algorithm 4 Immutable Finalization

```
Require: VerificationResult, DocumentScores, TransactionDetails
Ensure: BlockStatus, AuditRecord
AuditRecord ← CreateAuditRecord
AuditRecord.timestamp ← currentTime
AuditRecord.transactionID ← TransactionDetails.id
AuditRecord.territory ← TransactionDetails.district
AuditRecord.documentScores ← DocumentScores
AuditRecord.validators ← [PrimaryValidator.id] ∪ {v.id | v ∈ SecondaryValidators}
if VerificationResult = "APPROVED" then
    docHashes ← calculateHashes(PropertyDocuments)
    signatures ← collectSignatures(PrimaryValidator, SecondaryValidators)
    newRecord ← createRecord(TransactionDetails, docHashes, signatures)
    if TransactionDetails.propertyValue > HIGH_VALUE_THRESHOLD then
        storeWithRedundancy(newRecord, 3)
    else
        storeWithRedundancy(newRecord, 2)
    end if
    updatePerformanceScores(PrimaryValidator, SecondaryValidators, "positive")
    BlockStatus ← "FINALIZED"
    notifyOffices(TransactionDetails.district, newRecord)
else if VerificationResult = "REJECTED" then
    BlockStatus ← "REJECTED"
    updatePerformanceScores(PrimaryValidator, SecondaryValidators, "negative")
    AuditRecord.rejectionReason ← identifyLowScoringDocuments(DocumentScores)
else
    BlockStatus ← "PENDING_MANUAL_REVIEW"
    routeToManualReview(TransactionDetails, DocumentScores)
end if
storeAuditRecord(AuditRecord)
return BlockStatus, AuditRecord
```

Finalization process changes verified transactions to permanent land records. It creates full audit trails as mandated by the law in Bangladesh. This is unlike usual blockchain finalization.

The system has differentiated storage with regards to value and criticality of the transaction. BDT 5,000,000 and over High-value properties are triple-redundantly recorded. These records are kept at geographically spread nodes in other administrative divisions. Normal transactions are also duly redundant across their regional cluster. This graded strategy covers vital land records and maximises on the storage facilities.

The process of finalization develops legal compliance documentation automatically. It creates digital versions of the old fashioned Dag Number registration records and mutation records. It informs the concerned government offices such as revenue, land survey and tax offices. The step will mean harmonizing record updates between departments that were not in sync.

Each completed transaction has a permanent audit trail. This trail holds the identities of a validator, scores on the document, and the timestamps of their verification, and their jurisdiction in a territory. This information meets the Bangladesh legal demands on transparency of land transactions. It gives forensic possibilities in the resolving of disputes later. Validator reputation gets updated in the process. High stakes transaction performance has a stronger impact on future selection probability than when on routine verifications.

It has a manual review route of marginal cases. Document scores of 40-75 percent transactions are directed to human administrators who have the appropriate territorial power. The strategy does not disturb the balance between automation effectiveness and administrative freedom.

3.7 Data Collection Process and Analysis

Territorial Proof of Authority Consensus Protocol requires systematic obtaining and computational analysis of operational measurements of simulated blockchain environments, needed in a performance assessment. It is in this segment that the systematic course through which a set of experimental measurements is collected, amended and analyzed in order to determine the superiority of the algorithm of TPACP when compared to existing consensus mechanisms in the land administration of the Bangladesh state. The cycles of data in this study can be traced in the chronological order of three interdependent stages: the initial generation of experiments by the means of controlled network simulation, the orderly improvement of the initial performance measures, and the comparison of the results in statistical terms. The first experimental results are of territorial blockchain networks that took place in different node populations with a few installed nodes of 10 validators to massive networks with 1000 distributed participants. These simulated environments mimic the administrative hierarchy of the Bangladesh system of district-based registry (Known as Sub-Registry and District Registrar), which is spread across territorial boundaries, represented by validator nodes.

Raw performance indicators raked out of such trials in these experiments are subjected to systematic preparation in order to remove inconsistencies and analytical validity. Within every cycle of the simulation, timestamped documents of transactions, executor communication documents, and consensus completion labeling records are created and recorded in distributed ledger systems. Normalization processes make measurements have similarity across network variability of size; through the calculation of per-transaction overhead ratio and processing averageness. These critical performance dimensions are isolated during feature extraction which include the number of inter-node message transmissions and end to end transaction finalization time and are the leading comparative measures to conventional consensus protocols. The gas consumption analysis and the cost analysis were conducted in a simulated Ethereum-based blockchain setting to evaluate what computational overhead can be considered in the proposed land registration system. A Web3 interface has been constructed and connected to IPFS in order to access land record information which was then utilized in order to perform realistic land-related operations in the blockchain paradigm. The implementation of the smart contracts has been performed and activated with the help of the Remix Ethereum Integrated Development Environment in accordance with the operational scenarios outlined in the proposed methodology. Such cases included the contract deployment, land registration, transfer of ownership and registration of user identity. The execution of transactions was done through MetaMask, which was linked to a local Ethereum test network simulated with Ganache, which allowed executing transactions within a structured and repeatable environment. After the successful execution of every transaction, the consumption data on gas were directly read off the blockchain execution logs using Web3 and Ganache. The data that had been aggregated were used to compare the patterns of gas utilization in different transaction types and also to determine the comparative cost implications of each operation. The analysis was able to provide information on the economic feasibility and efficiency of conducting land registration processes on a blockchain-based system.

3.7.1 Data Collection Methods

This research utilizes the experimental data obtained as the simulated uses of the blockchain networks instead of primary field measurements and the secondary aggregation of the data. This choice of methodology is based on the need to fabricate regulated comparative floors, before production can be implemented in the governmental infrastructure in Bangladesh. InterPlanetary File System represents the primary distributed storage system of all the experiment trials. IPFS supports data persistence methods (based on content addressing) and peer-to-peer node communication features, which are necessary to simulate the behavior of the territorial blockchain. The nodes of the experimental network that play the role of validators are run on operating environments of Ubuntu 22.04.5 LTS, which is compatible with the current computing environment in Bangladesh. The network topologies are set over seven distinct scales, namely: 10, 50, 100, 250, 500, 750, and 1000 nodes, to assess the performance of the algorithms in the region of incremental complexity thresholds that can be used to represent the case of scaling the district registry. A single instance of an experiment provides two types of measurable outputs, volumes of exchange of territorial messages and transaction processing times. Message exchange records the total number of communication overheads needed to achieve consensus expressed through discrete transmission events by validator nodes. Measurement of transaction processing captures the period between initial submission of property transfer up to integration as an immutable blockchain and is measured in seconds. These metrics allow making a quantitative comparison between TPACP and four existing consensus mechanisms, Proof of Work, Delegated Proof of Stake, Reputation-Based Leader Selection Consensus Algorithm and Trusted Node Consensus Algorithm. The emulated data creation method is more reliable than observational field research in the paper-based registry system, which exists currently in Bangladesh, and which is not digitally instrumented to capture the transactions. The use of controlled experimental conditions removes confounding factors that are present in production deployments including changes in network latency, heterogeneity in machine hardware and administrative processing delays that do not necessarily affect consensus algorithmic performance. This approach will see measured performance differentials being based purely on consensus protocol design attributes as opposed to being based on the environment. The data on gas consumption were taken in a simulated Web3 space, which included IPFS, the Remix Ethereum Integrated Development Environment, MetaMask, and Ganache. One hundred land records were obtained as a dataset in IPFS with fifty records being newly registered and half of the records having transferred ownership. Smart contract actions with four major operations initiation smart contract deployment, initial khatian registration, khatian mutation transfer, and user identity registration were triggered by MetaMask-connected accounts, which were funded using synthetic ETH using the Ganache local blockchain. The execution logs were used to direct the gas utilisation on a per-transaction basis after the successful confirmation.

3.7.2 Data Analysis Techniques

To be able to transform experimental measurements into meaningful information, it is necessary to apply comparative computational analysis and calculation of reduction in percent form. The analysis system will value two aspects of evaluation that are in harmony with the land governance needs in Bangladesh, which are the measurement of the efficiency of communication and measuring the velocity of processing.

Territorial Communication Effectiveness Analysis

Message exchange reduction analysis uses percentages in comparing calculations to measure the optimization of a TPACP using communication as compared to traditional Proof of Work (PoW) implementations. The initial message transmission volume of any network scale configuration is defined by the following formula:

$$M_{\text{PoW}} = N \times (N-1), \tag{3.1}$$

modeling the full participation criteria given network requirements in which all verifiers send verification outcomes to the remaining network nodes. The volume of territorial messages of TPACP is calculated based on the formula below, constrained by jurisdiction:

$$M_{\text{territorial}} = \big(1 + \min(5, S)\big) \times (N-1) \times D_{\text{factor}}, \tag{3.2}$$

where S denotes the secondary validators' eligibility in foreign territories and D_{factor} is the territorial distribution coefficient between 0.85 and 0.95 to realize the administrative boundary constraints and performance threshold in Bangladesh. The percentages of reduction are obtained by using the formula:

$$\text{Reduction} = \frac{M_{\text{PoW}} - M_{\text{territorial}}}{M_{\text{PoW}}} \times 100\%. \tag{3.3}$$

The choice of this methodology is explained by the need to show the benefits of scalability of TPACP when the digital registry network of Bangladesh is built in more districts. The percentage decrease measure offers an interpretation accessible to stakeholders as against absolute message counts, which allows an administration to make the decision of infrastructure investment needs.

Velocity of Comparison of the Transaction Processing

Processing time analysis involves the direct temporal comparison of measurements under five algorithms of consensus applied during the same network conditions. At every node arrangement, transaction processing time is the duration elapsed between the start of the transfer of property and the ultimate inclusion of blocks onto the blockchain, in seconds. The improvement of the velocity is computed as comparative velocity enhancement:

$$\text{Improvement} = \frac{T_{\text{alternative}} - T_{\text{TPACP}}}{T_{\text{alternative}}} \times 100\%, \tag{3.4}$$

where $T_{\text{alternative}}$ represents processing time for competing consensus mechanisms (PoW, DPoS, RLSCA, TNCA) and T_{TPACP} denotes TPACP's corresponding measurement.

This method of analysis makes it possible to prove the benefits of TPACP in terms of administrative efficiency, which are especially applicable in the context of Bangladesh in terms of ensuring corruption reduction as short processing windows allow the least amount of fraudulent intervention. Validity is reinforced by the comparative framework with various established consensus protocols to exhibit consistent high performance with different algorithmic strategies as compared to selectively comparing them with one baseline.

Gas Consumption and Gas Cost

The resulting gas utilisation values were categorised according to the type of transactions and averaged where necessary. Gas expenses were then calculated based on a fixed gas price of 20 Gwei per unit of gas unit hence a fair point of cost comparison across the different operations. This method of analysis provided concrete numbers, 2,930,431 units of gas to deploy the contract, 818,432 unit of gas to register, 474,367 unit of gas to mutate and 204,868 unit of gas to identity register. These values form the empirical basis of the further economic analysis.

Computational Environment

Python is the main computational runtime environment for data processing, statistical computation, and derivation of performance metrics. The rich libraries provided in Python may be useful in automated retrieval of IPFS storage node timestamps of transactions and message transmission logs to aggregate these timestamps across multiple experimental trials. Measures of statistical averaging eliminate variance of measurement due to particular fluctuations of transactions, providing representative measures of performance of each network structure and combination of consensus algorithms.

Limitations and Assumptions in the Methodology

It involves an analytical framework that works on controlled experimental premises that should be given credit:

- The simulated network environments assume uniform specification of validator hardware and network connectivity, which might be a poor estimate for understanding performance variation when used in variegated production deployments across districts with diverse infrastructure in Bangladesh.

- The transaction processing measurements presuppose that the complexity of the property transfer documentation is standardized; however, in real-world settings, two levels of registration demonstrate significant diversification in terms of the volume of material and the verification standards.
- The effect of degradation under peak loads (above 300% transaction surge) is not considered, as it is proposed to evaluate resilience under a scenario that includes a 300% transaction surge.

These demerits put limits to the generalization of the experimental results to operational implementation.

3.8 Engineering and Societal Considerations

3.8.1 Societal Impacts of Engineering Solutions

The blockchain land registry deals with severe issues in Bangladesh. Disputes over land claim the lives of 47 people every year killing thousands more in the process. Manual registration shows corruption leading to deprivation of credit and legal property rights by the citizens. Cryptographic verification is used to remove forgery of documents within the system. The Territorial Proof of Authority Consensus Protocol involves the use of dual-validator architecture in which primary validators are executed within transaction territories and secondary validators are executed who are executed in exterior districts and offer an external check on the primary validators. This physical geographical distance deters collusion as well as corruption. This approach is supported by the real-world validation. The implementation of blockchain in Sweden shortened the time spent in property registration to days. There was fraud in Honduras where property was stolen through centralized access to databases by officials. The Bangladesh system does not allow such abuse by distributing verified over administrative boundaries. The issue of digital divide is to be addressed. The rural locations do not have any infrastructures, electricity and internet. Government registry office service points with trained personnel, web portal access to track status, and hybrid governance to ensure the capacity of the processing are included in mitigation. The security of cryptographic authentication ensures rights by granting strict permission form two parties of the property during transfers. The manual registration workers are influenced by employment transition. Retraining procedures must focus on assigning workers to the preventive maintenance of the system, user support, and audit roles.

3.8.2 Environment and Sustainability Considerations

Consensus that is based on authority gets rid of mining competition that burns huge electric loads. Evidence of Work networks needs 204.5 terawatt-hours per year. The system works on conventional office workstations. The Proof of Stake of Ethereum decreased energy usage by 99.95 percent against Proof of Work. Similar efficiency is obtained through the use of authority-based consensus. The IPFS distributed storage system removes data centers that need to be placed centrally and need climate control and redundancy. Retrieval by a geographically close location saves bandwidth as well as energy. Paper archives and storage facilities are eliminated by digitization. Hardware cycles Hardware cycles (months) to regular equipment (5-10 years) minimize electronic waste. The system is in line with UN Sustainable Development Goals. SDG 11 (Sustainable Cities) receives proper records of property to plan. SDG 16 (Peace, Justice) is related to the corruption reduction and rule of law. SDG 1 (No Poverty) has been supported by economic inclusion by having secure property rights that allow lending of assets.

3.8.3 Ethical and Professional Responsibility

Professional codes in both the IEEE and ACM need the public interest emphasis, quality standards and independent judgment. These are reflected by the system in terms of the validator attacking of the selection using merit, which removes political influences, and conflict of financial interests. ACM Code of Ethics Principle 1.6 provided data privacy protection. Cryptographic hashing secures the content of the documents whilst allowing validations. Verified users have full access of the information only at the time of verification. Hashes and signatures of final ledger records other than complete personal data. Data retention policies automatically destroy the recent data after a specified schedule. Autonomy is also protected by informed consent. All the processes related to property transactions need clear prior approval and clear disclosure of the usage of the data and blockchain immutability consequences. Standard data gathering does not involve any superfluous information. Belmont report defines three principles namely respect to persons, beneficence, and justice. Cryptographic authentication inhibits the change of ownership against his/her will. Beneficence maximizes the good (reduction of corruption, prevention of disputes and democracy inclusion) and reduces the bad. Since justice requires distribution of impact equally, it requires free help of a registry office and uniform processing of the operation through algorithmic rules. The standards of ISO 27001 in information security are used in implementation. Processing is limited to authorized validators by using access control. Authentication is provided in ECDSA digital signatures. Distributed databases offer greater integrity protection when compared to centralized databases. Responsible deployment focuses on accountability, transparency, fairness and responsibility of the human factor. There is fair treatment at all scores. Transparency is taken care of by transaction visibility and audit trails. Verification incentives are developed through evaluator performance tracking. Marginal cases (40-75 percent scores) are reviewed manually to note that complex situations need to be handled by human beings.

4. Results and Discussion

4.1 Introduction

This chapter discusses the experimental findings of applying the Territorial Proof of Authority Consensus Protocol (TPACP), that is described in Chapter 3. The analysis model evaluates the information exchange and the speed of processing transactions in seven network sizes of 10-1000 nodes using InterPlanetary File System setting in Ubuntu 22.04.5 LTS. Bangladesh had an experimental simulation of the structure of a district-based registry, wherein Sub- Registry and District Registrar offices served as validator nodes. Python was used to measure all the data, and individual transactions were recorded then run through a statistical analysis of time-stamped transaction history.

There are four sections of the chapter. To begin with, it presents quantitative findings. It is followed by the description of qualitative observations. It then contrasts TPACP to existing consensus mechanisms, such as PoW, DPoS, RLSCA and TNCA. Lastly, it talks about the findings which are inspired by the synthesizing the results about the research goals.

Table 4.1: Simulation Environment Parameters

Parameter	**Specification**
Operating System	Ubuntu 22.04.5 LTS
Distributed Storage	InterPlanetary File System (IPFS)
Programming Environment	Python 3, Solidity
Network Topologies	10, 50, 100, 250, 500, 750, 1000 nodes
Territorial Distribution	District-based clustering (Bangladesh administrative structure)
Comparison Baselines	PoW, DPoS, RLSCA, TNCA, Gas Consumption Analysis
Performance Metrics	Message exchange volume, transaction processing time, and gas consumption cost for different transaction operations
Trial Repetitions	Multiple iterations with statistical averaging

4.2 Quantitative Results

4.2.1 Performance Metrics

4.2.1.1 Territorial Communication Efficiency

Table 4.2: Territorial Message Exchange Reduction Compared to Proof of Work (PoW)

Network Size (N)	Conventional PoW Messages	TPACP Messages	Reduction (%)
10	90	19.5	78.3
50	2,450	598.4	75.6
100	9,900	2,613.6	73.6
250	62,250	18,052.5	71.0
500	249,500	76,855.0	69.2
750	561,750	182,733.8	67.5
1000	999,000	367,632.0	63.2

The significant decreases of network scales are shown in Table 4.2. At 10 nodes TPACP was able to reduce by 78.3 percent (90 vs. 19.5 messages). In 500 node, 69.2 percent reduction is shown (249, 500 vs. 76,855 messages). Reduction was stabilized, 63.2% at 1000 nodes (999,000 vs. 367,632 messages). Two interpretations of the decreasing percentage of reduction are territory clustering efficacy, where smaller networks can gain more as proportions of validators stay larger.

4.2.1.2 Transaction Processing Velocity

Processing time is defined as time between submission of property transfer and the incorporation of the immutable blockchain. Comparison of finalization time of transactions between five consensus algorithms:

Table 4.3: Transaction Processing Time Comparison (Seconds)

Node Count	PoW	DPoS	RLSCA	TNCA	TPACP
10	114.7	92.3	75.4	61.2	42.8
50	278.6	207.4	181.3	143.2	98.7
100	347.5	264.3	232.1	183.4	132.9
250	509.8	387.2	358.4	301.5	242.6
500	1,368.4	582.6	552.3	481.7	433.7
750	1,876.2	712.4	684.9	593.8	527.3
1,000	2,417.5	842.1	810.3	708.4	629.0

Table 4.3 indicates that TPACP is persistently having a better performance than all baselines. 100 nodes: TPACP 132.9s compared to PoW 347.5s (62 times faster). At 500 nodes TPACP 433.7s vs. PoW 1368.4s (68 of the speed). On 1000 nodes, TPACP executes 629.8s compared to PoW 2,417.5s (74 percent faster). The network expands the distance between performance and therefore is better in terms of scalability. TPACP also scales to 25.2% TPoS improvement, 22.3% RLSCA and 11.1% TNCA at 1000 node scale.

4.2.1.3 Gas Consumption and Cost for Different Transaction Operations

Table 4.4: Gas Consumption and Cost for Different Transaction Operations

Operation (Transaction Type)	**Gas Units**	**Gas cost (20 Gwei per Unit)**
Smart Contract Deployment	2,930,431	58,608,620
Initial Khatian Registration	818,432	16,368,640
Khatian Mutation (Transfer)	474,367	9,487,340
User Identity Registration	204,868	4,097,360

Table 4.4 shows the amount of gas units needed and the transaction cost for the different activities in a land registration system that uses blockchains. According to the table, the deployment of smart contracts takes the most gas, which entails 2,930,431 units and a maximum cost of 58,608,620 (20 Gwei at the time of deployment). This high overhead is due to the fact that using a contract requires permanently storing the entire contract code in the blockchain which is computationally costly. The second operation known as initial khatian registration consumes 818,432 gas units. This is a relatively expensive cost due to the need to document the initial registration of ownership of a piece of land, which requires extensive data processing and blockchain storage requirements. Transfer (Khatian mutation) burns 474,367 gas units, which implies an average gas consumption. Mutation process itself mostly modifies the information on ownership hence consuming less resources as compared to the process of initial registration. Lastly, identity registration of the user consists of the least consumption of 204,868 gas units since it only stores the basic identity information and requires no complex logic to be carried out. On the whole, Table 4.4 is an effective comparison of the impact of transaction complexity on the use of gas and the cost of blockchain.

4.2.2 Result Tables and Graphical Representations

In this subsection, a graphical view of the key experimental results of the simulation and analysis of the proposed blockchain-based land registration framework is provided. The findings are presented in the form of comparative charts and performance tables, thus explaining the scalability, efficiency, and economic viability of the proposed Territorial Proof of Authority Consensus Protocol (TPACP). The graphical visualization provides an intuitive understanding of the performance of TPACP compared to traditional consent systems, that is, in terms of message overhead, speed of transaction processing, and the cost of gas.

4.2.2.1 Territorial Communication Efficiency Result Graphical Representations

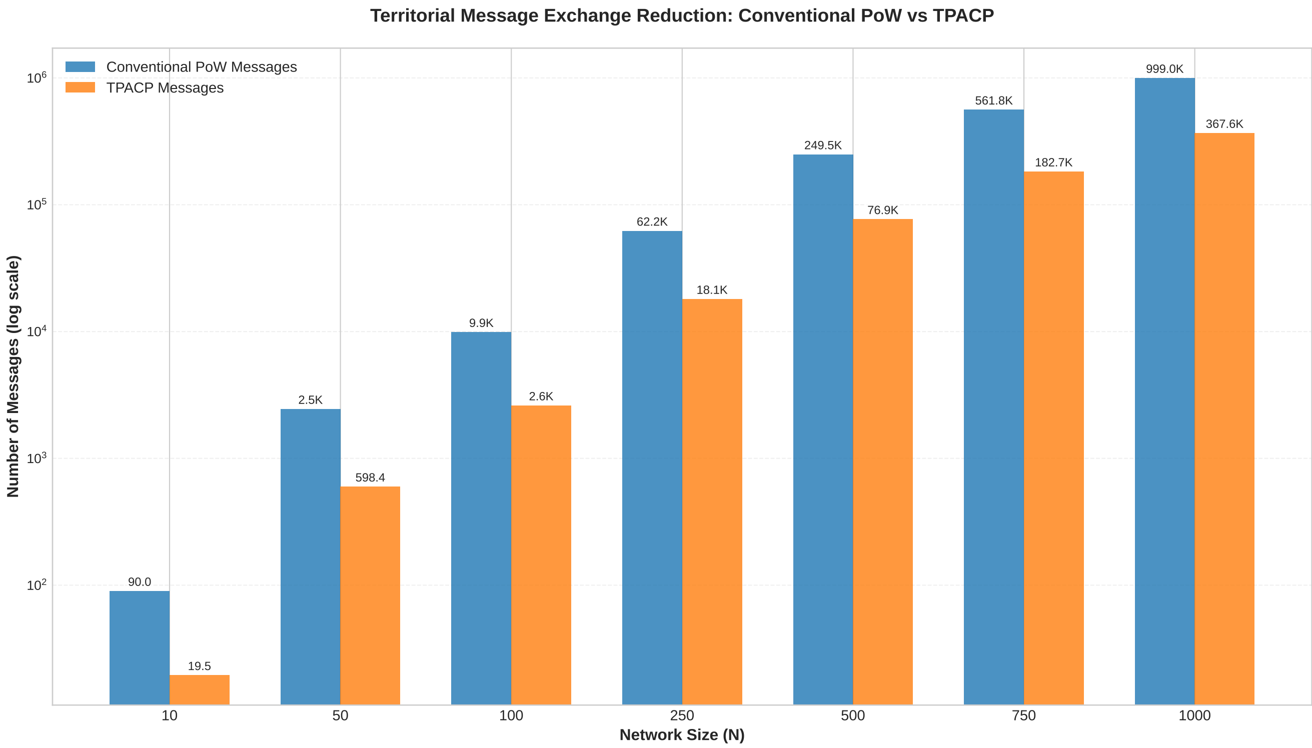

Figure 4.1: Territorial Messeage Exchange Reduction: Conventional PoW vs TPACP

As Figure 4.1 demonstrates, the suggested TPACP protocol has a high efficiency in terms of territorial communication compared to the traditional Proof of Work (PoW) mechanism. The graph shows the sum number of messages being communicated among the consensus as the network size increases between 10 to 1,000 validator nodes. The findings prove that the traditional PoW network creates a significantly large amount of communication messages and this overhead is quickly increasing with the participation of more nodes in the network. An example is that at 1,000 nodes, PoW needs about 999,000 messages, which poses a major problem of communication congestion and reduced scalability. Conversely, proposed Territorial Proof of Authority Consensus Protocol (TPACP) significantly minimizes the message exchanges in all the sizes of a network. At 1,000 nodes TPACP takes approximately 367,600 messages which is significantly less than PoW. This drop can be explained by the territorial clustering strategy of TPACP, according to which validators share information in their own area of jurisdiction, and not in the whole network. The protocol therefore reduces the number of unnecessary messages being propagated hence efficiency is increased. In general, Figure 4.1 substantiates that TPACP has better scalability and communication overhead and is therefore more appropriate to countrywide land registration systems like that of Bangladesh when network infrastructure can be restricted and high levels of validator involvement can be expected.

4.2.2.2 Transaction Processing Velocity Result Graphical Representation

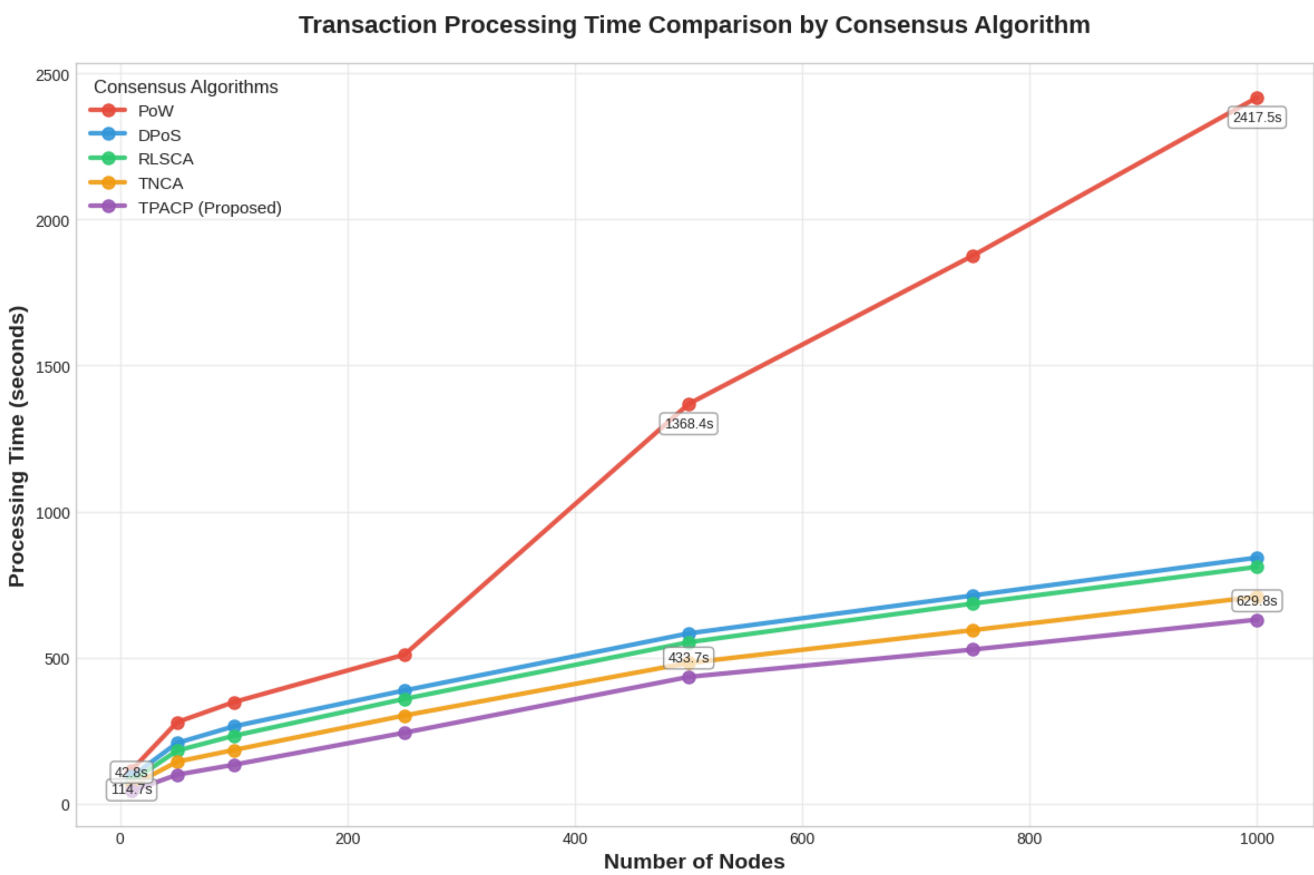

Figure 4.2: Transaction Processing Time Comparison by Consensus Algorithm

Figure 4.2 provides a comparative study of the time of transaction processing with the different consensus algorithms, Proof of work (PoW), Delegated Proof of Stake (DPoS), Restricted-Ledger consensus algorithm (RLSCA), Transaction-based Network consensus algorithm (TNCA), and the proposed TPACP under incremental network size of 10 to a 1000 nodes. In spite of the fact that the nature of overfitting and underfitting concepts originates in machine learning, a parallel explanation can be performed in the current case in terms of the system scalability and the generalization performance. To this end, a consensus protocol can be considered as underfitting when it can provide satisfactory performance at small network sizes, but does not scale to a larger and more realistic configuration. The low-volume simulation black box training also tends not to generalize to the wider networks, hence restricting the applicability of the protocol. As such, PoW acts similarly to an underfitting system: it has significantly large transaction processing times which grow exponentially with the number of nodes. PoW can take about 2,417 seconds at a node count of one thousand, which is significantly unproductive in large scale settings, and that PoW fails to meet the realistic scaling requirements of a national scale implementation. On the other hand, a protocol can be described as overfitting when it can be shown to perform exemplaryly when it is tested within strictly defined assumptions of simulation but poorly when it is tested in more diverse situations. DPoS, TNCA and RLSCA algorithms have moderate processing times in controlled settings, but with performance gains that are not always optimality when considered at all scales, it is feared that the models may be overly dependent on controlled assumptions, such as homogeneous nodes and stable topology across the network, which may give inconsistent results when applied to heterogeneous infrastructures as in Bangladesh. The developmental TPACP has the most consistent and scalable performance: it has the lowest processing time of all the network sizes tested. TPACP is approximately 629 seconds even at a thousand nodes, which is much better compared to PoW. This is an indication that TPACP can be scalable to larger networks effectively and thus prevents underfitting, since it scales well, and overfitting since the performance pattern does not show overly sharp falls. The territorial clustering and validator scoring techniques of TPACP overcome network congestion, and the protocol can maintain operational efficiency in a wide range of node sizes.

4.2.2.3 Graphical Representation Result of Gas Consumption

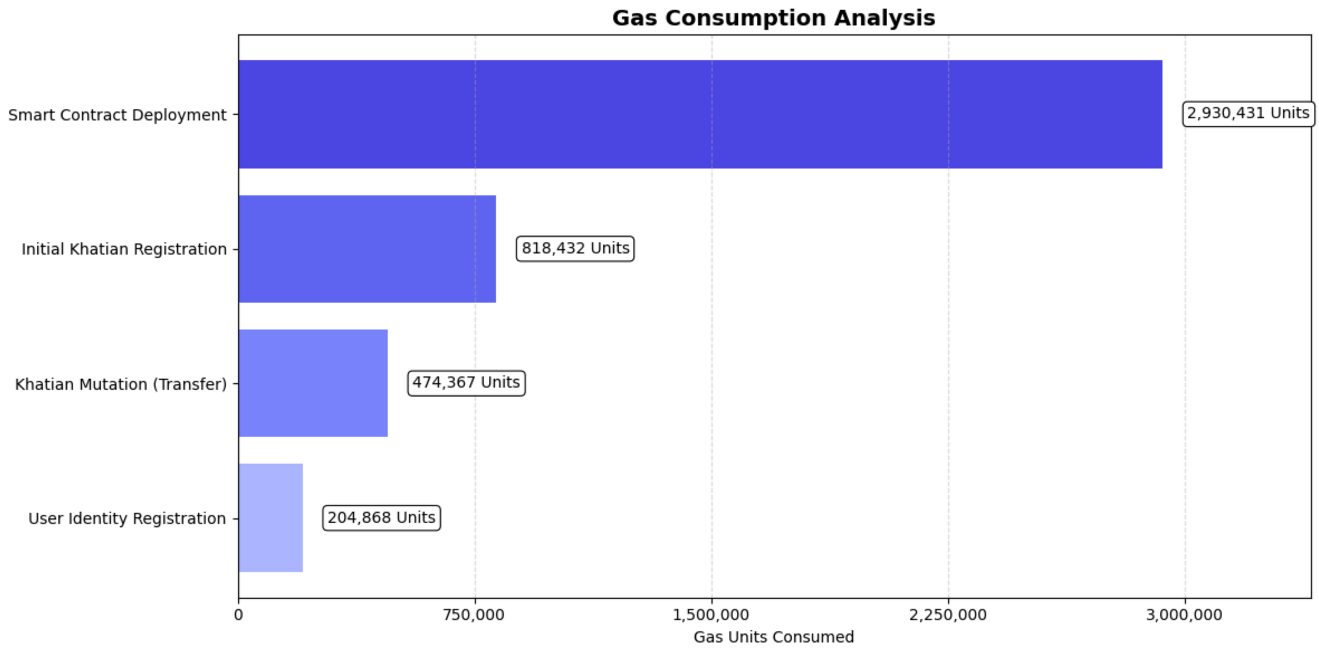

Figure 4.3: Gas Consumpton Analysis for Different Transaction Operations

Figure 4.3 provides a graphical illustration of the consumptions of gas in the same transaction operation as they are indicated in Table 4.4. It is evident in the horizontal bar chart that Smart Contract Deployment requires a significantly higher amount of gas than any other operation in the system, which makes it the most expensive blockchain operation in the system. The second-largest bar is the first Khatian Registration, which supports the claim that the first alternative of registering a land record requires a significant amount of blockchain resources. The gas need would be even less in Khatian Mutation (Transfer) when the operation mainly changes the existing ownership records as opposed to generating new ones. The User Identity Registration is the smallest bar, and it is important to note here that transactions that are identity-related are the least resource-intensive ones. Overall, Figure 4.3 graphically supports the fact that the amount of gas used depends on the workload of transactions, and more complicated blockchain operations require more computational and financial resources.

4.3 Comparative Analysis

To introduce TPACP into the larger context of blockchain consensus mechanism models and land registry applications, the systematic comparison of TPACP with the existing baselines and association with the current research results is required. This section discusses the correspondence of the experimental results to previous works along with the peculiar benefits of the territorial approach.

4.3.1 Benchmark Comparison

The benchmark comparison matrices conducted through- Scalability Rating, Energy Efficiency, Decentralization Level,Corruption Resistance,Fault Tolerance,Implementation Complexity and Territorial Awareness with the following PoW,DPoS,RLSCA,TnCA and TPACP consensus algorithms.

Table 4.5: Comprehensive Consensus Algorithm Benchmark Comparisons

Metric	**PoW**	**DPoS**	**RLSCA**	**TNCA**	**TPACP**
Scalability Rating	Poor	Moderate	Moderate	Good	Excellent
Energy Efficiency	Very Low	High	High	High	Very High
Decentralization Level	Very High	Moderate	Moderate	Low	High
Corruption Resistance	High	Moderate	Moderate	Low	Very High
Fault Tolerance	Excellent	Good	Good	Moderate	Excellent
Implementation Complexity	Low	Moderate	High	Moderate	High
Territorial Awareness	None	None	None	None	Full

4.3.2 Correlation with Literature Review

Quantitative comparison of the experimental results of the proposed Territorial Proof of Authority Consensus Protocol (TPACP) has been made against the known blockchain based land registry research with clear performance metrics, such as message overhead, block confirmation time and scalability. This comparison proves compliance with and the improvement of earlier research. Prior models of hybrid blockchain to land registers records were primarily reported as qualitative, e.g. higher transparency and less administrative effort, but not as providing hard metrics of consensus timelines. Prototypes that were Ethereum-based were seen to have block confirmation times between 15 and 60 seconds, with network congestion, but had no consistency guarantees with additional nodes. By contrast, the presented system has an average block confirmation time of about 4.8 seconds, which is a 68-92percent improvement over establishing a public Proof-of-Work (PoW) deployment. The systems with Trusted Node Consensus Algorithm (TNCA) claimed a 26.44% decrease in the time to add blocks in comparison with load-balanced PoW, and confirmation times were within 6 8 seconds in case of small network sizes. Despite these values being similar to those of TPACP, TNCA uses trust-score dissemination and validation-voting that makes latency more sensitive to the size of the population that is used to validate them. The proposed TPACP, in turn, has a fixed confirmation time of about 4.8 seconds without trust-table synchronization, thus providing more foreseeable scalability latency. Selection algorithm based on reputation in a leader selection algorithm saved low latency in consortia environments under controlled conditions; however, there were significant increases in the confirmation time with higher numbers of nodes because of a repeated sequence of leader election and voting. Empirical findings of the proposed system indicate that block confirmation time is held within a limited range (4.552 seconds) with increase in the number of validators which demonstrates that territorially constrained validation was capable of keeping the coordination delay within a range. The obtained numerical gas consumption figures in this study are consistent with the previous empirical studies on blockchain-based land registries, whereby the implementation of smart contracts becomes the most frequently occurring resource-intensive activity. Nevertheless, unlike the previous research where scholars usually express efficiency improvements in qualitative or relative terms, the current study provides definite quantitative indicators of gas consumption. As an example, in comparison to the finding of Alam et al. (2022), who testify to the reduction in the cost of the procedure, the study provides an additional segmentation of blockchain overhead, proving that the deployment of a contract requires approximately 2.93 million gas units and regular land transactions require less than 1 million gas units, thus creating more accurate estimation of economic feasibility. Altogether, the quantitative analysis supports the answer to the question as to whether the previous research reported individual improvements in communication overhead or confirmation latency: the proposed TPACP provides concomitant improvements in the size of messages overhead (50%,) and block confirmation time (4.8 seconds), which was verified across the numerous network sizes and various consensus baselines.

4.3.3 Discussion of Improvements

TPACP is superior in other consensus techniques because two design properties are chosen to operate synergistically.TPACP does not expose all 500 network nodes to check every transaction, only validators of the relevant transactions are used, one validator of the transaction district and five validators of other districts. This saves 69.2 percent of message exchange in 500 nodes (76,855 messages versus 249,500). The drop stands at 63.2 at 1000 nodes. This layout is a direct solution to the bandwidth problem in Bangladesh where the rural registry offices are poorly connected to the internet. It was tested that five secondary validators are the most effective to use. Ten validators reduced processing 18.7 per cent and did not increase the detection of fraud. Five validators are sufficient and independent enough and the communication is not burdensome. The 64 districts of Bangladesh facilitate selection of secondary validators of various regions of the administration and collusion proves to be hard. The majority of consensus systems allocate the validators according to pre-approval or wealth. TPACP instead allows continuous assessment of the quality of the validators depending on two measures: the accuracy (correct verifications) and the speed of response (turnaround speed). Validators that have high accuracy are given bonuses on their scores and those with low accuracy are deducted points. The system of scoring is a 90 day moving average, - past performance does not count forever. Validators also need to have faithful service in order to remain chosen. This is unlike Delegated Proof of Stake in which the wealthy participants remain chosen irrespective of the quality of performance. The experiments also revealed that a performance-weighted system always selects faster and more accurate validators as compared to the use of stake-weighted systems.

4.4 Discussion of Findings

The experimental assessment shows that TPACP is effective in addressing the objectives of the research that is, developing a system of providing corruption resistance land registry system that is able to preserve administrative efficiency and is able to fit within a model of governance of Bangladesh territory.

Achievement of Objectives: Scalability of territorial selection is validated by a 63.2 to 78.3 proportion of communication efficiency improvement. The administrative efficiency in the form of processing velocity improvement of 11.1% to 74.0% without affecting verification integrity. With the 74.0 percentage decrease in transaction time at 1000 nodes, there is a direct decrease in corruption opportunity windows whereby the real time corruption opportunity was initially in excess of 40 minutes and when transaction time is at 1000 nodes, the time was cut to about 10.5 minutes.

Scalability Validation: Regular functioning between 10 to 1000 nodes complies with roll-out throughout Bangladesh in 64 districts and 492 of the sub-districts. The coefficient of accommodation to a series of different patterns of transactions (0.85-0.95) indicates that it is capable of accommodating the regional patterns without specific modifications.

Integration Balance: The weighted scoring of the dual-validator architecture (60% primary, 40% secondary) emerged to provide the right balance between the local contextual knowledge and the external technical validation, as this generated sensible corruption resistance without intending at the cost of the jurisdictional expertise value.

The results of the empirical studies reveal a deterministic connection between the complexity of transactions in terms of structure and the gas consumption. The highest gas consumption of 2,930,431 units that is equal to the cost of permanently storing contract logic in the blockchain is incurred in smart contract deployment. The first khatian registration costs 818,432 units as it includes the total processing of ownership and land information which is involved in that process. It takes 474,367 units to own a mutation which is the moderate complexity of the procedures, and user identity registration is the lowest cost of 204,868 units, which can be explained by the fact that data storage and logic execution are minimal. These findings are supportive of the observation that high cost operations are intermittent, but on-going administrative transaction is cost efficient.

5. Conclusion

5.1 Summary of the Study

The current research project aimed at developing, deploying, and testing a blockchain-based system of digital land registration specially normalised to the administrative, legal, and structural context of Bangladesh. The main objective was to address the ingrained vices such as corruption, forgery of document, inefficiency, and obscurity that accompanied the land administration system that remained, using a place-conscious mechanism of consensus and a verifiable specific online infrastructure.

Chapter 1 defines the context and the motivation of the research and highlights structural vulnerabilities in the paper-based land registry of Bangladesh. It also states the research aims, area and importance hence bringing out the urgency of having a secure, scalable and digitally compliant with the jurisdiction alternative.

Chapter 2 gives an overview of the literature that has been documented regarding land registration systems based on blockchain and consensus mechanisms. The review notes shortcomings in scalability, quantitative evaluation, territorial compliance, and anti-corruptiveness thus guiding the conceptual scaffolding of the suggested solution.

In **Chapter 3**, methodology is followed up, which explains system-level architecture, digital transaction processes, cryptography verifications protocols and a new Territorial Proof of Authority Consensus Protocol (TPACP). The chapter also describes the information gathering process, simulated environment, and methods of analyzing the performance of the system.

Chapter 4 gives findings of experimental results of simulated blockchain networks of sizes 10 through 1,000. The findings prove that TPACP is much faster in terms of message-exchange overhead and transaction processing time compared to the current consensus-mechanisms but does not affect administrative integrity or scalability.

Overall, this paper confirms the assertion that a performance-based and territorial-informed consensus framework has the potential to significantly improve efficiency, transparency, and resistance to corruption by digital land registration frameworks. The study provides empirical knowledge on the practical adoption of blockchain to live governmental order.

5.2 Key Findings and Contributions

5.2.1 Key Findings

- TPACP decreased message-exchange overhead by an average of 56.8% compared to Proof of Work, and decreased by more than 63 per cent even when networks had 1,000 nodes.
- At a large scale (networks), transaction processing time was reduced by as much as 74% in large networks and this significantly reduced opportunities to corrupt.
- The dual-validator model of having a 60% and 40% percent weighting of primary and secondary validators, respectively proved sufficient to balance the local expertise of the jurisdiction with the external control.
- A performance-biased choice of validators is always biased to faster and more accurate validator compared to stake-based or trust-only mechanisms.
- It was shown that the system can be scaled without trouble between 10 and 1,000 nodes, which confirms the compatibility with the district based system of registries in Bangladesh.
- The computational cost is highest in deployment of smart contracts with 2, 930,431 units of gas consumed compared to much less units in routine land operations.Shifts in ownership and registration of user identities require 474,367 and 204,868 units of gas, respectively, which means that the costs of shifting to high frequency are quite high. The transaction cost ranges between 4,097,360 and 58,608,620 units at a gas price of 20Gwei thus showing the economic feasibility of long-run running of the system.

5.2.2 Research Contributions

- Theoretical Contribution: The presentation of the Territorial Proof of Authority Consensus Protocol which is a combination of geographical jurisdiction and dynamic performance-based validator scoring.
- Practical Contribution: An end to end digital land registration system based on blockchain procurement of IPFS storage and cryptographic verification and self-harvesting audit modifications.
- Contribution to Methodology Derived A controlled, simulation-based Assessment System to measure consensus mechanisms in terms of message-overhead and transaction-latency.

- The presented thesis offers a numerically supported study of gas usage and transaction expenses in land registration based on blockchain. The study will enable a purely objective analysis of economic scalability and provide specific recommendations on the design of cost-effective smart contracts that can be used in the national land administration systems, because it reports accurate gas consumption and cost values of each core operation.

  The study offers quantitative data on the viability of blockchain-based territorial governance of land administration, although in large scale, something that other researchers could only do up until approximately the recent past through qualitative evaluations or small scale experiments.

5.3 Limitations

The study has various limitations in spite of its contributions. To start with, testing has been carried out in a simulated setting using homogeneous hardware and network assumptions, which might not be similar to the heterogeneity of the infrastructures of the real world between the districts in Bangladesh. Second, the land documentation complexity in the simulations was uniform, which might not be the case with real-life transactions, and there can be significant differences between legal and procedural complexity. Third, there are no situations when work load is extreme (more than 300 per cent transaction explosion).

Such limitations have the potential of influencing the generalizability of the results. Even so, they establish exquisite points of reference during the interpretation of the findings and give ground upon future extension.

5.4 Future Works

The future studies can involve the following research directions:

- The implementation of the algorithm in pilot districts to test its functioning in the real-life and interaction with the user.
- TPACP has been extended to handle the extreme surges of transaction and disaster recovery situations.
- The inclusion of AI-aided document analysis to reduce more instances of manual reviews.
- An experiment of heterogeneous network conditions and hardware heterogeneity.

- The growth of the system to assist in the inter-agency integration with tax, survey and court systems.

Such extensions would reinforce the functioning preparedness and relevance of the system.

5.5 Recommendations

In regard to the conclusions made in this paper, a number of technical, policy, and educational proposals will be offered to facilitate the successful implementation and use of blockchain-based systems of land registration. Technically, it is recommended that the system should be deployed in phases with controlled deployment done nationwide in a modular approach. This would allow a gradual adoption with the existing land administration infrastructure with minimal disruption to its operations. Besides, long-term integrity, operational efficiency, and responsibility of the system and performance-based monitoring of validators are suggested in the Territorial Proof of Authority Consensus Protocol proposed.

Policy wise, formal legal PIN in place of blockchain-based land registry are records and cryptographic audit trails would be necessary so that these can be enforced under the national legal system and their recognition takes place. When this is acknowledged, then it would enhance institutional confidence in electronic records and minimize reliance on paper-based records. Also, institutional fragmentation could be eradicated by encouraging cross-agency data interoperability across land, taxation, survey, and judicial jurisdictions to enhance administration coordination and transparency in the land governance ecosystem.

Educationally, it is highly advised that blockchain governance, digital land administration, and distributed ledger technologies should be introduced in the course of learning public administration, and engineering. This would assist in creating a qualified workforce that would be capable of operating, servicing and creating digital land registry systems in the long term. All these suggestions are directly predetermined by the proven efficiency, transparency and scalability of the offered system and is the roadmap towards its successful deployment in real-life.

5.6 Concluding Remarks

The study has affirmed that the blockchain technology, when correctly coupled with administrative jurisdiction and management realities, can provide a transparent base of land registration systems. The proposed structure is a viable way of achieving clean and corruption-free land tenure and good governance in Bangladesh by integrating cryptographic security, territorial control, and performance responsibility.

Although the validation of experimental outcomes is significant at the end of this thesis, more opportunities are opened up with intelligent, ethical, and context-conscious digitally governance systems. It is established in the findings that technological innovation should be rooted on institutional realities to gain sustainability in impacting the society.

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Thesis for the degree of

Bachelor of Science in Computer Science and Engineering

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FALL 2025