A Blockchain-based Framework for Energy Trading between Solar Powered Base Stations and Grid

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ABSTRACT

The rapidly increasing mobile traffic across the globe has proliferated the deployment of cellular base stations, which has, in turn, led to an increase in the power consumption and carbon footprint of the telecommunications industry. In recent times, solar-powered base stations (SPBSs) have gained much popularity in the telecom sector due to their ability to make operations more sustainable. However, some potential energy benefits rendered by the SPBSs have not yet been realized. In areas with dense base station deployment or low mobile traffic, SPBSs store surplus energy, which, in most instances, gets lost due to limited charge storage capacity of the batteries. To limit the wastage of energy, an appropriate mechanism enabling the utilization of excess energy produced by these base stations can be adopted. To this end, we model a Base Station-to-Grid (BS2G) network in which the grid can utilize surplus energy spared by the SPBSs. To overcome challenges in regards to scalability, robustness, and cost-optimization, we propose using the blockchain technology to create the BS2G network. Blockchain is a distributed ledger designed to record transactions in a transparent, lightweight, and tamper-proof manner. To make energy trade between base stations and the grid cost-effective, a game-theoretical approach has also been adopted in this paper. The proposed model simplifies the process of energy trading while also making it cost-optimal.

CCS CONCEPTS

• **Networks** → *Peer-to-peer networks*; • **Hardware** → *Energy generation and storage*; **Smart grid**.

KEYWORDS

Base Station-to-Grid, Blockchain, Ethereum, Smart Grid, Energy Trading, Distributed applications, Consensus

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1 INTRODUCTION

Owing to the rapid increase in the number of cellular users, and consequently, the number of cellular base stations, the strain on the environment has been massive. This is primarily due to the heavy reliance of the majority of off-grid and bad-grid cellular base stations on diesel generators for their power requirements. The impact of the wide-scale use of diesel generators been twofold: 1) an increase in the operating cost and 2) an increase in the carbon footprint. In recent times, multiple solutions have been proposed to reduce the dependency of the base stations on diesel generators. Among them, the use of solar-powered base stations (SPBSs) has emerged as a promising one [5]. SPBSs have made telecom operations smart, sustainable, and green by reducing the reliance of off-grid BSs on diesel generators for their energy requirements.

SPBSs have made an extensive contribution towards energy efficiency in the telecommunications industry. However, in remote areas, particularly in low mobile-traffic areas, solar power utilized by the SPBSs is often less than the solar power generated. Some of the excess energy is stored locally by the SPBSs for emergency purposes, but most of it is wasted. In this work, the smart grid technology is envisioned as a solution to solve this issue and maximize energy efficiency. Smart grids are expected to be a cutting-edge power grid technology with the potential to facilitate energy trade between SPBSs and the grid. To allow SPBSs to trade their excess amount of energy with the grid, we introduce the concept of Base Station-to-Grid (BS2G) networks. BS2G is a framework that enables an SPBS to trade its excess energy with the electric grid in exchange for some monetary benefit. The primary advantage of such a network is that it can enable an SPBS to sell or purchase energy from the grid subject to its requirements. Via this network, surplus energy generated by the SPBSs can be transferred to the smart grids and stored in the Electric Storage Units (ESUs) [8]. This energy can later be used to meet the local neighborhood's energy requirements. In recent times, several energy-trading frameworks in the domain

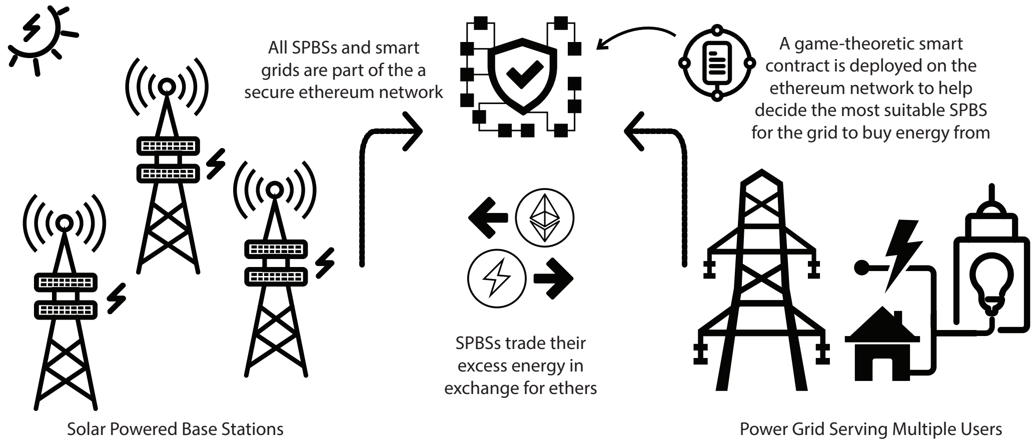


Figure 1: Proposed BS2G Framework

of smart grid energy trading have come to the forefront [16], [20], [22]. The game-theoretic frameworks adopted in the literature are, however, based primarily on classical game theory. Although such frameworks provide a suitable approach to resolve games involving multiple players with each player looking to maximize its gain, they are constrained by classical theory's inherent assumption that every player has knowledge of all sets of strategies and payoff functions. In real-life interactions, however, this assumption seldom holds. The evolutionary game theory (EGT) allows for a model that does not penalize the participants for having precise information about their own strategies only. In an evolutionary game, players can still change their strategies by comparing their current behavior strategy with the chosen alternative. Furthermore, the success of a classical game theory model depends on the ability of players to make rational choices. However, in the case of evolutionary theory, rational decision making is not a prerequisite.

In terms of network architecture, one significant drawback of existing frameworks is their dependence on centralized servers that may act as a single point of failure. Moreover, the energy exchange between the grids and the SPBSs would require a large number of financial transactions. For such a large number of transactions, the traditional method of storing every single energy transaction on a centralized database is not plausible [19]. Another significant issue with centralized frameworks is their lack of transparency and vulnerability to several kinds of malicious attacks. The security, scalability, and transparency concerns associated with centralized frameworks impede their reliability drastically.

To this end, the use of a distributed ledger technology (DLT), such as blockchain, is a promising option to register each energy or data transaction. Being immutable by design, blockchain can ensure that no entity can alter the transaction records or dispute its authenticity in the future. Another added advantage of using blockchain is that it can facilitate the adoption of cryptocurrency in such transactions [7]. The use of cryptocurrency, combined with the deployment of a game-theoretic smart contract on the blockchain network, can automate the process of energy trading between SPBSs and grids. By effectively modeling the dynamics of the energy exchange, adoption of an EGT in the smart contract further ensures: 1) optimality in terms of the price of energy, 2) efficiency in terms of the time taken to reach an evolutionary stable strategy, 3) fairness in the interactions between all the parties, and 4) compliance of all exchanges with a predefined set of rules.

1.1 Our Contributions

The major contributions of this work are as follows:

(1) This paper proposes a Base Station-to-Grid (BS2G) framework to limit the wastage of energy generated by the SPBSs.
(2) A blockchain-enabled energy trading model has been adopted to overcome the scalability, transparency, and security concerns associated with centralized architectures.
(3) A smart contract that facilitates the automation of peer-to-peer (P2P) energy trading has also been deployed on our blockchain-based BS2G network. These P2P energy trades help reduce the cost of energy to the grid as they do not require any third party involvement.
(4) The implementation of an Evolutionary Game Theory (EGT) in the smart contract further ensures cost-optimization in the energy trading environment. As opposed to other game-theoretic approaches, an EGT is more focused on the changing dynamics of the strategy adopted by the players, in this case, the SPBSs. This makes an EGT a suitable approach for our model that involves a multi-iteration competition among the SPBSs to win the energy trading task.

1.2 Organization

The rest of the work is organized as follows. In Section 2, we discuss the relevant works in the direction of sustainable base stations and game-theoretic energy trading frameworks for smart grids. Section 3 and Section 4 discuss the fundamental infrastructure of our proposed BS2G model and the implementation of a game-theoretic smart contract, respectively. Section 5 includes the results from our simulations, while Section 6 finally concludes this work.

2 RELATED WORK

The rapid increase in cellular traffic has made the need for energy-efficient and self-reliant BSs very evident. Presently, much research is being conducted to power BSs using renewable energy sources (RES) such as solar and wind energy [2].

The authors of [21] have proposed the use of an integrated photovoltaic (PV) system as a power source for BSs located in regions where the electricity from the grid is unavailable. As per their results, the PV system is capable of meeting the electrical load requirement of the base station. The authors have also carried out a financial analysis of the PV system and asserted it to be an affordable solution for off-grid base stations to meet their load requirements.

To determine the feasibility of using PV panels, the authors of [14] thoroughly study the power consumption and traffic profiles of several base stations that rely solely on renewable energy. In the paper, the authors focus on the dimensioning of PV panels in base stations located in remote locations. The paper also investigates the efficacy of using wind turbines in tandem with the PV panels.

In [18], Daniela Renga *et al.* have proposed a power supply system that consists of small units composed of solar renewable energy (RE) generators to power individual Base Stations (BSs). These generators are combined with energy storage units (ESUs) to sustain the BS operation during the night or other low production periods. To simulate their power supply system, the authors have developed a simple stochastic model of the daily RE production. Their simulations show that the mean production values help to differentiate an insufficient production system from a sufficient one, while the variance in production helps in estimating the system's performance.

In the domain of smart grids, various game-theoretic energy trading frameworks have come forward in recent years [16]. For example, the authors of [20] have proposed a novel game-theoretic framework to model the energy trading interactions of several storage units such as hybrid electric vehicles. The framework establishes a non-cooperative game between storage units and smart grid elements, where each storage unit's owner aims to maximize his/her utility by deciding the maximum amount of energy to sell. The framework further leverages an auction mechanism to determine the energy trading price. As per the simulation results presented in the paper, the proposed framework renders substantial performance enhancements over the conventional greedy approach.

The game-theoretic approach adopted in [22] makes use of a modified regret matching procedure to enable energy trading between users. This approach enables users with an energy-surplus to sell their remnant energy gathered from renewable sources at a profit while allowing users with an energy-deficit to get energy at a discounted price.

Although most of the works in the domain of energy trading rely on centralized architectures, some researchers have also shown interest in developing a blockchain-based decentralized network for P2P energy trading [9]. Jiawen Kang *et al.* [10] have put forth a P2P electricity trading system for EVs based on a consortium blockchain. Esther Mengelkamp *et al.* [15] have discussed the benefits and drawbacks of incorporating blockchain in energy trading techniques by simulating a blockchain-based local energy market (LEM). The authors of [12] analyze the feasibility of a decentralized approach to the energy trading market by evaluating their proposed blockchain-based electricity exchange market comprising of multiple electric vehicles and a grid. Blockchain has been used in their model to ensure scalability in the grid system and facilitate autonomy in the trading environment.

Although a few decentralized energy trading frameworks have surfaced in recent years, none of them have been implemented in the domain of BS2G energy trading. In this paper, we present a novel game-theoretic BS2G energy trading model based on blockchain. Blockchain has been used in our model since it is a decentralized, peer-to-peer (P2P) network that provides a secure transaction platform with no central or controlling authority [1], [17]. To the best of our knowledge, this is the first time blockchain has been used to model energy trading between SPBSs and smart grids.

3 SYSTEM MODEL

In the proposed system model, we consider a network that comprises of multiple SPBSs and smart grids. In the proposed model, each SPBS and grid alike, will act as both a producer and a consumer, i.e., as a prosumer [4], [6]. The user functions as a customer when the amount of energy it requires exceeds the amount of energy it generates. Moreover, the user may function as the seller if it holds a surplus amount of energy, i.e., the amount of energy it produces exceeds its energy requirement. Expenses may vary with the generation and consumption of energy owing to:

1. **Climatic conditions:** In comparison to the cold weather, the PhotoVoltaic (PV) panels generate more energy in the summer, which implies that there is a higher likelihood of surplus energy being generated during the summers. In addition, the load on the grid is higher during the summers due to higher energy requirements.
2. **Time of the day:** The demand for electricity, as well as the output from PV panels, varies with the time of the day. For instance, the presence of multiple users at home in the mornings leads to an increased demand for electricity, and consequently, an increased load on the grid.
3. **Balanced electricity grid:** The costs incurred for energy consumption should vary with time and season, i.e., the cost for energy should be higher during peak times as compared to the off-peak time.

3.1 BS2G Network Architecture

Let $\mathcal{P} = \{1, 2, \ldots, i, \ldots, N\}$ with $i \in \mathcal{P}$ represent the set of SPBSs and $\mathcal{Q} = \{1, 2, \ldots, j, \ldots, M\}$ with $j \in \mathcal{Q}$ represent the set of smart grids. All the N SPBSs and M smart grids are considered to be the part of an ethereum network, which stores all the data associated with energy transactions between SPBSs and the grid on its own. Furthermore, an unbiased node, not controlled by any party, known as a smart contract, is deployed across the network. A smart contract is executed whenever any node requests for some data or shares energy.

If $T = \{1, 2, \ldots, t, \ldots, 24\}$ denotes the set of 1-hour time-intervals in a day, then the amount of power generated during these timeslots by an SPBS i and a grid j can be represented as follows:

$$S_i = \left\{S_i^1, S_i^2, \ldots, S_i^{24}\right\}, \quad i \in \mathcal{P} \tag{1}$$

$$G_j = \left\{G_j^1, G_j^2, \ldots, G_j^{24}\right\}, \quad j \in \mathcal{Q} \tag{2}$$

The consumption profile of an SPBS i and a grid j can be represented in a similar fashion:

$$S_i' = \left\{S_i^{1'}, S_i^{2'}, \ldots, S_i^{24'}\right\}, \quad i \in \mathcal{P} \tag{3}$$

$$G'_j = \left\{G_j^{1'}, G_j^{2'}, \ldots, G_j^{24'}\right\}, \quad j \in \mathcal{Q} \tag{4}$$

To ensure the availability of power during periods of solar power unavailability, such as the night time, we assume that the SPBSs store a fraction of the surplus energy generated by them inside the batteries. Similarly, we assume that all smart grids are equipped with an ESU that enable the storage of electricity during times of peak production, i.e., when the production exceeds the consumption, and the release of energy when the consumption exceeds the production.

3.2 Classifying Buyers and Sellers

In this work, we model the BS2G exchange only, i.e., SPBSs are considered to be the sellers while the grids are considered to be the buyers. However, the SPBS may supply energy to the grid only if the amount of excess energy it holds exceeds the minimum storage threshold. The minimum storage threshold is the minimum amount of energy that an SPBS should store in its batteries for emergency purposes. If $\theta^t_{min,i}$ denotes the minimum storage threshold of an SPBS $i \in \mathcal{P}$, then the amount of energy that the SPBS can deliver, θ^t_i during the t^{th} timeslot is calculated as follows:

$$\theta^t_i = S^t_i - \left(S^{t'}_i + \theta^t_{min,i}\right) \tag{5}$$

Furthermore, the amount of energy required by the grid j, $\mathcal{Z}^t_j$ at time t can be calculated as follows:

$$\mathcal{Z}^t_j = G^{t'}_j + \mu^t_j - G^t_j \tag{6}$$

where μ^t_j represents the amount of energy available in the ESU connected to the j^{th} grid during the t_{th} timeslot.

4 GAME THEORY IN BS2G NETWORK

In our model, we use an evolutionary game theory (EGT) based smart contract to optimize the costs associated with energy trading between the smart grids and the SPBSs. Evolutionary game models provide a natural approach to problems in which the strategy adopted by the players changes over time, and the outcome for each player depends on the actions of others as well as its own. Since our network involves a competition between multiple SPBSs wherein each SPBS continuously changes its strategy to win the energy trading task, an EGT provides a promising model to ensure nash equilibrium among the players of our network. In our framework, smart grids employ the use of the EGT model to select the most beneficial SPBS from which to buy energy. Once the SPBSs reveal their energy prices, each grid selects an SPBS from which to purchase energy. Each grid's selection procedure is adjusted gradually, and an SPBS is chosen independently by the grids during the selection process. The probability of SPBS i being chosen by the grid j in t^{th} hour, $\pi^t_{i,j}$ is randomly initialised $\forall i \in \mathcal{P}$ and $\forall j \in \mathcal{Q}$. The overall demand for energy coming to the SPBS i at time period t, γ^t_i can be mathematically formulated as follows,

$$\gamma^t_i = \sum_{j=1}^{\mathcal{M}} \pi^t_{i,j} * \mathcal{Z}^t_j \tag{7}$$

The ratio of supply and the overall demand for SPBS i at t^{th} hour can be given by:

$$\sigma^t_i = \frac{\theta^t_i}{\gamma^t_i} \tag{8}$$

Algorithm 1 Blockchain-based BS2G Energy Exchange

Input: Production profile - S_i, and consumption profile - S'_i of each SPBS $i \in \mathcal{P}$, Production profile - G_j, and consumption profile - G'_j of each smart grid $j \in \mathcal{Q}$

Output: Final probabilities, $\Pi^t_{i,j}$ $\forall i \in \mathcal{P}$ and $\forall j \in \mathcal{Q}$

1: Every SPBS, $i \in \mathcal{P}$ calculates the amount of surplus energy it holds, θ^t_i, using eqn. 5 and broadcasts that information to all the nodes in the ethereum network.

2: Every smart grid, $j \in \mathcal{Q}$, calculates its energy requirement, $\mathcal{Z}^t_j$, using eqn. 6 and announces it to all the nodes in the ethereum network.

3: For all the smart grids and SPBSs, the probability that a grid j chooses SPBS i for energy trading $\pi^t_{i,j}$, is randomly initialised.

4: An EGT-based smart contract is deployed on the network to determine the final probabilities that satisfy the requirements of all the smart grids in a way that maximizes their utility. The calculations for the EGT model have been carried out in eqns. 7 to 15.

The net utility of grid j is calculated using the quadratic utility function established in [3], [13]. Depending on the value of θ^t_i, two cases can be considered:

Case 1: If $\theta^t_i \geq \gamma^t_i$, then the net utility is given as:

$$\lambda^t_i = \frac{1}{2}\sum_{i=1}^{\mathcal{N}} \epsilon_j \left(\mathcal{Z}^t_j\right)^2 \tag{9}$$

Case 2: If $\theta^t_i < \gamma^t_i$, then the net utility given as:

$$\lambda^t_i = \left(\sigma^t_i - \frac{\left(\sigma^t_i\right)^2}{2}\right)\sum_{i=1}^{\mathcal{N}} \epsilon_j \left(p^t_j\right)^2 \tag{10}$$

where ϵ_j is a predefined constant. If $\overline{\lambda}^t$ denotes the average utility, then:

$$\overline{\lambda}^t = \sum_{i=1}^{\mathcal{N}} \lambda^t_i \pi^t_{i,j} \tag{11}$$

Replicator dynamics for depicting buyers' selection dynamics can be formulated as follows:

$$\frac{\partial \pi^t_{i,j}}{\partial t} = \pi^t_{i,j}\left(\lambda^t_i - \overline{\lambda}^t\right) \tag{12}$$

Furthermore, approximate replicator dynamics can be formulated over several iterations using the following equation:

$$\pi^t_{i,j}(x+1) = \pi^t_{i,j}(x) + \chi_1 * \pi^t_{i,j}(x) * \left(\lambda^t_i(x) - \overline{\lambda}^t(x)\right) \tag{13}$$

where χ_1 is a parameter for adjustment, and x is the iteration number. For each iteration, i.e., for each value of x, we calculate the difference between the net utility and the avg. utility, until the

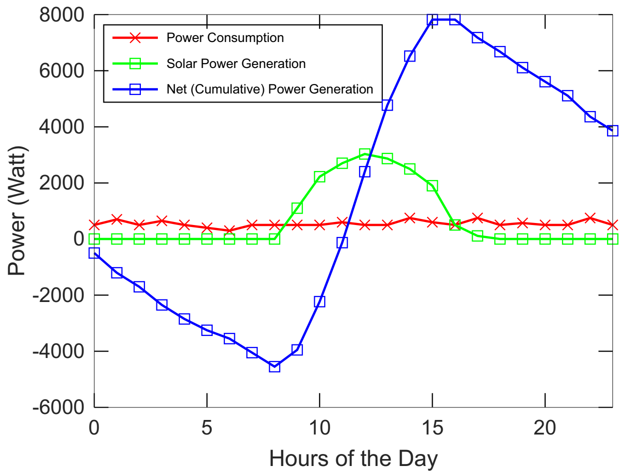


Figure 2: Power Profiles of an SPBS

terminating condition, as established in the following equation, is achieved:

$$\left| \lambda_i^t(x) - \overline{\lambda}^t(x) \right| < k \tag{14}$$

where k is a small positive number. The probability corresponding to the terminating value of x is the final probability, $\Pi_{i,j}^t$, which can be mathematically modeled as:

$$\Pi_{i,j}^t = \pi_{i,j}^t (x+1) \tag{15}$$

5 NUMERICAL ANALYSIS

5.1 Simulation Settings

The solar power generation profile of an 8 kW peak power photovoltaic (PV) base station has been taken from [14] while the power load profile for a remote telecom base station has been taken from [11]. It is important to note that the hourly power generation profile of the PV base station has been averaged over the month that capacitates the least power generation. In the months of peak power production, power generation values will be much higher.

The model that we use is built upon the generic ethereum framework that provides a public blockchain network based on proof of work consensus algorithm. In the future part of this work, we would consider a private network enabled with other consensus algorithms that are more effective in terms of computation. For simulating our game-theoretic smart contract, we consider an ethereum test network - Rinkeby, consisting of 4 SPBSs and 2 grids. Every SPBS can trade energy with any one of the grids in exchange for ethers (cryptocurrency). Since SPBSs can generate energy during day time only, we assume that our BS2G model is operational only during the day. To verify the scalability of the proposed solution, we have used the Titan XP GPU to run the model.

5.2 Performance Evaluation

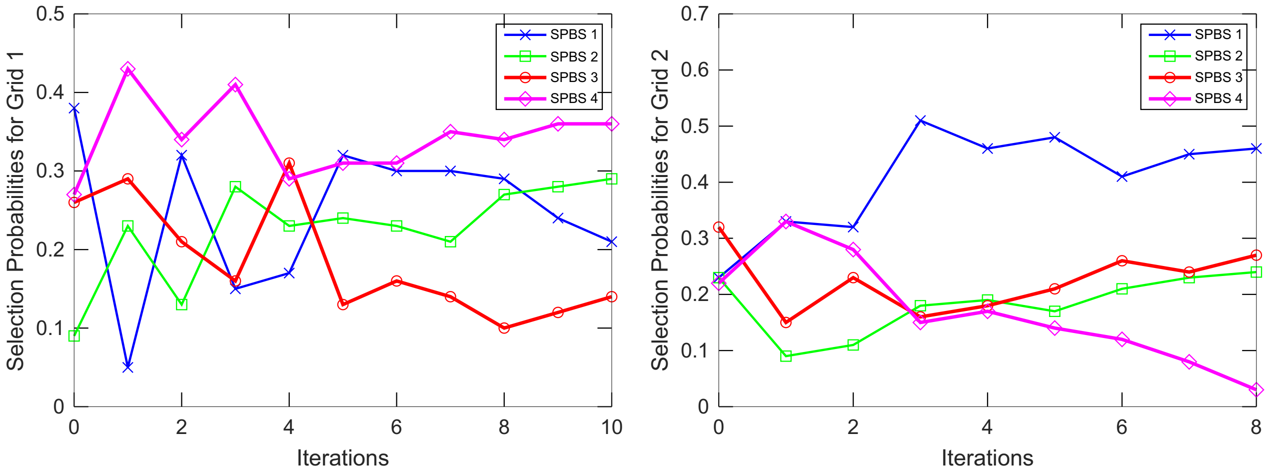
Figure 2 plots the hourly power consumption profile of a remote telecom base station as well as the solar power production profile of an SPBS. It can be inferred from the graph that even though solar power is available for a limited number of hours, the amount of solar power generated in those hours is more than sufficient to account for the power unavailability during the rest of the day. Since an SPBS cannot generate power in the early part of the day, initially, the net power generation of an SPBS is negative. Later, as the day progresses and the SPBS harnesses solar energy to generate power, the net power generation becomes positive. Even though the energy stored inside the battery depletes towards the latter half of the day, the SPBS remains energy surplus at the end of the day.

To further demonstrate the need for a BS2G framework, we consider the following case. An 8 kW peak production solar-powered base station can, on average, produce 5 kW of solar power every hour. Taking into account its immediate power requirements, around 4 kW of solar power of excess power is generated by a remote SPBS every hour. If we consider a pack of 12V 200Ah lead-acid batteries to store energy for emergency purposes, we need 12*200 = 2400Wh energy to recharge a single battery completely. However, assuming that the batteries have 70% depth-of-discharge (DoD), the energy requirement falls to 2400*0.70 = 1680Wh. Taking into account the losses associated with charging and discharging of a battery, we assume that the battery's efficiency is 80%. An 80% efficiency corresponds to an energy requirement of 1680/0.80 = 2100Wh to recharge a single battery. If we consider a battery pack comprising of 8 batteries, as is common with telecom base stations, then the energy requirement becomes 8*2100 = 16800Wh. For an SPBS with a 4 kW rating, this corresponds to a charge time of 16800Wh/4000W = 4.2 hours. These calculations demonstrate that an SPBS with access to six hours of sunlight could lose as much as two hours worth of solar power in a single day. It is important to note that these calculations have been carried out, keeping in mind the values for a low-traffic remote base station.

Figure 3 shows the variation in probabilities of a particular SPBS getting selected by the grid for energy exchange over multiple iterations. The variations in probabilities for grid 1 and grid 2 are shown separately in fig. 2(a) and 2(b) respectively. Initially, i.e., for iteration 0, the selection probabilities are random. However, over multiple iterations, the selection probabilities converge to their optimal value. The graphs show that as the iterations increase, the selection probabilities of both the grids continue to change. This change is attributed to the fact that all SPBSs update their energy trading price after each iteration in order to win the energy trading task. The algorithm assigns a higher selection probability to the SPBS whose energy prices are more favorable to the grid. The optimal values of probabilities are achieved when the grids achieve a stable state where they no longer change their selection strategy. Such a stable condition is referred to as an evolutionary stable strategy (ESS). For grid 1, the optimal probabilities were achieved in the 10^{th} iteration, i.e., the terminating value of x for grid 1 is 10. Similarly, it can be inferred from figure 2(b) that the terminating value of iteration number x for grid 2 is 8.

6 CONCLUSION

In this work, we propose a blockchain-based framework for secure and lightweight energy trading in a BS2G network. We have adopted the blockchain data structure in our model to overcome the limitations of traditional centralized architectures. These limitations include high response time, security risks, and high transaction



(a) Variation in Selection Probabilities for Grid 1

(b) Variation in Selection Probabilities for Grid 2

Figure 3: Variation in Selection Probabilities over Multiple Iterations

fees. Furthermore, we propose the use of an EGT, which iteratively calculates every grid's selection probabilities corresponding to all the SPBSs before converging to the optimal selection probabilities. An ethereum smart contract is used to ensure that the energy transactions between the grids and the SPBSs are secure and transparent. Although we have modeled only the BS2G exchange, the work can further be extended to model BS2BS, G2BS, and G2G networks.

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