A Distributed Framework for Energy Trading Between UAVs and Charging Stations for Critical Applications

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***Abstract*—Use of Unmanned Aerial Vehicles (UAVs) is rapidly increasing in various domains such as disaster management, delivery of goods, surveillance, military, etc. Significant issues in the expansion of UAV-based applications are the security of (IoT to UAV) communication, and the limited flight time of the UAVs and IoT devices considering the limited battery power. Standalone UAVs are not capable of accomplishing several tasks, and therefore swarm of UAVs is being explored. Security issues in the swarm of UAVs do not allow the applications to leverage the full benefits that one can offer. Several recent studies have proposed the use of a distributed network of UAVs to upgrade the level of security in the swarm of UAVs. In this paper, a framework for secure and reliable energy trading among UAVs and charging stations is presented. Advanced blockchain, based on the tangle data structure is used to create a distributed network of UAVs and charging stations. The proposed model allows the UAVs to buy energy from the charging station in exchange for tokens. If the UAV does not have sufficient tokens to buy the energy, then the model allows the UAV to borrow tokens from the charging station. The borrowed tokens can be repaid back to the charging station with interest or late fees. A game-theoretic model is used for deciding the buying strategy of energy for UAVs. Numerical analysis shows that the proposed model helps in providing increased utility for the swarm of UAVs and charging stations in a secure and cost-optimal way as compared to the conventional schemes. The results can eventually be applied to IoT devices that constantly need energy to perform under ideal conditions.**

***Index Terms*—Blockchain, decentralized ledger, peer-to-peer, energy trading, Stackelberg game, IOTA, tangle.**

I. Introduction

THERE has been a paradigm shift from manual work to automation in almost all domains of engineering in recent years [1], [2]. The use of UAVs has been instrumental in bringing this shift. For example, UAV's are being used in varied applications such as healthcare, military, surveillance, disaster management, etc. [3], [4], [5]. However, there are very few applications that are actually using UAVs to perform real-time and scalable tasks [6]. This is on account of the various fundamental issues related to using UAVs in real-life applications. The first and foremost issue is the limited flight time of the UAV, which is due to limited battery storage capacity [7]. The battery size in UAVs cannot be increased due to the weight limitations. If the weight of the UAV is large, it becomes difficult to fly the UAV at high altitude and for a long duration [8]. Various works have proposed the use of a swarm of UAVs instead of a standalone UAV for various applications [9]. Although the swarm of UAVs shows various benefits over standalone UAVs, the security issues in the swarm of UAVs are much higher than in the case of a single UAV [10], [11]. For longer flights or missions, UAVs require time to time charging. In such situations, UAVs can avail the service of intermediate charging stations [12], [13]. The traditional way of energy trading between UAVs and charging station is highly inefficient if the UAVs are used in a large number. In the traditional system, all the charging stations act in a standalone mode, and the UAVs are also not aware of the current energy availability at a particular charging station [14]. UAVs need energy at the minimum possible cost and in minimum possible time. This requires a strong peer to peer communication between the UAVs and the charging stations [15]. Therefore, few recent works propose the use of a distributed network of charging stations and UAVs. Some of the works in recent years have focused on the use of blockchain for UAV to UAV communication [16], [17]. Blockchain is a DLT (Distributed Ledger Technology) that allows secure peer to peer transactions among multiple entities that are in different geographical locations [18], [19]. Blockchain technology creates an immutable distributed ledger of all the transactions between the different nodes of the network [20], [21]. Every node can view all the transactions that are committed in the chain, but no node can tamper or change the data that is committed in the chain [22], [23].

Although blockchain proves to be highly efficient in creating a distributed network for energy trading among UAVs and charging stations, there are few fundamental limitations of blockchain that limit the use of this technology in such applications. Blockchain algorithm suffers from some fundamental drawbacks such as the latency of transaction confirmation, the scalability limitations, and the probabilistic nature of consensus algorithms [32], [33]. The consensus algorithm used in the

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blockchain is also very power-hungry [34]. Micro-transactions cannot be added in generic blockchain as the incentive given to the miners for such transactions ends up to be higher than the actual transaction value. Processing fees of transactions are increasingly high, and the size of the block is constrained, thereby limiting the use of generic blockchain for a large number of small transactions. Various works propose the use of other consensus algorithms such as Proof of Stake (POS), Proof of Burn (POB), or Proof of Elapsed Time (POET) to overcome the limitations of the generic blockchain. However, all these consensus algorithms follow the Proof of Work (POW) algorithm. A new distributed application cannot be created using the POS consensus process as none of the nodes in the network has any stake or cryptocurrency to put on stake. In this paper, we propose a novel application of a distributed network of charging stations and UAVs based on advanced blockchain or IOTA. IOTA is a type of DLT that uses a tangle data structure to store transactions. IOTA based DLT is equally secure and distributed as traditional blockchain, but at the same time, it provides low latency and consumes very less power as compared to generic blockchain [35]. Unlike normal blockchain, IOTA-based blockchain ledger does not have any miners to process transactions [36]. There is no transaction fee involved in IOTA, and micro-transactions are also possible. Following are the major contributions presented in this paper:

- A distributed network of charging stations and UAVs is proposed where they can interact and negotiate for charge price over the network. An IOTA based consensus is used to reach an agreement among the nodes in the network.
- UAVs are allowed to trade for energy with the charging station in exchange for tokens based on their immediate needs. If the UAV does not have sufficient tokens to buy the energy, then the model allows the UAV to borrow tokens from the charging station.
- The borrowed tokens can be repaid back to the charging station with interest or late fees. The charging stations are also allowed to vary the late fees based on the time of repayment to enhance their revenue.
- A game-theoretic model is proposed to parallelly enhance the utility and revenue of both the UAV and the charging stations.
- Simulation of the proposed model is implemented, and the numerical analysis is presented to prove that the proposed model is better than the traditional scheme.

The rest of this paper is organized as follows. Section II presents the recent related work in the area of UAV charging. Section III presents the overall procedure involved in a distributed network for energy trading between UAVs and charging stations. Section IV presents some prelims and background details related to IOTA technology and distributed networks. The proposed system model is discussed in Section V. Section VI presents the proposed game-theoretic model for energy trading among charging stations and UAVs in exchange for IOTA tokens. Section VI presents the strategy for optimal price formulation for the energy trading, which maximizes utilities of both UAVs and charging stations. The simulation setting and numerical analysis are presented in Section VII. The final conclusions are presented in Section VIII.

II. Related Work

In this section, a survey of all the existing literature related to UAV charging are presented along with their advantages and limitations. Myung Jae Shin *et al.* [29] present a framework based on machine learning and auction mechanism for scheduling energy requirements for a network of drones.

Nowadays, machine learning-based models are also used in UAVs in different ways. Based on the predictions made by the machine learning algorithms, an auction model is designed to allow the drones to bid for the energy. Authors in [26], present a collaborative scheme for choosing the station for drone charging. All the flying drones send their energy request to the cloud server, and the cloud decides about the allocation of UAVs to charging stations. The limitation of the model is that it is completely centralized, and all the activities of the UAVs are completely dependent on the decisions coming from the central cloud server. This would result in lot of latency that could be an issue in various critical applications of UAVs such as use of drones for healthcare and medicine delivery.

David Dominique *et al.* [25], present a contract based UAV charging system. The UAV is allowed to land on the charging pad in the designated position of orientation. The charging cost for the UAV and the revenue of the charging stations are not considered. Authors of [30] focus on reducing the route traveled by the UAVs for delivery, rather than increasing the flight time. The authors use the Travelling Salesman Problem (TSP) to calculate the minimum possible route for delivery. Fundamental features of the TSP are analyzed, and route distortion is defined.

Haider Mahmood Jawad *et al.* [37] focuses on the use of UAVs in agricultural applications. Electromagnetic induction (EM) is used to charge the drones on the fly to increase their flight time and communication distance. A magnetic resonant coupling technique is used as it allows high transfer power and helps in minimizing the energy loss in transit. Authors of [27] provide a detailed review of all the different wireless charging techniques being used for charging the UAVs on the fly. A detailed comparison of the working, advantages, and limitations of each technique is presented by the authors. Chiuk Song *et al.* [28] propose the ways of reducing the electromagnetic interference in wireless charging of UAVs. Strong electromagnetic fields are generated while transferring the energy from source to battery. Such fields might also deliver strong electric currents to the end-users.

Sheng Zhang *et al.* [24] propose a model for flexible wireless charging. The authors consider that the energy demand for UAVs is not always consistent and might change based on various factors. The fluctuations in energy consumption are considered, and an itinerary selection and charging association algorithm is proposed. Roberto G. Ribeiro *et al.* [31] proposes the use of UAVs in the mining industry. The periodic inspection of disasters in mines is a very important and difficult task. Drones can be used to inspect the leakage or other issues in mines. Solar-powered

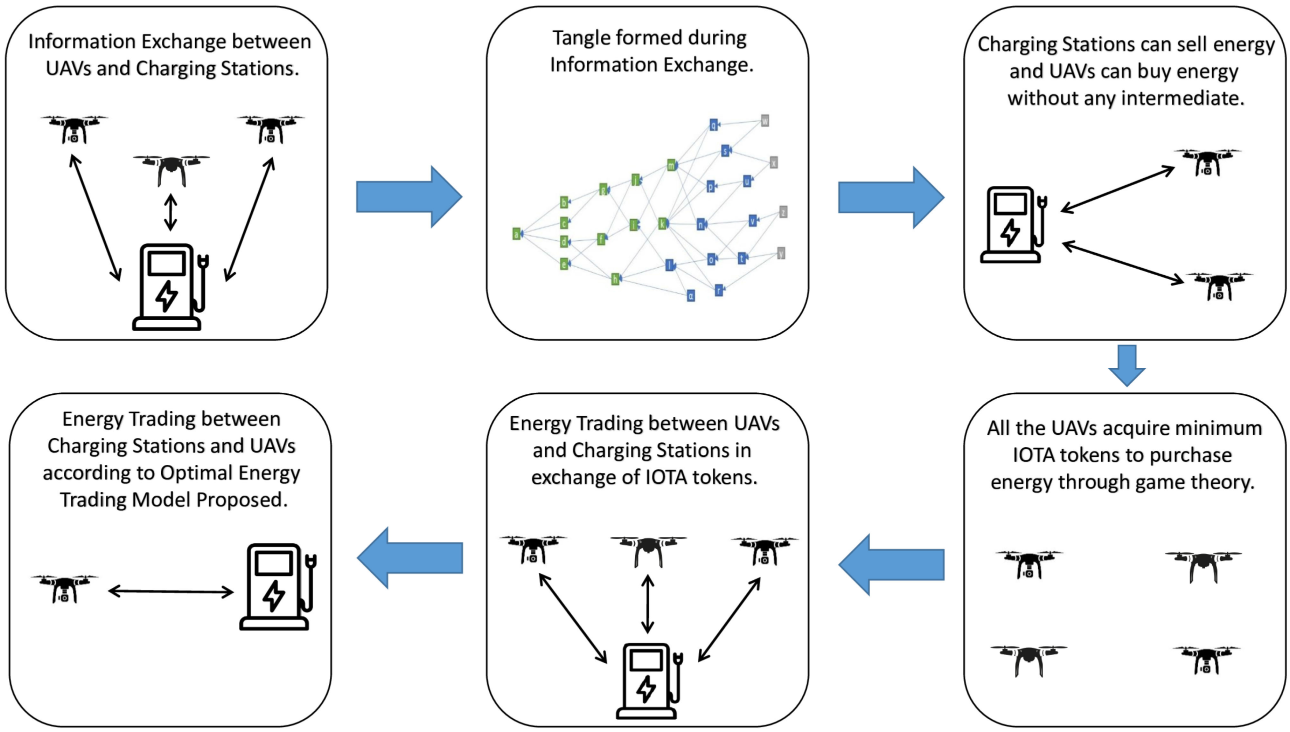

Fig. 1. Energy trading between charging stations and UAVs.

drones cannot be used in mines due to the unavailability of solar energy. High flight time is also required to perform an effective inspection. The authors propose a concise mixed-integer linear programming (MILP) model for charging station planning and drone routing.

There are several works that focus on enhancing the capabilities of UAVs in multiple domains. These works also focus on using the latest technologies to increase the overall battery life and flight time for the drones. However, most of these works use a centralized server or third-party cloud services to manage UAV communication. Moreover, there are very few works that focus on reducing the cost of UAV charging and increasing the revenue of the charging stations simultaneously. Centralized approaches are highly susceptible to data thefts and also act as a single point of failure. Existing literature lacks the concept of a distributed network of charging stations and UAVs where the nodes can securely request for energy and can negotiate or decide the price for charging. Furthermore, in existing literature, the price charged by the charging stations is considered as fixed. This restricts the charging stations from varying the price to increase their revenue. Therefore, we propose a distributed framework for UAV charging that is fair, cost-optimal, accurate, and secure. Additionally, we consider factors like dynamic pricing offered by the charging stations according to different use cases, which is discussed in the later section of the paper.

III. System Overview

Fig. 1 shows the steps involved in a distributed network for energy trading between charging stations and UAVs. Initially, after the charging stations and UAVs join the network, they start with an information exchange process. These messages are recorded on the IOTA tangle.

1) The first box shows the first step where the message passing or information exchange takes place between the charging stations and the UAVs. These messages include the information about charge requirement, criticality, a cost that drone is willing to pay, etc.
2) The second box shows the tangle creation to securely store the information that is being exchanged between the charging stations and the UAVs. All the messages encrypted and digitally signed to prevent the issues related to data integrity and non-repudiation.
3) The third box shows the possibility of energy trading in the peer-to-peer network between UAVs and charging stations in exchange for IOTA tokens without any intermediary or centralized controlling authority.
4) The fourth box shows that all the UAVs in the IOTA network acquire a minimum number of IOTA tokens to buy energy from the charging stations. If the UAVs do not have enough tokens, then they borrow IOTA tokens form the charging stations based on game theory.
5) The fifth box shows the occurrence of negotiations between UAVs and charging stations based on optimal price formulation strategy discussed in section VII.
6) The sixth box finally shows the actual allocation of a UAV to a charging station for energy trading.

IV. Background and IOTA Prelims

In the distributed network of charging stations and UAVs, the IOTA tangle is used to record and to process the large number of frequent micro-transactions. Tangle is a Directed Acyclic Graph (DAG) based distributed ledger [35]. Fee-less micro-transactions, asset transfer, and trusted identities are some of the features provided by the IOTA tangle. All the UAVs and charging stations act as nodes when they are connected to the IOTA network. All the UAVs can borrow energy from the charging station based on their energy requirements to increase their flight time. This process could be done without involving any centralized third party. The UAVs can buy energy from nearby charging stations when required [38], [39]. Next, we discuss a few prelims required to understand the proposed model and the solution framework.

A. Digital Identity

Digital identity is one of the important building blocks for any distributed ledger technology [40], [41]. The level of trust among the parties involved in energy transactions is ensured by their digital identity [42]. The security of a large amount of user data that is growing at a tremendous rate is often compromised when centralized and traditional identification methods are used [43]. A better alternative is the use of a verified digital identity stored on a distributed ledger. Also, the fees charged by the third parties that provide authentication and verification services are saved by using digital identity verification methods [44].

B. Tip Selection Algorithm

In the traditional blockchain, computing power is a major factor for verifying whether the user is making an authentic transaction or not [45], [46]. Miners are used for validating and adding new transactions in the next block. The task of mining is done by the new transactions in the IOTA tangle. All the nodes present in the network directly or indirectly approve the new transactions. This makes the participating nodes and the miner indistinct. This also prevents distributed denial of service (DDOS) attacks to the IOTA network as all nodes are equivalent, and no node has some special privilege. Any new transaction that enters in the tangle is required to select and approve two previous transactions. An edge is created between the selected transactions and the newly added transaction. The new transaction requires to solve a cryptographic puzzle to be approved as a transaction. Then the new transaction waits for its approval by the other upcoming transaction. A tip is used to refer to an unapproved transaction in a directed acyclic graph. The process of tip getting validated by the new transactions is decided by the tip-selection algorithm [35]. Therefore, tip-selection algorithms and the rate at which new transactions are added in the tangle decide transaction confirmation latency.

A rating is given to each transaction initiated by any node in the network using the tip selection algorithm. The rating is equal to the number of transactions that reference it. The transaction is considered important if its weight is larger than other transactions in the network. To select two non-conflicting tips for the verification of the newly arrived transaction is the aim of the tip selection algorithm used in IOTA. For any transaction X, the cumulative weight CW_X is defined as the own weight plus weight of transaction that approves it. For example if $X_2, X_3, X_4, \ldots X_N$ are the transactions that approve X_1. The weight of X_1 is W_{X1} and weight of $X_2, X_3, X_4, \ldots., X_N$ is $W_{X_2}, W_{X_3}, W_{X_4}, \ldots., W_{X_N}$ respectively, then

$$CW_{X_\alpha} = \sum_{a=1}^{\alpha} X_a + \sum_{b=\alpha+c}^{N} X_b \tag{1}$$

where, X_a be any event that approves event X_α directly and X_b be any event that approves event X_α indirectly.

C. Consensus Mechanism

For every distributed ledger technology, it is imperative to generate a level of trust among the nodes for the authenticity of the transactions [47]. The cumulative weight of the transactions calculated above is used to reach consensus in IOTA as compared to the proof-of-work (PoW) algorithm in a traditional blockchain [48], [49]. Consensus finality is referred to as a final agreement among all the network nodes. Blockchain never reaches consensus finality due to the issues of forking and pruning. In the generic blockchain, a block that is mined today or a transaction that is added to the main chain today, might get pruned and removed from the main chain after some time. There is no surety that the current transactions will remain in the main chain forever or not. Therefore, generic blockchain never reaches consensus finality. This is not the case in the consensus process followed in the IOTA network. In IOTA, when almost every participant present in the IOTA network declares that a particular transaction is more valid than other transactions, then consensus is achieved. In IOTA, the consensus is distributed in the tangle, and the participant is required to validate two past transactions for placing one's own new transaction in the network, as discussed above.

Apart from securing IOTA from the tip selection algorithm and cumulative weight-based consensus mechanism, a new security layer has been added to the IOTA consensus protocol to overcome the issue of conflicting tips. This security measure is a voting-based mechanism called as a shimmer. The traditional voting mechanism cannot automatically scale if the number of nodes in the network increases. Also, each node is required to know the other nodes in the network in case of traditional voting-based algorithms. In the shimmer algorithm, the peers tend to change their state based on the state of other peers and do not need to know the state of all the nodes in the network.

D. Transaction Procedure

Every charging station and the UAV has its own pseudo-anonymous, virtual, and private wallet, which stores IOTA tokens used for making transactions [50], [51]. The user has to create a secret password called seed (a string of 81 trytes) for using IOTA as a network [52]. IOTA is based on trinary or ternary computing. Trit is a digit in a base 3 (0 or 1 or 2). Tryte consists of 3 trit. It can be in one of 27 states consisting of 26 uppercase alphabets or digit 9. Each seed can create 9^{57} addresses and private keys using the IOTA address generation algorithm. Since it is public, users can send messages and tokens to other users using the address field in the transaction. Bundles are signed using unique private keys, for withdrawing IOTA tokens from address.

V. Proposed System Model

In this section, the complete system model is discussed, along with the roles of different components present in the IOTA network. The purpose of the proposed model is to balance the supply and demand of the energy required to charge the UAVs. The model focuses on increasing the overall flight time of the UAVs. A game-theoretic model is used to perform energy trading in a cost-optimal way.

A. Components of Proposed Energy Trading Model

1) Energy Nodes: A node can be either of UAV (buyer) or a charging station (seller). The UAV must have a minimum amount of IOTA tokens to buy energy from the charging station. If the UAV does not have the minimum amount of tokens, then it can borrow tokens from the charging station. The borrowed tokens need to be repaid back to charging stations with interest or late fees imposed by the charging station.

2) Energy Aggregator: The smart contract in the IOTA network acts as an energy aggregator. The work of the smart contract is that of a broker or a mediator between a buyer and a seller node. It helps in setting up a communication between two parties who want to share energy. The buyer and the seller interact directly via a smart contract without the presence of a third-party broker.

3) Smart Meters: Smart meters will incorporate the proposed pricing algorithm by considering the details such as energy already present in the account, amount of energy being traded and the charging price. The charging price and amount of energy being traded between UAV and charging station is according the the values calculated by the smart meter, as an intermediate broker.

B. Working of Proposed Energy Trading Model

In this section, various steps involved in the energy trading process are discussed step by step.

1) System Framework and Entry of Nodes in a Network: The users are registered on the IOTA network, and each user after registration becomes a unique entity node. Each node with a unique ID gets its public and private keys. Every node obtains a set of wallet addresses, and the distributed ledger stores all the information regarding energy requests and trading in mapping lists. Wallet addresses contain energy coins, and IOTA tangle stores all the transaction records of UAVs and charging stations. As discussed above, the wallet addresses are given to the nodes by the IOTA network as soon as they enter the network and desire to perform transactions. There are charging stations that act as energy suppliers for the UAVs. The UAV's are allowed to enter the network to trade energy with the charging station in exchange of IOTA tokens. If the UAV does not have sufficient tokens, then it can borrow tokens from the charging station to buy the required energy. The borrowed tokens are later repaid to the charging station with interest or late fees imposed by the charging station. The UAV that is neither willing to purchase the energy nor willing to borrow the tokens and does not have the minimum threshold amount of energy is not allowed to enter the network. This will act as a checkpoint to ensure that only the nodes satisfying the above-mentioned criteria enter the network, and the network is not flooded by more number of nodes.

2) Different Roles in Energy Trading Network: There are many nodes in the network which act either as a buyer node (UAVs) or a seller node (charging station). The energy-deficient UAVs buy the energy from the charging station in exchange for IOTA tokens. The token deficient UAVs can first borrow the tokens from the charging station and can then buy the energy in exchange for the borrowed tokens. The borrowed tokens need to be repaid back to the charging station with interest or late fees.

3) Exchange of Energy Between Buyers and Sellers: A smart contract's exchange function is responsible for all the transactions in IOTA. It takes a few parameters, like the address of the buyer and the amount of energy it wants to buy. The smart contract matches the buyer's (UAVs) requirements with the sellers present in the seller pool based on the charging price and late fees imposed by the seller (charging station).

4) Payment Security Plus Incentives and Rewards: The UAVs in the network after each transaction get the updated data of new seller nodes and information about the energy available with the new seller. Each transaction needs to be signed with a digital signature of the initiator.

5) Hashing in Energy Trading: For verification, each event or transaction carries a hash of the previous transaction as is done in the traditional blockchain [53]. This makes the transactions in the network tamper-free and immutable.

VI. Game Theory in Energy Trading Model

In the proposed energy trading model, UAVs act as buyers, and charging stations act as the sellers. The role of the charging station is to feed the energy in the UAVs. Each UAV has access to these charging stations, which have enough IOTA tokens. UAVs need to have sufficient IOTA tokens to request for energy. The charging stations provide IOTA tokens to the UAVs, which makes them capable of purchasing the energy from the charging station [54]. Energy trading between UAVs and charging stations is done depending on the present balance of tokens with the UAV and its previous transaction history. On-demand of UAVs, sufficient tokens are transferred from the charging station to the UAV's wallet address. UAVs can also request for the energy from the charging station in exchange for the tokens that they already have. In this section, the various steps and scenarios in energy and token trading among the nodes in the network are discussed.

A. Request for Tokens from Charging Station

Initially, a UAV D_i (an IOTA node that is in need of tokens) sends a request to the charging station and waits for an acknowledgment from the charging station. The detailed steps followed in the process of getting the tokens are discussed as follows.

1) D_i sends a request message along with other information about its own account address ID_i, all previously used transaction history $H_{i,k}{}_{k=1}^{K}$, number of tokens requested $amount_i$ and available number of tokens $credit_i$ to the charging station C_j.
   $D_i \rightarrow C_j \quad : \quad request_i = ID_i \parallel H_{i,k}{}_{k=1}^{K} \parallel amount_i \parallel credit_i$

2) After charging station gets the $request_i$ from UAV, it verifies the UAV's identity and previous transaction history from $H_{i,k}{}_{k=1}^{K}$ to check the UAV's account status.
3) The message "$TokenSharingSuccess$" is obtained only to that UAV D_i who is able to fulfill certain following necessary requirements:
a) There is a sufficient amount of $credit_i$, which must be a positive amount.
b) The account must be active and should have successfully completed the recent transactions with charging stations. The request is rejected if the UAV fails to complete the previous transactions.
4) A shared wallet SW_{tl} is created between charging station C_j and UAV D_i. The public and private keys are sent to UAV D_i. The charging station and UAV both have access to the shared wallet SW_{tl}. The shared wallet can be further reused for other transactions between charging station C_j and UAV D_i.
5) If all the requirements are fulfilled from UAV's side, then D_i receives a "$TokenRequestSuccess$" message M_i along with message signature M_{Sign} as a reply from charging station C_j which indicates that the UAV D_i is eligible for tokens.
$C_j \rightarrow D_i \quad : \quad response_j = SW_{tl} \parallel M_i \parallel M_{Sign} \parallel Timestamp$
where, $M_i = amount_j \parallel status_i \parallel t_i \parallel PR_i$
Here, M_i includes some information like amount $amount_i$, current wallet status $status_i$, repay time duration t_i in which UAV has to repay the tokens to charging station and otherwise it has to pay a late fee x_i, and previous records of repayment PR_i.

B. Energy Trading Using Borrowed Tokens

UAV D_i can now obtain the tokens from the shared wallet SW_{tl} for energy trading. All payments made via SW_{tl} wallet will get verified and recorded by the charging station C_j. The encrypted value of the token data is also added in PR_i by the charging stations. Following steps further, elaborate on the procedure:

1) The UAV D_i sends the acknowledgment of received tokens along with the "$TokenReceivedSuccess$" message M_j, message signature M_{Sign} to charging station C_j. Then charging station C_j verifies the certification as well as validates the duration of the wallet SW_{tl} used for payment.
2) The charging station C_j records information attached with a digital signature of this trade in the network such as the bill, the "$TokenRequestSuccess$" message M_i, address of wallet which is to receive the tokens.
3) The charging station C_j will compare the received success message M_j with the original success message in its record for verification via decryption technique. The charging station then checks the status $status_i$ of this M_j. If the UAV D_i has sufficient funds, then required tokens are transferred through the shared wallet SW_{pl} to charging station C_j. If it is not the case, a message is sent to charging station C_j stating "$NotEnoughFunds$."

C. Repayment of IOTA Tokens

After a certain duration of IOTA tokens shared by C_j, UAV D_i is encountered with a new message M_i^{new} with repayment information based on the following possibilities.

1) First Possibility: If the UAV D_i repays its tokens within repayment time t_i, then D_i is charged with a certain amount of interest y_i along with the principal amount.

2) Second Possibility: If UAV D_i is not able to repay the charging station C_j within time t_i, then credit-status of UAV will further degrade. The new credit-status value for the UAV will be updated as:

$$credit_{n+1}^i = credit_n^i - (q * amount_i) \tag{2}$$

where $credit_n^i$ denotes nth transaction's value of the credit, and q is a predefined constant greater than 0. The charging station generates a transaction record about this process, and adds to the address pool and appeared to the network. So, even if the UAV D_i finally finishes paying the tokens, it still experiences a fine amount.

3) Third Possibility: In the case when UAV, D_i is not able to repay the charging station's tokens for a considerably long period, then the charging station will put that particular UAV into the blacklist. This ensures that nodes in the future will not cooperate with this UAV for energy trading.

VII. Optimal Price Formulation

In this section, an optimal energy trading algorithm is proposed to increase the token revenue of both the UAVs and the charging stations. The proposed formulation also encourages energy trading among UAVs and charging stations by optimizing the various parameters such as rate of interest y_i, late fee x_i, and amount of tokens shared [55]. The UAVs with insufficient tokens, borrow the required tokens from charging stations. UAVs likewise need to boost their profitability by asking the appropriate token amount. Similarly, the charging stations trade IOTA tokens and charge with interest rate of y_i and late fees x_i in a way that enhances their revenue.

A. Problem Formulation

The energy given by a charging station C_j to UAV D_i is denoted as A_i. The minimum energy demand for UAV D_i is denoted as Q_i^{min} and p_i is a given cost of the energy requested by UAV D_i. The fulfillment capacity of UAV D_i is indicated as:

$$u_f = d_i \ln\left(\frac{A_i}{p_i} - Q_i^{\min} + \phi_i\right) \tag{3}$$

where, $d_i{>}0$ and $\phi_i{>}0$ are the factors predefined for UAV D_i. The utility of D_i is defined as:

$$u_i = \sigma_i\left(u_f - y_j A_i t_i\right) - (1 - \sigma_i)\, x_j A_i \tag{4}$$

where σ_i is repayment capacity of a UAV D_i, i.e., its ability to repay the tokens in assigned time t_i. The records of previous transactions comprise of token repayment record denoted by $RP_i(s, f)$, where s denotes the number of times that UAV D_i repaid tokens successfully within repayment time, and f is the number of failures in repaying the tokens. The repayment capacity σ_i of a UAV D_i can be defined as the number of times that UAV repaid tokens successfully (s) upon total number of transactions between UAV D_i and charging station C_i $(s+f)$. The value of σ_i can be calculated with the help of token repayment record $RP_i(s,f)$ for UAV D_i as follows.

$$0 < \sigma_i = \left(\frac{s}{s+f}\right) \leq 1 \tag{5}$$

The value of y_j refers to the extra tokens charged by the charging station C_j as interest based on the time t_i for which the UAV was allowed to use the tokens. The x_j denotes the fine amount, i.e., late fee given by the UAV D_i in case of delay in repayment. The late fee x_j given by the UAV D_i is defined as the difference between the time at which UAV D_i made repayment and time given by charging station C_j to UAV D_i to repay the tokens, multiplied with the interest rate y_j at which UAV D_i borrowed tokens form charging station C_j for time t_i. The correlation between the value of y_j and x_j is given as follows.

$$x_j = \eta_i * (\mathcal{T}_i - t_i) * y_j \tag{6}$$

where $\mathcal{T}_i$ is the time at which the UAV D_i made token repayment to charging station C_j and η_i >1 is a predefined constant.

The utility of the charging station comprises of the extra tokens charged from UAV D_i as interest, and fine amount if D_i can't repay the requested tokens in time t_i. The overhead of charging station is given by

$$\Psi_j = A_i * t_i * c_i \tag{7}$$

Here, c_i is the unit cost of tokens requested by UAV D_i from the charging station. Accordingly, the monetary advantages of the charging station, C_j are characterized as follows.

$$u_j^{cs} = z_j\left(y_j A_i t_i - \Psi_j\right) + (1 - z_j)\, x_j A_i \tag{8}$$

where, z_j is the credit score for UAV D_i given by the charging station C_j and its value should lie in the range from 0 to 1. The value of z_j is determined from the previous completed transactions by UAV D_i in the network. The higher credit score brings the higher value of z_j.

Behavior or action of one entity affects the decision of others as both charging stations, and the UAVs want to maximize their economic benefits and profitability, respectively.

In this paper, a Stackelberg game approach is used to maximize the economic benefit of both UAVs and charging stations. The Stackelberg game formally tells us about the staggered basic leadership procedures of various independent decision-makers (i.e., followers) in light of the choice taken by the main player (leader) of the Stackelberg game. We, at that point, determine the Stackelberg balance of the planned game [56]. Here, the charging station is the seller energy node, and the UAV is the buyer energy node. The charging station C_j sets its decision of interest rate y_j, and fine amount x_j for every UAV D_i separately. The UAVs observe the decision of the charging station and react with the best outcome of the energy A_i as per the late fee x_j given by the charging station. The overall structure of the game $\mathcal{G}$ is defined as follows.

$$\mathcal{G} = \left\{(D \cup \{C\}), \{u_i\}_{i\in\mathbf{I}}, \left\{u_j^{cs}\right\}_{j\in\mathbf{J}}, A_i, x_j\right\} \tag{9}$$

The target functions for the charging stations and UAVs are denoted as follows:

$$\begin{aligned} &\text{Charging Station: } \max_{x_j} \sum_{j=1}^{\mathbf{J}} u_j^{cs}(x_j) \\ &\text{s.t. } x_j \geq 0 \\ &\text{UAV: } \max_{A_i} u_i(A_i) \\ &\text{s.t., } A_i > Q_i^{\min} p_i - \phi_i p_i \end{aligned} \tag{10}$$

B. Problem Solution

Backward induction methodology is used to get the equilibrium of game defined in Eqn. (9). By differentiating u_i from Eqn. (4) with A_i, we get:

$$\frac{\partial u_i}{\partial A_i} = \frac{\sigma_i d_i}{A_i - Q_i^{\min} p_i + \phi_i p_i} - \sigma_i y_j t_i - (1-\sigma_i)\, x_j \tag{11}$$

Further differentiating u_i with respect to A_i, we have:

$$\frac{\partial^2 u_i}{\partial A_i^2} = -\frac{\sigma_i d_i}{\left(A_i - Q_i^{\min} p_i + \phi_i p_i\right)^2} < 0 \tag{12}$$

As the second derivative of u_i is negative, we will obtain a strictly concave function. We acquire the optimal methodology using the following equation:

$$\frac{\partial u_i}{\partial A_i} = 0 \tag{13}$$

By solving Eqn. (13) the relation between UAV D_i's favorable amount of tokens A_i, and late fee x_j given by charging station C_j is expressed as follows.

$$A_i = \frac{\sigma_i d_i}{\sigma_i y_j t_i + (1-\sigma_i)\, x_j} + l_i \tag{14}$$

where,

$$l_i = Q_i^{\min} p_i - \phi_i p_i \tag{15}$$

Substituting Eqn. (14) into Eqn. (8) utility of charging station u_j^{cs} is changed as follows:

$$\begin{aligned} u_j^{cs} = &\frac{\sigma_i d_i\left[z_j y_j t_i - z_j t_i c_i + (1-z_j) x_j\right]}{\sigma_i y_j t_i + (1-\sigma_i) x_j} \\ &+ l_i[z_j y_j t_i - z_j t_i c_i + (1-z_j)\, x_j] \end{aligned} \tag{16}$$

Further we simplify the Eqn. (16) as follows:

$$u_j^{cs} = \frac{r_1 y_j - r_2 + r_3 x_j}{\sigma_i y_j t_i + (1-\sigma_i)\, x_j} + r_4 y_j - r_5 + r_6 x_j \tag{17}$$

where,

$$\begin{aligned} r_1 &= \sigma_i d_i z_j t_i \\ r_2 &= \sigma_i d_i z_j t_i c_i \\ r_3 &= \sigma_i d_i\,(1 - z_j) \end{aligned}$$

$$\begin{aligned} r_4 &= l_i z_j t_i \\ r_5 &= l_i z_j t_i c_i \\ r_6 &= l_i (1 - z_j) \end{aligned} \tag{18}$$

By double differentiating u_j^{cs} with respect to x_j,we have

$$\frac{\partial^2 u_j^{cs}}{\partial x_j^2} = -\frac{2 r_2 \eta_i}{(\sigma_i + \eta_i - \sigma_i \eta_i)\, x_j^3} < 0 \tag{19}$$

If $l_i < 0$, then we have:

$$\begin{aligned} \lim_{x_j \to 0} u_j^{cs} &= -\infty \\ \lim_{x_j \to +\infty} u_j^{cs} &= -\infty \end{aligned} \tag{20}$$

When $l_i < 0$, for

$$0 < x_j < \left[-\frac{r_2 \eta_i^2 t_i}{(r_4 + r_6 \eta_i t_i)(\sigma_i + \eta_i - \sigma_i \eta_i)} \right]^{1/2}$$

we have,

$$\frac{\partial u_j^{cs}}{\partial x_j} > 0$$

and for,

$$x_i > \left[-\frac{r_2 \eta_i^2 t_i}{(r_4 + r_6 \eta_i t_i)(\sigma_i + \eta_i - \sigma_i \eta_i)} \right]^{1/2} \tag{21}$$

we have,

$$\frac{\partial u_j^{cs}}{\partial x_j} < 0 \tag{22}$$

respectively.

The utility function u_j^{cs} is found to first increase to certain maxima, and then it starts decreasing with the increase in the value of x_j. This proves that the utility function u_j^{cs} is convex in nature. The following equation gives the optimal pricing for energy sharing.

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{23}$$

By solving Eqn. (23), the late fee x_j given by the charging station is changed as follows.

$$x_j = \left[-\frac{r_2 \eta_i^2 t_i}{(r_4 + r_6 \eta_i t_i)(\sigma_i + \eta_i - \sigma_i \eta_i)} \right]^{1/2} \tag{24}$$

If $l_i > 0$ then $x_j < 0$. Therefore, we have $x_j = 0$. For simplicity, optimal strategy of the charging station can be rewritten as:

$$x_j = \begin{cases} 0, l_i > 0 \\ \min\left(\left[-\frac{r_2 \eta_i^2 t_i}{(r_4 + r_6 \eta_i t_i)(\sigma_i + \eta_i - \sigma_i \eta_i)} \right]^{1/2}, x_j^{\max} \right) \\ , l_i \leq 0 \end{cases} \tag{25}$$

and also the value of extra tokens charged as interest i.e., y_j by charging station C_j is as follows:

$$y_j = \frac{x_j}{\eta_i * (\mathcal{T}_i - t_i)} \tag{26}$$

Algorithm 1: Optimal Energy Trading Algorithm.

Let $x_j^* = 0$, $u_j^{cs*} = 0$, $A_i^* = 0$, $u_i^* = 0$
for $i = 1 : \mathbf{I}$ **do**
  for $x_j^* = 0 : x_j^{max}$ **do**
    if $l_i > 0$ **then**
      $x_j^* = 0, A_i^* = 0$
      break
    else
      Charging Station C_j adjusts energy A_i according:
      $A_i^* = \frac{\sigma_i d_i}{\sigma_i y_j t_i + (1-\sigma_i) x_j} + l_i$
    end if
    UAV D_i updates their utility according:
    $u_i^* = \sigma_i (u_f - y_j A_i^* t_i) - (1 - \sigma_i) x_j^* A_i^*$
    Charging station C_j updates its utility according:
    $u_j^{cs*} = z_j (y_j A_i^* t_i - \Psi_j) + (1 - z_j) x_j^* A_i^*$
    if $u_j^{cs} \leq u_j^{cs*}$ **than**
      Records maximum utility and optimal late fee
      $u_j^{cs} = u_j^{cs*}, u_i = u_i^*, A_i = A_i^*, x_j = x_j^*$
      break
    else
      $u_j^{cs} = u_j^{cs*}, u_i = u_i^*, A_i = A_i^*, x_j = x_j^*$
    end if
  end for
end for
Stackelberg Equilibrium is achieved

To accomplish the Stackelberg Equilibrium (SE), the charging station needs to communicate with UAVs [57]. Algorithm 1 is introduced to give a distributed path to all the UAVs and the charging station to obtain the unique Stackelberg Equilibrium iteratively.

VIII. Numerical Analysis

A. Simulation Settings

For assessing the performance of P2P energy trading between charging stations and UAVs, the simulation results are presented in this section. In our model, we have considered a network consisting of j charging stations and i UAVs. The predefined factors d_i and ϕ_i for UAV D_i lie in an interval of [1,5] and [5,7] respectively. The token repayment time, i.e., t_i for any UAV, lies in the interval [5,9] months. The cost of the energy requested by UAV D_i is p_i lies in the interval [6,15] dollars. The minimum energy demand for UAV D_i is Q_i^{min} and lies in an interval of [50,60] kJ. The predefined credit grade factor relies upon D_i's credit grade denoted by z_j and lies in the interval of [0,1]. The entire code for network creation is written in python.

B. Performance Evaluation

Results generated by the simulation of the model are compared and evaluated in this section. Consider in a network there is 1 charging station and 4 UAVs that need the energy to complete their task. The UAVs which do not have enough tokens to buy energy will borrow the IOTA tokens from charging station over late fee x_j with repayment time t_i. The late fee of x_i is calculated

TABLE I
RELATED WORK ON UAV CHARGING

Year	Authors	Unique Features
2016	Zhuzhong Qian *et al.* [24]	Efficient Charging Association algorithm for charging UAVs based on energy demand of UAVs.
2017	David Dominique *et al.* [25]	Contract Based Scheduling of UAVs to the Charging Stations.
2018	Jinyong Kim *et al.* [26]	Scheduling UAVs to the Charging Stations through a centralized cloud server.
2018	Maxim Lu *et al.* [27]	Detailed Review of different wireless charging techniques used for charging UAVs.
2018	Chiuk Song *et al.* [28]	Wireless Charging of UAVs by strong electromagnetic fields by reducing EMI.
2019	MyungJae Shin *et al.* [29]	Machine Learning to understand the UAV network and Auction Model for optimising cost.
2019	Sungwoo Kim *et al.* [30]	Application of Travelling Salesman Problem to reduce the distance traveled by the UAVs.
2019	Haider Mahmood Jawad *et al.* [28]	A Magnetic Resonant Coupling Technique for wireless power transfer to Charge UAVs.
2019	Roberto G. Ribeiro *et al.* [31]	Application of UAVs in Mining and Mixed-Integer Linear Programming Model for charging UAV.

TABLE II
LIST OF ACRONYMS

Notation	Meaning
X	Transaction
W_X	weight of transaction X
CW_X	Cumulative Weight of the transaction X
I	Total number of UAVs in IOTA network
J	Total number of charging stations in network
D_i	i^{th} UAV in the network
C_j	j^{th} charging station in the network
ID_i	Account address of UAV D_i
$H_{i,k}{}_{k=1}^{K}$	Transaction history of UAV D_i
$amount_i$	Number of tokens requested by D_i from C_j
$credit_i$	Available number of tokens with UAV D_i
$request_i$	Request message from D_i to C_j
SW_{tl}	Shared wallet for IOTA tokens between D_i and C_j
M_i	$TokenRequestSuccess$ Message form C_j
M_{sign}	Message signature form C_j indicating that D_i is eligible for tokens
$Timestamp$	Time at which C_j sends message to D_i
$response_j$	Response message form C_j to D_i
$status_i$	Status of current wallet SW_{tl}
PR_i	Previous records of repayment related to D_i
q	Predefined constant
A_i	Energy given by charging station to UAV D_i
p_i	Cost of energy requested by UAV D_i
Q_i^{min}	Minimum energy demand for UAV D_i
ϕ_i	Predefined factor for UAV D_i
d_i	Predefined factor for UAV D_i
u_i	Utility value of UAV D_i
σ_i	Repayment Capacity of UAV D_i
t_i	Repayment time given to UAV D_i
y_j	Interest rate at which D_i borrowed tokens for time t_i
x_j	Late fee given by UAV D_i in delay of repayment
s	Number of times that UAV repayed tokens successfully
f	Number of times that UAV failed in repaying the tokens
η_i	Predefined constant
$\mathcal{T}_i$	Time at which D_i makes repayment to C_j
u_j^{cs}	Utility value of Charging Station C_j
z_j	Predefined credit grade factor relied upon UAV D_i
Ψ_j	Overhead of charging station C_j
$\mathcal{G}$	Stackelberg game

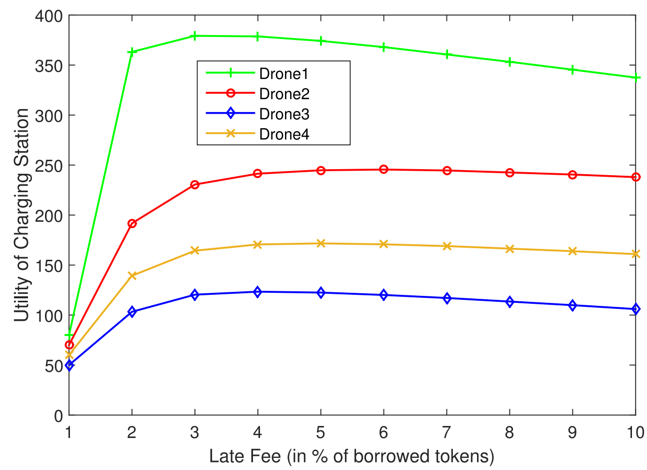

Fig. 2. Utility of charging station over change in late fee to UAVs.

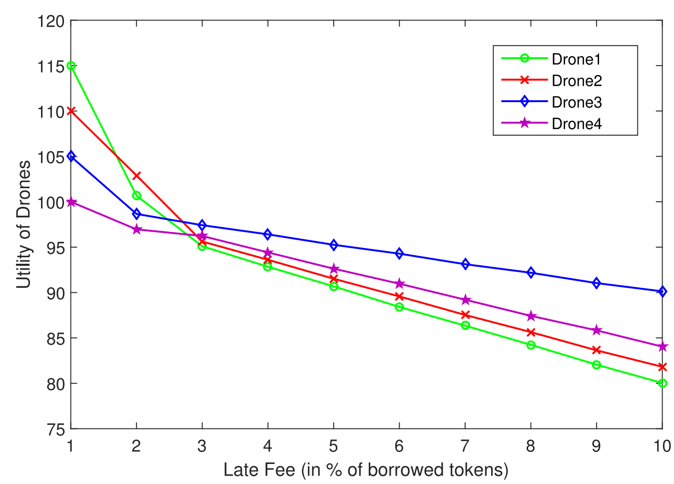

Fig. 3. Utility of UAVs over the change in a late fee.

in proportion to the borrowed tokens. Fig. 2 shows the change in the value of utility of charging station u_j^{cs} over change in late fee x_j. The value of utility of charging station u_j^{cs} increases initially and then decreases with the increase in a late fee. This is so because as the value of x_j increases over some threshold, the UAVs are less motivated to accept the tokens. Therefore, the utility of the charging station starts decreasing after a certain increase in the value of x_j. Finally, the appropriate value of late fee x_i should be imposed on UAV D_i according to Algorithm 1, which results in maximizing the utility of charging stations.

Fig. 3 shows the change in the value of utility of UAVs u_i over the change in the value of late fee x_j to UAVs. From Eqn. (4), it is observed that with the increase in the value of late fee x_j, there will be a decrease in the value of utility of UAVs. So optimal value of late fee x_j is negotiated with charging station C_j through Algorithm 1, which results in maximizing the utilities of both UAVs and charging stations. Fig. 4 refers to the change in energy given by the charging station to UAVs over the increase

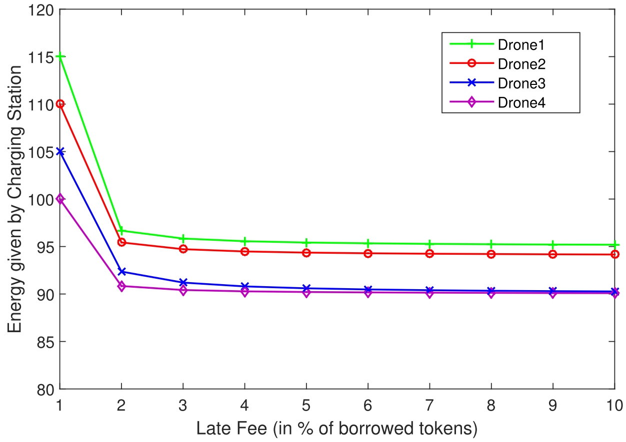

Fig. 4. Energy given by charging station over change in late fee.

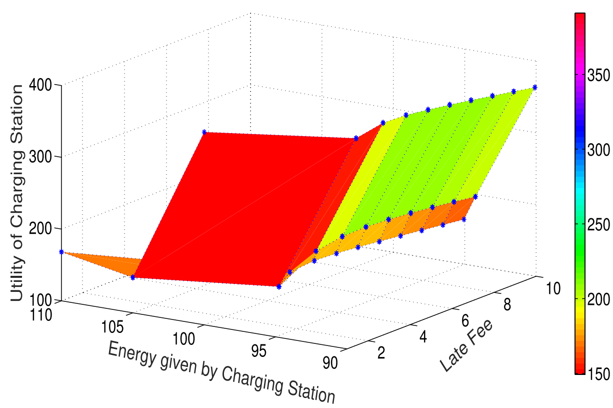

Fig. 5. Utility and energy given by charging station over change in late fee.

in the value of late fee x_j. This is so because the UAVs expect less energy A_i as the value of x_j increases. From the Eqn. (14), it is interpreted that the relation between energy given by charging station A_i and late fee are inversely proportional to each other. In order to acquire the minimum energy required by UAV D_i, i.e., Q_i^{min}, it should negotiate the energy A_i at optimal late fee value x_j through Algorithm 1.

Fig. 5 shows a change in the utility value of charging station and energy given by charging station to UAVs with the increase in the value of late fee x_j. The utility value of the charging station increases initially and then decreases with the increase in the value of the late fee. The energy A_i given by charging station to UAVs will be inversely proportional to late fees. So with an increase in the value of late fee x_j, there will decrease in energy given by the charging station. This finally results in a decrease in the utility of the charging station. Therefore, the optimal late fee value x_j is charged by charging station from UAVs, in order to maximize its utility based on Algorithm 1.

Fig. 6 shows the comparison of utility value of charging station u_j^{cs} in random and proposed model. In the random model, the value of late fee x_j and energy given by charging station A_i to UAV are selected randomly and are not changed, which results in a lower utility value than the value through proposed model. However, in the proposed model, the value of late fee x_j

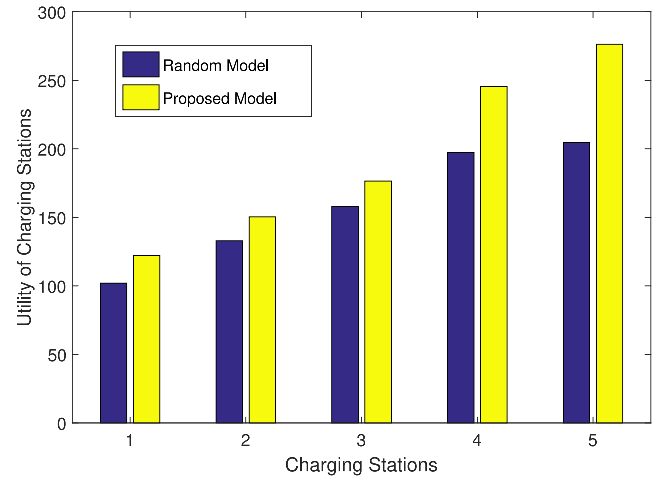

Fig. 6. Comparison of utility of charging stations in random and proposed model.

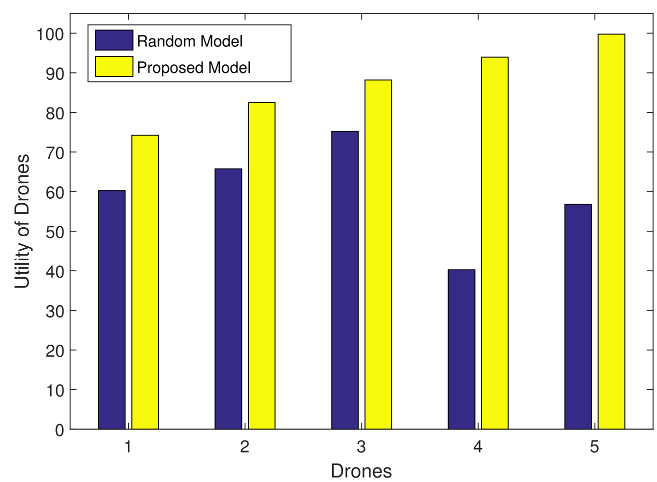

Fig. 7. Comparison of utility of UAVs in random and proposed model.

changes with the change in energy given by charging station A_i to UAVs. This continues until the values of the utility of charging stations and UAVs are maximum. Similarly, Fig. 7 presents the comparison of the utility value of UAVs u_i in the random and proposed model.

IX. Conclusion

In this paper, we have proposed a distributed framework for energy trading between UAVs and charging stations. We have used an IOTA based tangle data structure to create a distributed network. IOTA tokens are shared between the different entities in the network. The UAVs can borrow the tokens from the charging station and can purchase energy using those tokens. UAVs need to return the tokens to the charging station in a predefined time. UAVs also need to return some extra tokens as interest for using the tokens. If the UAVs fail to repay the tokens in a predefined time, a fine is charged by the charging station. The fine rate is the motivating factor for the charging station to give tokens to the UAVs. UAVs expect more tokens in less fine, and the charging stations expect high fine. A game-theoretic approach is applied to this scenario to maximize the profit of both UAVs and charging stations. Numerical results prove that the proposed model to give better revenue to the UAVs and charging stations as compared to its counterparts. The overall utility of the drones and the charging stations is enhanced based on the numerical analysis. We expect that the proposed scheme can be generalized to accommodate IoT devices. In particular those devices that are used in critical applications such as healthcare systems.

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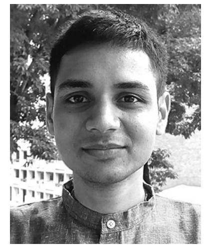

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