Abstract: In this paper we develop a trade model that integrates peer to peer energy trade with Electric Vehicle (EV) charging infrastructure. As an energy distribution network may not allow energy transfer among microgrids, in the proposed trade model, each microgrid operates one local charging station and microgrids form coalitions to trade EV charging requests among themselves for the optimal utilisation of renewable energy. Our main contribution is a multifaceted marketplace using blockchain where prosumers, microgrids and EVs participate in energy trade. Using blockchains, we present distributed scalable computation methods for trade decisions which are robust against malicious and faulty participants.

1 Introduction

In this paper we unify the trade models for peer to peer energy trade and EV charging and discharging using blockchains. Our motivations are as follows:

Trade restriction: Peer to peer energy trading is usually restricted among peers connected at the lowest level of the energy distribution network. There are a number of technical and regulatory barriers to such peer to peer trading. Technical barriers arise due to the design and operation of the physical electricity distribution network infrastructure. The electricity network has a hierarchical structure which is designed so that power flows in one direction from the transmission network to the primary distribution network, and finally to the secondary (low voltage) distribution network, where users are connected to different phases of an unbalanced three-phase system. Most distribution networks worldwide are operated radially, with constraints on the network voltages, power flows, and fault levels in order to maintain acceptable levels of power quality and reliability [1, 2]. There are also a number of regulatory barriers which may impede or prevent peer to peer trading. In a utility-owned electricity network, it is necessary for all users to comply with local grid codes and electricity market regulations, which are typically designed to facilitate traditional, centralised electricity market arrangements [3, 4].

Renewable energy for EV charging: EVs are introduced to reduce greenhouse gas emission. The practice of charging EVs with non-renewable energy resources is a contradiction to such premise.

Enforcement of trade decisions: Energy trade decisions are made using energy production and consumption forecast information. Energy trade decisions state the prescribed energy production (shared with other peers) or consumption for each peer. It is necessary to use an enforcement mechanism to encourage peers to comply with prescribed energy production or consumptions.

We address these concerns with EV charging and peer to peer energy trade by developing a unified trade model. In this trade model, each microgrid operates one EV charging station and they form coalitions to trade EV charging requests. A coalition allows a microgrid to delegate the EV charging request to another microgrid in the same coalition. Our main contributions are as follows:

Multifaceted trade model: We have developed a multifaceted trade models that allows prosumers, microgrids and EVs to participate in energy trade in the same platform.

Better revenue for microgrids: We show that trade of charging requests among microgrids brings better revenue for the microgrids.

Distributed computation of trade decisions: We have developed distributed algorithms for computation of coalition structure over the microgrids and charging station allocation to EVs.

Security and scalability: We have used blockchain channels to improve scalability. We also show that the proposed trade platform is secure against malicious and faulty participants.

The paper is organized as follows: in section 2 we discuss relevant literature, in section 3 we discuss the trade model, in section 4 we describe how to use blockchains to implement the trade model, in section 5 we present experimental evaluation and we conclude the paper in section 6.

2 Related literature

Quick-charging strategy for charging stations on highways was studied in [5]. EV queue management problem for load balancing among charging stations while minimizing charging time of EVs was analyzed in [6]. The problem of designing survivable network for charging station network was studied in [7] as it finds the minimum number of stations to be maintained to keep the station network connected. A pricing model for charging for load balancing based on frequency regulation signals from electricity grid was developed in [8]. EV queue management problem using computational game theory was solved in [9]. A survey on economy driven approaches such as auction, Stackelberg games, potential games to solve the EV charging scheduling problem was presented in [10].

In cooperative peer energy exchange problem [11] we need to find coalitions among the peers and peers in each coalition trade energy among themselves. In the non-cooperative energy trade problem [12] both the buyers and the sellers want to maximize their respective gains. A combinatorial double auction for peer energy trade was proposed in [13]. Trading strategies for energy market among peers was analyzed in [14]. Blockchain was used to develop peer to peer energy trade in [15, 16].

This paper advances the state of art by introducing a trade platform that allows prosumers, microgrids and EVs to interact and trade energy. It also improves scalability, security and robustness of the trade platform by using blockchains.
3 EV charging and peer to peer energy trade

The integrated trade model is illustrated in figure 1. Peers (houses) trade energy among themselves as they form a microgrid. We use the model of microgrid used in [17] and affiliation of a house to a microgrid is fixed. A microgrid, on behalf of its peers buys or sells energy from and to the utility grid. Each microgrid supports an EV charging station. A coalition is a partition over the microgrids such that microgrids in each coalition are situated in close proximity and the price for EV charging in each coalition is the same. At every iteration (after each fixed time interval, say 15 minutes) the following steps are repeated:

Step 1: In each microgrid, a peer informs an aggregator (another peer in the same microgrid) about its forecasted energy requirement for the next time interval.

Step 2: Microgrids interact among themselves to decide the coalitional structure using the aggregated energy requirement information and historical EV charging information. Each aggregator decides the price for energy to be bought or sold in its microgrid and the price for EV charging in the coalition.

Step 3: Next, actual energy transfer among peers in each microgrid and energy transfer among the utility grid and microgrids occur. Also, at this step EVs charge their batteries. A EV sends its request to find a charging station to any peer of a nearby coalition and the coalition allocates a charging station within its microgrids.

Note that first two steps are executed at the beginning of each iteration and these two steps are assumed to take negligible amount of time. But step 3 takes almost the full duration of each iteration.

Step 4: Next step is executed just before the current iteration finishes (say one minute before current iteration finishes). The total valuation of each coalition is computed and it is divided among microgrids in each coalition using Shapley value.

Step 5: After utility settlement in each coalition in step 4, each microgrid distributes its share of such utility among its peers.

Next we present formal definitions of this trade model.

3.1 Trade between microgrids

We use these parameters to describe trade between microgrids using EVs.

\[ M = (M_1, \ldots, M_n) \] A set of \( n \) microgrids

\[ \Pi = (\pi_1, \ldots, \pi_k) \] Be a \( k \) partition of the microgrids where \( |\pi_i| = x \) and \( x + x = n \).

\[ \theta^t_i \] Probability that one EV will request charging at \( M_i \) at the time \( t \).

\[ E^t_i \] Energy generation at \( M_i \) at time \( t \).

\[ D^t_i \] Energy demand at \( M_i \) at time \( t \).

\[ G = (N, L) \] Road network with landmarks \( N \) and road segments \( L \).

\[ C(M_i) \in N \] Central location of the microgrid \( M_i \).

\[ \text{Len}(N_x, N_y) \] Length of shortest path between \( N_x \) and \( N_y \).

**Definition 1.** Coalition structure over the microgrids is the partition \( \Pi \) such that the following conditions holds:

1. for all \( \pi_i \), for all pairs \( (M_x, M_y) \) where \( M_x \in \pi_i \) and \( M_y \in \pi_i \), \( \text{Len}(C(M_x), C(M_y)) \leq \Delta \).
2. For all pairs \( (\pi_i, \pi_j) \in \Pi \), \( \pi_i \cap \pi_j = \emptyset \).
3. \( \cup_{\pi_i \in \pi} \pi_i = M \).

**Definition 2.** Valuation of a coalition \( \pi_i \in \Pi \) at time \( t \) is given by the following equation:

\[ V^t(\pi_i) = \frac{1}{1 + |\text{Exp}_1 - \text{Exp}_2|} \tag{1} \]

where \( \text{Exp}_1 \) and \( \text{Exp}_2 \) are defined as follows: for any coalition \( \pi_i \), let,

\[ \pi_i^+ \subseteq M_x \in \pi_i^+ \text{ if } E^t_x - D^t_x \geq \delta \]

and

\[ \pi_i^- \subseteq M_x \in \pi_i^- \text{ if } E^t_x - D^t_x < \delta \]

where \( \delta \) is the energy in kWh to fully recharge an EV. Now we define \( \text{Exp}_1 \) and \( \text{Exp}_2 \) for a coalition \( \pi_i \) as follows:

\[ \text{Exp}_1 = \sum_{M_x \in \pi_i^+} (1 - \theta^t_x) \text{ and } \text{Exp}_2 = \sum_{M_x \in \pi_i^-} \theta^t_x \]

**Definition 3.** At time \( t - 1 \), the objective of the trade among microgrids is to find a coalition structure \( \Pi^* \) such that \( \sum_{\pi_i \in \Pi^*} V^t(\pi_i) \) is maximal.

3.2 Peer to peer energy trade within a microgrid

We use the following parameters to describe peer to peer energy trade within a microgrid.

\[ (P^t_{1}, \ldots, P^t_{n}) \] The set of \( n \) peers in the microgrid \( M_j \).

\[ e^t_{i,j} \] Energy generation at the time \( t \) in the peer \( j \) in the microgrid \( M_j \).

\[ d^t_{i,j} \] Energy consumption at the time \( t \) in the peer \( j \) in the microgrid \( M_j \).

\[ Q^j_1, Q^j_2 \] Price of energy per kWh for buy and sell within the microgrid \( M_j \).

\[ Q^j_3, Q^j_4 \] Price of energy per kWh for buy(sell) from(to) the utility grid.

**Definition 4.** Prices to buy or sell energy within a microgrid and from the utility grid satisfies the following equation:

\[ Q^j_3 \geq Q^j_1 \geq Q^j_2 \geq Q^j_4 \]

**Definition 5.** \( X^j = (X^j_1, \ldots, X^j_\epsilon) \) be a vector where \( X^j_\epsilon \in [0, 1] \) where \( \epsilon > 0 \). \( X^j \) is called the coordination vector which denotes control over energy consumption of each peer. \( c^t_{i,j} \) denotes the minimum energy demand for each peer.

\[ Q^j_3 \geq Q^j_1 \geq Q^j_2 \geq Q^j_4 \]
We define utility of a microgrid in terms of its dependencies on the utility grid.

**Definition 6.** We define utility of a microgrid $M_j$ as

$$U(M_j) = \frac{1}{1 + \left| \sum_{p_i \in M_j} e_i^t - \sum_{p_i \in M_j} X_i^{P_{i,j}} \right|}$$

The main objective of peer to peer energy trade is to maximize the utility of the microgrid. In the next section we use blockchain to integrate these two energy trades.

## 4 Blockchain implementation of the trade model

We divide an entire day into equal durations, say each duration is 15 minutes and there are 96 durations. At the beginning of every duration, the blockchain computes the coalition structure over the microgrids. Peers of each microgrid will announce its energy requirement for the current duration as transactions among them. A random peer will compute the coalition structure using such energy requirement information and historical demand for EV charging. After completion of coalition structure computation, the blockchain will accept charging requests from EVs. A EV can make such request using tokens it has bought using any other fiat currency. A EV will announce its recharging request by creating a new transaction. A peer in the blockchain will decide the appropriate recharging location and it will send the tokens back to the EV using a new transaction which will mention where the EV should recharge. Next, we will discuss details of how the same blockchain will compute coalition structure and how it will also allocate stations to EVs for recharging.

### 4.1 Blockchain peer to peer network

The blockchain peer to peer network will consist of a set of EVs $\{EV_1, \ldots, EV_T\}$, a set of microgrids $M$ and sets of peers $(P_i^j)$ in each microgrid $M_j$. The neighbourhood of the network is as follows:

1. Each microgrid will include all other microgrids with a fixed distance (δ) as its neighbour in the peer to peer network.
2. Each peer $P_i^j$ in the microgrid $M_j$ will be neighbour of all peers in $M_j$ and it will be a neighbour of $M_i$.
3. Any EV $EV_i$ will be neighbour of any fixed size subset of peers corresponding to the microgrids.

We use proof of work as the consensus method.

### 4.2 Channels in a microgrid

We will use payment channels to record energy requirement information in each microgrid. Payment channels are developed in blockchain to improve its scalability. A payment channel can keep secure record of transactions between two parties in offline, i.e., without updating the blockchain. A payment channel between a peer $P_i^j$ and its microgrid $M_j$ has the following features:

1. **Opening transaction**: First, two parties form a multi-signature address ($P_i^j, M_j$) and it requires authorization from both parties to transfer from the multi-signature address. Both parties create an initial transactions to fund this multi-signature address but they do not broadcast it to the blockchain network.
2. **Secret and Hash**: Each parties will create a secret (a string) and its hash using its private key. They will exchange the hash.
3. **Commitment transaction**: Commitment transactions ensures that a party can leave the channel at any time without losing tokens. Say both parties are willing to transfer 5 tokens to the multi-signature address. $P_i^j$ will create a commitment transaction where it will pay itself 5 tokens from the multi-signature address and the rest to another multi-signature address. Further, it will create a transaction from the second multi-signature address where all tokens of the second multi-signature address will be transferred to $M_j$ after 100 new blocks in the blockchain or if $P_i^j$ can tell the secret of $M_j$, $M_j$ will create a mirrored commitment transaction. They will exchange the commitment transactions. After exchanging the commitment transactions, the parties will announce the opening transaction to the blockchain.
4. **Transaction update**: Parties can update commitment transaction by exchanging secrets and hashes of new secrets.
5. **Closing transaction**: The channel closes if either party announces a commitment transaction to the blockchain. The advantages of payment channels are as follows:
   - It improves scalability of blockchain as only the opening transaction and one commitment transaction (to close the channel) is needed to be recorded in the blockchain.
   - Channels are secure as a party can not close the channel with old transactions.

We will use channel to record energy requirement information between a microgrid and a peer within it as follows:

1. Let $Elec$ be the maximum kWh electricity that a peer can sell to other peers in a microgrid or the maximum kWh electricity that a peer can buy from the microgrid for a fixed time duration.
2. A channel between a peer $P_i^j$ and its microgrid $M_j$ will require two multi-signature address $Add_1$ and $Add_2$.
3. Both parties will create opening transactions of amount $Elec$ to the multi-signature address $Add_1$.
4. Both parties will create a secret and exchange its hash.
5. If the peer expects to import energy of $x$ kWh for the next duration then it will create a commitment transaction as follows:
   - It will send $Elec + x$ tokens to itself and $Elec - x$ tokens to the second multi-signature address $Add_2$. Then it will create a transaction from $Add_2$. In this transaction, $M_j$ can take all tokens in $Add_2$ after 100 new blocks or if $P_i^j$ can tell the secret of $M_j$, $M_j$ will also create a mirrored transaction and they will exchange these commitment transactions.
6. After each duration a peer can update its energy requirement by updating the commitment transaction and exchanging secrets for the last commitment transaction.

A microgrid $M_j$ will collect the energy requirement information from its peers by updating channels between them. It aggregates such information for coalitional structure generation.

### 4.3 Coalitional structure computation

We will use valuation of a coalition defined in equation 1 in the algorithm to generate coalitional structure. Note that valuation of a coalition is a most 1 which indicates that the number of microgrids with excess energy and there is no EV who wants to recharge at these
microgrids is almost equal to the number of microgrids with energy deficit and there are EVs who want to charge at these microgrids. Value of a coalition gets lower as the difference between these two numbers grows. The coalition structure generation algorithm starts with a random coalitional structure and improves it by swapping neighbouring microgrids between two coalitions. It is as follows: First value of each coalition is calculated. Then each coalition with worst value is selected for swapping microgrids in neighbouring coalition. Swapping between two complementary coalitions stops when number of microgrids with excess energy becomes minority in the coalition with initially excess energy and vice versa.

The above algorithm to generate coalition structure is executed by several peers (microgrids). First we introduce a numbering mechanism of the microgrids to explain this distributed execution method.

- Each microgrid is assigned an unique number less than Z_1 (positive integer). We denote this number as I(M_j).
- Identification number of each microgrid is

\[10 \times \text{Modulus}(I(M_j), B + \text{Max}(|I(M_i)|)) + I(M_j)\]

where B is the current height of the blockchain (i.e., number of blocks currently at the blockchain), Max(|I(M_i)|) is maximum allocated fixed unique number to the microgrids.

Note that for any height of the blockchain the above rules generate unique numbers to the microgrids. The identification numbers of the microgrids change as the blockchain height is increased. Using the above procedure, the coalition generation procedure is as follows:

- Let Limit_1 be an unique positive integer.

### Example of sinks: Limit_1 is 2. M_1 and M_2 act as sinks. M_1 creates a transaction T_x_1 and send it to M_2 with lowest identification number. M_3 forwards T_x_2 to M_1 by creating a new transaction T_x_3 with input T_x_2.

#### 4.4 Charging station allocation

The procedure of station allocation is as follows:

1. A EV announces its energy requirement by a transaction to a microgrid in close proximity to itself or the desired location.
2. After receiving the transaction from a EV, a microgrid forwards the transaction to the microgrid with lowest identification number in its coalition.
3. The microgrid with the lowest identification number executes the following algorithm for station allocation:

### 4.5 Observations

Note that the above described procedure of coalition formation and station allocation procedure has the following properties:

**Distributed:** Both procedures are executed in distributed fashion.

**Scalability:** We used channels to improve scalability of blockchain.

**Security:** Both procedure is secure against malicious participants as all peers must agree on the outcome of the execution of both procedures. The usage of identification number improves the scalability of...
Algorithm 2: Station allocation

Data: A coalition \( \pi_j = M_1, \ldots, M_k \), energy requirement in the coalition as \( \{ e^t_{i,j}, d^t_{i,j} \} \), \( \theta^t_j \) probability that a EV will request for recharging at \( M_j \) at \( t \), \( Tx \) be the transaction from the EV \( EV_x \) forwarded to the sink \( M_y \in \pi_j \)

Result: Station allocation

begin
\[
\begin{align*}
\text{Vacant}_i &= 1 \text{ if } e^t_{i,j} - d^t_{i,j} \geq Z \text{ otherwise it is 0.} \\
\text{Count} &= 0 \\
\text{Allocated} &= \emptyset
\end{align*}
\]

for Each recharging request from EVs do
\[
\begin{align*}
\text{Count} &= \text{Count} + 1 \\
\text{if } \text{Count} \leq \sum (\text{Vacant}) \text{ then} \\
&\text{Allocate } M_i \text{ at the price } Q_1 \text{ to the EV if} \\
&\text{Vacant}_i = 1 \text{ and } M_i \notin \text{Allocated and} \\
&M_y \text{ create a transaction } Tx' \text{ with input} \\
&M_x \text{ label 'Station field' of } Tx' \text{ with public key of} \\
&M_i \\
\text{else} \\
&\text{Allocate randomly at the price } Q_3
\end{align*}
\]
end

the system as only a few peers execute complex procedures to reduce the computational overhead. A peer acting as a ‘sink’ may crash but such event can be detected using existing procedures of distributed computing. But this approach ensures that all functional peers acting as ‘sinks’ can continue execution trade decisions despite few faulty peers.

5 Evaluation

We will show that the proposed trade model brings better utility for the microgrids. We use a set of random connected graphs with 100 nodes and average degree 10 as a set of road network. In each edge we place a number of microgrids proportional to the length of the edge. \( \delta \) is the mean distance among all pair of microgrids. Figure 4 shows the data used to model energy supply/demand of the microgrids over one day. We assign the probability that an EV will request charging at a microgrid uniformly at random. We show the improvement in the utility of coalitions adjusted by Algorithm 1 in Figure 5 for 5 road networks. It clearly shows that the algorithm improves the utility of coalitions.

6 Conclusion

In this paper we presented a blockchain based energy trade platform that allows microgrids to form coalitions and a microgrid can delegate EV charging request to another microgrid in the same coalition. In future we will extend this trading platform for energy trade among microgrids.

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