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Distributed double auction for peer to peer energy trade using blockchains

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Abstract—**In this paper we use the blockchain technology to develop a peer to peer energy trade platform without a trusted third party. Our main contribution is a novel distributed double auction mechanism which allows any peer to act as an auctioneer and the blockchain mechanism ensures that a peer behaves lawfully while acting as an auctioneer. Using experimental evaluation we show that (1) the distributed auction converges quickly, (2) it minimizes energy loss due to long transmission, (3) computational overhead due to employing a blockchain is negligible, (4) it is efficient and (5) it can implement trade restrictions imposed by the energy distribution network.**

Index Terms—**Microgrid energy trade, Blockchain, Double auction**

I. INTRODUCTION

Power grids worldwide are undergoing a fundamental shift away from the traditional centralised system where energy is supplied by large, controllable power plants to a decentralised system based on weather dependent, non-controllable renewable energy sources. Peer to peer energy trade [1], [2] can enable a more decentralized operation of the power system, better utilisation of grid assets, and improved integration of distributed energy resources via local energy balancing. Our objective is to develop a trading platform for such peer to peer energy trade.

We investigate double auction [3] as a trade model for peer to peer energy trade. In double auction, buyers (who need energy) and sellers (who have excess energy) submit their reservation price (and amount to energy to buy or sell) to an auctioneer. A buyer's reservation price is the maximum price it will pay for energy and a seller's reservation price is the minimum price at which the seller will sell its energy. The auctioneer decides on the price for energy exchange and subsets of the buyers and sellers who will trade. We may use McAfee's mechanism [4] to determine the winner (who trades energy and at what price) of a double auction. There are several problems with a centralized double auction for peer to peer energy trade as follows:

- **Robustness:** Centralized auction is not robust as failure of the auctioneer would fail the entire trade operation.
- **Trust on the auctioneer:** The auctioneer may collude with a few peers to alter the result of the auction. Hence peers must evaluate their trust on the auctioneer.
- **Local Price:** Price for energy exchange may be determined by peers who are long distance apart from other peers. We will use [4] to determine winner of the double auction. According to this mechanism the price for energy trade is determined by bids of a buyer and seller pair such that (a) buyer's bid more or equal to the seller's bid and (b) there is not other buyer-seller pair who satisfies the first condition. In a large network, it may happen that such a pair of buyer-seller peers are situated at distant locations from other peers. Due to long distance from other peers they may not engage in energy trade. Hence such price should not be used for energy transfer for the entire peer network.
- **Local exchange:** Peers who are located at distant locations from each other may trade energy and it will cause energy loss due to long transmission distances.
- **Security:** It is difficult to ensure security of information shared in peer to peer energy trade. Also, such a trade platform is vulnerable to cyber attacks.

In this paper we propose a blockchain based distributed double auction for peer energy trade [2] to mitigate these problems. Blockchain [5] mechanism allows us to securely store transaction records between two peers in a peer to peer network. Security of blockchain maintained transaction record is guaranteed by encryption and distributed consensus protocol. Blockchain mechanism eliminates the requirement of a trusted third party to verify a transaction between two parties. In the proposed distributed double auction, any peer may act as the auctioneer and the blockchain mechanism ensures that each peer acts lawfully while it acts as an auctioneer. In this paper we present the following results:

- **Blockchain based double auction:** We present a blockchain infrastructure to support a distributed peer to peer auction where any peer can act as an auctioneer and several local double auctions are executed in parallel and asynchronous fashion. Blockchain mechanism ensures each auctioneer follows the prescribed rules to determine winners of each auction. Also, blockchain maintain secure records of bids and result of winner determination problem of the double auction.
- **Local trade:** The proposed distributed double promotes local energy trade to minimize energy loss due to transmission. It reduces the distances among the pair of buyer-seller peers whose bids determine the price for energy exchange and the peers who trade energy at this price.
- **Convergence:** The distributed auction solves the double auction in an iterative fashion. We show that such iterative process ends quickly.

- **Computational overhead:** We show that number of peers in each of auction for the distributed double auction is much less than the centralized auction and it remains approximately constant if we increase the number of peers. Hence the proposed distributed auction has negligible computational overhead as it uses a blockchain.
- **Efficiency:** We show that distributed double auction can be as efficient as a centralized double auction. We measure the efficiency of the auction in terms of standard deviation of energy prices.
- **Efficiency and trade neighborhood trade off:** We use a method to control the trade neighbourhood of each peer, i.e., the set of peers whose energy requirement information will be used to determine whether or not it can buy of sell energy. Such control method can realize the energy trade restrictions that the energy distribution network imposes on the peers. We analyse the trade off between efficiency and trade neighbourhood size.

The paper is organized as follows: In section 2 we discuss relevant literature. In section 3 we discuss the double auction process for energy trade among peers. In section 4 we present a brief description of the blockchain mechanism. In section 5 we present the blockchain based distributed auction. In section 6 we present experimental evaluation. In section 7 we conclude the paper with future research direction.

II. RELATED LITERATURE

Peer to peer energy exchange improves the reliability of renewable energy sources and reduce dependency on the utility grid. In cooperative peer energy exchange, peers exchange energy to maximize the social utility. The non-cooperative version of this problem requires designing a market where peers can trade their energy. Multi-agent systems is used to solve cooperative energy exchange among peers. In this problem [6] we need to find coalitions among the peers and peers in each coalition trade energy among themselves. In the energy trade problem [3] both the buyers and the sellers want to maximize their respective gains. [7] proposed a combinatorial double auction for peer energy trade. [1] proposed trading strategies for energy market among peers. Peters et al. [8] shown how the the broker agent can learn the bidding price in the smart grid market. [9] proposed learning mechanisms for the electric suppliers to bid in the electric market. [10] proposed energy trading protocol based on a energy trading policy. [11] showed intelligent usage of energy storage to facilitate improve energy trading among peers. In this paper we proposed a blockchain based energy trade mechanism. It advances the state of art in peer energy trade in several directions. Our distributed double auction computes the winner determination problem in a distributed fashion which facilitates local energy trading among the peers, more peers are able to trade compared with a centralized double auction and the distributed double auction is more scalable than the centralized auction. Other peer energy trade mechanisms are non-cooperative games [12], Stackelberg games [13], convex optimization [14] etc.

Blockchain mechanism was proposed in [5]. The first blockchain mechanism [5] uses proof of work as the distributed consensus protocol. Peercoin (https://peercoin.net/) introduced the proof of stake protocol which uses stake as the vote power instead of computing resource [15].

III. DOUBLE AUCTION AND ENERGY TRADE

Let,

$M = (M_1, \dots, M_x)$	The set of x peers
$G = (M, E)$	An undirected graph with set of peers as its nodes and E be the set of edges. G will represent the energy distribution network.
$t = (t_1, t_2, \dots)$	Discrete time instances
$\delta^{t_a}(M_i)$	Energy requirement for the peer M_i at time t_a.

$\delta^{t_a}(M_i) < 0$ then it indicates that M_i needs energy of amount $\delta^{t_a}(M_i)$ at the next time instant. If $\delta^{t_a}(M_i) > 0$ then it indicates that M_i will have surplus energy of amount $\delta^{t_a}(M_i)$ at the next time instant and it wants to sell such energy to other peers.

In a double auction market let n buyers and n sellers attempt to trade identical goods. In such a auction,

$B = (B_1, \dots, B_n)$	set of n buyers
$S = (S_1, \dots, S_n)$	set of n sellers
$R(B_i)$ (positive number)	reservation price of buyer B_i, i.e., B_i will buy one unit of the good for the maximum price $R(B_i)$
$R(S_i)$ (positive number)	reservation price of seller S_i, i.e., S_i will sell one unit of the good for the minimum price $R(B_i)$.
$(R(Z_i), X(Z_i)) \vert Z_i \in B \cup S$	denotes a bid where $X(Z_i)$ is positive integer indicating the amount of good the buyer of the seller wants to buy or sell respectively

We may solve the winner determination problem for double auction [4] as follows:

- We sort the reservation prices for the sellers in an increasing order. Let $R(S_1) \geq R(S_2) \geq \cdots \geq R(S_n)$. This sorted seller's reservation price list will be called the seller curve.
- We sort the reservation prices for the buyers in a decreasing order. Let $R(B_1) \leq R(B_2) \geq \cdots \geq R(B_n)$. This sorted buyer's reservation price list will be called the buyer curve.
- Let the seller curve and the buyer curve intersect at x on the seller curve and at y on the buyer curve, i.e., $R(B_y) \leq R(S_x)$.
- Sellers $S_1, S_2, \dots, S_{x-1}$ should sell their goods to buyers $B_1, B_2, \dots, B_{y-1}$ at the price $(R(B_{y-1}) + R(S_{x-1}))/2$.

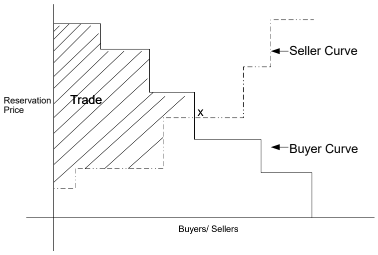

Fig. 1. Winner determination process of double auction. The buyer and seller curve intersect at x and the sellers in $(S_1, \ldots, S_x)$ trade with buyer $(B_1, \ldots, B_x)$.

- The quantity $Z'(S_i) \leq Z(S_i)$ that a seller $S_i \in (S_1, S_2, \ldots, S_{x-1})$ can sell is determined as follows:

$$Z'(S_i) = \begin{cases} Z(S_i) & \text{if } \sum_{i=1}^{y-1} Z(B_i) \\ & \geq \sum_{i=1}^{x-1} Z(S_i) \\ Max(0, Z(S_i) - \theta_i) & \text{if } \sum_{i=1}^{y-1} Z(B_i) \\ & < \sum_{i=1}^{x-1} Z(S_i) \end{cases} \tag{1}$$

  where $\theta_i = (\sum_{i=1}^{x-1} Z(S_i) - \sum_{i=1}^{y-1} Z(B_i))/(x-1)$ denotes the share of oversupply for the seller S_i.

Following from [16], we may use a non-cooperative game to determine $X(Z_i)$ in the above procedure. The reservation prices of the buyers and the sellers can be modelled as the strategies of the buyers and sellers in a non-cooperative game. As shown by [16], Nash equilibrium exists for such a game and efficient algorithms are proposed to guide the buyer and the sellers to quickly converge to an approximate Nash equilibrium. In this paper we do not investigate such strategies of the buyers and the sellers. Our objective is to formulate this centralized auctioning process in a distributed fashion using blockchain.

IV. BLOCKCHAIN MECHANISM

Blockchain uses unspent transaction output (UTXO) data structure to express transactions. If a peer say A wants to transfer fund of amount x to another peer B then the following procedure is followed:

1) A discovers the public key of B.
2) A constructs a transaction T with a set of inputs $IN = t_1, \ldots, t_k$ such that (a)in all transactions $t_i \in IN$ A is the recipient, (b)sum of transfer amounts of transactions in IN is at least x and (c)there is no transaction $t_i \in IN$ such that t_i is input to another transaction.
3) After constructing the inputs, A chooses B's public key to indicate that recipient of this transaction is B.
4) Finally, A signs the transaction with its private key.

The above procedure has two features (a) unspent input transactions insure that A has enough fund to execute this transaction and (b) A's signature ensures that A indeed wants to execute this transaction. After constructing transaction T, A announces it to the blockchain network. Other peers in the blockchain network validate T using the following procedure:

1) They check if all transactions in IN is unspent, i.e., in the blockchain if there is any transaction whose input includes at least one transaction from IN. In such a case a peer will discard this transaction.
2) They check if signature of A is valid using A's public key and whether B is a valid peer using B's public key.
3) If T passes these checks then a peer will add T to a new block and the block will be added to the blockchain.

The above procedure insures that A can not double spend a transaction and distributed consensus protocol ensures that a peer can not recognize an invalid transaction as a valid transaction. Distributed consensus protocol insures that honest peers will discard block created by a dishonest peer which contains invalid transaction(s). It is assumed that honest peers are the majority of the blockchain network and hence they can discard invalid blocks.

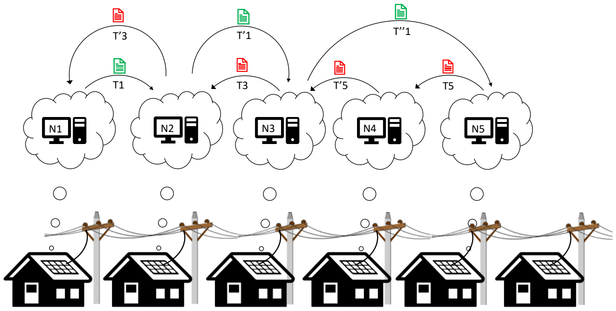

Fig. 2. A peer informs other peers about its energy supply/demand requirement using transactions. Any peer can act as an auctioneer if it receives multiple supply and demand transactions from other peers. If a peer fails to solve a double auction then it forwards its unspent transactions to another peer. If it succeeds to solve the double auction then it sends appropriate tokens to the peers.

V. BLOCKCHAIN BASED DOUBLE AUCTION

Figure 2 shows the overview of our method for peer to peer energy trade. It is as follows:

1) Houses equipped with energy generators form a blockchain peer to peer network for energy trade. Houses in close proximity (w.r.t the energy distribution lines) with each other become neighbours in this peer to peer network.
2) Energy surplus or deficiency information are encoded as blockchain transactions and a peer (a house) sends such a transaction to a neighbour to express its energy need. For example $N1$ sends the transaction $T1$ to $N2$ to express that it has energy surplus and $N3$ sends the transaction $T3$ to $N2$ to express its energy deficiency.

3) Upon receiving enough energy requirement information from its neighbours a peer executes the double auction winner determination algorithm. For example, $N2$ executes such algorithm with input transactions $T1, T3, T'5$.
4) If a peer finds winner of such an auction then it creates appropriate transactions to reflect such winner. For example, $N2$ finds that $N3$ and $N5$ should consume energy and $N1$ should sell its excess energy. It makes transactions $T'1, T''1$ and $T'3$ to reflect this result.
5) If a peer fails to determine the winner of a double auction then it will forward its unspent transactions to a neighbour. Such a neighbour may have more energy requirement information and may be able to solve the double auction. For example, $N4$ received the energy deficiency information from $N5$ as the transaction $T5$ but it could not solve the double auction. Hence $N4$ forwards such information to $N3$ as the transaction $T'5$, who solves the double auction.

Now we present a detailed description of this method.

A. Transaction data structure

We represent the blockchain peer to peer network as an undirected graph $H = (M, E)$ where $M = (M_1, \ldots, M_x)$ is a set of x peers and $E \subset M \times M$ is the set of edges among these peers. Two peers share an edge if they are neighbours in the physical peer network or situated at close locations. It will be assumed that two neighbours of the blockchain peer to peer network can trade energy among themselves without any restriction imposed by the energy distribution network. In the general blockchain a peer can send tokens to any other peer. But in this peer to peer network, a peer can only send tokens to its neighbours. But all peers can verify these transactions. We impose such restriction to minimize the distances among peers whose energy requirements decide whether or not they can buy or sell energy. We use the existing data structure for blockchain used for Bitcoin [1] with several additional fields are shown in Table 1.

A transaction with requirement field 0 will denote energy consumption information from the smart meter of each house (peer). Each peer will submit regular energy consumption data at regular intervals. Hence the number of transactions indicating meter reading will be fixed and equal for every house. Say such number of transactions is 288 (i.e., meter reading after every 5 minutes in a day). Each peer will be endowed with 288 mint tokens during a fixed time in a day, say at 0001 Hours. It can use one such mint token as the input transaction to create a transaction indicating its meter reading. In all such transactions, a peer can choose any neighbour as the recipient and $Consumption$ data field will be used to record energy consumption information from the smart meter. All other additional data fields mentioned in the above table should be empty and such transaction can not be used as input for another transaction.

$Requirement \in (-1, 1, 0)$	It will denote the type of a peer. -1 indicates that buyer and 1 indicates seller. 0 indicates energy consumption information from the smart meter of an house.
$Reservation$	It will indicate the reservation price of the peer.
$Trail$	It will indicate how many local auctions an energy requirement information can participate.
$Auctioned$	It will be a positive random number if the local double auction was successful. It will be -1 otherwise.
$Price$	It will indicate the price for energy trade
$Origin$	Stores the public key of the peer who has announced the energy requirement information
$Expired$	0 indicates the transaction has not expired yet, otherwise 1
$Time-limit$	The time duration for which a transaction remains active (i.e., not expired)
$Consumption$	Energy consumption (it is empty for transactions with $Requirement$ -1 or 1)

TABLE I

ADDITIONAL DATA FIELDS IN TRANSACTION DATA STRUCTURE

Each transaction (with $Requirement$ field -1 or 1) will denote the bid for one predefined units of energy (say 10 kWh). A peer expresses the value of its bid using the $Reservation$ field of the transaction. Life cycle of a transaction is illustrated in fig 3. **At time t_0:** Every day, at a certain fixed time all peers are endowed with a fixed number of mint tokens. Say every day at 0001 Hours each peer is endowed with 10 mint tokens. During next 24 hours a peer uses such mint tokens to express its energy requirement. To do so, a peer will create a new transaction with input as one of these mint tokens. Hence if we expect that a peer will trade at most 10 kWh energy (total energy it will buy or sell) in one day and every transaction express the proposal of buying or selling 1 kWh energy then, each peer will endowed with 10 tokens(or 10 transactions where each transaction represents one token). As shown in fig 3 peer m_1 was given the mint token $T1$ at time t_0.

At time t_1: m_1 uses $T1$ as the input transaction to create a new transaction $T2$ which states that m_1 ($origin$ is public key of m_1) wants to sell surplus energy ($Requirement = 1$) and its reservation price is 10. It marks $Trail$ as 0, $Auctioned$ and $Price$ as -1. Reservation price will be measured in terms of any currency as Cents. This means m_1 will sell 1 kWh energy for at least 10 Cents. m_1 sends $T1$ to its neighbour m_2 (m_2 is the recipient of t_1 as m_1 broadcasts $T1$ to its neighbours in the blockchain peer to peer network).

At time t_2: Next, m_2 fails to solve the double auction as it can not match $T2$ with any other transaction. It creates a new transaction $T3$ to forward the energy requirement information of $m1$ to another neighbour $m3$. It creates $T3$ with $T2$ as the input transaction and copies all data from $T2$ except the trail field. It increases the trail field by 1.

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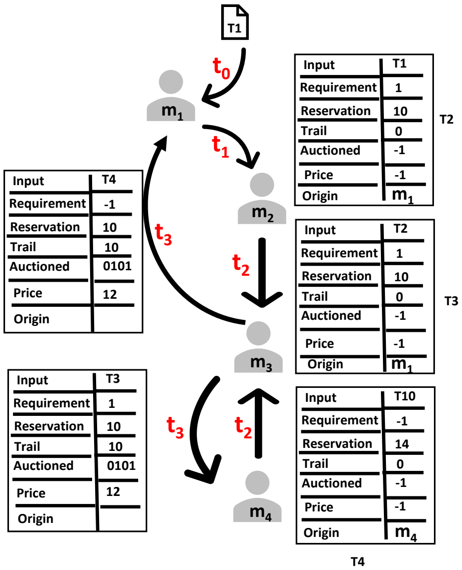
[1] https://en.bitcoin.it/wiki/Main_Page



Input	T1
Requirement	1
Reservation	10
Trail	0
Auctioned	-1
Price	-1
Origin	m_1

Input	T2
Requirement	1
Reservation	10
Trail	0
Auctioned	-1
Price	-1
Origin	m_1

Input	T10
Requirement	-1
Reservation	14
Trail	0
Auctioned	-1
Price	-1
Origin	m_4

Input	T4
Requirement	-1
Reservation	10
Trail	10
Auctioned	0101
Price	12
Origin	

Input	T3
Requirement	1
Reservation	10
Trail	10
Auctioned	0101
Price	12
Origin	

Fig. 3. Life cycle of a transaction. Edges are marked with time of transaction.

At time t_3: $m3$ also received another transaction $T4$ and it solves the double auction using $T3$ and $T4$. It finds the price 12. Now m_3 creates two transactions $T5$ and $T6$. It sends $T5$ with requirement -1, trail as maximum allowed trail value and Auctioned as any random number and price as 12 to the peer m_1. $T5$ indicates the result of the double action as it indicates m_1 can sell 1 WKwat energy for the price 12. Similarly, $T6$ indicates m_4 can use 1 kWh energy for the price 12.

Note that,

- Energy requirement information can be forwarded to distant peers gradually by increasing the Trail data field.
- The movement of a transaction, i.e., distance between the creator of an energy requirement information and the peer who matches it with another such information can be restricted using the trail field. For example, m_3 acts as an auctioneer for the energy requirement information from m_1 and m_4 because its distance (number of edges in the shortest path of the peer to peer network) is less than maximum trail number.
- Transactions expires after a fixed duration, say 30 mins. If the current time is more than 30 mins of the creation time of a transaction then it will expire. $Time - limit$ field in the transaction data structure denotes such time duration.
- Transactions expires after its trail number becomes equal or more than maximum allowed trail number.

B. Distributed consensus protocol

We will use proof of work distributed consensus protocol to create and maintain blockchain. Distributed consensus protocol ensures that peers of a blockchain peer to peer network reach consensus about validity of a transaction, i.e., they all agree that the transaction is valid or invalid. Also, miners compete to add new blocks to the blockchain as there is a financial reward for doing so. The distributed consensus protocol determines winners of such a race to add new blocks to the blockchain. It may happen that two or more miners may add a new block almost at the same time. Such an event creates fork in the blockchain, i.e., the chain splits into multiple chains. The distributed consensus protocol eliminates such fork. In proof of work, a miner have to solve a puzzle before it can add a new block to the blockchain. Complexity of puzzles can be controlled to modify the average time needed to solve it. In this paper we use proof of work protocol. Briefly the protocol is as follows:

1) Each miner maintains a blockchain head which is the block whose distance(shortest path) from the first is the maximum.
2) If a miner gets a new block(say B) it does the following: (a)If the parent block of the new block is the most recent block of the blockchain then it add B as its child and recognize B as the blockchain head. (b)If the parent block (say A) of the new block is not the most recent block of the blockchain then it add B as a child of A. But it does not change the blockchain head.
3) If it creates a new block (say B) then it add it as a child of the current blockchain head and recognize B as the blockchain head.
4) If any time, the block whose distance from the first block is maximum is recognized as the blockchain head.

C. A peer's workflow

We summarize the work flow of a peer : It executes four processes p_1, p_2, p_3 and p_4. (P_1): This process verifies blocks. If the peer receives a block then it must verify that all transactions in that block is correct. If a peer can verify that a block is correct then it augments its blockchain with this new block and broadcast the block to its neighbours. (P_2): This process keeps record of new transaction which are not added to the blockchain. A peer may receive transactions from its neighbours and it updates a list of undocumented transactions with such transactions. This list will be updated by input from P_1 as transactions in a valid new block is removed from this list. (P_3): This process creates transactions to announce its energy supply/demand requirement, solves double auctions (using Algorithm 1) and if it fails to solve the double auction then create transactions to forward its unspent supply and demand transactions to a neighbouring peer and it broadcasts such transactions or smart contracts to its neighbours. (P_4): This process creates blocks. This process (a) verifies undocumented transactions and (b) groups a fixed number of transactions into a new block. If a peer can create a new block then it augment its blockchain with this new block and broadcast the new block to its neighbours. This process can be interrupted by P_1 if the peer receives a new valid block which contains transactions used to build the new block under construction.

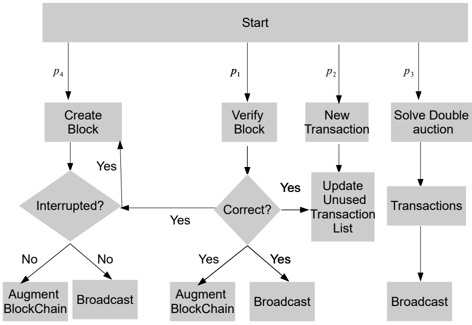


Fig. 4. peer's workflow

D. *Actual energy transfer and payments*

Note that the outcome an auction only indicates how much energy a peer should consume or contribute. But the actual energy consumption may be different and it will be recorded as transaction with Requirement field 0. We propose to create smart contract for payments. Given the result of each auction, the peers can form a smart contract among them. For example if the result of the auction states that peer m_i should sell x units of energy at price y between time $[t_1, t_2]$ and m_j should buy x units of energy at price y between time $[t_1, t_2]$ then, the smart contract will involve two parties m_i and m_j, it will be funded by m_j with crypto-currency of value $x * y$. This smart contract will be triggered by energy consumption information from m_i and m_j and such information will decide the actual payment. For example, say m_i only contributes $x_1 < x$ units of energy. Hence it will be paid $x_1 * y$ tokens and $(x - x_1) * y$ tokens will be sent back to m_j. Such a crypto-currency can be part of the blockchain infrastructure for energy trade and peers must buy these tokens with any other currency (i.e., \$). But the tokens used for energy trade information and auction is free as each peer is endowed with fixed number of tokens to express their future energy needs and actual energy consumption every day at a fixed time. Sidechains [17] can be used to implement this form of payment for peer to peer energy trade.

VI. EXPERIMENTAL EVALUATION

We collected energy consumption data from 100 houses. We collected the energy demand (in kWh) and energy produced (in kWh) by solar panels at each house in every five minutes. fig 5 shows the energy surplus or deficiency (in kWh) for every 5 minutes. We simulate a proof of work based blockchain, energy distribution network and peers using agent based modelling and asynchronous event simulation in Python. We use three types of buyers (sellers) and sizes of each type of buyers (sellers) are the same. Reservation price for each type of buyer or seller is given in table 2.

```
Algorithm 1: Centralized double auction
Data: $R(B_i, t_j)$ and $R(S_i, t_j)$ reservation price of buyer
      $B_i$ and seller $S_i$ at $t_j$ respectively
Result: Trade among buyers and sellers
begin
    Sort Reservation price of buyers with decreasing value
    Sort Reservation price of sellers with increasing value
    if $\exists i : R(B_i, t_j) \leq R(S_i, t_j)$ then
        Peers from 1 to $i$ trade at price
          $(R(B_i, t_j) + R(S_i, t_j))/2$ and according to the
          rules mentioned in section 3
```

Value	Parameter
[10,15,20,25,30,35,40]	7 sets of peers
[10,20]	Minimum and maximum bid amount
[12,13],[10,11],[16,17]	Buyer behaviours
[12,14],[10,13],[14,16]	Seller behaviours
[10,15,20,25,30,35,40]	maximum $Trail$
$Time - limit$	1 iteration

TABLE II
PARAMETERS USED IN THE EXPERIMENTAL EVALUATION.

First we show the convergence result of the auction procedure. We execute multiple local auctions in distributed and asynchronous fashion. If a node fails to find the winner of a local auction then it forwards the energy requirement information to a neighbour. Thus it may take several local auctions to match an energy demand. Hence it is important to measure the number of auctions it takes to match an energy demand. fig 6 shows the convergence time for double auctions for 10,15,20,25,30,35 and 40 houses. The physical distribution

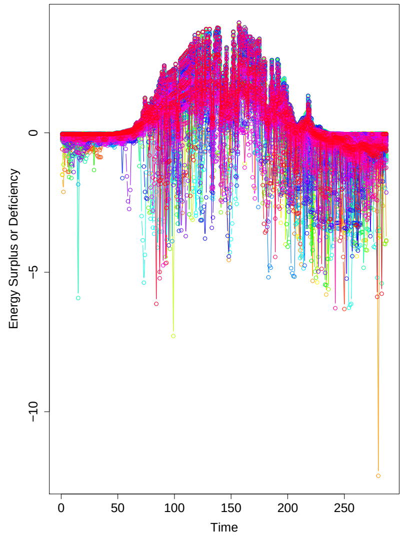


Fig. 5. Energy surplus or deficiency data: calculated as the difference between energy demand and energy production at each house.

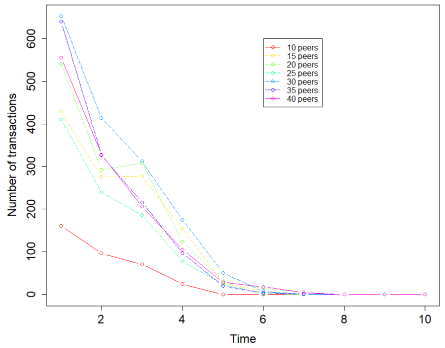


Fig. 6. Convergence time for double auction

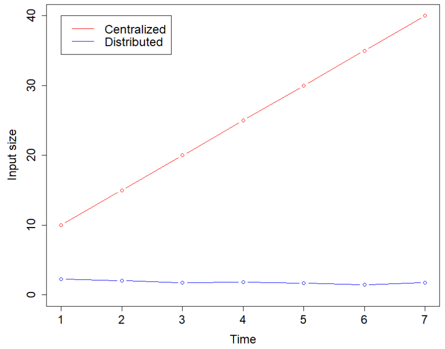


Fig. 7. Input size for distributed auctions.

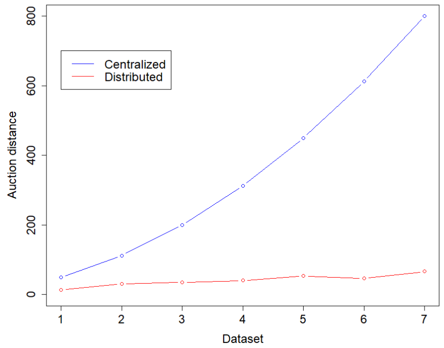


Fig. 8. Distances among peers who participate in a local auction.

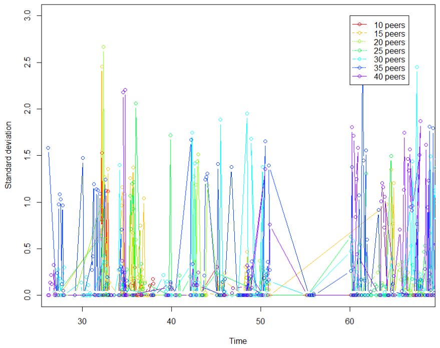


Fig. 9. Efficiency of the distributed auction

network of these houses are line graphs. In fig 6, we plotted the number energy demand transactions which matched with energy supply transactions w.r.t number of auctions. Number of auctions is collected from the ’Trail’ field of the transaction data. We found that for all sets of houses it takes 6 auctions to match 95% energy demands.

Next we measure the computational overhead at every node due to using blockchain based distributed auction. It is measured as the input size for each local auctions. As shown in fig 7, we found that input size is between .05% to .2% of the input size for centralized double auction. Hence computational overhead for local auctions is much lower than centralized auction.

Now we measure the performance of our method in terms of distances among the houses who participate in each local auction. We aim to minimize such distances to minimize energy loss due to transmission and also, houses located at long distances from each other may not exchange energy and their energy requirement information should not be used to determine if they can buy or sell energy. As shown in fig 8, such a distance remains approximately constant for the distributed double auction for 7 sets of peers of size 10,15,20,25,30,35,40 with maximum trail number 5. It shows that trail number in the transaction data structure can efficiently control such distance. In case of centralized double auction, such distance increases as number of peers are increased.

Next we analyze efficiency of the distributed algorithm in terms of differences of the price determined by the local auctions. In a centralized auction bids from all peers are used to determine price for energy trade. But in distributed auction, each local auction only uses bids from a subset of peers. Hence prices for energy trade can differ for these local auctions. We measure the efficiency of distributed double auction as the standard deviation of prices for energy trade at various local auctions. As shown in fig 9, we found that standard deviation is between [0,1.5]. We also observe that standard deviation is large with high number number of peers with energy surplus. We also observed that we can lower the standard deviation by lowering the difference between maximum and minimum bid value.

Next we show the trade off between maximum trail number and efficiency of the distributed double auction. In sets of

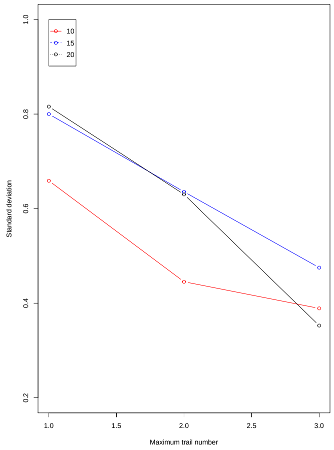


Fig. 10. Trade off between efficiency and maximum trail number

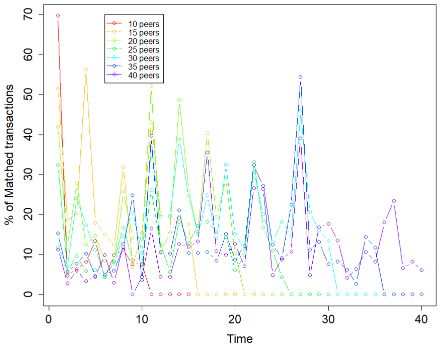


Fig. 11. Number of matched transactions

houses of sizes 10, 15 and 20 respectively, we simulate energy trade with maximum trail number 3,4 and 5. As shown in fig 10, standard deviation of prices from local auctions decreases as we increase the maximum trail number. Thus depending on the topology of the distribution network we can set appropriate maximum trail number to increase the efficiency of the distributed auction method.

Finally we show the number of satisfied energy requirement requests, i.e., request to sell energy is approved by the auction and vice-versa. Fig 11 shows the % of such satisfied energy buy or sell requests for 7 sets of peers. We found that on average 20% requests are satisfied and all energy sell requests are satisfied. It shows that our solution does not prevent sell of any surplus energy if there is a demand for it.

VII. CONCLUSION

In this paper we proposed a blockchain assisted distributed double auction to facilitate peer to peer energy trade. We use blockchain to compute the double auction winner determination problem in a distributed and asynchronous fashion. We showed that this distributed auction promotes local energy transfer more than a centralized auction. We showed that the distributed auction quickly converges and computational overhead is negligible. In future we will extend this distributed auction with strategies for peers to improve their utilities.

VIII. ACKNOWLEDGEMENT

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