A Blockchain-Enabled Fog Computing Model for Peer-to-Peer Energy Trading in Smart Grid

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Abstract. The advancement in renewable energy sources (RESs) technology have changed the role of traditional consumers to prosumers. In contrast to the traditional power grid, the Smart Grid (SG) network provides a platform for peer-to-peer (P2P) energy trading between prosumers to buy or sell energy according to their requirements. The potential benefits of P2P energy trading can be realized through an efficient service provider of the communication network infrastructure. However, the current communication network is a trustless environment and thereby is unable to fully support the P2P energy trading requirements. Existing techniques in P2P energy trading with blockchain suffers from large network delay due to large network size; this further affects the network performance for P2P trading. In this paper, we present a novel Blockchain-Based Smart Energy Trading (BSET) algorithm along with a Blockchain-Enabled Fog Computing Model (BFCM) for P2P energy trading in Smart Grid. The proposed BSET algorithm provides a fully trusted minimum latency communication network that enables the prosumers to trade energy within their local premises. The algorithm was implemented using iFogSim, Truffle, ATOM, Anaconda, and Geth and evaluated against state-of-the-art communication network models for P2P energy trading. The simulation results revealed the effectiveness in terms of secure trading and network latency.

Keywords: Smart grid, smart meter, cyber-physical system, fog computing, blockchain, cryptography, cloud computing, microgrid, Internet-of-Things.

1 Introduction

Nowadays, the increasing demand for timely electrical energy consumption and monitoring has given rise to the role of a smart grid network over the traditional grid. The traditional grid is a centralized and one-way transmission of energy. Whereas the SG network is distributed two-way transmission of energy and information. Where prosumers and consumers have a major role to play in buying and selling energy in a decentralized manner. The current SG network extends the controlling, computation, monitoring and sensing of the information and electrical energy flow in a bidirectional way when compares to a traditional network where different buyers and sellers participate in the auction and bidding. SG when enabled with Information and Communication Technology (ICT) and Cyber-Physical System (CPS) has become an autonomous and resilient energy trading system. The different and independent stakeholders can unite and build a trustworthy relationship to exchange the required electrical energy as per the end-user requirement in real-time. The existing state-of-the-art SG system requires a distributed platform for storing, processing, and controlling a large amount of information and energy to make the system reliable for P2P energy trading. This can be possible with the use of Fog Computing (FC) acting as the middleware layer at the edge of prosumers and consumers in a Neighbourhood Area Network (NAN), Building Area Network (BAN), Household Area Network (HAN), and Local Area Network (LAN) [1]. FC nodes can transmit the data in a real-time mode with a single hop count. This makes the SG network efficient for the performance related to energy trading and exchange of information between prosumers and consumers as they require minimum service latency, network usage and an efficient secure channel [2]. Next, to secure the energy trading transaction in the SG network blockchain can play a major role by acting as a decentralized system along with the FC environment. Recent studies have not evaluated the underlying blockchain performance for QoS requirement in P2P energy trading in an FC environment. Therefore, to meet the above-mentioned challenges we have proposed a novel paradigm using blockchain in the FC environment. The proposed work includes a novel BSET algorithm along with a BFCM for P2P energy trading in SG.

2 Background and Related work

This section includes the research work related to P2P energy trading mechanism, auction of available energy between different distributed prosumers and consumers, along with blockchain-based techniques bidding techniques used in an SG network and CPS. Recent work related to energy trading shows that it is quite complex to design a decentralized P2P trading system that keeps an optimum balance between economic efficiency and data privacy [3] [4]. Network size, latency and security are the major features that affect the overall performance of P2P energy trading. Some of the recent works for energy trading have been highlighted under this section. In [5], the authors proposed a novel approach using a Hyperledger Fabric (HF) to strengthen the collaboration and coordination of the SG network with CPS. Furthermore, they designed a novel framework for peer-to-peer energy trading mechanism. In [2], the authors proposed a negotiation protocol for a double auction mechanism with additional security features for secure energy trading in the SG network between prosumers and consumers. The novel protocol is comparable with SG technology. Similarly, in [6], the authors proposed a peer-to-peer trading system method that minimizes the risk of energy loss and maximizes the profit and benefits for both buyers and sellers. The risk in energy distribution is measured using Markowitz portfolio theory and modified Sharpe ratio. The proposed work focuses on maximizing the benefit for prosumers and uses the particle swarm optimization technique.

In [7], the authors proposed a two-stage optimization model for maximizing the utilities with optimal strategies in peer-to-peer energy trading between prosumers and consumers in the power systems likes, microgrids, and SG network. The above model was implemented using a distributed algorithm. In [8], the authors conducted a detailed description of the problem related to peer-to-peer energy trading in a decentralized power system. The existing model for energy trading between prosumers and consumers lacks the real-world implementation of sharing energy using the model between different customers and sellers. In [9], the authors explained the potential of machine learning in the distributed environment to solve the issues involved in the energy trading problem between the different prosumers and consumers. They addressed several issues of the SG network such as resource allocation, communication schemes, the privacy of user data, and negotiation between the seller and buyers.

3 Conventional Energy Trading Model

This section discusses the conventional way of P2P energy sharing between the communities using smart meters in an SG network. See Fig. 1 for the conventional trading involving different communities.

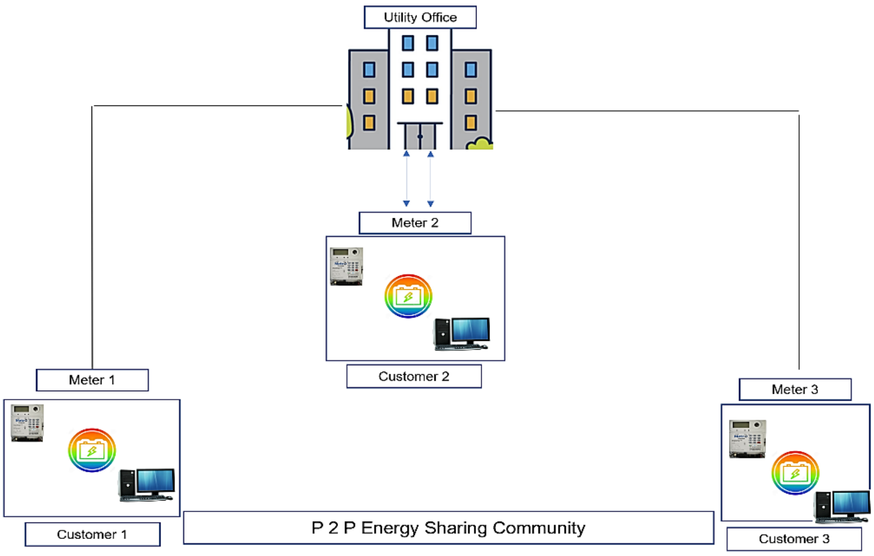

Fig. 1. Conventional P2P energy trading

Fig. 1 shows the conventional way of P2P energy trading between the different communities i.e., the different distributed customers. Where one of the customers acts as prosumers and another one-act as consumers. The smart meters are further connected to utility offices. However, this conventional way of P2P energy trading suffers from the various QoS requirements i.e., service delay, and network usage for efficient P2P energy trading between the buyers and sellers of electrical energy in the SG network.

In general, energy trading is conducted between different microgrids. Where both producers and consumers participate in using the energy supply from smart meters to measure consumption. The conventional energy trading model lacks secure private communication and energy transaction between prosumers related to P2P energy trading.

4 Blockchain-Enabled Fog Computing Model (BFCM)

In this section, we discussed the proposed advanced P2P energy trading system model which utilizes the concept of blockchain and FC to meet the network, latency and security requirement for energy trading involving smart meters. FC acting at the edge of networks transfers the electrical data in a single hop count Here in this system model, we have used blockchain technology to secure the user's anonymity and privacy for securing information during trading. See Fig. 2 for an advanced blockchain-based P2P energy trading system.

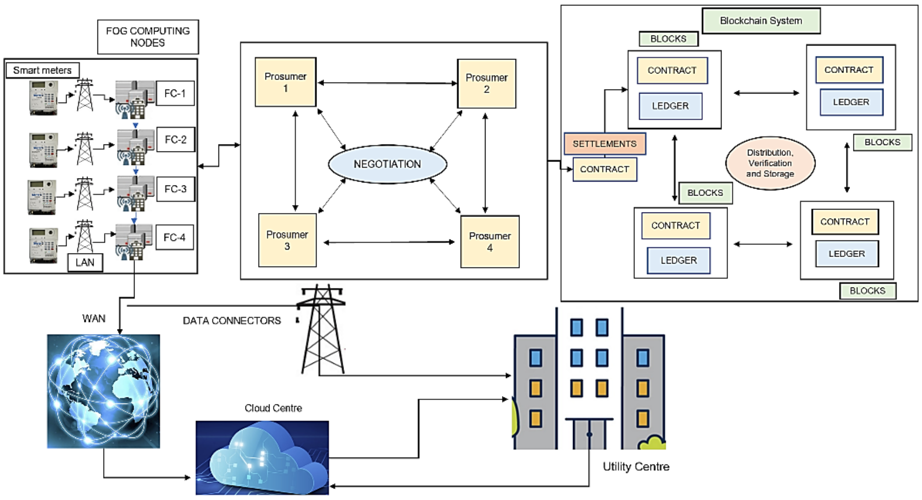

Fig. 2. Blockchain-enabled fog computing model for P2P energy trading in smart grid

Fig. 2 shows the novel advanced blockchain-based P2P energy trading model. The model consists of a secure data transmission channel that uses blockchain-based technology. The blockchain here used for electrical data distribution, settlements of contracts, recording of transactions that occurred, data and user verification along with storage of blocks. Where FC nodes are used for minimizing the service latency and network usage at the edge of the smart meter deployed in the SG network. Next, the energy available for trading is transferred to prosumers and consumers in a real-time mode where negotiations are conducted for the auction of available energy to sell. The advanced model will help in achieving QoS requirement by minimizing the bottlenecks which affect the performance of the energy trading and achieve the best configuration for the system. Each prosumer can share his/her energy usage information which can be used by other neighbours with a secure channel using the blockchain model.

5 Blockchain-Based Smart Energy Trading (BSET) Algorithm

This section discusses the design and development of the BSET algorithm. The functioning of the proposed novel algorithm is divided into three different algorithms for the performance evaluation of efficient P2P energy trading between prosumers. Moreover, the time complexity of the proposed BSET algorithm for encryption function is $O(N)^2$ and for decryption function is $O(N)^3$.

Algorithm 1: Negotiation protocol of two users begin inside fog computing (FC) environment. In this part, the seller generated a contract and final contract based on the offer and counteroffer for negotiation with the buyer.

Algorithm symbols notations

$FCon$: Final contract
$Con^{QK}_{i,j}$: Contract
o' : Counteroffer
o: Offer
Θ_k: Task

Start
For task Θ_k , seller j generates an offer o to buyer i
if i accept o then
generate a contract $Con^{Q_k}_{i,j}$ based on o
$FCon^{tmp}_{i\Theta_k,} = FCon^{tmp}_{i,\Theta_k}$ o $Con^{\Theta_k}_{i,j}$;
$FCon^{tmp}_{j,\Theta_k} = FCon^{tmp}_{j,\Theta_k}$ o $Con^{\Theta_k}_{i,j}$;
return;
else
i generate a counteroffer o' to j
if j accepts o' then
generate contract $Con^{\Theta_k}_{i,j}$ based on o
$FCon^{tmp}_{i,\Theta_k} = FCon^{tmp}_{i,\Theta_k}$ o $Con^{\Theta_k}_{i,j}$;
$FCon^{tmp}_{j,\Theta_k} = FCon^{tmp}_{j,\Theta_k}$ o $Con^{\Theta_k}_{i,j}$;
return
else
return null; /* no contract is formed */
end if
end if
End

Algorithm 2: Final contract determination begins between the peers in FC. This part of the algorithm deals with the final contract determination and contract determination deadline.

Algorithm symbol notations

$FCon_{i,\Theta_k}^{tmp}$: temporary contracts
$FCon_{i,\Theta_k}^{fn}$: Final contract determination using FC
$Dl'(\Theta_k)$: Contract determination deadline
$FCon$: Final contract
$Con_{i,j}^{QK}$: Contract
Θ_k: Task
FC : Fog computing

Start
for task Θ_k, buyer i sort temporary contracts in $FCon_{i,\Theta_k}^{tmp}$;
while t < $Dl'(\Theta_k)$ /*t is the real-time*/
  if all temporary contracts in $FCon_{i,\Theta_k}^{tmp}$, have been processed then
    return;
  else
    if $\sum_{c \epsilon FCon_{i,\Theta_k}^{fn}} c{:}\,cp > E_{\Theta_k}$ then
      return;
    else
get the next temporary contract C from $FCon_{i,\Theta_k}^{tmp}$;
i sends a transaction request message to j; U
i gets a reply message from j;
  if j confirms the contract, then
      $FCon_{i,\Theta_k}^{fn}$ <- $FCon_{i,\Theta_k}^{fn}$ U C; /* using FC */
      $FCon_{j,\Theta_k}^{fn}$ <- $FCon_{j,\Theta_k}^{fn}$ U C; /* using FC */
    end if
  end if
end while
End

Algorithm 3: Encryption and decryption of electrical data using blockchain for secure communication between peers. The data is encrypted and then decrypted using a private blockchain and different cryptographic operations. The encryption algorithm is used to encrypt the meter data and readings from the outside world. The algorithm performs security of data transmission between smart meters, meter management system, and consumers using the blockchain. The electrical data is encrypted using private-public key arrangements the data is encrypted and then decrypted as per the user requirement.

Algorithm symbol notations

S_m : Smart Meters
K_{sym} : Symmetric key
K_{pub} : Public key
$F_n K_{pub}$: Fog node public key
$Encrypt_{Sym}$: Symmetric encryption
$Encrypt_{Asym}$: Asymmetric encryption
C: Ciphertext

C_K : Cipher key
$F_n K_{prvt}$: Fog node private key
C_s : Cloud server
ST_m : Smart Meters
FC_n: Fog computing nodes
E_{DP} : Electrical energy data packet
FC_n: Fog computing nodes
$SPARK$: Real-Time Analyzer (RTA)
S_m_D: Smart meter data

1. **Start**
2. (FC-based blockchain system is created)
3. Data classification Using 2-PCA Linear SVM
4. **if** ($ST_m = Malicious\ electric\ data$) then
5. get geo-location and send the data for verification to FC_n using SPARK
6. FC_n allocates the E_{DP} to F_s
7. **else if** ($ST_m == Authorized\ electric\ data$)
8. then
9. E_{DP} send to FC_n to C_s
10. **end if**
11. **function** Encryption (S_m_D)
12. **if** S_m confirms E_d storage over blockchain then
13. Generate a K_{sym}
14. $C <- Encrypt_{Sym}$ (S_m_D , K_{sym})
15. $C_k <- Encrypt_{Asym}(K_{sym}, F_n K_{pub})$
16. **else**
17. do no operation
18. **end if**
19. **end function**
20. **function** $DECRYPTION$ (C, C_k, $F_n K_{prvt}$, K_{sym})
21. K_{sym} <-$Decryption_{Asym}(C_k, F_n K_{prvt})$
22. S_m_D <- Decryption (C, K_{sym})
23. **end function**
24. **End**

6 Results and Discussion

This section discusses the results and simulation of the BSET algorithm in the iFogSim simulator. Next, we have used Anaconda (Python), Geth version 1.9.25, Ganache, Truffle (Compile) and ATOM as a text editor for creating smart contracts. iFogSim is an open-source simulator used for creating physical topology design, resource placement, and packet allocation by creating different edges, networks, nodes, and devices with cloud and fog sever. A detailed comparative analysis is conducted between FC and cloud-related latency, malicious node percentage, and network usage. The simulations are conducted between different prosumers at different physical topology configurations. Furthermore, the malicious node percentage increases with an increase in the number of prosumers. See Fig. 3 represent the physical topology configuration.

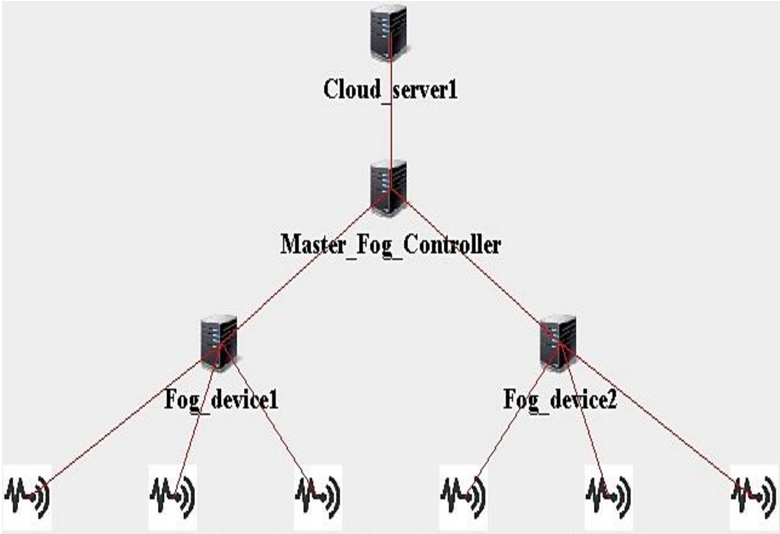

Fig. 3. iFogSim GUI configuration for physical configuration

Fig. 3 shows the physical topology for configuration built in the iFogSim simulator. The configuration is solely based on the concept of a proposed system. The figure shows the fog devices connected with a cloud server and the smart meters embedded at the prosumers place. See Fig. 5 for average latency performance.

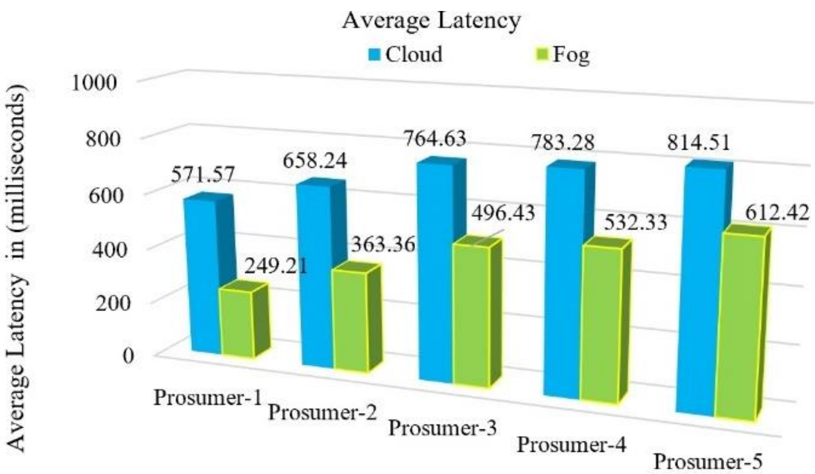

Fig. 4. Average latency performance evaluation

Fig. 4 shows the average latency comparison between different prosumers during P2P energy trading in fog and cloud computing environment. The FC easily outperforms the cloud in terms of latency.

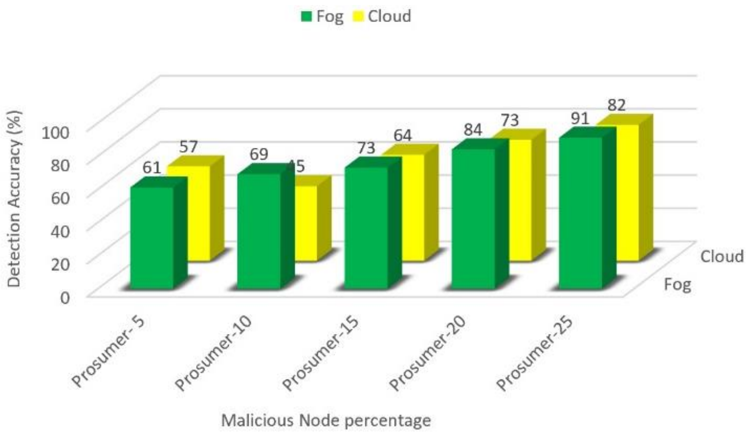

Fig. 5. Malicious node percentage vs detection accuracy in fog and cloud environment

Fig. 5 shows the malicious node percentage in fog and cloud along with the detection accuracy in percentage. The figure shows that the detection accuracy in fog nodes is much greater when compared to the cloud for different distributed prosumers.

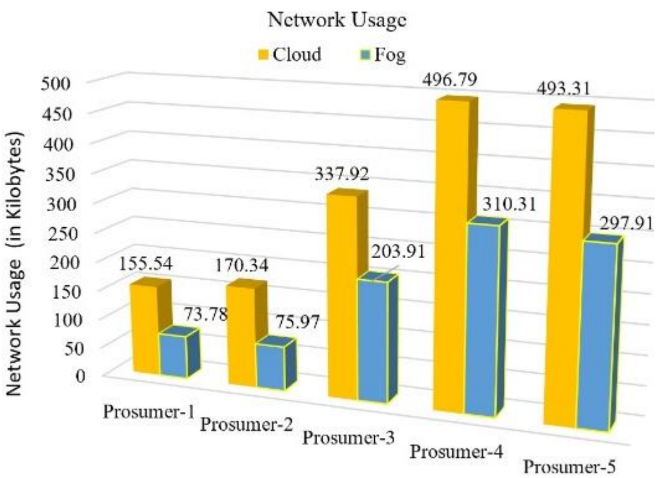

Fig. 6. Network usage in P2P energy trading for different prosumers in fog and cloud

Fig. 6 shows the network usage by the different prosumers in P2P energy trading using fog and cloud. The FC easily outperforms the cloud in terms of network usage.

7 Conclusion

To overcome the limited communication, network efficiency, and data privacy issues of the SG network a fully distributed energy trading system using FC and blockchain is proposed. Next, we have proposed a novel Blockchain-Based Smart Energy Trading (BSET) algorithm. The algorithm is further divided into three other major sub-algorithms. 1) Negotiation protocols between two users 2) Final contract determination between the peers and 3) Encryption and decryption of electrical data using blockchain for secure communication. The main contribution of the proposed work is to improve P2P energy trading by providing a secure communication channel among prosumers along with determining the latency and network usage requirement.

Acknowledgements

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