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Virtual Microgrids: A Management Concept for Peer-to-Peer Energy Trading

Kelvin Anoh†, Augustine Ikpehai†, Dragana Bajovic‡, Olamide Jogunola†, Bamidele Adebisi†, Dejan Vukobratovic‡ and Mohammad Hammoudeh†
†School of Engineering, Manchester Metropolitan University, M1 5GD UK
‡Faculty of Technical Sciences, University of Novi Sad, Serbia
†[k.anoh, a.ikpehai, b.adebisi, m.hammoudeh]@mmu.ac.uk, olamide.jogunola@stu.mmu.ac.uk
‡[d.bajovic, d.vukobratovic]@uns.ac.rs

***Abstract*—The proliferation of distributed energy resources (DERs) and smart technologies has enabled the integration of microgrid generation into the energy supply chain. This paper proposes the use of energy trading agents (ETA) in the overlaying communication system in a neighbourhood area network (NAN) in which a number of microgrids (MGs) are grouped together into logical clusters called virtual MGs (VMGs) to minimize operational costs. To decouple the communication network from the grid topology and study the communication performance, each VMG is assigned an ETA such that prosumers in a VMG exchange messages only with the ETA rather than uncontrolled messaging in the network. Although this reduces the amount of network traffic, a key question is on how to determine the optimal location of the ETAs. For VMGs of regular shapes, we formulate this as a simple minimization problem of Euclidean distances of regular shapes. Our results show that by employing ETAs, the model reduces the distance traversed by a prosumer by 40%.**

***Index Terms*—Virtual microgrids (VMG), energy trading agent (ETA), Peer-to-peer (P2P), agent, distributed energy resources (DER), energy, distance, cost, communication.**

I. INTRODUCTION

The traditional economy of scale approach to energy production is rapidly giving way to smaller and distributed generation through microgrids (MGs) [1]. In particular, distributed energy resources (DER) from wind, solar and hydro including other sources are increasingly being integrated to compliment the conventional supply from the main grid. That also has ability to reduce operational cost and carbon footprints [2], [3] as well as yield economic value to asset owners. Thus, the adoption of MG is motivated by a combination of economic and technological incentives.

On the economic front, the MG offers opportunity to take advantage of price elasticity of energy demand at various times of the day/week [4] to sell or buy energy at favourable prices. This is one of the key features of next generation MGs which will be equipped with communication and computational capabilities to deliver an intelligent power infrastructure [3], [5]. An MG may operate in island or grid-connected mode, however, future MGs will also support peer-to-peer energy trading and sharing (P2P-ETS) in which customers are allowed to play multiple roles to produce, consume or share energy.

Although P2P is a decentralized architecture well known within the communication industry, it is applicable in energy trading [6]–[8]. In this paper, we attempt to redefine the MG architecture for P2P-ETS by employing a logical network structure. To decouple the communication network from the grid topology, MGs are grouped into logical clusters called virtual MGs (VMGs). Each VMG is then assigned an energy trading agent (ETA) such that prosumers in a VMG exchange messages only with the ETA rather than flooding the network with multicast or broadcast messages. An ETA in this context is a piece of software or hardware capable of interacting with other agents on one hand and VMGs including prosumers within it on the other [9] for the purpose of setting up energy transaction. The goal is to complete the energy transactions with minimum data exchange and computational demands [10]. The ETA-based strategy will enhance the control of the commercial operation of the MG trader [11].

This work describes five ETA implementation approaches in transactive energy networks. In particular, we suggest five different state-of-the-arts for ETA technologies. These include wireless access network ETAs, PLC gateway ETAs, energy router ETAs, hybrid PLC-wireless ETAs and narrowband (NB) Internet of Things (IoT) ETAs. Since power lines are integral part of the MGs, the ETAs can be included in power line communication (PLC) modules and embedded in the energy assets. Based on voltage levels (HV, MV and LV), PLC signals do not cross different voltage level boundaries [12], thus creating own separate subnets (by default) for data communication. In the future, it is expected that communication system will influence energy trading decisions of trading peers.

The ETA-based VMG proposed in this study maps these decentralized abilities of a communication network design. Decentralized architecture allows addition and operation of new units without the reconfiguration of the whole system [8]. It holds part of the trading information (e.g. energy prices and peer ID), then allows transaction directly among peers. Modern energy networks use communication technologies to effectively manage, automate and control energy consumption. Different studies [5]–[7], [13] are now being carried out to improve the P2P energy trading technology for future smart cities. In fact, agent-based techniques are used to design decentralized control schemes [8] and will be explored further in this study for network parameter performances.

To recapitulate our main contributions, we $i)$ redesign the MGs convention into VMGs, $ii)$ assign distributed ETAs to each VMG to reduce network resources consumption $iii)$

reduce distance traversed in the energy network by energy trading prosumers with potentials of reducing energy consumption, time and money wastage and $iv)$ we describe five different ETA implementation models.

The remaining parts of this paper are organised as follows. In Section II, the proposed architecture is described while Section III presents the model parameters including the simulation results with the conclusion following in Section IV.

II. PROPOSED AGENT-BASED P2P ARCHITECTURE

The conventional MGs exist on voltage levels (HV, MV and LV). For MGs with DERs, the concept of flat architecture [14] can be adopted for P2P energy trading design architecture since the energy level may be admissible under LV rating. Meanwhile, the coordination and control of energy trading among peers is efficiently facilitated using communication systems [3]. The present architecture for communication in smart grids is lateral to the present-day MG topology convention. This poses restriction on who can buy from whom and other communication constraints. However, by melting the topology-based MG architecture into logical VMG architecture, communication agents can help to redefine the MG architecture and achieve cheaper energy transaction with minimal resources. In the following, we describe the possible communication architectures and the benefits that can be obtained.

A. Wireless Access Network-based agent

Fig. 1a shows a large energy trading area comprising many energy trading peers. These peers are assumed to be randomly distributed within the area. In terms of using communication to facilitate energy trade, each peer may require to traverses the entire large area for possible cheapest energy price. Typically, such large area may involve using one central entity for communication. In the conventional centralized communication, all peers query the same central entity. Such centralized communication architecture leads to two major problems [8]. These are powerful central controller requirement and single point of failure. In other words, the communication cost is usually high and the system may not be flexible/scalable. One of the ways of solving this problem involves breaking up the large area into small areas and using distributed ETAs to manage each small area. Being distributed, the central communication burden is significantly reduced.

To explore the benefits of this scheme for a given large area, consider ETAs introduced (Fig. 1b) in the area to collate local energy selling prices (SP) from the energy generating peers. The ETA maintains a glossary of the SPs where a member peer of a VMG can obtain this information from. Assuming that all peers are fully connected, the ETA maintains an adjacency matrix of lesser complexity than the adjacency matrix in the larger area operating with a central entity.

Let all the peers $\mathcal{P}$ be located at the vertices $\mathcal{V}$ of an energy trading graph $\mathcal{G}$ connected over edges $\mathcal{E}$ such that $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ where $\{v_1, v_2, \cdots, v_N\} \in \mathcal{V}$ and $\{\mathcal{P}_1, \mathcal{P}_2, \cdots, \mathcal{P}_N\} \in \mathcal{P}$ such that $(\mathcal{P}_i, \mathcal{P}_j) \in \mathcal{E}$ if $\mathcal{P}_i$ can trade with $\mathcal{P}_j$. For any set of peers that can trade with other peers, we represent this using the so-called adjacency matrix $\mathbf{A} = [a_{ij}]_{N\times N}$. In this case, if there exists a connection between any two peers $\mathcal{P}_i$ and $\mathcal{P}_j$ then $a_{ij} = 1$, else $a_{ij} = 0$ in the $\mathbf{A}$. Now, considering an area of possible ETA coverage, with peers $\mathcal{P}_i, \forall i = 1, 2, \cdots, N_p$ where N_p is the number of peers within k^{th} VMG, one can estimate the total distance covered from one reference peer $(\mathcal{P}_i)$ to all other peers within such one VMG.

Let the distance covered by the reference peer, $\mathcal{P}_i$, when searching for $\mathcal{P}_j$ that has the cheapest energy SP for transaction be d_{ij}. Supposing that there exists no ETA in the VMG, $\mathcal{P}_i$ communicates $\mathcal{P}_j$ by flooding the network. In such case, the worst possible total distance traversed to reach $\mathcal{P}_j$ is

$$\mathcal{D}_T = \sum_{j=1}^{N_p} \sum_{i=1}^{N_p-1} d_{ij}^k \ \forall k = 1, 2, \cdots, N_{mg}, \tag{1}$$

where N_{mg} is the number of VMGs into which the large area is divided. Notice that in one VMG and given a reference peer $\mathcal{P}_i$, there are only $N_p - 1$ peers which it can query for cheapest energy price. Clearly, the first problem becomes how to minimize the hopping distance within such VMG. Recall that to maintain balance in energy network,

$$E_g^{(k)} + E_b^{(k)} = E_c^{(k)} + E_s^{(k)} \quad \forall k = 1, 2, \cdots, N_{mg} \tag{2}$$

where E_g is the energy generated, E_b is the energy bought, E_c is the energy consumed and E_s is the energy sold. We rewrite (2) in terms of the total energy generated as follows

$$E_g^{(k)} = E_c^{(k)} - E_b^{(k)} + E_s^{(k)} \quad \forall k = 1, 2, \cdots, N_{mg}. \tag{3}$$

Let the $C_g^{(k,t)}$ $\forall k = 1, 2, \cdots, N_{mg}$ and $\forall t = 0, 1, \cdots, T-1$ be the minimal cost of $E_g^{(k,t)}$ quantity of energy available in any VMG at time t. Based on this, it follows that the price of $E_g^{(k,t)}$ units of energy is

$$Q_g^{(k,t)} = Q_c^{(k,t)} - Q_b^{(k,t)} + Q_s^{(k,t)} \qquad \begin{array}{l} \forall k = 1, 2, \cdots, N_{mg} \\ \forall t = 0, 1, \cdots, T-1 \end{array} \tag{4}$$

where $Q_g = C_g \cdot E_g$, $Q_c = C_c \cdot E_c$, $Q_b = C_b \cdot E_b$, $Q_s = C_s \cdot E_s$ and, C_c, C_b and C_s are costs associated with energy consumed, bought and sold respectively. Let the total energy available to a prosumer be $E_a^{(i)} = E_g^{(i)} + E_b^{(i)}$ $\forall i = 1, 2, \cdots, N_p$. Then the excess energy available at node $\mathcal{P}_i$ can be expressed as $E_e^{(i)} = E_a^{(i)} - E_c^{(i)}$ which can be sold or shared.

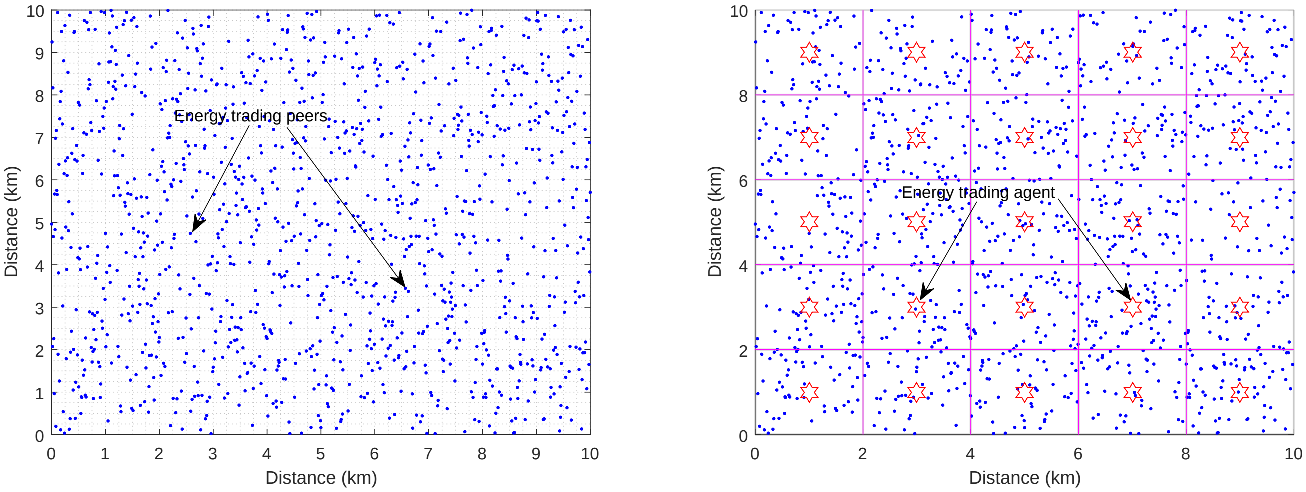
Our goal is to minimize the total distance travelled and energy network resources consumed when finding suitable energy trading peer. In such case, we can rewrite (1)

$$f\left(\mathcal{D}_{T,k}^o\right) = \min\ \mathcal{F}\left(\mathcal{D}_T^k\right) \ \forall k = 1, \cdots, N_{mg} \tag{5a}$$

$$s.t.\ \ Q_a^{(i)} > 0 \ \forall i = 1, \cdots, N_p \tag{5b}$$

$$Q_e^{(i)} > 0 \quad \forall i = 1, 2, \cdots, N_p \tag{5c}$$

where $\mathcal{F}(\cdot)$ is the cost of traveling $\mathcal{D}_T$ distance to find cheapest energy, $\mathcal{D}_T^o$ is the optimal distance and $f(\cdot)$ is the reduced costs $\forall k = 1, \cdots, N_{mg}$. When $C_a^{(i)} = 0$, then the monetary cost of $E_a^{(i)}$ units of energy becomes $Q_a^{(ij)} = C_a^{(ij)} \cdot E_a^{(ij)} = 0$; this is equivalent to energy sharing from peer $\mathcal{P}_i$ to peer $\mathcal{P}_j$. Intuitively, one of the simplest ways of achieving (5c) is by renegotiating the fundamental centralized network architecture to a form of decentralized information control/database. For



(a) Trading area showing the distribution of peers

(b) Energy trading area split into virtual microgrids with agents

Figure 1: Distribution of energy trading peers in a large area showing virtual microgrids under the control of energy trading agents

example, by dividing the large area of energy network into smaller units and assigning an ETA to each small division as shown in Fig. 1. The ETA holds the temporal energy price of each peer and the ID of the peer but no more; peers query the ETA of the closest and cheapest energy price to itself. When found, querying-peer contacts the cheapest-peer directly thus saving the costs of traversing the entire network. This also improves the processing time, reduces network congestion/failure, etc. These small divisions are VMGs. The criteria for optimal number of peers in such small network units including the energy cost was earlier shown in [5].

If the VMG area is in the form of a square with sides d_k $\forall k = 1, \cdots, N_{mg}$, then by siting an ETA at the centre leads to

$$\mathcal{D}_T^a = \frac{\sqrt{2}}{2} \sum_{j=1}^{N_p} d_{j,k} \quad \forall k = 1, 2, \cdots, N_{mg} \tag{6}$$

where $\mathcal{D}_T^a$ is the optimal distance of ETA to all the peers in k^{th} VMG. The (6) holds only when peers are uniformly distributed within the VMG. Now considering the entire large area which we divided into N_{mg} VMGs, then the total possible distance a peer can travel becomes

$$\mathcal{D}_T^A = \sum_{k=1}^{N_{mg}} \mathcal{D}_{T,k}^a = \frac{\sqrt{2}}{2} \sum_{k=1}^{N_{mg}} \sum_{j=1}^{N_p} d_{j,k}. \tag{7}$$

However, the ETA covers some distance $\sum_i \left| \mathcal{D}_T^{a,k} - d_{i,k} \right|$ to obtain the energy prices and peer ID $\forall j$, thus

$$\begin{aligned} \mathcal{D}_T^o = & \sum_{j=1}^{N_p} \left\{ \left(\mathcal{D}_T^{a,k} - d_j \right) + \sum_{i=1}^{N_p} \left| \mathcal{D}_T^{a,k} - d_{i,k} \right| \right\} \\ & \forall k = 1, 2, \cdots, N_{mg} \end{aligned} \tag{8}$$

where $\mathcal{D}_T^o$ is the total optimal distance cost incurred by distributing ETAs, one per VMG. Comparing (1) and (8), since $\sum_{j=1}^{N_p} \left| \mathcal{D}_T^{a,k} - d_{j,k} \right|$ may be shorter than $\sum_{j=1}^{N_p} \sum_{i=1}^{N_p} |d_i - d_j|$ $\forall k = 1, \cdots, N_{mg}$ then the distance covered by any i^{th} prosumer to obtain the cheapest energy price in a VMG when using an ETA is significantly reduced compared to the distance traversed within the VMG when operated without an agent. The idea to employ an agent with updated information about energy prices will help individual peer keep own energy price at a purchasable price given what others sell.

B. Energy router agent

Instead of radio access network approach, the agent can be embedded within the fusing module of an energy internet. For example, the concept of energy router was introduced recently by [15]. The key function of energy router is fusing energy that comes from different resources [16]. Energy router has three main components, namely energy distribution unit, intelligent power management (or decision making unit) and communication network configuration and management unit. The agent shall reside within the communication unit (see Fig. 2) which will enhance energy routing through the intelligent power management unit. Each router can act as a supplier or consumer (which fits into the paradigm of P2P energy trading since passive energy consumers become active energy producers). However, the role (producer or consumer) performed by an energy router at a time is determined by the energy flow.

C. PLC Gateway Agent

We have seen in Fig. 2, that the energy router uses a communication channel (of Zigbee, Ethernet or wireless LAN) in addition to the power cables to enable energy transactions [15]. One of the ways of simplifying such architecture is by using power line communication (PLC) [17] which is able to communicate data signals over power cables [18].

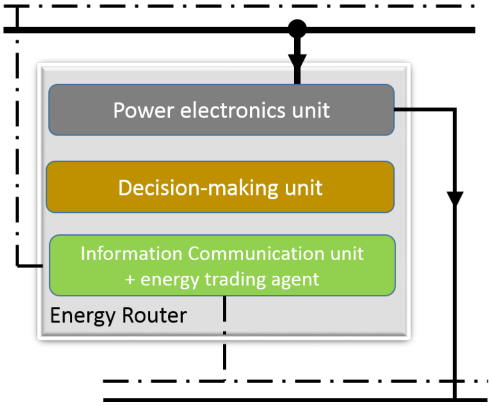


Figure 2: Energy router with the three fundamental functional units and energy trading agent

Recently, PLC gateways are now being deployed to replace data concentrators used in smart metering [12] for energy control/transactions and automation through electrical power lines. PLC gateways have the capability to connect non-PLC devices to PLC devices. With such facility, we consider deploying PLC gateway agents in the proposed VMGs. Power line channels shall then transfer data communication among energy trading peers. This approach decentralizes communications and also supports P2P communication and energy trading. The costs described above need to consider several other factors. These include, type of cables involved in the network, the channel and whether it is narrowband or broadband PLC channel.

D. *Hybrid Wireless and PLC module agent*

It was suggested in [13] that both the wireless and PLC communication channels can be harnessed cooperatively to achieve higher throughput, capacity and received signal integrity. While using the energy router with PLC gateway functionality, we suggest that the module can cooperate with wireless access module to achieve higher reliability. On the other hand, wherein one technology may not function optimally, an alternative module can be deployed.

E. *NB-IoT agent*

In the case of NB-IoT architecture, the agent may be typical of the three classes of communication devices described in [19] or any other machine type communication (MTC) system. The NB-IoT devices have the potential of reusing small portions of already assigned LTE spectrum [19]. Meanwhile, the model described here allows a full duplex transmission among energy trading peers.

III. SIMULATION RESULTS AND DISCUSSIONS

Let the area under investigation be a square. We model the distance hopped by each prosumer request as the parameters of the VMG size whose diagonal lengths such are 50m, 200m and 500m. Assuming that the agent is centrally located within a VMG and that the prosumers within this VMG are independently and uniformly distributed around the ETA at distances $d_{ij} = \{d_{1,1} \leftarrow \{d_{2,1}, d_{3,1}, \cdots, d_{N_p-1,1}\}\}\ \forall j = 1, \cdots, N_p$ where $d_{1,1}$ is the reference prosumer. Thus, the distance of a reference node from itself is designated as $d_{1,1} = 0$ and the maximum distance from that reference node is d_{ij}. Assuming a VMG of diagonal regular square size $d_{1,1} < \ell_k \leq d_{ij}$ $\forall k = 1, \cdots, N_{mg}$, and with ETA centrally located, then the maximum distance subtended by a prosumer from the ETA can be realized as $\frac{\sqrt{2}}{2}(\ell)$; the worst separation distance between a prosumer and an ETA. Since the large distance can be split into a varying number of VMGs with limited number of prosumers, then $\frac{\sqrt{2}}{2}(\ell)$ varies with the number of divisions. This concept is demonstrated in Fig. 3 for different number of divisions.

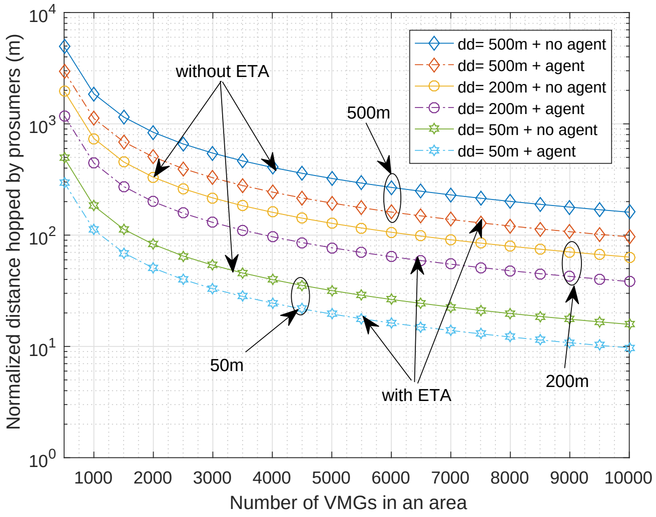


Figure 3: Distance cost of prosumers hopping to other peers within VMG of varying sizes (with 5×10^4 prosumers in total).

In Fig. 3, it can be noticed that dividing a large area into a number of VMGs reduces the total distance traversed by a prosumer request whether ETA is used or not. For example, if a large area with a total of 5×10^4 prosumers is divided into 500 VMGs of diagonal distance $500m$, the total distances the prosumers will be $\simeq 4.95 \times 10^3 m$. However, if the same area is divided into 10000 VMGs the total distance covered becomes $\simeq 161\ m$. Also, as the average diagonal distance of the VMG increases (e.g. from 50m to 500m), the total distance cost increases. Next, considering when the model is operated with an ETA in each VMG, the distance traversed is thus reduced by 40% than when operated without an ETA. Thus, operating a large energy trading area with distributed agent control minimizes the network resources spent during transactions.

In this light, the performance cost in terms of node density is shown in Fig. 4. We observe that as the node density is decreasing (in other words when the number of VMG is increasing), the total distance reduces.

Finally, we present the variation of the number of prosumers in a given VMG based on the large area size. For example, give an area of 80×10^3prosumers divided into 100 VMGs, the node density per VMG is found as 800. However, if the large area is divided into 1000 instead of 100 then the node density per VMG is 80. This is demonstrated in Fig. 5. For other

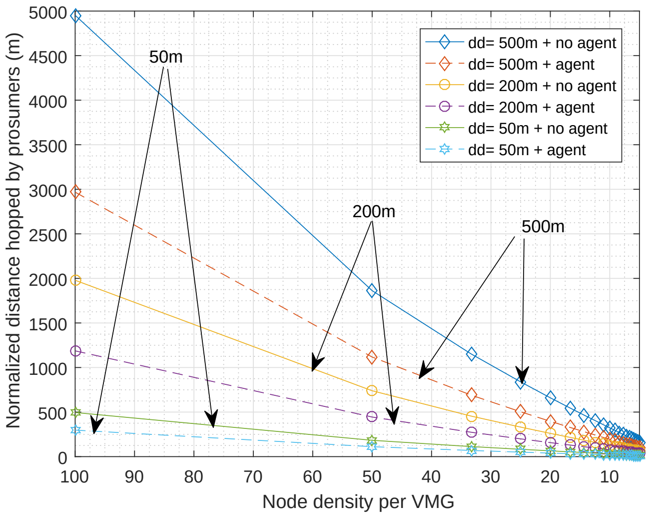


Figure 4: Distance covered in terms of node density (with 5×10^4 prosumers in total).

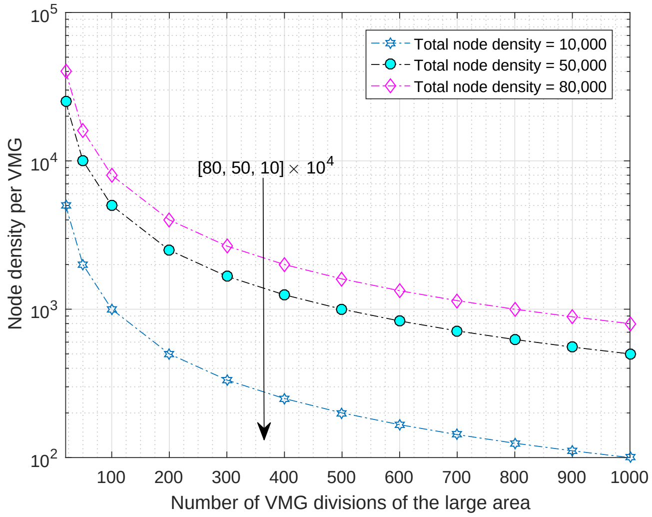


Figure 5: Node density variation per VMG for different sized large areas

differently sized large areas (e.g. 50×10^3 and 10×10^3), the node density vertically decreases as the number of total area node density decreases as shown in the plot.

IV. CONCLUSION

In this paper, we investigated how to minimize the cost of energy network resources in P2P-ETS using ETA in the communication network access. The MGs are regrouped into VMGs and an ETA is assigned to each VMG. For all transaction-related messages, the peers in each VMG only communicate with the ETA. We employed this approach in various cluster sizes ranging between 5 and 100 energy trading prosumsers and studied the performance of the VMG in terms of distance traversed by a prosumer request. The performance costs are then compared with typical VMG without ETA. The results showed that the proposed technique can reduce communication distance travelled by a prosumer request can also be reduced by 40 %. Lastly, we showed that prosumer density decreases for increasing number of VMGs.

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