Dynamic Data Aggregator Unit Selection in Smart Grid: An Evolutionary Game Theoretic Approach

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***Abstract*—In this paper, the problem of dynamic data aggregator unit selection in smart grid is studied using a dynamic evolutionary game theoretical model. The smart meters at the customer-end form the entire population of evolutionary game. The strategy of each smart meter evolves by choosing a different data aggregator unit in order to communicate with the meter data management system. Using the proposed dynamic data aggregator unit selection (DARTS) scheme, there exists stable solution for evolutionary equilibrium. Using the proposed DARTS scheme, the delay in service improves 82.3% and the communication load to each DAU reduces 69.23% than using without any game theoretic approach.**

***Keywords*—Data Aggregator Unit, Evolutionary Game, Smart Meter, Dynamic Selection, Meter Data Management system, Smart Grid Communication**

I. Introduction

The traditional electrical grid needs to be modified as a modernized electrical grid, termed as *smart grid* [1]–[3], to augment the efficiency, reliability, and robustness of the power systems. Unlike the existing electrical grid, in which energy is distributed unidirectionally to customers by the main grid having a centralized system, in smart grid with duplex communication infrastructure, the large scale traditional electrical grid used for energy distribution is divided into micro-grids having bi-directional electricity exchange facilities. In smart grid, it is desired that each micro-grid serves a small geographical area, and fulfills the demand of the customers in that area to relax the load of the main grid. The customers can also request energy to the micro-grid flexibly with the help of distributed energy management systems.

For distributed energy management, each customer requires to send his/her energy consumption information to the micro-grid in real-time. The smart meters send the energy consumption profile to the data aggregator units (DAUs) [4], in order to send the information to the meter data management system (MDMS) [5]. The buffer-size of each DAU is limited, and each smart meter also has the constraint of limited processing speed.

It is required to design a proper data aggregator unit selection scheme. In smart grid, the communication load, i.e., the energy consumption information of the customers, over a data aggregator unit depends on the number of smart meters, i.e., customers, connected to the data aggregator unit. Therefore, we propose an *evolutionary game-theoretic dynamic data aggregator unit selection* (DARTS) scheme. Using the proposed scheme, each smart meter selects a DAU from the available DAUs to send the customer's energy consumption information to the MDMS with reduced delay, and the total communication load is distributed properly over the available DAUs in smart grid.

II. Related Work

In the last few years, lot of research work on smart grid emerged, viz., [4]–[12]. Some of the existing literature are discussed in this Section. Misra *et al.* [4] proposed a distributed dynamic pricing mechanism (D2P) for charging PHEVs. They used two different pricing schemes, namely home pricing scheme and roaming pricing scheme. Niyato and Wang [5] formulated a scheme for cooperative transmission of meter data to the utility provider. In their proposed scheme, after receiving data from the DAU, the MDMS estimates the supply-demand curve, and optimizes the real-time price to maximize the utility of the micro-grid. Ahmed *et al.* [8] studied the communication architecture using cooperation between smart relays to support energy trading in smart grid. Such and Hill [12] proposed that efficient and economic operation of an electric energy distribution system can be improved with the implementation of wind generation and storage devices. They did not focus on any communication architecture that helps to send information to the customers from the micro-grid, and the information from the micro-grid to the customers.

In the existing literature, no work has been reported on the problem of dynamic DAU selection which helps the customers and the micro-grid to communicate within themselves with less delay in getting energy services and less overhead to the data aggregator units.

III. System Model

We consider a energy distribution system of coalition [9] consisting of single micro-grid and multiple customers. Each customer is equipped with a *smart meter*. The smart meter collects the information of the energy consumption profile of the appliances at the customer-end using home area network (HAN), and sends the information to the *data aggregator unit* (DAU) using neighborhood area network (NAN). The DAU sends the aggregated information to the *meter data management system* (MDMS) using wide area network (WAN). The schematic diagram of smart grid communication architecture is shown in Figure 2. We consider that each DAU has multiple

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ReqMsgType	CustomerID	ReqEnergy	FinalSelectFlag
1 byte	4 byte	2 byte	1 byte

(a) *Request* message by a smart meter

AckMsgType	MDMS_ID	Price	AckFlag
1 byte	4 byte	2 byte	1 byte

(b) *Acknowledgment* message by a MDMS

Fig. 1: Message formats in proposed dynamic data aggregator unit selection scheme

dedicated channels, and the channel capacity is the same for all the channels.

Each smart meter $s \in \mathcal{S}$, where $\mathcal{S}$ is the set of smart meters connected to the micro-grid, i.e., the MDMS, within a coalition, chooses a DAU dynamically to send the energy consumption information of the customers to the MDMS. We consider that there are $|\mathcal{D}|$ number of DAUs, where $\mathcal{D}$ is the set of available DAUs in a coalition. We assume that each DAU $d \in \mathcal{D}$ has $\mathbf{C}_d$ number of channels. The number of channels is fixed for each DAU $d \in \mathcal{D}$. Mathematically,

$$\mathbf{C}_1 \triangleq \mathbf{C}_2 \triangleq \cdots \triangleq \mathbf{C}_d \triangleq \cdots \triangleq \mathbf{C}_{|\mathcal{D}|} \triangleq \mathbf{C} \quad (1)$$

We define the total channel capacity of each DAU $d \in \mathcal{D}$, i.e., $\mathbf{C}_d^{total}$, as follows:

$$\mathbf{C}_d^{total} = \mu \mathbf{C}_d, \quad \forall d \in \mathcal{D} \quad (2)$$

where μ is the channel capacity per single channel. We assume that, at time slot $t \in T$, where T is the set of time slots in a day, each DAU $d \in \mathcal{D}$ uses a linear pricing model. The price coefficient, $p_d(t)$, i.e., price to be paid for connection by each smart meter to a DAU $d \in \mathcal{D}$, is a linear function of the ratio of the number of smart meters connected to DAU d, i.e., $\mathcal{S}^d(t) \subseteq \mathcal{S}$, and the available smart meters in the coalition, $\mathcal{S}$.

$$p_d(t) = f\left(\frac{\mathcal{S}^d(t)}{\mathcal{S}}\right), \quad \forall d \in \mathcal{D} \quad (3)$$

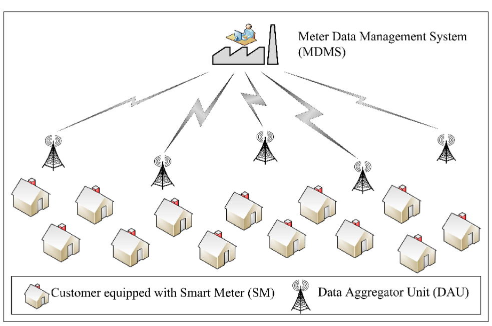


Fig. 2: Schematic diagram of smart grid communication architecture

With the increase in the number of smart meters connected to each DAU d, i.e., $\mathcal{S}^d(t)$, the price coefficient, $p_d(t)$, increases. On the other hand, with the increase in $\mathcal{S}^d(t)$, the delay in communication between DAU d and the MDMS, i.e., τ_d also becomes higher due to the increase of queue length of the messages. Hence, each smart meter $s \in \mathcal{S}^d(t)$ has to wait for longer duration of time to get the energy service from the micro-grid or the energy service-provider. We consider that using the proposed framework of DAU selection, the network congestion and the service delay in smart grid decrease. In this scenario, the pricing coefficient, $p_d(\cdot)$, plays a major role in dynamic data aggregator unit selection. The price paid by the smart meter s, i.e., $p^s(t)$, for the communication service can be different for using different DAUs to communicate with the MDMS.

Communication between the micro-grid and the Customers

We assume that the smart meters communicate with the data aggregator units (DAUs) using IEEE 802.11b protocol, which is a Wi-Fi wireless network communication technology used for neighborhood area network (NAN). To complete energy trading successfully, each smart meter $s \in \mathcal{S}$ placed at the customer-end sends a *request message* to the MDMS through the selected DAU, which acts as a router in the smart grid communication architecture. The request message format is shown in Figure 1(a). Based on the requested amount energy to the micro-grid, the MDMS decides the price per unit energy, and sends an *acknowledgment message* to the smart meters through the DAUs with information about the price per unit energy. The acknowledgment message format is shown in Figure 1(b).

IV. Proposed Dynamic Data Aggregator Unit Selection Game

A. Game Formulation

To study the interaction between the DAUs and the smart meters for selecting the DAUs dynamically, we use a dynamic evolutionary game theoretic approach. Here, the set of DAUs $\mathcal{D}$, acting as players, forwards the energy request messages of the smart meters $\mathcal{S}$ at the customer-end to the MDMS, i.e., the micro-grid. Each smart meter $s \in \mathcal{S}$ acts as another player, needs to choose an appropriate DAU, dynamically, to reduce the delay in energy service of the micro-grid, and to utilize the available channel capacity in the smart grid. The *population share* of each DAU $d \in \mathcal{D}$, i.e., $\eta_d(t)$, using the proposed *dynamic data aggregator unit selection* (DARTS) scheme is defined in Definition 1.

Definition 1. *In the proposed DARTS scheme, the population share of each DAU $d \in \mathcal{D}$, is defined by the ratio of the number of smart meters connected with the DAU d, i.e., $|\mathcal{S}^d(t)|$, and the total number of smart meters in the coalition, i.e., $|\mathcal{S}|$. Mathematically,*

$$\eta_d(t) = \frac{|\mathcal{S}^d(t)|}{|\mathcal{S}|}, \quad \forall d \in \mathcal{D} \quad (4)$$

The elements in the *population share vector*, $\vec{\boldsymbol{\eta}}(t)$, defined in Definition 2, act as the total population in the proposed DARTS game, and define a foundation to obtain the equilibrium solution for the game of evolution, i.e., dynamic evolutionary game.

Definition 2. *In the proposed DARTS game, the population share vector, $\vec{\boldsymbol{\eta}}(t)$, is defined the vector with $|\mathcal{D}|$ number of elements of population share in a coalition. Mathematically,*

$$\vec{\boldsymbol{\eta}}(t) = \left[\eta_1(t), \eta_2(t), \cdots, \eta_d(t), \cdots, \eta_{|\mathcal{D}|}(t)\right]^T \quad (5)$$

In particular, given the channel capacity of each DAU $d \in \mathcal{D}$, the smart meters $\mathcal{S}$ compete to share the available channel capacity of the selected DAU d. We use a dynamic evolutionary game, as the proposed approach can capture the dynamics of the chosen DAUs, i.e., strategies chosen by smart meters $\mathcal{S}$, based on the available information and rational bounds on the smart meters $\mathcal{S}$. Hence, each smart meter $s \in \mathcal{S}$ slowly evolves by changing the population share of each DAU $d \in \mathcal{D}$, $\eta_d(t)$, if the smart meter s observes that its payoff is less than the average payoff of all the smart meters $\mathcal{S}$ in the coalition. In the proposed scheme, DARTS, the evolutionary equilibrium is considered as the optimum solution, which confirms that all the smart meters receive similar payoffs in the coalition. The strategic form of the proposed DARTS scheme, i.e., $\boldsymbol{\theta}$, is defined as follows:

$$\boldsymbol{\theta} = \langle (\mathcal{S} \cup \mathcal{D}), [p^s(\cdot), \mathcal{U}_s(\cdot)]_{s\in\mathcal{S}}, [\eta_d(\cdot), p_d(\cdot), \mathscr{B}_d(\cdot)]_{d\in\mathcal{D}} \rangle \quad (6)$$

The components of the strategic form $\boldsymbol{\theta}$ are as follows:

i) Each smart meter $s \in \mathcal{S}$ chooses a DAU $d \in \mathcal{D}$, dynamically, to be connected with MDMS, and to send the energy consumption request messages from the customer-end to the micro-grid.

ii) The price to be paid by each smart meter $s \in \mathcal{S}$, $p^s(\cdot)$, is evaluated using the following equations:

$$\begin{aligned} p^s(\cdot) &= p_d(\cdot), \qquad \text{if } s \in \mathcal{S}^d(\cdot) \\ &= \alpha_s \frac{|\mathcal{S}^d(\cdot)|}{|\mathcal{S}|} = \alpha_s \eta_d(\cdot) \end{aligned} \quad (7)$$

where $\alpha_s \geq 1$, and α_s is a constant for smart meter $s \in \mathcal{S}$.

iii) The set of smart meters choosing the DAU $d \in \mathcal{D}$, i.e., $\mathcal{S}^d(\cdot)$, contributes population share, $\eta_d(\cdot)$, in the total population of the proposed DARTS scheme.

iv) Each DAU $d \in \mathcal{D}$ decides the price coefficient, $p_d(\cdot)$, based on the population share of the DAU d in the dynamic data aggregator selection game.

v) The payoff of a smart meter $s \in \mathcal{S}$ is determined by its net utility, $\mathcal{U}_s(\cdot)$. On the other hand, the payoff of a DAU $d \in \mathcal{D}$, i.e., $\mathscr{B}_d(\cdot)$, is determined by the average utility of the connected smart meter, $\mathcal{S}^d(t) \subseteq \mathcal{S}$, at time instant $t \in T$.

1) Utility function of a smart meter: For each smart meter $s \in \mathcal{S}$, we define the utility function $\mathcal{U}_s(\cdot)$ as a *concave function*, which signifies the quantified satisfaction of smart meter s on channel capacity consumption. For choosing a particular DAU d, the net utility of each smart meter s is expressed as the difference between the revenue function of the smart meter s, i.e., $\mathcal{R}_s(\cdot)$, and the cost function of the smart meter s, i.e., $\mathcal{C}_s(\cdot)$. Mathematically,

$$\mathcal{U}_s(\cdot) = \mathcal{R}_s(\cdot) - \mathcal{C}_s(\cdot), \quad s \in \mathcal{S} \quad (8)$$

Using dynamic evolutionary game, each smart meter s tries to maximize its satisfaction factor by choosing the DAU d having higher payoff of the utility function $\mathscr{B}_d(\cdot)$. Consider that a smart meter, i.e., $s \in \mathcal{S}$, selects the DAU $d \in \mathcal{D}$, and another smart meter, i.e., $\tilde{s} \in \mathcal{S}$, where $\tilde{s} \neq s$, selects another DAU $\tilde{d} \in \mathcal{D}$ for sending the energy information to the MDMS. Hence, if the payoff of the DAU d is higher than the payoff of the DAU $\tilde{d}$, i.e., $\mathscr{B}_d(\cdot) > \mathscr{B}_{\tilde{d}}(\cdot)$, the smart meter s has higher satisfaction factor than the smart meter $\tilde{s}$, i.e., $\mathcal{U}_s(\cdot) > \mathcal{U}_{\tilde{s}}(\cdot)$. Therefore, the properties that utility of a smart meter s, i.e., $\mathcal{U}_s(\cdot)$, must satisfy are as follows:

i) The utility function of each smart meter $s \in \mathcal{S}$, i.e., $\mathcal{U}_s(\cdot)$, is considered to be a non-decreasing function, as each smart meter s tries to maximize its satisfaction factor. We consider that population share changes from $\eta_d(\cdot)$ to $\tilde{\eta}_d(\cdot)$, where $\eta_d(\cdot)$ and $\tilde{\eta}_d(\cdot)$ are the current population share and new population share of the DAU d, respectively. Mathematically,

$$\frac{\delta \mathcal{U}_s(\cdot)}{\delta \tilde{\eta}_d(\cdot)} \geq 0 \quad (9)$$

ii) The marginal payoff of the utility function of each smart meter s, $\mathcal{U}_s(\cdot)$, is considered to be a decreasing function, as at marginal condition, if a smart meter chooses to select a different DAU, the payoff of the utility function decreases with change in population share of the DAUs $\mathcal{D}$. Mathematically,

$$\frac{\delta^2 \mathcal{U}_s(\cdot)}{\delta [\tilde{\eta}_d(\cdot)]^2} < 0 \quad (10)$$

iii) The cost function of each smart meter s, i.e., $\mathcal{C}_s(\cdot)$, yields higher value with the increase price coefficient of the DAU d, $p_d(\cdot)$. With the increase in price coefficient of DAU d, $p_d(\cdot)$, the price to be paid by the each smart meter s also increases, as shown in Equation (7). Therefore,

$$\frac{\delta \mathcal{C}_s(\cdot)}{\delta p^s(\cdot)} \geq 0, \text{ and } \frac{\delta \mathcal{U}_s(\cdot)}{\delta p^s(\cdot)} < 0 \quad (11)$$

We consider that the revenue function of smart meter s, i.e., $\mathcal{R}_s(\cdot)$, as a concave function. Therefore, we define the revenue function of smart meter s, i.e., $\mathcal{R}_s(\cdot)$, as follows:

$$\mathcal{R}_s(\cdot) = |\mathcal{S}| \tan^{-1}\left(e^{\frac{\dot{\eta}_d(\cdot)}{\eta_d(\cdot)}}\right) \quad (12)$$

where $\dot{\eta}_d(\cdot)$ is defined as the change in population share of the DAU $d \in \mathcal{D}$. Mathematically,

$$\dot{\eta}_d(\cdot) = \tilde{\eta}_d(\cdot) - \eta_d(\cdot), \quad \forall d \in \mathcal{D} \quad (13)$$

The cost function of each smart meter $s \in \mathcal{S}$, i.e., $\mathcal{C}_s(\cdot)$, is defined as follows:

$$\mathcal{C}_s(\cdot) = p^s(\cdot)|\mathcal{S}^d(\cdot)|, \quad \forall s \in \mathcal{S}^d(\cdot) \quad (14)$$

Hence, we get the utility function of each smart meter $s \in \mathcal{S}$, $\mathcal{U}_s(\cdot)$, as follows:

$$\begin{aligned} \mathcal{U}_s(\cdot) &= \mathcal{R}_s(\cdot) - \mathcal{C}_s(\cdot) \\ &= |\mathcal{S}| \tan^{-1}\left(e^{\frac{\tilde{\eta}_d(\cdot) - \eta_d(\cdot)}{\eta_d(\cdot)}}\right) - p^s(\cdot)|\mathcal{S}^d(\cdot)| \end{aligned} \quad (15)$$

Lemma 1. *The value of population share of each DAU $d \in \mathcal{D}$, i.e., $\tilde{\eta}_d(\cdot)$, follows the property defined as follows:*

$$0 < \tilde{\eta}_d(\cdot) \leq 1 \quad (16)$$

Proof: We consider the population share of each DAU d, $\tilde{\eta}_d(\cdot)$, as shown in Equation (4). We know that $\mathcal{S}^d(\cdot) \subseteq \mathcal{S}$. Therefore, we conclude:

$$\begin{aligned} |\mathcal{S}^d(\cdot)| &\leq |\mathcal{S}| \\ \text{or,} \quad \tilde{\eta}_d(\cdot) &\leq 1 \end{aligned} \quad (17)$$

On the other hand, we consider that a subset of the available smart meters $\mathcal{S}$ chooses each DAU $d \in \mathcal{D}$, i.e., $\mathcal{S}^d(\cdot) \neq \{\phi\}$. Hence, we conclude:

$$\begin{aligned} & |\mathcal{S}^d(\cdot)| > 0 \\ \text{or,} \quad & \tilde{\eta}_d(\cdot) > 0 \end{aligned} \tag{18}$$

Therefore, the value of population share of each DAU $d \in \mathcal{D}$, i.e., $\tilde{\eta}_d(\cdot)$, satisfies the condition: $0 < \tilde{\eta}_d(\cdot) \leq 1$. ■

2) Utility function of a DAU: For each DAU $d \in \mathcal{D}$, the utility function, $\mathscr{B}_d(\cdot)$, signifies the utilization factor of the available channel capacity of the DAU d. Here, we consider that the payoff of the utility function, $\mathscr{B}_d(\cdot)$, is transferable, i.e., the *transferable utility* defined in Definition 3, among the DAUs $\mathcal{D}$ in the coalition. With the increase in the number of smart meters connected with the DAU d, i.e., $|\mathcal{S}^d(\cdot)|$, the payoff of the utility function $\mathscr{B}_d(\cdot)$ increases, as the DAU d earns higher revenue using a limited channel capacity, and the utilization factor of the available channel capacity is also higher. Mathematically,

$$\frac{\delta \mathscr{B}_d(\cdot)}{\delta |\mathcal{S}^d(\cdot)|} > 0 \tag{19}$$

Therefore, we define the utility function of a DAU $d \in \mathcal{D}$, $\mathscr{B}_d(\cdot)$, as follows:

$$\mathscr{B}_d(\cdot) = \sum_{s \in \mathcal{S}^d(\cdot)} \frac{|\mathcal{S}^d(\cdot)|}{|\mathcal{S}|} \mathcal{U}_s(\cdot) = \sum_{s \in \mathcal{S}^d(\cdot)} \tilde{\eta}_d(\cdot) \mathcal{U}_s(\cdot) \tag{20}$$

Considering the transferable utility, defined in Definition 3, we evaluate the payoff of the average utility function of available DAUs $\mathcal{D}$, i.e., $\bar{\mathscr{B}}(\cdot)$, in the coalition. We define the average utility function of the coalition, $\bar{\mathscr{B}}(\cdot)$, as follows:

$$\bar{\mathscr{B}}(\cdot) = \sum_{d \in \mathcal{D}} \tilde{\eta}_d(\cdot) \mathscr{B}_d(\cdot) \tag{21}$$

Definition 3. *The transferable utility is considered to be the average payoff of the utility function of the players available within a coalition. Using transferable utility, we consider the overall payoff of the utility functions of the available players in a coalition, in spite of considering the individual payoff of each player, individually.*

In the proposed scheme, DARTS, we consider the payoff of the average utility function of the coalition, $\bar{\mathscr{B}}(\cdot)$, while not considering the individual payoff of the utility function of each DAU $d \in \mathcal{D}$, i.e., $\mathscr{B}_d(\cdot)$.

3) Replicator dynamics of dynamic data aggregator unit selection scheme: Using dynamic evolutionary game theoretic approach, each DAU $d \in \mathcal{D}$ forms a population share, i.e., a *replicator* defined in Definition 4.

Definition 4. *A replicator acts as a player in the evolutionary game, is able to reproduce itself through the process of mutation and evolution, i.e., evolution. A replicator with higher payoff is able to reproduce itself quicker than any replicator with lower payoff.*

We model the reproduction procedure in evolutionary game using a ordinary differential equation, defined as *replicator dynamics*. We define the replicator dynamics of DARTS as follows:

$$\frac{\delta \eta_d(\cdot)}{\delta t} = \lambda \eta_d(\cdot) \left[\mathscr{B}_d(\cdot) - \bar{\mathscr{B}}(\cdot) \right] \tag{22}$$

where λ is a constant, controls the speed of the smart meters $\mathcal{S}$ in observing and adopting the DAU selection and $\lambda > 0$, and $\eta_d(\cdot)$ is the current population share of the DAU $d \in \mathcal{D}$.

In the proposed scheme, DARTS, using dynamic evolutionary game, the evolutionary equilibrium is evaluated by a set of fixed values of the replicator dynamics, i.e., Pareto optimal solution of the dynamic evolutionary game. Based on the replicator dynamics, we conclude that the evolutionary equilibrium solutions are stable in nature. Therefore, to reach the stable evolutionary equilibrium solution, each smart meter $s \in \mathcal{S}$ choose strategy, i.e., evolves, over time depending on the replicator dynamics. At evolutionary equilibrium, the payoff of each smart meter s, i.e., individual players in the population, is equal to the average payoff of the smart meters. Therefore, after reaching the stable evolutionary equilibrium point, each smart meter $s \in \mathcal{S}$ does not change its strategy, i.e., dynamically chosen DAU $d \in \mathcal{D}$, to evolve further.

B. Existence of Evolutionary Equilibrium Solution

We determine the existence of evolutionary equilibrium solution in the proposed scheme, DARTS, by considering the properties of dynamic evolutionary game theory [13], as shown in Theorem 1.

Theorem 1. *Given the fixed size of the population, i.e., the number of smart meters, $\mathcal{S}$, there exists a stable solution for evolutionary equilibrium. Therefore, at a stable equilibrium solution point the proposed DARTS scheme must satisfy the following constraint:*

$$\frac{\delta \eta_d(\cdot)}{\delta t} = 0, \quad \forall d \in \mathcal{D} \tag{23}$$

Proof: We know that each DAU $d \in \mathcal{D}$ must satisfy the constraint given in Equation 23. Therefore,

$$\lambda \eta_d(\cdot) \left[\mathscr{B}_d(\cdot) - \bar{\mathscr{B}}(\cdot) \right] = 0, \quad \forall d \in \mathcal{D} \tag{24}$$

We define λ to be a constant, and $\lambda > 0$. We also consider that the population share of each DAU d is always greater than zero, i.e., $\eta_d(\cdot) > 0$. Hence, we get,

$$\mathscr{B}_d(\cdot) - \bar{\mathscr{B}}(\cdot) = 0, \quad \forall d \in \mathcal{D} \tag{25}$$

Therefore, we rewrite Equation (25) as follows:

$$\mathscr{B}_d(\cdot) = \bar{\mathscr{B}}(\cdot) = \sum_{d \in \mathcal{D}} \tilde{\eta}_d(\cdot) \mathscr{B}_d(\cdot) \tag{26}$$

Hence, we get,

$$\mathscr{B}_d(\cdot) = \frac{\begin{array}{c} \tilde{\eta}_1(\cdot)\mathscr{B}_1(\cdot) + \cdots + \tilde{\eta}_{d-1}(\cdot)\mathscr{B}_{d-1}(\cdot) + \\ \tilde{\eta}_{d+1}(\cdot)\mathscr{B}_{d+1}(\cdot) + \cdots + \tilde{\eta}_{|\mathcal{D}|}(\cdot)\mathscr{B}_{|\mathcal{D}|}(\cdot) \end{array}}{1 - \tilde{\eta}_d(\cdot)} \tag{27}$$

Hence,

$$\mathscr{B}_d(\cdot) - \mathscr{B}_k(\cdot) = \tilde{\eta}_k(\cdot)\mathscr{B}_k(\cdot) - \tilde{\eta}_d(\cdot)\mathscr{B}_d(\cdot) \tag{28}$$

where $d \neq k$, and $d, k \in \mathcal{D}$. Using dynamic evolutionary game theory, we know that $\mathscr{B}_d(\cdot) = \mathscr{B}_k(\cdot)$, where $d \neq k$. Therefore, from Equation (28), we get,

$$\tilde{\eta}_k(\cdot) = \tilde{\eta}_d(\cdot) \tag{29}$$

where $d \neq k$, and $d, k \in \mathcal{D}$. Equation (29) provides the evolutionary equilibrium solution which signifies that the population share of each DAU d is the same in the DARTS scheme. Equation (29) can be rewritten as follows:

$$\tilde{\eta}_1(\cdot) = \tilde{\eta}_2(\cdot) = \cdots = \tilde{\eta}_d(\cdot) = \cdots = \tilde{\eta}_{|\mathcal{D}|}(\cdot) \tag{30}$$

■

C. Algorithms

In order to reach the stable solution point of the proposed dynamic evolutionary game, each smart meter $s \in \mathcal{S}$ needs to choose appropriate DAU $d \in \mathcal{D}$, dynamically. Due to this dynamic nature of the proposed DARTS scheme, the population share of each DAU $d \in \mathcal{D}$, i.e., $\tilde{\eta}_d(\cdot)$, changes or evolves gradually. Hence, the population share of each DAU $d \in \mathcal{D}$ changes from $\eta_d(\cdot)$ to $\tilde{\eta}_d(\cdot)$, where $\eta_d(\cdot)$ and $\tilde{\eta}_d(\cdot)$ are the current value and the new value of the population share of the DAU d, respectively. In the proposed scheme, DARTS, each smart meter $s \in \mathcal{S}$ and each DAU $d \in \mathcal{D}$ needs to execute Algorithms 1 and 2, respectively.

Algorithm 1: DARTS Algorithm for smart meter

Inputs : α_s: Constant factor in price function
$\mathscr{B}_d(\cdot)$: Utility function of the chosen DAU d
$\bar{\mathscr{B}}(\cdot)$: Average utility function of the coalition
λ: Constant for controlling the speed of change in population share
$\mathcal{S}$: Set of smart meters in the coalition
Outputs: d^{select}: Dynamically selected DAU d
$\mathcal{U}_s(\cdot)$: Utility function of smart meter $s \in \mathcal{S}$

if $\mathscr{B}_d(\cdot) \neq \bar{\mathscr{B}}(\cdot)$ **then**
  $\tilde{\eta}_d(\cdot) = \eta_d(\cdot) + \lambda\eta_d(\cdot)\left[\mathscr{B}_d(\cdot) - \bar{\mathscr{B}}(\cdot)\right]$;
  if $rand() < \frac{\mathscr{B}_d(\cdot) - \bar{\mathscr{B}}(\cdot)}{\mathscr{B}_d(\cdot)}$ **then**
    // $rand()$ function generates a random value between 0 and 1 ;
    Choose another DAU $k \in \mathcal{D}$ // where $k \neq d$;
  else
    Choose the DAU $d \in \mathcal{D}$ again ;
  end
  Calculate $\mathcal{U}_s(\cdot)$ using Equation (15) ;
else
  // Evolutionary equilibrium state reached ;
  Choose the DAU $d \in \mathcal{D}$ again ;
end
return;

Algorithm 2: DARTS Algorithm for DAU

Inputs : $\tilde{\eta}_k(\cdot)$: Population share of DAU $k \in \mathcal{D}$
$\mathscr{B}_k(\cdot)$: Utility function of the chosen DAU k
$\mathcal{S}^d(\cdot)$: Set of smart meters chose DAU d
$\mathcal{S}$: Set of available smart meters in the coalition
$\mathcal{U}_s(\cdot)$: Utility function of smart meter $s \in \mathcal{S}$
Output: $\mathscr{B}_d(\cdot)$: Utility function of the chosen DAU d
$\bar{\mathscr{B}}(\cdot)$: Average utility function of the coalition

$\mathscr{B}_d(\cdot) = \sum_{s \in \mathcal{S}^d(\cdot)} \tilde{\eta}_d(\cdot)\mathcal{U}_s(\cdot)$ // Calculate $\mathscr{B}_d(\cdot)$
$\bar{\mathscr{B}}(\cdot) = \sum_{d \in \mathcal{D}} \tilde{\eta}_d(\cdot)\mathscr{B}_d(\cdot)$ // Calculate $\bar{\mathscr{B}}(\cdot)$
return

V. Performance Evaluation

A. Simulation Parameters

For performance evaluation, we consider a randomly generated position of the smart meters and the DAUs on a MATLAB simulation platform, as shown in Table I. In this work, we assumed that each smart meter chooses a DAU, randomly, to be connected with the MDMS.

TABLE I: Simulation Parameters

Parameter	Value
Simulation area	10 $km \times$10 km
Number of MDMS	1
Number of DAUs	5
Number of smart meters	200
Number of channels per DAU	50
Evolution speed control factor (λ)	>0
Constant for price function (α_s)	1

B. Benchmark

The performance of the proposed scheme, DARTS, for dynamic data aggregator unit selection by the smart meters is evaluated by comparing with an another scheme, i.e., fixed selection of data aggregator unit without any game theoretic approach (WDARTS). We refer to these different data aggregator selection policies as DARTS, and WDARTS, through the rest of the paper. We show that the Proposed DARTS scheme performs better than WDARTS scheme.

C. Performance Metrics

Connected smart meter per DAU: The smart meters select the data aggregator units (DAUs), dynamically, to send the energy consumption information to the MDMS. By selecting DAUs dynamically, the message load to the each DAU is distributed.

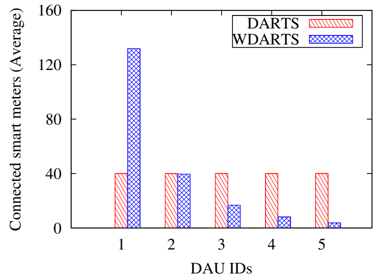
Delay in service per DAU: We define the delay in service using the time difference between the time at which the message is submitted to the selected DAU by the smart meters and the time when the DAU gets the corresponding acknowledgment message from the MDMS.

Population share of DAUs: Using the evolutionary game proposed in DARTS, the population share of each DAU is defined with the ratio of the smart meters connected with the DAU and the total available smart meters in the coalition.

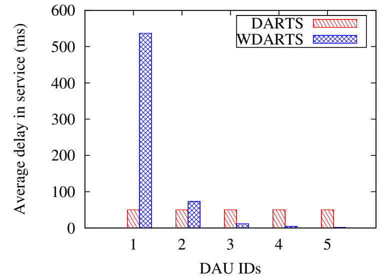
Payoff of the utility function of DAUs: Based on the payoff of the utility function of each DAU, and the average payoff of the available DAUs in the coalition, each smart meter chooses its strategy, i.e., selects an appropriate DAU, dynamically.

D. Results and Discussions

For the sake of simulation, we consider that the data rate using IEEE 802.11b protocol is 2 $Mbit/s$. Figure 3(a) shows the number of smart meters connected with each DAU. From Figure 3(a), we conclude that using the proposed scheme, DARTS, the communication load on each DAU is distributed properly. On the other hand, using fixed selection of DAU, i.e., WDARTS scheme, the communication load is higher for some of the available DAUs, and the communication load is low for some DAUs. Therefore, we infer that communication load is properly distributed, and is improved by 69.23% using DARTS, than using WDARTS. As the communication load is distributed using proposed DARTS scheme, the service delay is almost same for all the available DAUs as shown in Figure 3(b). Delay in service reduces by 82.3% for the available DAUs using DARTS, than using fixed selection of DAUs scheme, i.e., WDARTS. Figure 4(a) shows that the initial population share of the DAUs are selected randomly. However, within a few iterations, i.e., 20-25 iterations, the population share of each DAU reaches the evolutionary equilibrium state, and

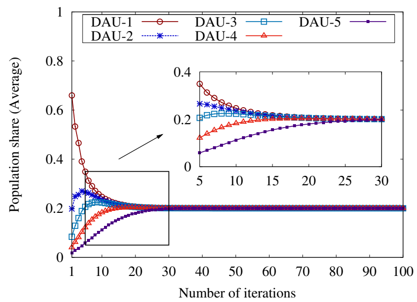


(a) Connected smart meters

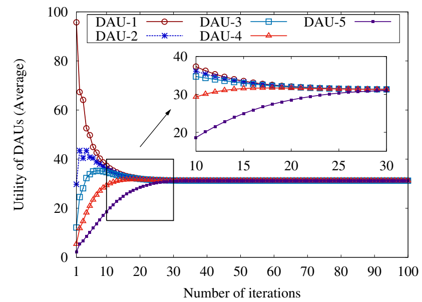


(b) Delay in service

Fig. 3: Performance of each DAU



(a) Population share of different DAUs



(b) Utility of different DAUs

Fig. 4: Evolution in strategy of each DAU

remains stable. Therefore, from Figure 4(a), we conclude that the smart meter selects the appropriate DAU dynamically, and also satisfies the evolutionary equilibrium condition. Figure 4(b) shows that the payoff of utility function of each DAU satisfies the evolutionary equilibrium points. The proposed DARTS scheme reaches the evolutionary equilibrium within a finite iteration, as show in Figure 4(b).

VI. Conclusion

In this paper, we formulated a dynamic evolutionary game theoretic approach to study the problem of data aggregator unit selection, dynamically, by the smart meters in smart grid. Based on the proposed approach, i.e., DARTS, we showed how each smart meter can evolve its strategy, i.e., select an appropriate DAU, in order to reach the evolutionary equilibrium state. The simulation results show using our proposed approach, how the communication load over each DAU can be distributed, and delay in energy service yields improved results.

Future extension of this work includes understanding how the energy consumption information of the customers by a smart meter can be delivered to the MDMS using multi-hop communication through different DAUs available in the coalition.

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