

On Delay Sensitivity Clusters of Microgrid Data Aggregation Under LTE-A Links

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Abstract—Accurate analysis and classification of delay sensitivity of the data sent from smart meters is a two-fold challenging problem which contains analytics and network latency dimensions. In the case of resilient community microgrids, vitality of the energy consumption and power usage data is further evident so to make proactive decisions to entail smooth transitions between islanded and non-islanded modes of the microgrids. In light of these, this paper analyzes smart microgrid data aggregation against time intervals to determine the delay sensitivity of aggregated messages sent over microgrid networks via LTE and LTE+ links. To meet the latency requirements, we propose a Time of Use (ToU)-aware and unsupervised learning-backed microgrid data aggregation scheme to cluster the message of the same delay sensitivity and prioritize bursts with respect to delay sensitivity to achieve low delay overhead for high and moderately delay sensitive messages. Through simulations, we have shown that by using ToU-aware model, microgrids can prioritize 247% more critical consumption requests in order to keep stable operations during islanded mode.

Index Terms—Smart microgrid, cost minimization, LTE microgrid communication.

I. INTRODUCTION

Microgrids are automated, reliable distributed energy resources that are mostly used in rural areas where the grids cannot reach due to terrain issues or cost [1]. Playing a key role on green renewable energy usage and storage on backup battery units such as solar and wind power [2], microgrids operate as part of a utility grid or switch to islanded mode if the energy is cut off from the power grid. Under the islanded operation mode, a microgrid continues to supply power to the consumers, ideally until the utility grid gets restored. Under the islanded mode, the energy is limited to the stored energy within the microgrid (or what is provided through an overlay topology), thus distributing limited power to consumers to avoid power starvation [3]. Another energy distribution way for microgrid is to transfer electricity through an electrical vehicle battery to mitigate the cost of peak hours energy utilization [4].

Real time data analytics is of paramount importance in smart grid and microgrid networks [5]. Smart grid technology enhances the power distribution systems with advanced communication grounds within the grid [6]. Any fault within a microgrid infrastructure must be reported to control centres immediately to direct power to alternate sources [7]. Latent or faulty aggregated consumption data transfers may result in an islanded operation of the microgrid to force cut off electricity distribution to certain customers. Data analytics

backed-decision support is critical in healthy operation of microgrid networks [8].

Advanced metering infrastructure (AMI) allows for the consumption data to be sent in real time from residential premises to the power distributor [9]. This helps scale power generation and distribution where allowing consumers to view and adjust their consumption patterns [9]. Smart Meters help analyze overload patterns and lower the extent of the outages [1].

Delays in communications for real time power consumption values for microgrid topologies is critical under the islanded operation mode. Delays may result in inefficiencies in the power supply from the microgrids. Implications of heavy demands on the grid include transformer overloading and non-regulated / unexpected loads on distribution lines. Furthermore, insufficient supply is inevitable in the case of non-regulated and consistently high power consumption as transformer overloading and exceeded conductor capacities could be expected. While dynamic demand response is a widely investigated topic on the power grid, dynamic control of a microgrid to switch between the islanded and non-islanded modes is crucial [10]. To this end, achieving low latency in communicating heavy demands is critical particularly in maintaining service quality and resiliency targets for community microgrids [11].

In this study, we analyze the smart microgrid data aggregation and classify the power consumption data according to delay sensitivity. We cluster the data with an unsupervised clustering algorithm into Time Sensitive, Moderate Sensitive and Delay Tolerant categories according to consumption and time-of-use schemes to achieve lower delay rates for the time sensitive and moderately sensitive messages. We finally evaluate the delay tolerance cost model. We find that by prioritizing consumption data according to delay sensitivity helps microgrid remain operational during islanded mode.

The rest of the paper is organized as follows. Section II presents the previous and related work. In Section III, the proposed model is presented in detail whereas Section IV presents numerical results and discussions. Finally, the paper is concluded in Section V alongside future directions.

II. RELATED WORK

The closest study to this paper investigated delay sensitivity and traffic prioritization aspects of smart microgrid technologies by a framework for microgrids using wireless heterogeneous networks [8]. According to that study, aggregated data is clustered and prioritized on the basis of sensitivity. The study highlights the criticality of the data delivery for the packets of sensitive class to be identified, queued and processed ahead of other data.

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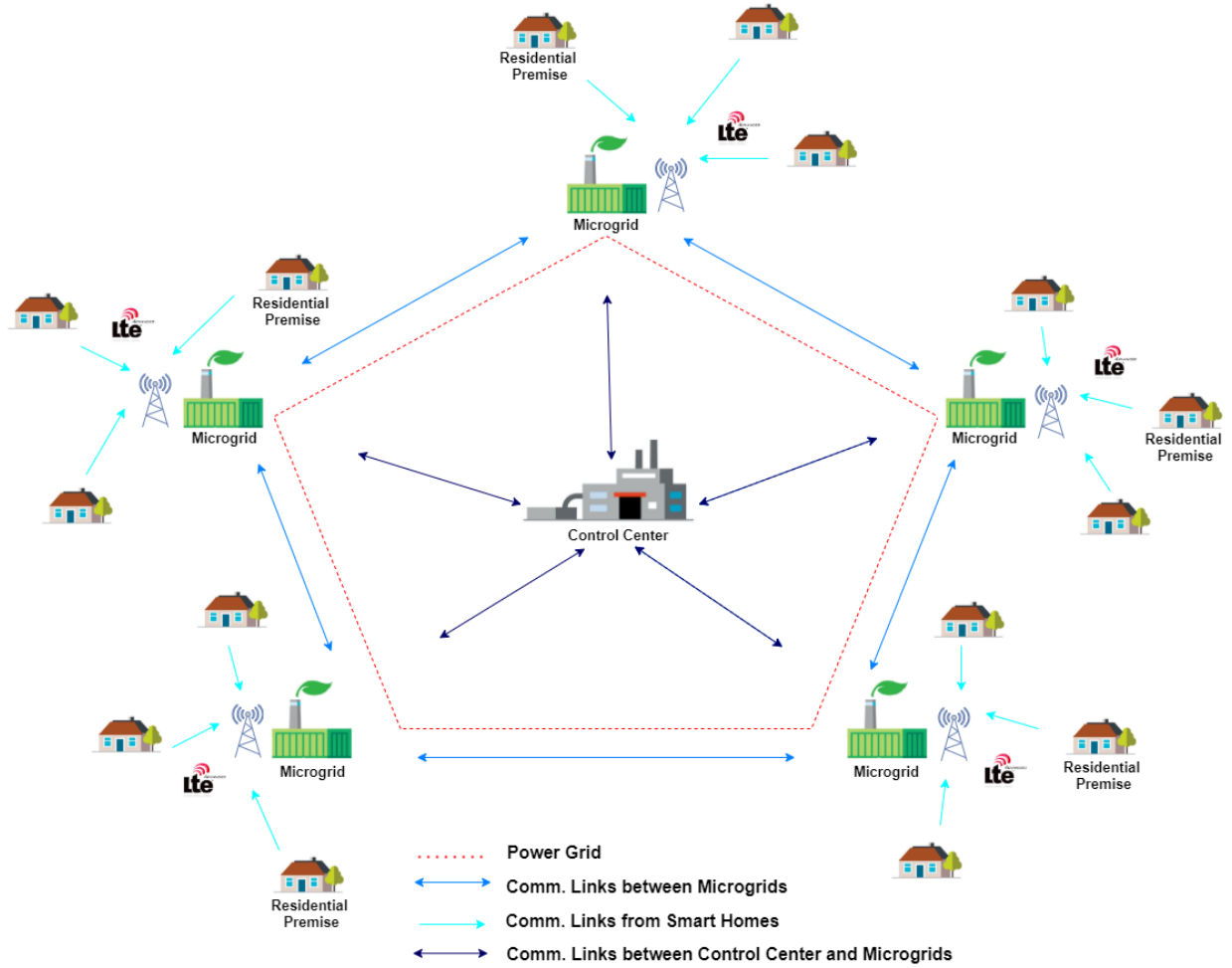


Fig. 1: Communication infrastructure

Similarly, the authors in [12] analyze the consequences of data transmission delays when microgrids switch to islanded mode due to power quality losses and costs. In light of these, the study proposes a queuing model for clustered electrical power data for faster processing of prioritized data packets by avoiding delays.

Islanded mode microgrids need to be able to keep their communications with control centers and other microgrids to maintain their power performance levels stable. The study in [13] analyzes the impacts of communication delays of an islanded microgrid. To this end, the authors introduce a small-signal model to find delay limits where a microgrid can maintain stability in operations.

III. PROPOSED METHODOLOGY

In this section, we explain the proposed methodology which builds on power consumption and time of use-based clustering for microgrid data aggregation. We analyze the optimization models where we evaluate the clustered data according to delay sensitivity and data transfer latency performance with LTE and LTE+ Networks. General concept is illustrated in Fig. 1. The microgrids are connected to the main grid topology where they can communicate with the control center and among each other.

Smart Power Meters generate consumption data at minute granularity that require real time communicated across the microgrids and the control center. Fig.2 presents the workflow for both models.

A. Delay Sensitive Data Aggregation

Following upon data collection from smart meters, an unsupervised machine learning algorithm (which is K-Means in this study) is leveraged to cluster the data under k priority clusters. A widely known model, K-Means aim to form regular shaped k clusters with respect to a distance metric by running multiple iterations [14]. Under both models, we set k to 3, to cluster the data into three delay sensitivity labels. We introduce 2 models for Delay Sensitivity: Model 1 (Fig.2(a)) is referred to as the unsupervised learning-backed whereas Model 2 (Fig.2(b)) is referred to as time of use-driven and clustering-backed. Both schemes aim to classify the consumption data into 3 delay sensitivity segments according to importance for stability of microgrids.

1) *Unsupervised Learning-backed Delay Sensitivity:* In this part of the clustering, we use consumption values per hour to apply K-means algorithm. The clustering output in Fig.3 is used to add a label to each data point a value between 1 and 3 where 1 is the high consumption cluster labeled as

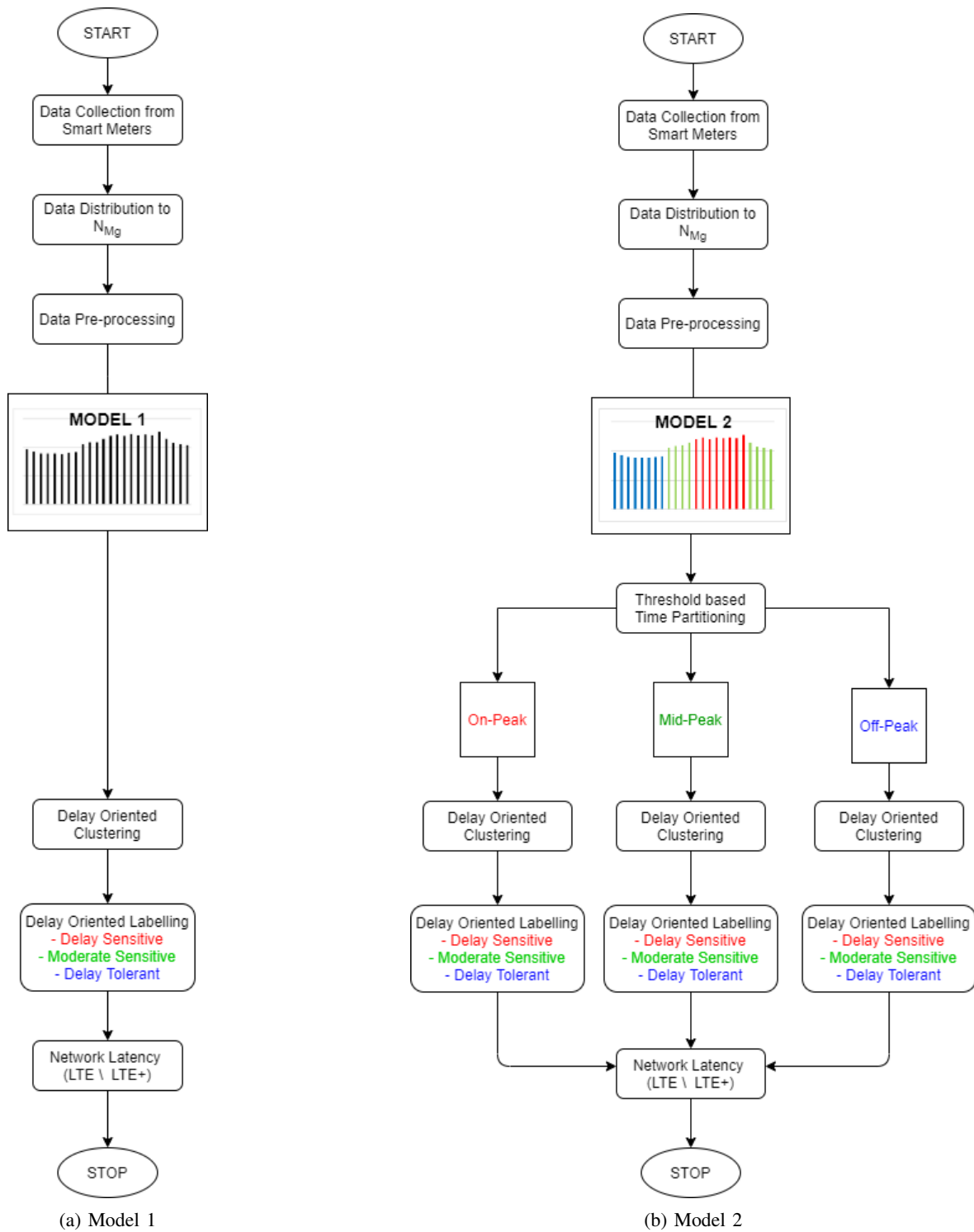


Fig. 2: Model Flow Charts

delay sensitive, 2 is the medium consumption cluster named moderate sensitive and 3 are called the delay tolerant where the consumption values are the expected regular consumption values. The outputs are then analyzed by microgrid assignments to check their delay implications on microgrids.

2) *Time of Use Based Delay sensitivity*: The consumption data is divided into 3 parts by following the Hydro Ottawa's definition for time of use intervals [15]. To label the data,

we define thresholds according to total consumption per hour. Once the threshold values are set, data is labeled according to the calculations in (1). The highest consumption values recorded between 1 PM and 8 PM labeled as high peak, mid-peak from 9 AM-1 PM and from 9 PM-midnight whereas the period between midnight until 8 AM is referred to as off peak.

TABLE I: Notations used in the paper

Notations	Definition
Mg_i	Microgrid i
$X(t')$	Consumption value at t' minutes
$X(t)$	Consumption value at t hours
D	Delay Latency Value
k	Delay Sensitivity Clusters
$\Delta_{Total-LTE}$	Total Delay Cost for LTE Network
$\Delta_{Total-LTE+}$	Total Delay Cost for LTE+ Network

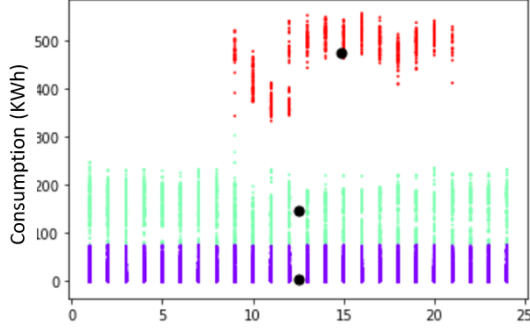


Fig. 3: K-Means Result of Model 1

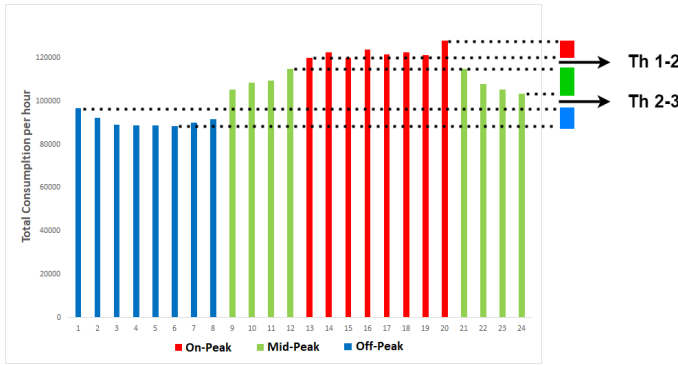


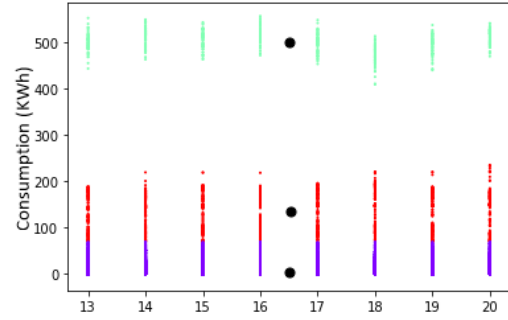
Fig. 4: Peak Time Prioritization Thresholds

$$\tau = \begin{cases} \text{HighPeak} & X(t) > Th_{1-2} \\ \text{MidPeak} & Th_{1-2} > X(t) > Th_{2-3} \\ \text{OffPeak} & Th_{2-3} > X(t) \end{cases} \quad (1)$$

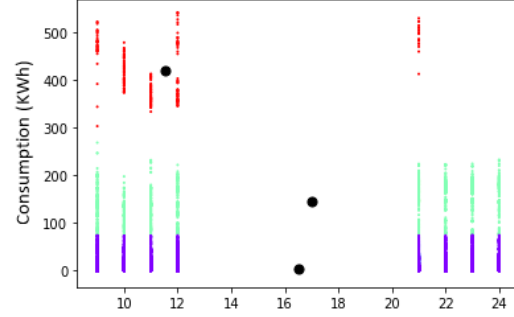
$t = 1, 2, 3, \dots, 24$

Once the data are labeled with time of use feature, we apply k-means algorithm to cluster each peak time segment. This differences between Model 2 and Model 1 are explained in Section III-A1. The data is labeled by the results in Fig.5 with their delay tolerance levels using the following values: delay sensitive, moderate sensitive and delay tolerant.

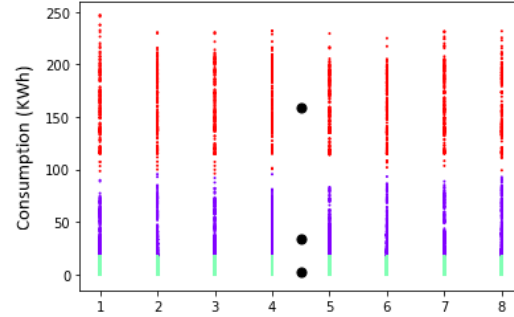
In Model 2, similar consumption values are clustered in the same group through unsupervised learning in light of the ToU features leading to each group having its own delay sensitive data different than Model 1 (see Section III-A1). Consequently, the ToU-driven approach deems Model 2 to be more realistic in taking its course on delay-sensitive clustering.



(a) On-Peak



(b) Mid-Peak



(c) Off-Peak

Fig. 5: K-Means Results of Model 2

TABLE II: Delay values per medium

Notations	Value
D_{DS-LTE}	0.005 Seconds
D_{DM-LTE}	0.05 Seconds
D_{DT-LTE}	0.1 Seconds
$D_{DS-LTE+}$	0.005 Seconds
$D_{DM-LTE+}$	0.01 Seconds
$D_{DT-LTE+}$	0.05 Seconds

B. Network Delay Cost Calculation

The network delay cost is calculated by multiplying the total delay cost for each difference between 2 models of the delay sensitivity level. There are different levels of latency values under LTE and LTE+ networks for each delay sensitivity level as reported in Table II.

The delay cost is calculated for the delay tolerance levels and the number of respective delay sensitive data sent to microgrids in each communication medium. The following calculations pave the way to determine the delay costs.

Total delay cost of each sensitivity level for LTE and LTE+

settings are calculated in the order of equations (2), (3), (4), (5) where the notations can be seen at Table I:

$$\Delta_{k-LTE} = (\{N_k\}_{M_2} - \{N_k\}_{M_1}) * D_{k-LTE}, \quad \forall k \in \{DS, DM, DT\} \quad (2)$$

$$\Delta_{Total-LTE} = \sum_k \Delta_{k-LTE}, \quad k \in \{DT, MD, DS\} \quad (3)$$

$$\Delta_{k-LTE+} = (\{N_k\}_{M_2} - \{N_k\}_{M_1}) * D_{k-LTE+}, \quad \forall k \in \{DS, DM, DT\} \quad (4)$$

$$\Delta_{Total-LTE+} = \sum_k \Delta_{k-LTE+}, \quad k \in \{DT, MD, DS\} \quad (5)$$

The total delay cost for LTE is received by adding all total delay cost values received from each delay component as in (3) and (5) for LTE and LTE+, respectively.

IV. PERFORMANCE EVALUATION

A. Dataset and Pre-Processing

Consumption information in this study is taken from UMass Smart Dataset [16] where electric consumption data is collected for 24-hour period from 443 different houses. Data is aggregated for every minute of a one day cycle. In the raw data, the consumption is given in KW and time is stamped with Unix time format. The Unix time format is converted to regular 24 hour basis and each data entry per minute is labeled from 1 to 1400 minutes, which represents each minute in a 24 hour day. With pre-processing, the houses which have zero consumption during the whole period are dropped and the data is reduced to 395 houses. Each aggregated consumption data is tagged with its corresponded house IDs labeled from 1 to 395, which are then distributed among 5 microgrids Mg_i where $i = 1$ to 5, equally for power resource assignment. Each microgrid distributes energy to 79 residential premises respectively.

B. Performance Results

Labeled data is first considered for both cases of the clustering models among the Microgrids the residential premises are connected to separately. The delay oriented data is evaluated with relevant latency values according to their delay sensitivity values in Table III.

TABLE III: Comparison of Aggregated Data among 2 Models

Priority	Period	Delay Sensitivity	Number of Measurements
1	All	Time Sensitive	713
2		Moderate Sensitive	5387
3		Delay Tolerant	562700
1	On-Peak	Time Sensitive	2473
2	Mid-Peak	Moderate Sensitive	8393
3	Off-Peak	Delay Tolerant	557934

In this model, all time sensitive consumption data is coming from residential units that are connected to Mg_4 . (Table IV) Moderate data is spread between Mg_1 , Mg_4 , and Mg_5 where the other two microgrids hold no delay sensitive data. The rest of the consumption data are labeled delay tolerant which are

normal daily usage values scattered among all the microgrids. The results in Fig.7 show that the data sent from premises receiving power from Mg_4 are at risk if the sensitive data are not sent on time which can cause improper planning and power starvation at the microgrid under the islanded mode.

TABLE IV: Time Sensitivity per Microgrid for Model 1

Time Sensitivity	Mg 1	Mg 2	Mg 3	Mg 4	Mg 5
Time Sensitive	-	-	-	713	-
Moderate Sensitive	1880	-	-	2496	11
Delay Tolerant	110880	113760	113760	110551	113749

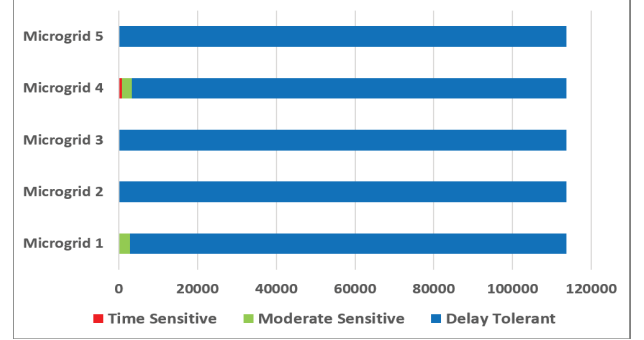


Fig. 6: Consumption per microgrid for Model 1

When data are analyzed for the ToU-based model, (Table V) both Mg_1 and Mg_4 have time sensitive consumption values, where all microgrids (including these two) face moderate sensitive usage. Majority of the data is of regular use which are delay tolerant and will not interfere with the regular operation of the microgrids. Fig. 6 shows that all microgrids are at risk of going into power off modes if the demand cannot be met by the stored resources under the islanded mode.

TABLE V: Time Sensitivity per Microgrid for Model 2

Time Sensitivity	Mg 1	Mg 2	Mg 3	Mg 4	Mg 5
Time Sensitive	1209	-	-	1264	-
Moderate Sensitive	1197	36	1455	3771	1934
Delay Tolerant	111354	113724	112305	108725	111826

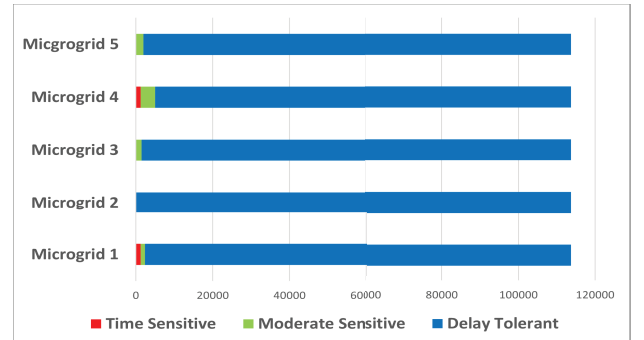


Fig. 7: Consumption per microgrid for Model 2

Table VI presents the delay costs for our proposed scheme under LTE and LTE+. In total, the results show higher delay costs when LTE is used. Fig.8 illustrates the cost differences between each medium. The time sensitive data costs are equal under both LTE and LTE+; however, LTE+ outperforms LTE

TABLE VI: Delay Cost Results

Period	Time Sensitivity	Model 2	Model 1	Δ	Δ LTE	Δ LTE +
On-Peak	Time Sensitive	2473	713	%247	8.8	8.8
MidPeak	Moderate Sens.	8393	5387	%56	150.3	30.06
Off-Peak	Delay Tolerant	557934	562700	-0.8%	-476.6	-238.3
				Total:	-317.5	-199.44

for moderate sensitive and delay tolerant data due to the increased speed and less latency commitment. The amount of daily time sensitive and moderate sensitive data rates are not high compared to delay tolerant data points. On the other hand, even one delayed high consumption time sensitive packet can cause damage to the operations of an islanded mode microgrid if the consumption needs cannot be met.

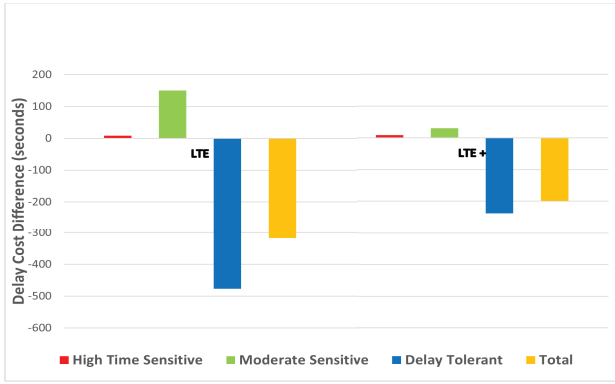


Fig. 8: Delay cost comparison of LTE and LTE+ networks over Microgrid Data in seconds

Model 1 results in delay sensitive data cluster only between 9 AM and 9 PM where the consumption is the highest as shown in Fig. 3. On the other hand, under Model 2, 247% increase in time sensitive data and 56% increase in moderately time sensitive data is obtained as also presented in Table VI. This phenomenon is due to clustering after setting peak time thresholds where all time sensitive data within the 24 hour period gets under consideration. Thus, the delay sensitive consumption values under Model 2 are more realistic while also reducing total delay costs by 317.5 and 199.4 seconds under LTE and LTE+ links, respectively. Under Model 2, the microgrids lead to high consumption values with shorter delays, thus improving operations in the islanded mode and responding to the switching decisions as needed.

V. CONCLUSION

Microgrids can handle certain amounts of power distribution under islanded mode and communication delays on heavy demands may cause a microgrid to drain its energy resources. In this paper, Time of Use-driven clustering is applied to three time periods (On-Peak, Mid-Peak, and Off-Peak) depending on time-based consumption in Model 2 instead of clustering the whole time period in Model 1. Thus, delay sensitive data in limited time period can be enlarged to the entire time window of observation. Each time period of Time of Use-driven clustering can emerge new time delay sensitive patterns in terms of peak consumption values under each time period. Numerical results demonstrate that 247% larger time sensitive

data patterns and 56% larger moderately time sensitive patterns are obtained by the proposed Model 2 when compared to Model 1. The total communication delay of critical microgrid data packages under Model 2 are decreased up to 317.5 and 199.4 seconds for LTE and LTE+ according to Model 1, respectively. Since delay sensitive data are critical for healthy operations of smart microgrids, anticipation of compromising behaviour against this aggregation strategy is being considered in our on going agenda.

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