Quantifying the Effects of Communication Network Performance in Vehicle-to-Grid Frequency Regulation Services

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***Abstract*—Recent advances in communication systems and the proliferation of plug-in electric vehicles (PEVs) hold a promise to support power systems operations with vehicle-to-grid (V2G) applications. However, such ancillary services have tight communication requirements (low-latency, high reliability) as the aggregated PEVs need to respond to market signals within seconds and bad communication system performance lead to financial losses. In this paper, we consider a frequency regulation application in which PEVs are charged and discharged according to actual market signals. We assume that a market operator sends signals through 4G/LTE network to an aggregator located at a parking lot, who, as a next step, delivers data packets to electric vehicle supply equipments (EVSEs) via a local Wi-Fi network. In the final phase, each EVSE communicates with PEV battery management unit via power line communications. By adopting communication delay and packet loss profiles from measurement and simulation studies, we examine the impacts of communication system performance on V2G performance. The results show that packet losses significantly lowers precision score, while there is a need for faster networks if multiple aggregators participate at the same time.**

***Index Terms*—vehice-to-grid (V2G), network performance modeling, electric vehicles, smart grid**

I. INTRODUCTION

The United Kingdom and other major economies are transforming their electricity systems to achieve net-zero goals by promoting renewables and plug-in electric vehicles (PEVs). The increasing shares of distributed generation resources and decommissioning of thermal power plants inherently contributes to a reduction in power system inertia which comes from the rotating mass of synchronous machines [1]. As a result, power grids become more vulnerable to small scale disturbances and there is an urgent need to make a step change to introduce new products and services that proactively involve demand-side flexibility for balancing services [2].

Recently, the notion of using large-scale energy storage units to replace thermal power plants has gained popularity [3]. Similarly, PEVs can join ancillary services markets to provide a buffer zone when there is a supply-demand mismatch. In a typical V2G session, each PEV responds to market signals by charging or discharging its battery according to the needs of the grid [4]. On the other hand, two major challenges exist: (i) due to the minimum power requirement of service contracts (MW-scale), only the aggregation of vehicles can furnish enough resources [5]; and (ii) underlying communication network needs to facilitate bi-directional energy transfer within seconds to meet market deadlines (presented in Table I). If, due to communication system delays or packet losses, the market deadline is not met, both the grid operator and the PEVs face financial losses. In this paper, we present a case study in which PEVs located in a parking lot responds to market signals obtained from PJM [6]. Market operator communicates with an aggregator through 4G/LTE network. Inside the charging lot, an aggregator employs a Wi-Fi network to collect data from each electric vehicle supply equipment (EVSE) about the availability of each PEV. Finally, EVSE uses power line communications (PLC) to interact with PEV's battery management system. By using previous measurement and simulation studies, we quantify the impacts of the communication network performance (delays, packet losses) on the precision of frequency regulation event.

TABLE I
EXAMPLES OF NEW ANCILLARY SERVICES AND ASSOCIATED REQUIREMENTS [7].

Region	Power Req.	Response Speed	Duration
Ireland	1-5 MW	2 sec	Duration
UK	1-50MW	1 sec	15 min
PJM	0.1+MW	2 sec	Until Sust.
Australia	N/A	0.5-1sec	6 sec

Recently, there has been an increasing body of literature on PEV market participation and bidding strategy and communication and security of aspects of V2G systems. In [8], the availability and reliability of PEVs as ancillary services providers in the presence of aggregators is investigated. In [9] a bidding strategy in California's ancillary services market is implemented with 30 PEVs. Bidding coordination is further examined in [10] and [11], however, the performance of the communication system is not taken into account. The work presented in [12] is closest to our study, in which authors assume an imperfect communication network and quantified the impacts of delays in ancillary services. However, in the presented model, market operator directly communicates with each EVSE, and corollary, when the number of PEVs increases, the communication congestion leads to long delays.

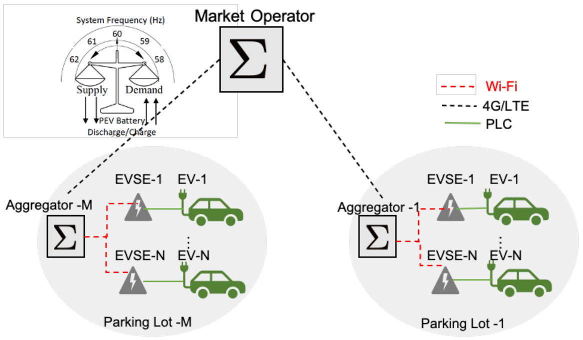

Fig. 1. Vehicle to grid and communication systems overview.

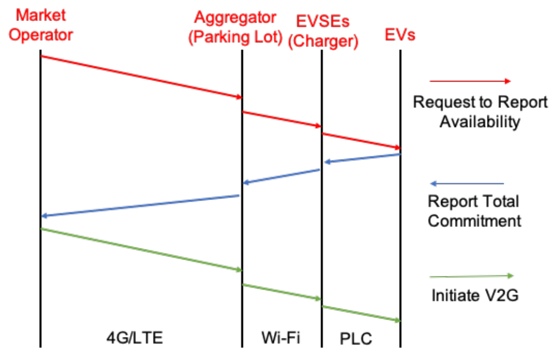

Fig. 2. Message exchange for V2G session.

In [13] and [14], a simulation studies are presented to measure the performance of wired and wireless communication technologies inside a relatively smaller PEV parking lot. In [15], performance assessment study was carried out by utilizing one of the UK's major wireless carriers. In this study, data packages of various sizes are delivered from a server to client located at different locations in the city of Edinburgh. Finally, PEVs demand can be coordinated to tackle issues like "Duck Curves" in regions with high solar energy penetration [16].

II. SYSTEM OVERVIEW

A. *Communication Infrastructure Outline*

In this paper, the following communication infrastructure is assumed. First, a number of PEVs are assumed to be stationary at a parking lot connected to an electric vehicle service equipment (EVSE) via standard level 2 chargers ([17], [18]). Each vehicle's battery management system communicates with the corresponding EVSE via standard power-line communication protocols such as ECHELON or MAXIM (see [19]). Second, an aggregator located at each charging station communicates with each EVSE via a local area communication solution such as Wi-Fi or ethernet ([14] and [13]). Due to its cost-effectiveness, we assumed that Wi-Fi is deployed to facilitate communications between EVSE and aggregators. Third, a wireless wide area network is needed to exchange information between aggregators and market operators. For this case, we assume that there exists a 4G network as described in [15]. System overview is depicted in Fig. 1.

B. *V2G Communication Messages*

To facilitate energy transfer between PEVs and the grid in a timely and reliable manner, the following messages are assumed to be exchanged between the concerned entities. As shown in Fig. 2, market operator sends a message to the aggregator located at the parking lot to gather information about PEV's availability to participate in an upcoming V2G session. Next, each aggregator forwards this message to each EVSE. It is noteworthy that, market operator could communicate directly with each EVSE. However, as reported in [12], reaching out with hundreds of EVSEs would lead to excessive delays due to limited wireless channel resources and collision of packages. Next, each EVSE reports its status back to aggregator which is consolidated and send back to market operator. As a final step, market operator processes gathered information and send the final signal to initiate V2G energy session.

C. *Communication System Performance*

In this paper, communication system performance is measured by two metrics, namely average end-to-end communication delays and packet loss ratios. In V2G regulation sessions, grid operators sends a series of signals (e.g., charger or discharge) to participants. If communication delays are long, aggregators would take inaccurate action. Similarly, if regulation signals are lost during the transmission, then no action would be taken. For the aforementioned performance metrics, we use published results obtained from measurement and simulation studies as follows:

1) Market Operator to Aggregator: As described above, market operator sends frequency regulation signals using wireless communication network such as 4G/LTE. In [15], the performance of 4G/LTE network in the United Kingdom was analysed. End-to-end delay and packet loss measurements were conducted for various packet sizes (from 50 bytes to 2000 Bytes), different signal strength levels (weak (-118 dBm), medium (-105 dBm), and strong (-69 dBm)), and both for user datagram protocol (UDP) and transmission control protocol (TCP). According a related simulation study [13], the typical amount of information would be around 1-1.5KB and composed of data for voltage, current, station ID, Charger ID, meter status, etc. Moreover, similar to [12], UDP is used as the transport protocol transmit frequency regulation messages. In Table II, average one way delay for each signal strength level is presented. Furthermore, packet losses for UDP is measured as 5.35% for strong signal, 6.8783% for medium signal, and 8.06% for poor signal cases.

2) Aggregator to EVSEs: Inside the parking lot, aggregator can communicate with EVSEs via either wired communications such as ethernet (IEEE 802.3 10 or 100 Mbps) or wireless options such as Wi-Fi (IEEE 802.11 54 Mbps). In [13], communication network (Wi-Fi and ethernet) inside a PEV parking lot is simulated using OPNET. It is noteworthy that even though ethernet-based communications provide low-

TABLE II
AVERAGE ONE-WAY DELAY (MS) PERFORMANCE.

Wide Area (4G/LTE) [15]			**Local Area [13]**		**Charger [19]**
Strong S.[1]	Medium S.	Poor S.	Ethernet	Wi-Fi	PLC[2]
245	286	329	3.34	95.1	65

[1] Simulation results for 40 PEVs. For Wi-Fi case, it is assumed that there is one access point for every 40 PEVs. Ethernet speed is 100 Mbps, Wi-Fi speed is 54 Mbps.

[2] Results for Maxim 220 VAC, J1772 standard.

latency connectivity Wi-Fi networks are commonly used due to lower capital cost. In this study, we assume Wi-Fi is used inside the parking lot with the delay measurements presented Table II.

3) EVSE to PEV: Contrary to previous communication parts, there have been efforts towards the standardisation of EVSE to PEV communications. Some standard initiatives include the Society of Automobile Engineers (SAE), and International Standards Organisation and International Electrotechnical Commission (ISO/IEC). In this paper, we consider standards defined in SAE J2836/1 and J2847.1 which uses J1772 connectors [17] and power line communications [19]. In [19], both the Echelon PL3170 and the MAX2990 power line carrier modules were tested. Due to its superior performance in communication delays, we assumed that each EVSE uses MAXIM 220 VAC (J1772) technology. In this case, the average communication delay becomes 65 ms as shown in Table II. It is noteworthy that presented communication scheme does not include delays related to processing of received data at each node (e.g., aggregator etc.). However, such delays are usually in the order of microseconds and excluded in the calculations [12].

III. CASE STUDIES

To quantify the impacts of underlying communication system performance, we consider actual frequency regulation signals in PJM region which is one of the major regional balancing authority in the United States [6]. We use sample dataset from the University of Delaware's V2G toolbox [20] which was recorded during V2G operations in April 2013. The regulation signal shows the power charge or discharge levels and normalised to the range of -1 (10kW vehicle to grid) and +1 (10kW grid to vehicle).

As a first evaluation, we examine how communication delays impact the regulation signals. It is assumed that market operator sends signals at each second and the aggregator responds after the message exchange is completed. In Fig. 3, impacts of communication system delays are depicted and the difference between instructed and executed signals are shown. It is noteworthy when the variability in the instruction signals increase, the executed signal differs more often.

Next, this difference in executed and instructed signals are quantified in terms of percentage of error. Recall that errors occur due to delays and packet losses. When the latter one occurs, it is assumed that the previous action is repeated (alternatively no action would be taken). In Fig. 4, errors that are lower than 20% typically due to communication delays while larger scale errors occur because of UDP packet losses. Notice that if the station participation is around 1 MW, the typical error due to delays is around 200 kW or less, while this value could go up to MW-scale due to packet losses. If multiple stations participate at the same V2G sessions, then mismatch would be exponentially grow.

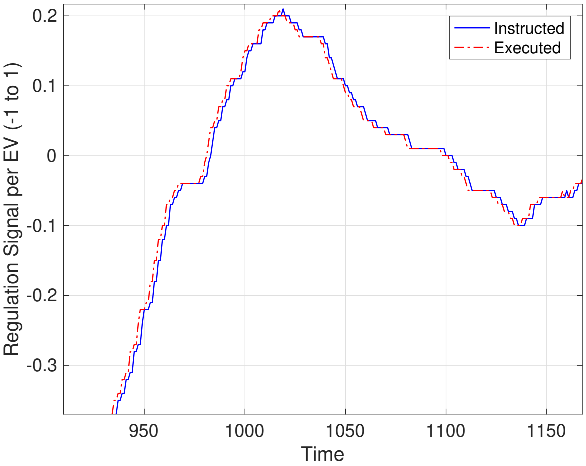

Fig. 3. Impacts of communication delay performance on frequency regulation market signals.

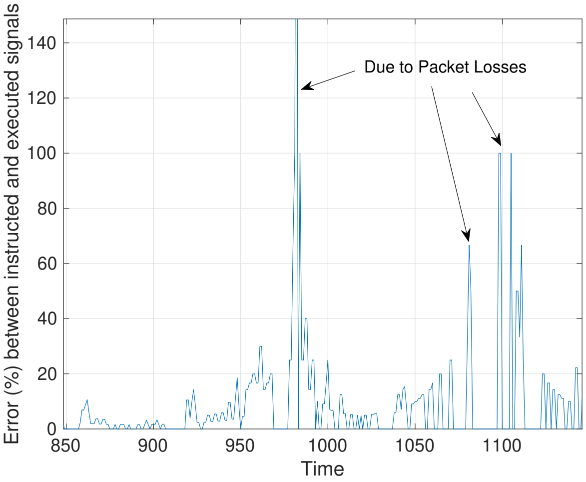

Fig. 4. Percentage of error in executed signal with respect to instructed signal.

As a last evaluation, we calculate the precision score metric (P_S) which is used to measure how accurately the aggregators respond. If a minimum score is not met, then no payment is due. Above the minimum threshold, payment is proportional to the precision score. In PJM markets, precision score P_S is calculated based on the following formula:

$$P_S = 1 - \frac{1}{N} \sum_{i=1}^{N} \left| \frac{I[i] - R[i]}{C} \right|,$$

where N is the total number of signals during a V2G session, C shows the average absolute values of instructed signals, $I[i]$ is the $i^{\rm th}$ instruction and $R[i]$ is the corresponding execution. Note that if the instructed and executed signals are the same ($I[i] = R[i], \ \forall i$), then precision would be 1 (or 100%). In Fig 5, we present the precision score for each signal strength levels. Since packet losses can occur randomly throughout the V2G session, we run calculations for 100 times to capture the randomness in packet losses and present average precision scores. It can be observed that precision score increases with lower packet losses. The results further indicate there there is a need for communication infrastructure that can support lower latency and higher accuracy data delivery.

IV. CONCLUSIONS

In this paper, we quantified the impacts of communication systems in a typical vehicle to grid application. We assumed that, as a first step, a market operator sends signals via a 4G/LTE network to an aggregator located at a parking lot. Second, the aggregator disseminates messages to each EVSE to gather information about their availability. For the second case, we assumed that Wi-Fi (IEEE 802.11) was used as the local area network. Last, each EVSE communicates with PEV's battery management unit via existing PLC technologies. For the described communication system, we calculated end-to-end delays and packet loss rations using data from related literature. Case studies were carried out by using actual market signals from PJM and we showed that the impacts of packet losses significantly lowers the accuracy of the V2G session measured by precision score. The impacts of communication delays, on the other hand, depends on variability of market signals and signal execution deadlines. The proposed network performs well for 2 second deadline, however, faster communications are needed for tighter market deadlines. As a future work, we will consider TCP as the transport protocol and consider different local area network technologies for EVSEs to aggregator communications. Furthermore, we will investigate different market signals and deadlines.

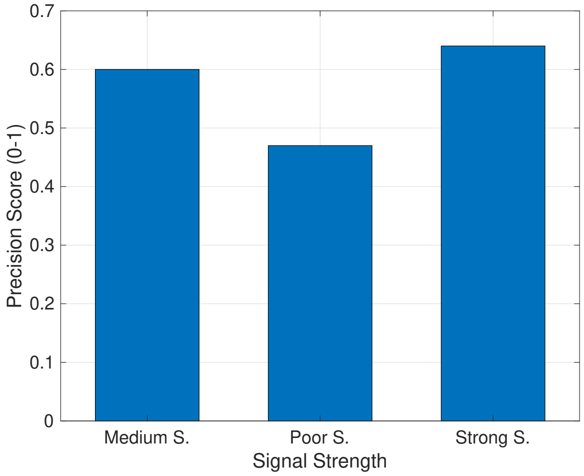

Fig. 5. Precision score for different signal levels.

REFERENCES

[1] H. Beltran, S. Harrison, A. Egea-Àlvarez, and L. Xu, "Techno-economic assessment of energy storage technologies for inertia response and frequency support from wind farms," *Energies*, vol. 13, no. 13, p. 3421, 2020.

[2] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renewable and sustainable energy reviews*, vol. 69, pp. 144–155, 2017.

[3] T. Xu, W. Jang, and T. Overbye, "Commitment of fast-responding storage devices to mimic inertia for the enhancement of primary frequency response," *IEEE Trans. on Power Systems*, vol. 33, no. 2, pp. 1219–1230, 2017.

[4] S. Han, S. Han, and K. Sezaki, "Development of an optimal vehicle-to-grid aggregator for frequency regulation," *IEEE Trans. on smart grid*, vol. 1, no. 1, pp. 65–72, 2010.

[5] D. M. Steward, "Critical elements of vehicle-to-grid (v2g) economics," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2017.

[6] Pjm regulation market. [Online]. Available: https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market/regulation-market.aspx

[7] L. Meng, J. Zafar, S. K. Khadem, A. Collinson, K. C. Murchie, F. Coffele, and G. M. Burt, "Fast frequency response from energy storage systems-a review of grid standards, projects and technical issues," *IEEE Trans. on Smart Grid*, vol. 11, no. 2, pp. 1566–1581, 2019.

[8] C. Quinn, D. Zimmerle, and T. H. Bradley, "The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services," *Journal of Power Sources*, vol. 195, no. 5, pp. 1500–1509, 2010.

[9] N. DeForest, J. S. MacDonald, and D. R. Black, "Day ahead optimization of an electric vehicle fleet providing ancillary services in the los angeles air force base vehicle-to-grid demonstration," *Applied energy*, vol. 210, pp. 987–1001, 2018.

[10] M. Ansari, A. T. Al-Awami, E. Sortomme, and M. Abido, "Coordinated bidding of ancillary services for vehicle-to-grid using fuzzy optimization," *IEEE Trans. on Smart Grid*, vol. 6, no. 1, pp. 261–270, 2014.

[11] J. Donadee and M. D. Ilić, "Stochastic optimization of grid to vehicle frequency regulation capacity bids," *IEEE Trans. on Smart Grid*, vol. 5, no. 2, pp. 1061–1069, 2014.

[12] K. Ko and D. K. Sung, "The effect of cellular network-based communication delays in an ev aggregator's domain on frequency regulation service," *IEEE Trans. on Smart Grid*, vol. 10, no. 1, pp. 65–73, 2017.

[13] M. A. Ahmed, M. R. El-Sharkawy, and Y.-C. Kim, "Remote monitoring of electric vehicle charging stations in smart campus parking lot," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 1, pp. 124–132, 2019.

[14] M. A. Ahmed and Y.-C. Kim, "Performance analysis of communication networks for ev charging stations in residential grid," in *Proceedings of the 6th ACM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications*, 2017, pp. 63–70.

[15] M. Zeinali, I. S. Bayram, and J. Thompson, "Performance assessment of uk's cellular network for vehicle to grid energy trading: Opportunities for 5g and beyond," in *IEEE International Communications Conference*, 2020.

[16] I. S. Bayram, F. Saffouri, and M. Koc, "Generation, analysis, and applications of high resolution electricity load profiles in qatar," *Journal of Cleaner Production*, vol. 183, pp. 527–543, 2018.

[17] I. S. Bayram and I. Papapanagiotou, "A survey on communication technologies and requirements for internet of electric vehicles," *EURASIP Journal on Wireless Communications and Networking*, vol. 2014, no. 1, p. 223, 2014.

[18] C. Kong, I. S. Bayram, and M. Devetsikiotis, "Revenue optimization frameworks for multi-class pev charging stations," *IEEE Access*, vol. 3, pp. 2140–2150, 2015.

[19] R. Pratt, F. Tuffner, and K. Gowri, "Roadmap for testing and validation of electric vehicle communication standards," *World Electric Vehicle Journal*, vol. 5, no. 4, pp. 1025–1033, 2012.

[20] University of delaware v2g toolbox. [Online]. Available: http://www1.udel.edu/V2G/Tools.html