1 Vehicle-to-grid systems: ancillary services and communications

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1.1 Introduction

Recent studies have shown that about 70% of the total oil extracted worldwide is consumed in the transportation sector [1]. With rising oil prices, USA and many other countries have set long-term plans to electrify their transportation system and manufacture electric vehicles (EVs) to reduce their oil consumption. It is foreseen that by 2013, approximately 700,000 grid-enabled electric vehicles will be on the road in USA. The expected trend in the automotive market share for EVs is shown in Figure 1.1 [2]. A large number of EVs can not only help to reduce the amount of oil and gas consumption but also provide great opportunities for the power grid, as the batteries of millions of EVs can be used to boost *distributed electricity storage*. Depending on the type and class, the battery storage capacity for an existing EV varies from 1.8 kW [3] to 17 kW [4, 5]. Note that, currently, the only major electricity storage unit in most power grids are the pumped storage systems [6].

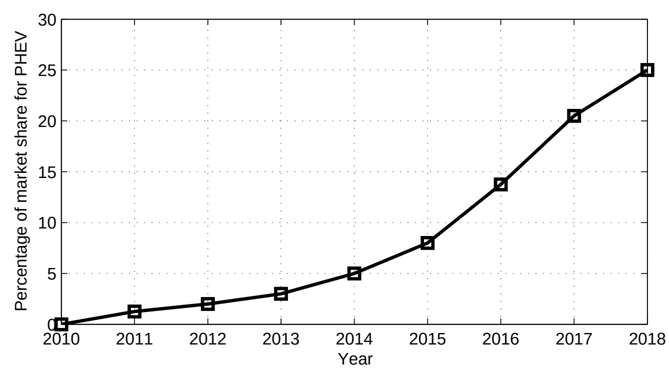

Figure 1.1 Expected increase in market share for electric vehicles in the USA.

In general, the EVs have the capability to work in two main modes of operation: *stand-alone mode* and *grid-connected mode* [7]. These two modes and their transition cycles are shown in Figure 1.2. In the stand-alone mode, the storage capacity of EVs is used as a back-up energy source at the time of electricity shortage or blackout. In addition, it helps to smooth down possible fluctuations in local renewable generation units, such as rooftop solar panels and wind turbines [8, 9, 11, 10]. In the grid-connected mode, the EV storage units can be synchronized with the grid to participate in *demand-side management* programs [12, 13] or to provide reserve power capacity and other *ancillary services* [14, 15, 16, 17] in a distributed vehicle-to-grid (V2G) infrastructure. Our focus in this chapter is on EVs' grid-connected operation mode in V2G systems.

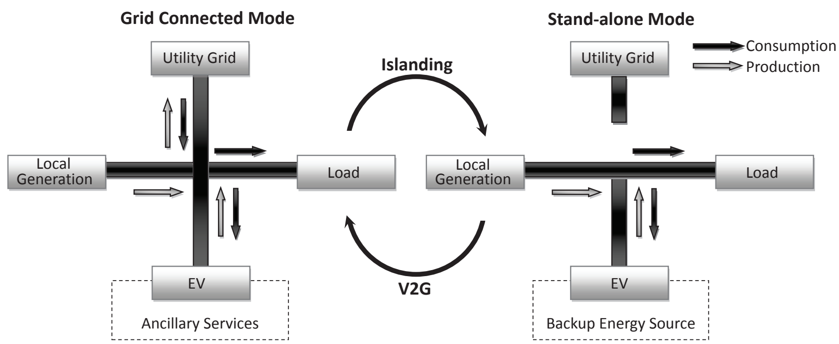

Figure 1.2 Operating modes in the future home energy systems in presence of EVs.

In order to be successful, the V2G systems require a reliable and secure communications and networking infrastructure, which enables *two-way message exchanges* among EVs and the grid operation, control, and monitoring centers [18]. The type of message exchanges and the communications technologies and architectures needed mainly depend on the ancillary services provided and the centralized and distributed management strategies to be implemented. In this chapter, we will overview such services and a variety of existing communications technologies that facilitate efficient and practical V2G systems in future smart grid systems. The rest of this chapter is organized as follows. In Section 1.2, we overview different types of ancillary services that can be offered in future V2G systems. In Section 1.3, we compare two different V2G system architectures to be implemented, by introducing EV aggregators and their different roles in V2G programs. Different communications and networking technologies to support V2G systems are discussed in Section 1.4. Research challenges and open problems are discussed in Section 1.5. The chapter is concluded in Section 1.6.

1.2 Ancillary services in V2G systems

As has been mentioned before, a key benefit of a V2G power system is to facilitate and encourage EVs participation in offering various ancillary services to the power grid through adequate communications. To start, in this section, we will overview different services that can be potentially offered in a V2G power system.

- *Reserve power supply*: A large-scale V2G system can help maintain the balance between supply and demand in power grid by injecting power. For example, by simultaneously discharging their batteries, hundreds of EVs will be able to provide the additional power required by a medium-sized factory at a certain time period, acting similar to a so-called *spinning reserve* power generation source in the existing power distribution systems [19]. While the supply capacity for each individual EV is small, a synchronized aggregated capacity can be both noticeable and manageable as we explain in Section 1.3.
- *Peak shaving*: A group of EVs can also participate in peak shaving by coordinating charging and discharging of their batteries. Note that, in general, the operation cost of a grid highly depends on the *peak-to-average* ratio (PAR) in aggregate load demand [20]. For example, as shown in Figure 1.3, there is usually at least one major peak in a daily residential load demand profile, e.g., in the afternoon. To assure reliable service, the grid generation capacity should essentially match these peak demands. Therefore, a high PAR can significantly increase the generation cost, as the grid will be highly underutilized most of the times. By charging their EV batteries at off-peak hours and discharging them at peak-hours, the EVs can significantly help reducing the PAR.

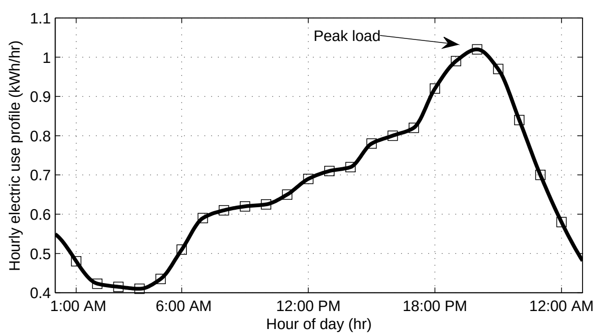

Figure 1.3 Hourly average residential load profile in Southern California [21].

Peak shaving participation can be coordinated by implementing various demand-side management (DSM) programs [12, 22, 23, 24, 25, 26, 27]. The impact of EVs on DSM programs will be significant, as the charging load of EVs is expected to *double* the average residential load in the near future [14]. Interestingly, such major load is *controllable*, as EV charging can be potentially scheduled using advanced *energy-consumption scheduling* (ECS) features in smart meters [12, 26].

- *Renewable energy integration*: Due to the stochastic and intermittent nature of solar and wind-power generation, their large scale integration into the current power grid requires large-capacity storage systems [28, 29]. Take wind power as an instance, its stochastic nature is due to the changes in wind speed, since other on-site condition changes are relatively slow [30]. For example, a recent measurement in Crosby County in Lubbock, Texas showed that the wind speed in this region can fluctuate between 2 to 12 meters per second within a few hours [29]. While a centralized control using a massive battery bank is very expensive, and thus may not always be practical, a distributed V2G power storage system can be implemented to solve this problem.

To achieve a better wind-power penetration, He et al. proposed a multiple time-scale pricing model in [31]. They considered a power grid with two types of energy sources: conventional and wind-energy sources. The conventional energy is drawn from two sources: base-load generation and peaking generation, with generation cost c_1 and c_2 per unit, respectively. Peaking generation is typically from fast-start generators (e.g., gas turbines), with a higher generation cost, and thus $c_2 > c_1$. Due to the start-up time and ramp rate of generators, the base-load generators are scheduled day-ahead for each T_1 slot of the next day, and the generation cost c_1 contains the start-up cost and other operating costs. In real-time scheduling of each T_2 slot, peaking generation and wind generation are used, as needed, to clear the balance between demand and the base-load generation. Clearly, with a distributed V2G storage system in place, the EVs can be charged in off-peak hours as a base-load and discharged at peak hours to act as an extra power source to help the peaking generator, and thus reduce the cost of power generation.

- *Regulation*: A V2G system can help to regulate frequency and voltage in a power grid. In the USA, the grid frequency needs to be maintained very close to its nominal frequency of 60Hz. Any deviation from this requires actions by the grid operator [32, 33]. If the frequency is too high, then there is too much power being generated in relation to load. Therefore, the load must be increased or the generation must be reduced to keep the system in balance. Currently, such regulation is achieved mainly by increasing power generation via turning on fast-responding generators, which is very costly. Alternatively, EVs can help by charging their batteries and increasing the load demand. On the other hand, if the frequency is too low, then there is too much load in the system and the generation must be increased or the load reduced. This can be done by terminating charging or starting discharging a number of EVs connected to the grid. Such adjustment is called frequency regulation [34, 32, 33], as shown in Figure 1.4. It is usually performed frequently, e.g., once every few seconds [28, 35]. Note that, the focus in frequency regulation is to remove *small mismatches* between supply and demand. Major load following is achieved separately via *economic dispatch* of major generators [36].

  A large group of EVs can also help the power grid to regulate voltage. In the power system operation, voltage profile is strongly correlated with *transmission and distribution system losses*. The voltage drops from the normal voltage 110 V (in the United States and Canada) when the load and consequently transmission losses increase [37]. This can cause damage to the grid equip-

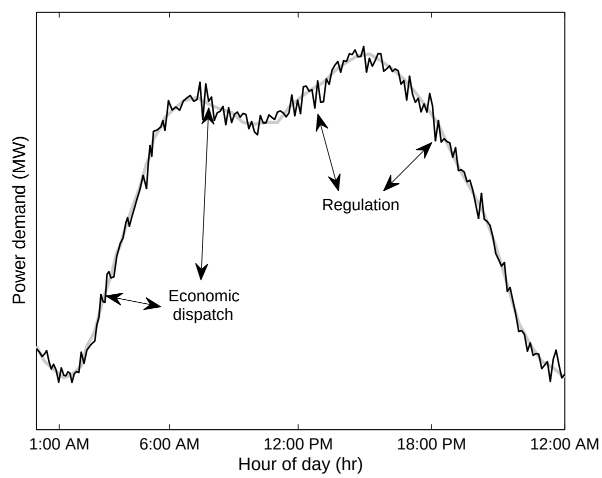

Figure 1.4 Frequency regulation by adjusting active power supply and load demand.

ments and user appliances. Voltage drops can be compensated by adjusting (injecting or consuming) *reactive power* across the power grid. Interestingly, given the right power electronics devices in place, EVs can help by changing their reactive and active power load, without any major impact on their battery life [38]. This makes reactive power compensation a very promising ancillary service in the future V2G systems [39, 40].

1.3 V2G systems architectures

Various ancillary services that we listed in Section 1.2 can be provided and managed by using either *direct* or *inderect* V2G system architectures [5], as illustrated in Figures 1.5 and 1.6, respectively. In a direct architecture, there exists a *direct line of communication* between the grid system operator and the vehicle, so that each vehicle can be treated as a deterministic resource to be commanded by the grid system operator. Under this paradigm, each vehicle is allowed to individually bid and perform services while it is at the charging station. When the vehicle leaves the charging station, the contracted payment for the previous full hours is made and the ancillary service contract is ended until the next time when the vehicle is parked and available again. The direct and thus deterministic architecture is conceptually simple, but it has recognized problems in terms of *near-term feasibility* and *long-term scalability* [5]. The challenges with direct architecture are two-fold. First, the amount of signalling and control task overhead imposed on the grid operator is significant and overwhelming, as the operator needs to directly interact with a larger number of individual EVs

[35]. As these millions of vehicles engage and disengage from the grid, the grid system operator must constantly update the contract status, connection status, power availability, state-of-charge, and driver requirements to contract the power it can command from the vehicle [5]. Second, geographically distributed nature of vehicles and their limited individual storage capacity is incompatible with the existing contracting frameworks with minimum 1 MW threshold for many ancillary services hourly contracts [19].

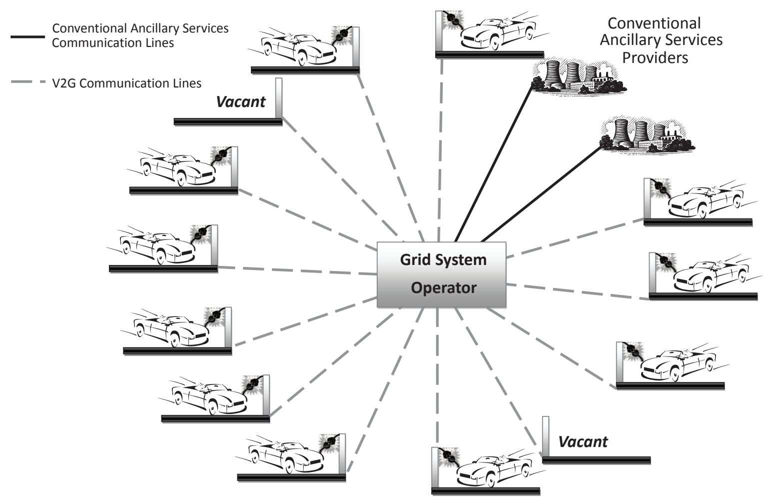

Figure 1.5 Direct V2G system architecture without using aggregators.

The alternative indirect V2G system architecture involves several aggregators as shown in Figure 1.6. In this regard, each aggregator aggregates the ancillary services provided by individual EVs to make a single controllable power resource. This architecture is indirect as aggregators are intermediate between the vehicles and the grid operator. The aggregator receives ancillary service requests from the grid system operator and issues *charging or discharging commands* to contracted vehicles that are both available and willing to perform the required services. Alternatively, the aggregator may interact with its corresponding vehicles through *smart pricing*, where the prices are set according to the grid's service requests [33]. Given an estimate of the EV participation, the aggregator can then *bid* to perform ancillary services for the power grid at any time, while the individual vehicles can engage and disengage from the aggregator as they arrive at and leave from charging stations. The individual EVs are then compensated according to, e.g., the number of minutes that they have participated in offering ancillary services. As such, this aggregative architecture attempts to address the key problems with the direct architecture that we mentioned earlier. In fact, the larger scale of the aggregated V2G power resources commanded by aggregator, the more improved reliability of aggregated V2G resources connected in parallel; this allows the grid operator to treat the aggregator just like a *conven-*

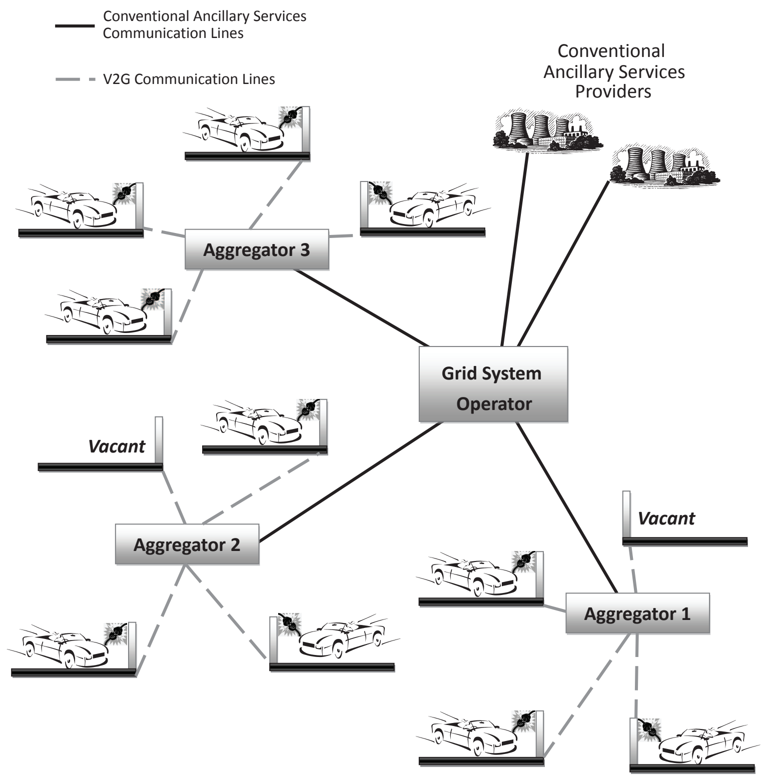

Figure 1.6 Indirect V2G system architecture involving several aggregators.

tional ancillary services provider. It means that the aggregator can utilize the same communication infrastructure for contracting and command signals that conventional ancillary services providers use, which eliminates the concern of additional communications workload placed on the grid operator [5].

1.3.1 Aggregation scenarios

The key elements in an indirect V2G system architecture are aggregators. They act as interface between the grid and several EVs. In general, an aggregator may take one of the following three roles in an indirect V2G system:

- it may represent the grid operator;
- it may represent a group of EVs;
- it may act as an independent dealer.

The first case is a common scenario in the current literature [32, 41, 42, 43]. By representing the grid operator, the aggregator tries to coordinate ancillary service to best serve the grid. This includes maximizing EV participation in providing ancillary services while minimizing the cost of obtaining such services.

In addition, the aggregator tries to keep the quality of supply within the set limits. This means that voltage has to be kept within upper and lower limits in all points of the distribution network, and the power flowing through transformers, cables, overhead lines, and other network components must not exceed their limits. The grid operator also aims at minimizing energy losses [44].

Alternatively, an aggregator may represent a *coalition* of EVs to maximize their profit when offering ancillary services. Such an aggregator can enter the ancillary service market and negotiate with the grid operators on behalf of its EVs in order to receive the best offer [45]. In order to be successful, the aggregator should assure *efficiency* and *fairness* among the participating EVs.

Finally, an aggregator can be an *independent entity*, representing neither the grid nor the EVs, e.g., as in [19, 28, 46]. In this scenario, an aggregator acts as a coordinator and dealer, trying to maximize its own profit. A number of parties might want to serve as such aggregators: an automobile manufacturer or automotive service organization, who are increasingly using on-vehicle telematics to deliver information services between repairs; a battery manufacturer/distributor, who could offer battery replacement discounts in exchange for sharing part of the profit in providing ancillary services; a cell phone network provider, who might provide the communications functions and whose business expertise focuses on automated tracking and billing of many small transactions distributed over space and time cell phone networking, similar to the V2G in terms of communications, control, value per transaction, and billing [28].

1.3.2 Charging scenarios

Depending on how EVs and aggregators interact, there can be different charging scenarios. In [47], the main charging control methods are classified as follows:

- opportunity charging;
- price-signal charging;
- load-signal charging;
- renewable energy-signal charging.

The opportunity charging scenario assumes that electric vehicles charge their batteries at fixed rates and efficiency as soon as they are parked and continue charging until the battery pack is fully charged. Clearly, no communication takes place and no V2G ancillary services are offered by these vehicles. The price-signal-based charging presumes a one- or two-way communication network available and is based on the *real-time*, *day-ahead*, or *time-of-use price* of electricity tariffs [12]. In this scheme, the EVs passively listen to the aggregator's broadcast of the pricing information for both active and reactive power. Once the price of offering electricity is high enough, the EVs may consider injecting (selling) electricity back to the grid. With the load-signal charging, the EVs may receive direct commands on the charging or discharging rates or their allowed ranges. Similar to the price-signal-based charging scenario, availability of a communication network is presumed with the load-signal charging. Last but not the least, renewable-energy-signal charging is based on the premise that the EVs can be charged *exclusively* using renewable energy, with EVs acting as an energy sink. During windy or sunny conditions, the EV fleet absorbs bulk power generated by wind and solar farms. During low-renewable-power conditions, the vehicles charge at a slower rate [47]. This scenario can be implemented not only in a V2G system, but also in a stand-alone islanding scenario, as shown in Figure 1.2, where the EVs use the excessive renewable local power generation for charging their batteries at off-peak hours. In that case, the charging command signals may come directly from the local renewable power generator.

1.4 V2G systems communications

Considering the indirect architecture in Figure 1.6, communications in a V2G system may include message exchanges between the grid operator and the aggregators and between each aggregator and its corresponding group of EVs. The former can be done using the existing communication infrastructure for contracting and command signals that conventional ancillary services providers use, mostly based on fiber-optic and broadband communications [5]. However, the latter may involve a variety of communication technologies as we explain next.

1.4.1 Power-line communications and HomePlug

Broadband communication over power line, also known as power-line communication (PLC), is a technology that utilizes existing power line conductors for data transmission [48]. High-frequency data signals are superimposed on top of the distribution voltage. Typically, transformers prevent the PLC signals' propagating, and thus making it difficult to use such communications over high-voltage lines. However, PLC can be transmitted well across medium-voltage lines, providing a desirable last-mile service that can then be tied to the nearest wide-area communications network. Recent implementation of the PLC technology mainly limits the communication data transmission over residential-side power lines only leading up to neighborhoods. This has successfully helped to reduce the damaging antennae effect from medium-voltage power lines [5]. With a PLC infrastructure in place, the command and price signals can be sent by aggregators towards the residential PLC receivers, such as HomePlug devices, which have been widely deployed recently [49]. The PLC technologies have also particularly found several applications in home energy management, including handling message exchanges between EVs and aggregators [50].

1.4.2 Wireless personal-area networking and ZigBee

ZigBee refers to a combination of high-level wireless communication technologies and protocols using small, inexpensive, and low-power digital radios based on the IEEE 802.15.4-2006 wireless personal area networking standard [51]. ZigBee operates in both the 2.4 GHz and 900 GHz frequency bands, which enjoys the flexibility of choosing the most proper frequency band in noisy radio environments [5]. ZigBee is mainly designed for sensing and automation applications, including home-energy management. The ZigBee transmission rates of 20–250 kbps are fast enough to transmit the updated data, e.g., one every second that is required for frequency and voltage regulation services. The range for the ZigBee communications can be as large as 400 m, making it adequate to reach every EV in a large parking lot with only a small number of transceivers [52]. Moreover, the use of wireless technology has offered the flexibility to allow adding more devices to the network without modifying its structure. Using two-bytes local addressing, ZigBee can accommodate up to 65,000 devices on a single network [53]. Experience to date indicates that ZigBee is reliable for home appliances and shows remarkable performance [54], making it a good candidate for automated demand-response applications [55].

While ZigBee is a general technology with a variety of applications, there are also recently proposed customized low-power wireless communications technologies, specifically for smart grid applications. One example is presented in [56], where the authors tailor wireless personal area networking protocol for load-management problems. In this regard, they introduce *power update*, *power request*, and *power command* message frames to carry information such as frequency and voltage-regulation commands, pricing information, service and usage deadlines, power-scheduling information, power-usage duration, power-curtailment information, charging and discharging rates, and number of appliances [56].

1.4.3 Z-Wave

Z-Wave is a proprietary wireless communications protocol designed for automation and energy management in residential and light commercial environments, involving lighting, security, heating, ventilating, air conditioning (HVAC), and electric vehicles [5]. The Z-Wave technology is optimized for reliable and low-latency communication of small data packets for low-data-rate communications. Z-Wave devices can automatically set up an ad hoc mesh network which allows a highly implementation flexibility. Z-Wave operates in the sub-gigahertz frequency range, around 900 MHz. This means that it competes with some cordless telephones and other consumer electronics devices, but avoids interference with IEEE 802.11 and other systems that operate on the crowded 2.4 GHz band [57].

1.4.4 Cellular networks

The cellular network is a widely available long-range wireless data transmission infrastructure with high coverage, making it a good option for highly mobile devices such as EVs [5]. With the cellular connectivity, EVs can inform aggregators about their trip schedules, e.g., when and where they will be parked and connected to the grid, in advance. Moreover, as pointed out in Section 1.3.1, cellular network providers can serve as aggregators, focusing on automated tracking and billing of many small distributed transactions. Cellular network-based V2G systems can also benefit from the existing cell phone applications for EV management, e.g., those provided by General Motors and OnStar for Chevrolet Volt on iPhone, Blackberry, and Droid devices. Such applications currently have the capability to monitor state of charging and to adjust charging (and possibly discharging) schedules, e.g., based on electricity pricing information [58]. These features can be coordinated by the aggregator via commands sent from the cellular towers as illustrated in Figure 1.7. This will require minimum changes in the existing communications infrastructure [59].

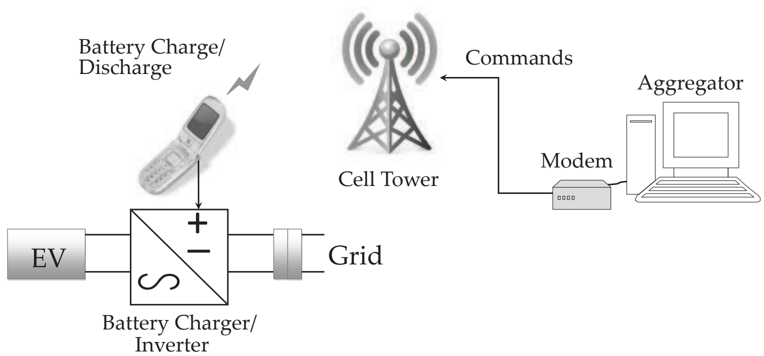

Figure 1.7 Interactions among an aggregator and an EV over cellular network.

1.4.5 Interference management and cognitive radio

Since some of the existing V2G communications technologies and home area networking devices utilize the same frequency bands, wireless interference and congestion can be a major issue in a network populous area. For example, the 2.4 GHz band for ZigBee can interfere with IEEE 802.11 b/g/n Wi-Fi and Bluetooth technologies. The higher frequency band for ZigBee and the frequency band for Z-Wave also interfere with each other and with cordless phone services [5, 60]. Therefore, the coexistence strategies (such as dynamic and distributed channel allocations) between various technologies need to be carefully designed and implemented. In addition, cognitive radio techniques can be used for spectrum sharing across different V2G and home-area networking technologies [61].

1.5 Challenges and Open Research Problems

In order to fully benefit from the new opportunities that EVs can offer to smart grid, there are two types of challenges that need to be addressed: (i) fulfilling the *communications needs* to facilitate efficient interactions among EVs, aggregators, and utilities by either adjusting the existing technologies (such as those mentioned in Section 1.4) or developing new communications technologies; (ii) using the available V2G communications infrastructure to *coordinate* the interactions among EVs to efficiently offer the various ancillary services mentioned in Section 1.2. Next, we explain these two types of challenges in details.

1.5.1 Fulfilling communications needs

The requirements for V2G communications can be identified with respect to five key factors: *bandwidth*, *latency*, *reliability*, *security*, and *mobility*.

The United States Department of Energy has recently estimated that the bandwidth required for V2G communications can be up to 100 kbps per EV [62]. Furthermore, it is estimated that the latency in V2G communications needs to be as low as two seconds, in particular when EVs offer ancillary services. Although there are some ongoing related research, e.g., in the United States National Institute of Standards and Technology [63], there is still no comprehensive study in the existing literature to investigate the capabilities of various communications technologies in fulfilling the bandwidth and latency requirements mentioned above. As the number of EVs increases in a neighborhood, achieving these requirements can become even more challenging due to the need for higher bandwidth. Some of the tools and techniques that have recently been proposed to support higher bandwidth and lower latency in V2G and smart grid communications systems include cognitive radio and spectrum sharing [64, 61], MIMO communications [65], and using multiple orthogonal frequency channels [66]. Moreover, reliability in V2G communications systems should be moderately high, i.e., in the 99 percent to 99.99 percent range [62]. Reliable communications can be achieved by using reliable transport layer protocols, such as TCP, or through enhanced error detection, error correction, and source coding at lower layers [63].

Security is another key challenge in V2G communications. In fact, although the two-way communication capabilities and distributed intelligence in V2G systems can improve efficiency and offer new opportunities such as users' participation in ancillary service market, these new features can also create new vulnerabilities in the power infrastructures if they are not accompanied with proper security enforcements. Some of the security concerns in V2G systems are as follows. First, to assure user's privacy, the charging status and the EVs' locations should not be disclosed to any unauthorized third party. Second, it is critical to avoid unauthorized discharging of vehicles' batteries by potential intruders. Third, given the fact that EVs are one of the most common types of *controllable* *load*, V2G systems need to be strictly protected against the recently introduced *distributed Internet-based load altering attacks* [67]. This latter case refers to a scenario where a hacker uses a software intruding agent to remotely access the EVs through the V2G communications infrastructure and to *simultaneously trigger the charging phase* for a large number of EVs to cause a major *load spike* in the power grid. If the system is not protected, such attack can degrade power quality, damage utility and consumer equipment, and even cause a blackout.

In addition to certain levels of bandwidth, latency, reliability, and security, V2G systems present additional requirements due to mobility, which are not needed in most other smart grid communications applications. Because most EVs will likely charge at a variety of locations, including their home premises, office parking lots, and other public or private locations during long-distance travel, it will be important to maintain compatibility of communications technologies in V2G systems [62]. On the other hand, although most existing V2G applications focus on vehicle and grid interactions only when the vehicles are parked and are connected to the grid, a vehicle-to-vehicle or a vehicle-to-roadside communications infrastructure [68, 69] may find interesting new applications in the future smart grid, for example by tracking EVs' movements and charging levels in order to forecast where and when the new charging load of each EV will be connected to the power grid.

1.5.2 Coordinating charging and discharging

To be effective, the operation of a large group of EVs need to be coordinated when they offer ancillary services. In general, such coordination can be done in either a *centralized* or a *decentralized* fashion as we will explain next.

In a centralized control scenario, a utility or an aggregator can remotely control users' EVs by sending appropriate command signals that enforce charging and discharging of batteries when needed. Some of the recent studies on central optimization of EVs' operations are provided in [70, 71, 72]. There are various challenges that need to be addressed in this line of research. First, they need to make sure that all EVs maintain some minimum charging level at all time. Note that, participation in ancillary services becomes undesirable for users if it makes them unable to use their vehicles when they need to, e.g., in case of an emergency. Second, given the flexibility needed to be offered to users, the coordination of EVs requires to take into account the *randomness* in availability of EVs, as some EVs may leave the V2G system and some new EVs may join it at any time. This important aspect is particularly under-explored and needs to be further investigated. Third, a major concern for users is the depreciation of their EV batteries due to participation in ancillary services. Therefore, the number of charging and discharging cycles imposed on each user must be minimized.

Centralized coordination schemes may not always be scalable. Moreover, users can be reluctant to relinquish full control of their EVs to utilities and aggregators [73]. Therefore, a decentralized control approach can be more desirable in V2G systems. It can not only provide more scalable solutions with reduced control overhead on utilities and aggregators, but also allow users to maintain full control of the operation of their own electric vehicles, thus further encouraging users to participate in V2G systems and various ancillary service programs. The main challenge in decentralized coordination of EVs' charging and discharging is to implement elaborate pricing rules that can leverage optimal EVs' operations without direct involvement of utilities and aggregators. As recently shown in [33, 74], *game theory* and *mechanism design* have promising applications in this line of research, where we can design good pricing strategies by understanding users' rational reactions to various pricing and incentive mechanisms.

1.6 Conclusion

In this chapter, we discussed the advantages of vehicle-to-grid systems in terms of providing various ancillary services such as reserve power supply, peak shaving, integration of renewable energy sources, and frequency and voltage regulation. We also introduced two general vehicle-to-grid system architectures, namely, direct and indirect, where the latter is more scalable and involves aggregators. Such aggregators can represent the grid operator, the EVs, or independent dealers. Furthermore, we summarized several vehicle-to-grid system communications technologies such as power line communications, HomePlug, ZigBee, Z-Wave, cellular, and cognitive radio. The advantages and applications of each technology was discussed. Finally, a wide range of challenges and open research problems were discussed with respect to not only V2G communications requirements such as bandwidth, latency, reliability, security, and mobility but also centralized and decentralized coordination of EVs' charging and discharging in order to assure effective participation of users in large-scale offering of various ancillary services.

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