Software Defined Wi-V2G: A V2G Network Architecture

***Abstract*—The valley-to-peak difference in power consumption is a crucial problem in load regulation and control for a power grid. By allowing electric vehicles (EVs) to charge during off-peak hours and feed power back into the grid during peak hours, Vehicle-to-Grid (V2G) technology can help to shave the power peak. Long-distance communication is essential for data exchange between dispersed EVs and charging stations for the realization of V2G systems. However, because of the high mobility of EVs, the high-volume data transmission required and the limitations of the third-party infrastructure, it is challenging to achieve efficient and effective

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Digital Object Identifier 10.1109/MITS.2018.2806638
Date of publication: 20 April 2018

communication. To address these challenges, we propose a new V2G network architecture based on software-defined networking (SDN) technology. (1) We use an IEEE 802.11 WiFi-based long-distance (WiLD) network with the TDMA scheme as the backhaul network, and (2) we partially replace the road side units (RSUs) with some of the WiLD nodes to provide access for, and to rapidly broadcast data to, EVs. In addition, we propose: (3) a two-stage flow table mechanism and a double roaming mechanism to address the mobility demands of V2G network terminals; and (4) a rapid data transmission scheme for communication from charging stations to EVs. A testbed was built to validate the proposed network architecture. Experimental results show that the communication time delay is in the order of milliseconds and that the reliability is higher than 99.9%.

I. Introduction

Peak-shaving is an effective method of ensuring the stability of a power grid. However, with the sharp growth in power loads, the peak-to-valley difference in the load on the power grid is increasing year by year, making peak shaving much more difficult. The development and utilization of new energy sources further increase the difficulty of grid peak modulation [1]. Vehicle-to-Grid (V2G) technology offers a new approach to peak shaving for power grids. In a V2G network, the exchange of data and energy between electric vehicles (EVs) and the power grid can be controlled in both directions. EVs can be charged by the power grid during off-peak hours and can feed power back into the grid during peak hours, thus helping to balance the peak load. The charging process requires smooth communication between the EVs, the power supply equipment and the grid. In this regard, several factors, such as charging locations, charging characteristics and the various vehicle and grid stakeholders, must be considered. Thus, communication is critical in V2G networks. Moreover, the communication in V2G networks has several distinct features.

- Large number of EVs. It is estimated that the California power grid needs to charge 200000 EVs simultaneously, and its stored power is still sufficient to charge an additional 273000 EVs [2].
- High mobility of EVs. Mobility is the main demand of EVs, and their speeds can reach more than 100 kilometers per hour. The movement of terminals causes temporal fluctuation in the allocation of resources. To guarantee network performance, the system must be able to adapt to changes in the network.
- Low-delay communication. There are many kinds of data to be communicated, including control and regulation demands from grid operators, the number of available EVs, battery type and capacity characteristics (such as rated capacity, available capacity, voltage, and charge/discharge current), state of charge, arrival and departure time predictions, electricity prices, and authorization information. These data are subject to real-time constraints and must be transmitted in a timely manner.
- Large scale. The power grid is ubiquitously distributed, and EVs can operate in the city, in the country, on mountains or on highways. A V2G network must be able to monitor the status of EVs and evaluate the available electricity storage capacity.
- Compatibility with different terminals (EVs) to support EV heterogeneity. At the same time, the data of the different enterprises involved, such as power providers, charging/discharging stations, and EV manufacturers, should be isolated from each other to maintain security.

At present, there are not yet any V2G communication standards in force. The existing Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication technologies mainly use Internet of Vehicles (IOV) communication technologies, such as WiFi, Dedicated Short Range Communications (DSRC), Bluetooth, and cellular networks, whereas the transmission from the infrastructure to the power grid mainly relies on cable technologies, such as active optical fibers. Table 1 summarizes five communication technologies that could be used in a V2G network and compares the advantages and disadvantages of these solutions.

A cellular mobile telephone network such as a Long Term Evolution (LTE) network must rely on third-party facilities. DSRC is unsuitable for communications over a large-scale area because of its short communication distance (only dozens of meters) and insufficient bandwidth (a maximum of 27 Mbps). Power line carriers, telephone lines and active optical fibers or other cable networks have shortcomings such as high costs and limited geographical locations. Therefore, broadband wireless technology is the most suitable solution for V2G communication.

A WiLD network [3] is an IEEE 802.11 WiFi-based multi-hop wireless mesh network in which the distance between adjacent nodes is long (dozens to hundreds of kilometers). The nodes use high-power IEEE 802.11n wireless cards and high-gain directional antennas to realize long-distance signal transmission. Because the length of a single hop can be dozens to hundreds of kilometers and because of the high bandwidth (300 Mbps in general and up to 600 Mbps with IEEE 802.11n), low cost, delay predictability and wide coverage area [4], such networks can be used as wide-area backhaul networks.

In addition, to cope with the enormous amount of data, high mobility, high real-time demands, heterogeneity and security demands in V2G networks, we introduce SDN technology into the V2G field. With separation of the control and data planes and a centralized control strategy, the SDN approach can support high real-time demands and variable data applications. With virtualization technology, an SDN scheme can be used to integrate the computing and storage resources of the network and to realize effective control and management of the entire network. At the same time, SDN techniques can be effectively combined with cloud computing and big data technologies, which can further improve network performance and facilitate the future expansion of the V2G network architecture.

Thus, based on the above considerations, in this article, we construct a hybrid network architecture that combines a WiLD network with a V2G network based on SDN. The main contributions are as follows.

> With separation of the control and data planes and a centralized control strategy, the SDN approach can support high real-time demands and variable data applications. With virtualization technology, an SDN scheme can be used to integrate the computing and storage resources of the network and to realize effective control and management of the entire network.

First, we propose a V2G network architecture based on a WiLD network with an SDN scheme. Some traditional RSUs are replaced with WiLD nodes. Thus, the WiLD nodes and RSUs together provide network access for the EVs. The EV can connect to an RSU to send out upward traffic in a timely manner, and the data from charging stations can be rapidly broadcast to nearby EVs. Meanwhile, the WiLD network itself is used as the backhaul network. The WiLD network can increase networking flexibility, reduce the dependence on a third-party network infrastructure for the V2G network and reduce costs for EV users.

Second, we propose a two-stage flow table mechanism and a double roaming mechanism to address the mobility demands of V2G network terminals.

Third, we propose a rapid data transmission scheme for communication from charging stations to EVs. With a combination of multicast and broadcast transmission modes, data can be sent from charging stations to nearby EVs in a timely fashion.

Finally, a simulation testbed was built to validate the proposed network architecture. The experimental results show that the communication time delay is in the order of milliseconds and that the reliability is higher than 99.9%.

II. Network Architecture

A. Problem Description

The traffic transmission in a V2G network has some specific demands, such as high bandwidth (>50 Mbps), real time (<2 s), high reliability (99.0–99.99%)[2], it is challenging to achieve efficient and effective communication. And the existing wireless network technologies have some disadvantages in meeting V2G transmission demands. Power Line Carrier (PLC) communication has a low bandwidth, high signal attenuation, and low reliability with respect to noise interference. Telephone line transmission has a low bandwidth and poor flexibility and is not particularly feasible for application in larger public charging stations. The bandwidth of Zigbee communication technology is low and is unable to satisfy the increasing bandwidth demand. Mobile cellular communication systems such as 4G and 5G must rely on third-party facilities. Moreover, because WiLD network nodes are cheap (a few tens of dollars) and can be mass produced, the cost of constructing a WiLD network is much lower than that of renting a third-party network in the long run. Finally, DSRC is unsuitable for communication over large-scale areas because of its short communication distance (only dozens of meters). Thus, all of these technologies have disadvantages in one or two aspects. By contrast, a WiLD network with SDN technology can overcome all of these disadvantages.

The 2P-MAC protocol is the MAC protocol that is most commonly used in WiLD networks [3], and nodes using this protocol follow the TDMA scheme. Each network node has two phases: SynTx and SynRx. The duration of each phase is fixed. During the SynTx (SynRx) phase, all network interfaces in a node must transmit (receive) simultaneously. All nodes switch from one phase to the other at a fixed time. In a long-distance network using the 2 P-MAC protocol, the transmission delay is predictable, and we can determine whether that delay will satisfy the real-time performance demands of the system.

Table 1. V2G communication solutions and characteristics.

Technologies	Power Line Carrier	Telephone Line	Zigbee	Cellular Mobile Telephone Network	DSRC
Third-party infrastructure needed	√	√	×	√	×
High bandwidth	×	×	×	√	√
High reliability	×	√	√	√	√
High flexibility	√	×	√	√	√
Low cost	√	√	√	×	√
Suitable for large-scale area	×	√	×	√	×

Thus, based on the features of V2G networks and WiLD networks using the 2P-MAC protocol with SDN technology, we construct our network model Wi-V2G with the architecture as shown in Figure 1, where V2I, V2V and I2I communications refer to vehicle-to-infrastructure, vehicle-to-vehicle and infrastructure-to-infrastructure communications, respectively.

B. Overall Network Architecture

In our network architecture, as shown in Figure 1, we partially replace the road-side units (RSUs) with WiLD nodes. The remaining RSUs and EVs can still use one of the traditional protocols used in IOV networks, such as DCRC. Thus, the WiLD nodes and RSUs together provide network access for the EVs. Because the transmission distance of a vehicle is short, when the transmission distance of an EV cannot directly reach a WiLD node, the EV can connect to an RSU to send out upward traffic in a timely manner. By virtue of the wide and long-distance coverage features of the WiLD network, the traffic from the power grid can be transmitted downward directly to the EVs via broadcasting without passing through the RSUs. Meanwhile, the WiLD nodes that replace RSUs also act as edge switches and are responsible for EV access and data transmission in the network. The EVs and charging stations are connected by the backhaul network, which consists of WiLD nodes.

Taking advantage of the broadcast feature of WiLD nodes, we present a combined multicast-broadcast message transmission mechanism (which will be described in section III). Using this mechanism, data regarding charging station state (surplus or lack) and policies (step tariffs, charging or discharging rewards, etc.) can be sent to the EVs in a timely fashion. Then, the EVs can independently choose to charge or discharge based on planning. At the same time, because the WiLD nodes can cover long distances, we propose a double roaming mechanism to guarantee the continuity of communication when the EVs are roaming between access nodes, whether intra-domain or inter-domain (which will be described in section IV A). This minimizes the impact on the network when terminals are roaming.

The SDN controller in the network is responsible for centralized management and control of switches. The SDN controller includes a northbound interface connecting to the application service in the cloud of the higher level, and a southbound interface connecting to the backhaul network switches and a variety of control management modules in the network. The SDN controller receives connection and transmission requests from switches or application services in the upper layer, calls the corresponding control management module to generate transmission strategies, and eventually forms a flow table. Thus, it can control the forwarding of data by the switches and manage the entire Wi-V2G network.

C. SDN-Based Network Management Architecture

To facilitate network management and control, we divide the architecture of the software-defined Wi-V2G network into a control plane and a data plane, as shown in Figure 2.

The control plane is composed of a software-defined primary controller and intra-domain controllers. The data plane is composed of software-defined WiLD network switches, RSUs, EVs and charging stations.

We divide the entire network into different domains according to different regions, different access devices (EVs

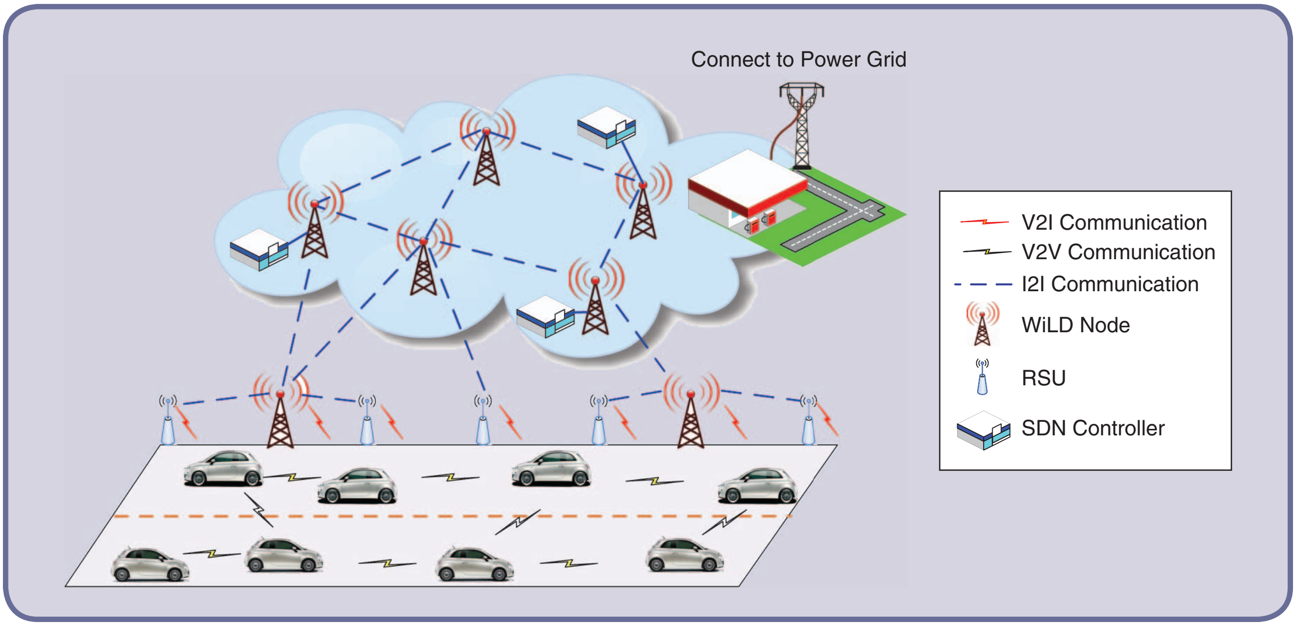

FIG 1 Actual application scenarios of the software-defined Wi-V2G network.

or charging stations) and the actual division demands of the enterprise (such as charging stations belonging to different companies being divided into different domains). To realize the data isolation of different domains from each other, we assign Virtual Local Area Networks (VLANs) to these domains on demand. The VLANs are constructed based on the needs of different enterprises, such as power providers, charging/discharging stations, and EV manufacturers. Each enterprise can be assigned one or more VLANs if necessary. Each domain corresponds to at least one VLAN and has an associated intra-domain controller. Only the EVs and charging/discharging stations that are allowed by a enterprise can join a VLAN belonging to that enterprise. Thus, some data can be transmitted only within their own VLAN and will not be received by devices outside of that VLAN. The intra-domain controller is responsible for SDN-based network management and control operations such as data forwarding and traffic control. If there is traffic from other domains, the intra-domain controller reports the corresponding traffic data to the primary controller. The primary controller sends a flow chart and implements inter-domain communication. Thus, in this architecture with a two-stage flow table mechanism, the primary controller and intra-domain controllers can reduce the communication time delay between switches and controls in the SDN approach and break the network performance bottleneck (as will be described in section IV, B and C).

D. The Advantages of Our Design

- Centralized and flexible network management. By means of SDN-based centralized network management, an optimal network resource allocation strategy can be generated to provide precise guidance for the charge and discharge times of EVs. Furthermore, with the two-stage flow table mechanism and the wireless roaming solution, high network flexibility can also be achieved.
- Low infrastructure costs. The use of a WiLD network as the backhaul network can avoid dependence on a third-party infrastructure and save on network rental costs. Furthermore, WiLD nodes are low in price [3], thereby reducing the overhead for EV users.
- Adaptability to the mobility characteristics of EVs for seamless roaming. In this article, we propose a two-stage flow table mechanism and a wireless roaming solution for EVs to guarantee network access and rapid data transmission.
- Real-time transmission of the states of charging stations. To send power supply or demand information from charging stations to EVs in a timely fashion without the broadcast affecting network performance, we propose a combined

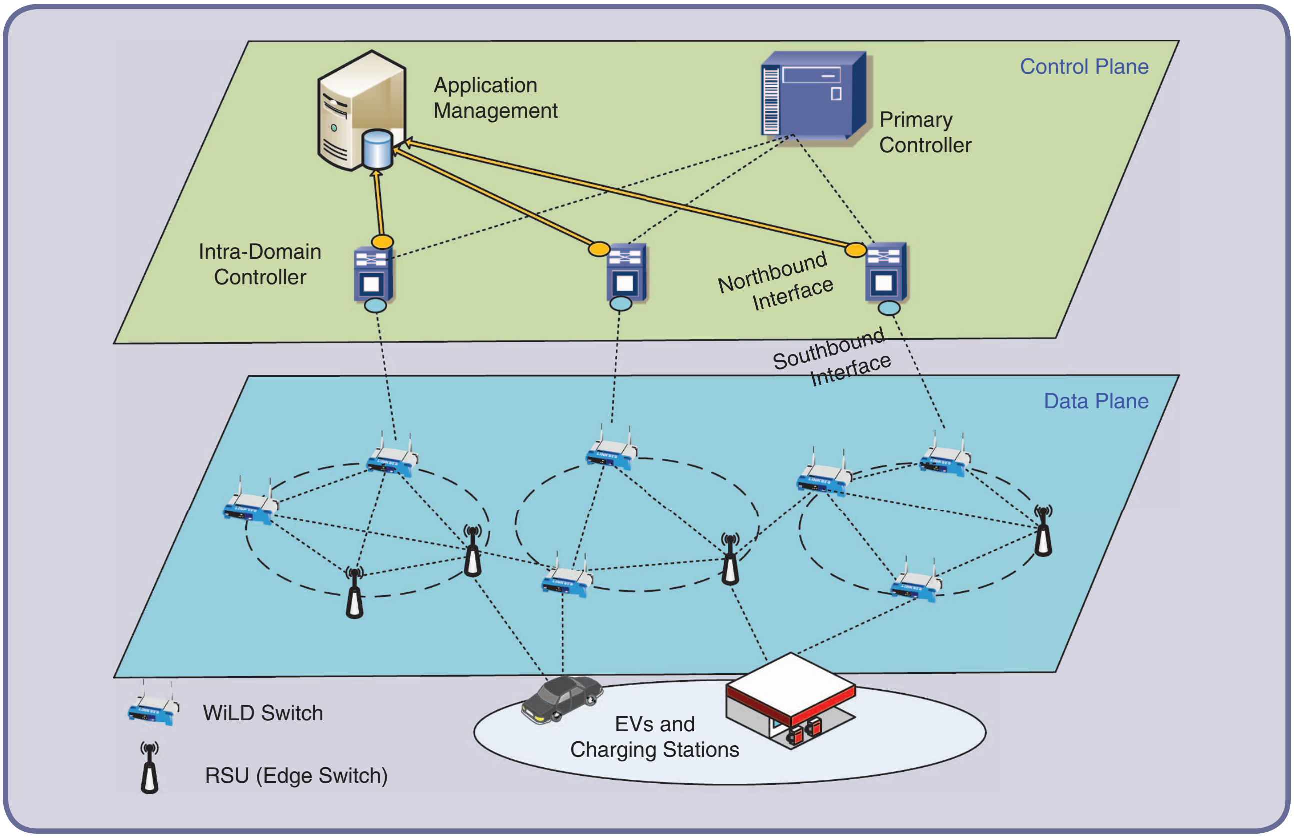

FIG 2 Architecture of the software-defined Wi-V2G network.

In our experiment, we measured delivery rates and the end-to-end delays of state information transmitted from charging stations to EVs.

forward mode that relies on VLAN multicasting and WiLD nodes that act as access nodes for broadcasting. Thus, the states of the charging stations can be transmitted to the corresponding EVs in real time (within 2 s).

III. Operation Modes of the Network

A. Conventional Operation Mode

When receiving transmission requests from terminals through the northbound interface, the SDN controller formulates data transmission strategies according to the transmission demands and sends these strategies and configuration information to the switches in the form of flow tables. Each switch forwards data in accordance with the flow table sent by the controller.

B. Broadcast Coverage Mode

Broadcast coverage mode is a specialized transmission mode for the state information and scheduling demands of charging stations. A WiLD node can be used to cover multiple RSUs; it can broadcast the power supply and demand state information of the charging stations to the EVs in a timely fashion. Then, the EVs can choose to charge or discharge. Another difference compared with the conventional network operation mode is that the data flow transmission demands are issued by cloud services instead of by network equipment. The state information of the charging stations is transmitted to the corresponding WiLD nodes in one or more VLANs via multicast. Then, the WiLD nodes, acting as edge switches, broadcast this information. Upon receiving the broadcast data, each EV can decide whether it is necessary to go to the nearest charging station.

1. The Construction of a Hierarchical Multicast Topology

Based on the Practical Internet Coordinates (PIC) algorithm [5], we calculate the network coordinates of the nodes and map them onto a 2D geometric plane. Using the network coordinates of the nodes, we can calculate the geometric distances between nodes and prepare for the subsequent construction of a hierarchical multicast topology.

There are two types of nodes, RSUs and WiLD nodes, each with a different processing capacity and coverage. To reduce the influence of the terminal node dynamics (frequent entries and departures), we choose some WiLD nodes with high data processing capabilities and relatively stable characteristics, called backbone nodes, and use them to construct a backbone network with a low time delay and high bandwidth. We refer to this as the backbone layer. Other nodes, which are responsible for the EVs access and are referred to as access nodes, are connected to their nearest backbone nodes, forming the access layer. The access nodes include all of the RSUs and some of the WiLD nodes. Backbone nodes are responsible not only for their own data transmission but also for providing relay and forwarding services for other backbone nodes and access nodes. Access nodes transmit only their own multicast data and do not provide services to other nodes.

Each access node is connected to a backbone node with a minimum geometric distance. To reduce the computational complexity, we use a simple clustering algorithm (such as k-means) to aggregate the backbone nodes into several clusters according to the geometric distances between nodes. First, according to the distances from the access node to each cluster center, each access node determines which cluster it belongs to. Then, the access node finds the nearest backbone node in that cluster and creates a multicast link. We refer to the backbone node as the father node of the access node. Thus, a backbone-access hierarchical network with a multicast topology is formed.

2. Multicast-Broadcast Data forwarding Mechanism

The intermediate nodes (access nodes and backbone nodes) obtain flow tables from the controller via the OpenFlow protocol, and each node then transmits its data to the corresponding interfaces according to its flow table. Backbone nodes transmit data via multicast, and access nodes broadcast their data to EVs.

IV. Key Technologies

A. Mobility Management Technology

Traditional VLAN division methods can only be configured artificially in advance, which not only limits the mobility of the wireless network but also increases maintenance costs. After this static configuration, because broadcast traffic is sent to the roaming area, network traffic in this area is greatly increased. This may lead to a broadcast storm and reduce the quality of the wireless communication channel and the capacity of the network.

In this article, we propose a networking architecture for the roaming of EVs. It allows the SDN controller to control the flows at the EVs. With the use and modification of flow table entries, we realize EV roaming without interruption of data transmission during the roaming process. Our method can enhance the range of IP address use for each EV based on WiLD nodes and reduce the number of IP changes.

During the initialization of the network, all equipment is placed online by the controller. The initialization process is shown in Figure 3. After initialization, the controller starts up the management application for the northbound interface and configures VLANs for the entire network. The VLAN division is based on actual conditions, such as the distances between the pieces of network equipment, the division demands of the enterprises, and network management demands. Charging stations belonging to different enterprises are assigned to different VLANs, and charging stations, RSUs and WiLD nodes within a particular scope are grouped into the same VLAN. At the same time, to ensure communication quality, we assign a specialized management VLAN for the primary SDN controller and the secondary intra-domain controllers. The management VLAN covers the entire network, has the highest priority, and is responsible for the transmission of messages between controllers and switches.

The roaming inside a VLAN is divided into RSU roaming and WiLD roaming, which we call the double roaming mechanism, as shown in Figure 4. When an EV roams between RSUs but within the range of a WiLD node, it is not necessary to exchange any data, and the IP address of the EV also remains unchanged. Only when it roams between WiLD nodes does an EV need to reconnect to a new WiLD node. Because the WiLD nodes have greater coverage, they can greatly reduce the frequency of IP changes in the VLAN.

The wireless roaming process that occurs when switching between WiLD nodes is summarized as follows:

- While an EV is maintaining its current connection with a WiLD node, the EV can detect the signal strength that it is receiving and decide whether to switch to another WiLD node depending on the contrast between the signal strengths.
- When deciding to switch, the EV sends roaming information to the WiLD node to which it is connected before disconnecting from it. This roaming information includes the EV and the WiLD node that is its roaming destination. Then, the currently connected WiLD node reports this information to the controller after receiving it.
- The EV disconnects from the current WiLD node. When the current WiLD node receives information with the address of that EV as its destination address before receiving a notification of roaming success from the EV, the current WiLD node will cache that information and return an ACK message to the informations source node. Thus, the roaming process is invisible for the source node.
- When it establishes a wireless connection with the new WiLD node, the EV is assigned a new IP address, and the EVs information is sent to the controller through the new WiLD node. Thus, the controller becomes aware that the EVs roaming process has been completed.
- The controller notifies the original WiLD node to forward the information received after disconnecting from the EV

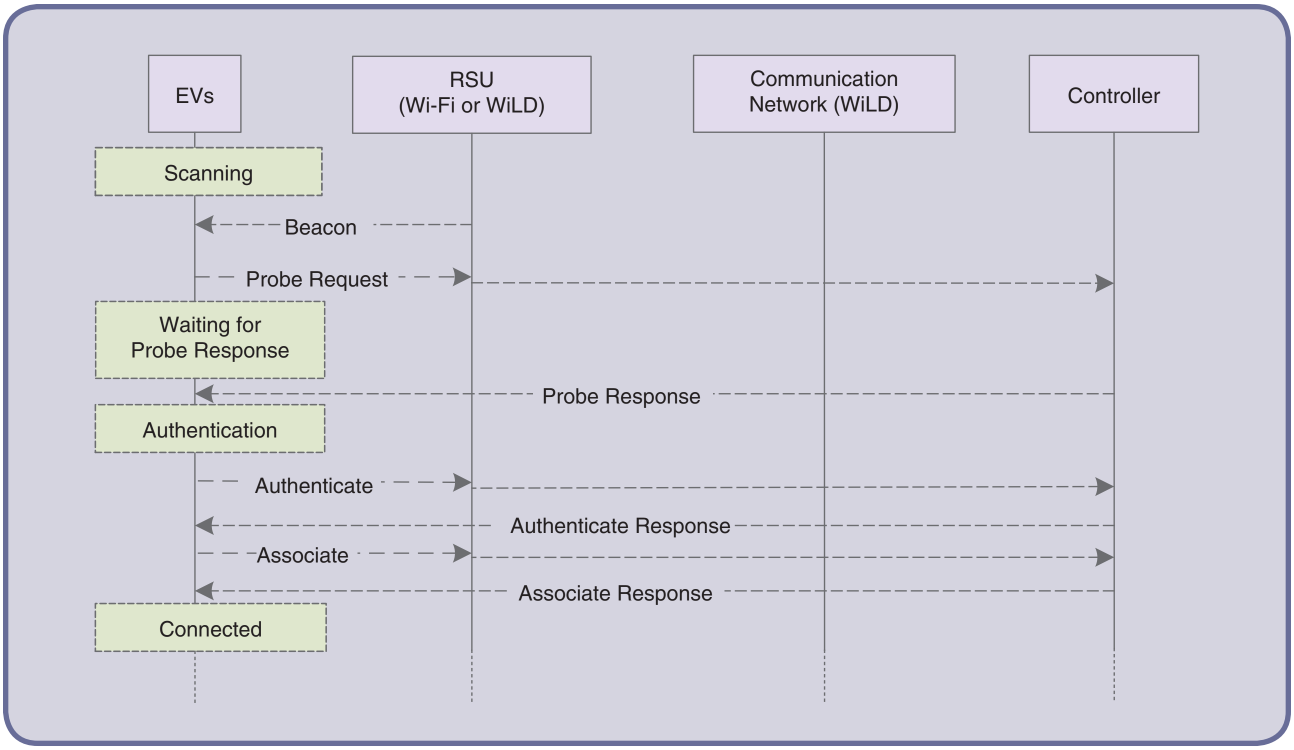

FIG 3 The sequence diagram of initialization.

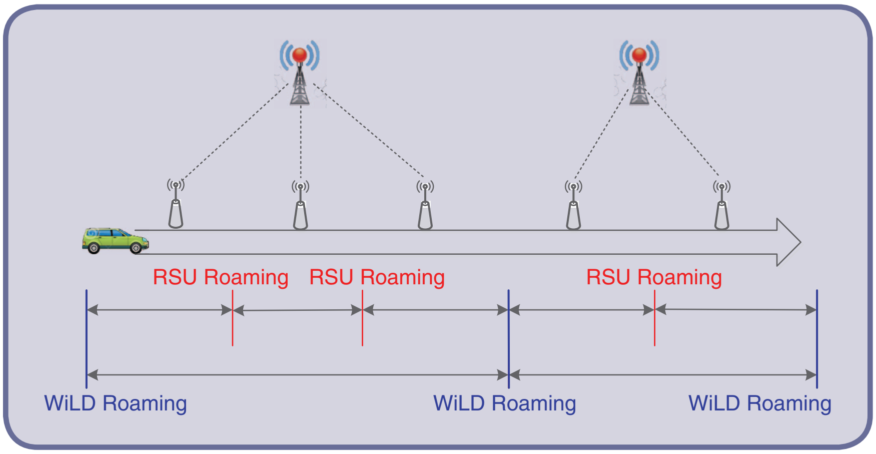

FIG 4 Double roaming mechanism.

to the WiLD node to which the EV is currently connected and, ultimately, to the EV.

After the internal roaming process within a VLAN is completed, the equipment information management database immediately updates the related entry for the corresponding EVs. However, because the mobile terminal does not cross into a different VLAN when roaming, it simply needs to update the entry of the RSU to which the mobile terminal belongs.

When a mobile terminal connects to an adjacent RSU and discovers that the VLAN with which that RSU is associated is not the terminals original VLAN, inter-VLAN roaming occurs. The RSU will inform the mobile management application on the local controller to update the topology. The mobile management application will record the terminals information before and after roaming and calculate the topology after roaming. The controller modifies the flow table and then sends a topology change request to the VLAN management application. The VLAN management application modifies the VLAN. After the VLAN topology update has been completed, the inter-VLAN roaming process is complete.

Following the process just described, the proposed scheme dynamically updates the network configuration according to the access location of each terminal.

B. Two-Stage Flow Table Mechanism

Unlike in a traditional SDN network, because of the mobility of the EVs and the real-time demands, we must shorten the effective time for real-time traffic without influencing the fixed flow table. This will increase the packet processing capability of the controller and avoid excessive processor loads that would affect overall performance. To this end, we set up a secondary flow table cache in the software-defined WiLD-V2G controller and store the flow tables with the highest usage frequencies in the buffers of the WiLD switches. This can shorten the computing time, reduce the routing computation time of the controller and improve operation efficiency.

The proposed two-stage flow table mechanism of the controller works as follows: When a data flow enters a switch, flow table matching begins (as shown in Figure 5, ①). If the match is successful, the data flow is sent to the corresponding switch port according to the flow table (②in Figure 5); if the match fails, the data flow is sent to the controller by the switch based on the OpenFlow protocol (③ in Figure 5). Then, the controller will perform two-stage flow table matching. First, the controller will determine whether the data flow can match the first-stage flow table in its cache. The controller writes the flow entry with the highest use frequency to the flow table cache, which reduces the computing time of the logical path for some data flows, thereby improving network performance. The setup of the cache flow table in the controller is based on real-time demand. If the data flow can match the flow table in the cache, the controller sends the logical link create command for the flow table entry that is directly involved. If the match between the data flow and the cached flow table fails, then the controller will calculate the corresponding logical link

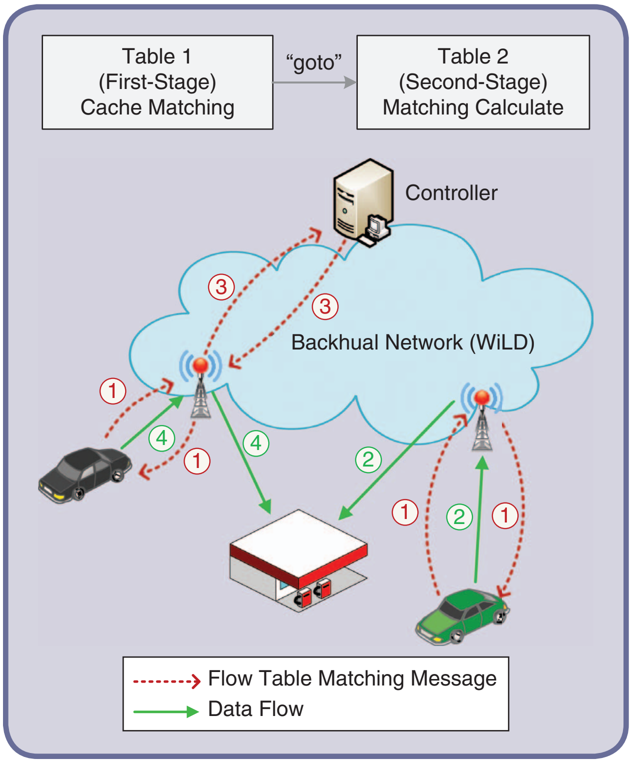

FIG 5 Two-stage flow table transmission mechanism.

in the second-stage flow table and send the result to the relevant switches according to the OpenFlow protocol. Finally, the data flow will be sent to the corresponding switch port as specified by the result (④in Figure 5).

C. Flow Table Design to Support Multicasting

As shown in Figure 6, the controller establishes a multicast tree according to the existing multicast tree algorithm and then inputs the interface ID of each relay node into the flow table. Afterward, the flow table is sent to each corresponding relay node. Once a relay node receives multicast data, it sends those data from the interface specified in the flow table. Thus, multicasting is implemented.

V. Testbed and Simulation Results

A. Testbed Deployment

To validate and test the proposed software-defined Wi-V2G architecture, a simulation platform was established. Because it is difficult to build a Wi-V2G network with long-distance nodes and multiple vehicles, we used the emulation software Exata to construct the simulation platform. Exata is a network simulation system designed by Scalable Networks Technologies Inc. for simulating new wireless communication technologies. It accurately reproduces the behavior of a real network. Thus, simulation results obtained using this platform are applicable to practical situations.

We chose an expressway segment in China on which to deploy the Vi-V2G network, where the nodes could communicate without obstruction. The area chosen for the experiment is shown in Figure 7. For clarity, we show only 5 WiLD nodes and 4 RSUs in the figure. The communication protocol used between RSUs and EVs and between RSUs and other RSUs was DSRC with IEEE 802.11p, whereas the protocol used between RSUs and WiLD nodes and between WiLD nodes and other WiLD nodes was IEEE 802.11n. In our test, the number of WiLD switch nodes and the number of EVs were 20 and 120, respectively. The distances between charging stations and EVs ranged from 40 km to 240 km. The movement speed of each EV was distributed randomly between 20 km/h and 120 km/h. Similar to [6], we injected an OpenFlow-like protocol into Exata to construct an SDN network. Only one of the WiLD switches served as the SDN controller to control the network. Four WiLD switches (nodes 1, 2, 3 and 4) served as RSUs connecting to EVs. The EVs were randomly distributed on the roads. The time slot length for the phases of all nodes was 20 ms.

In our experiment, we measured delivery rates and the end-to-end delays of state information transmitted from charging stations to EVs. The end-to-end delay can be divided into the transmission delay and the queuing delay, and

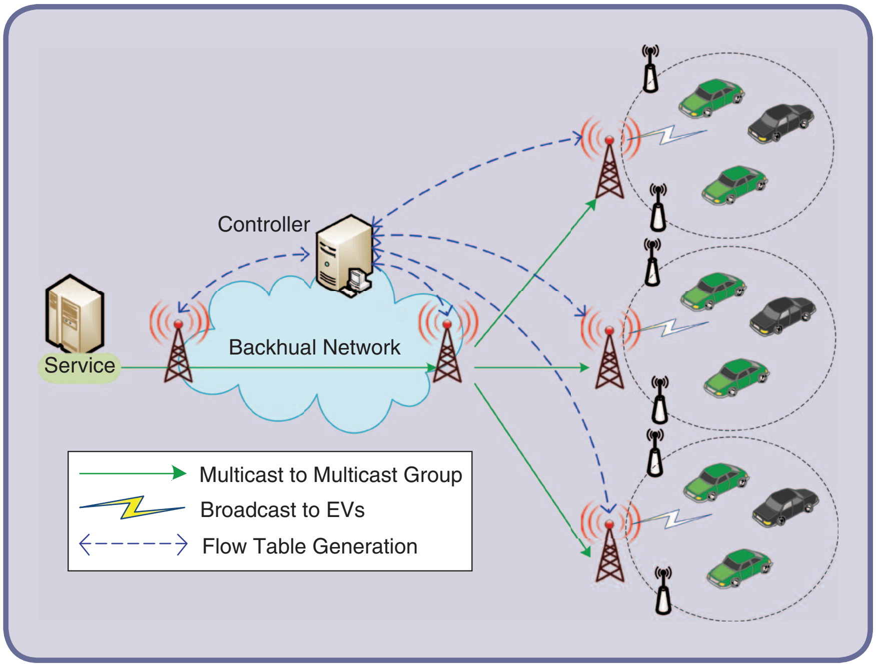

FIG 6 Multicast and broadcast relay of the network.

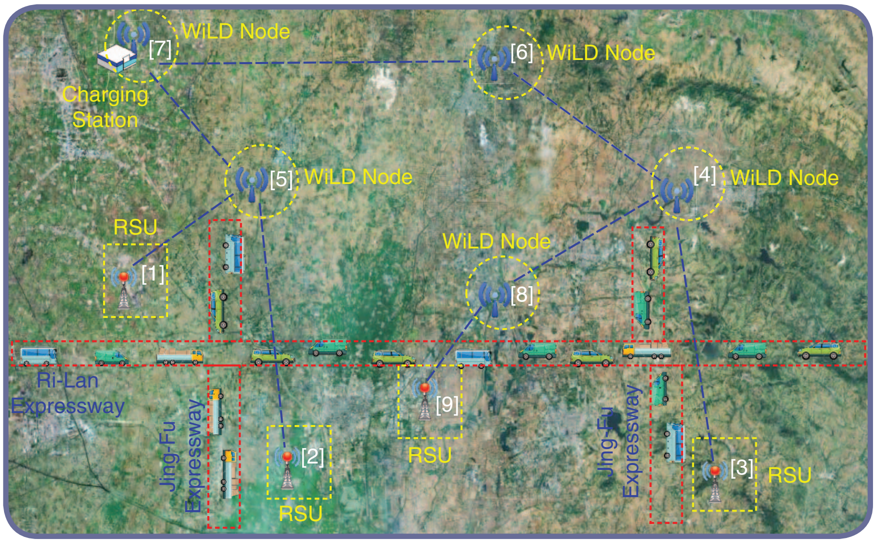

FIG 7 Experimental area.

its length is equal to the sum of all of its component single-hop delays. The one-hop delay can also be divided into two parts: the link transmission delay and the data queuing delay. When the 2 P-MAC protocol is used, the one-hop delay is fixed [7].

The methods such as WiLD without SDN, LTE and DSRC haven't been used to the V2G network communication before. So, there are no existing references to compare with. Thus, we compared the performances of the V2G network architecture we proposed (which we call WiLD with SDN in the figures) with a traditional WiFi network serving as both the access network and the backhaul network without SDN (WiFi without SDN in the figures), a cellular mobile telephone network using the LTE protocol and a DSRC network serving as both the access network and the backhaul network (DSRC in the figures).

B. Experimental Results

1. Network Reliability Experiment

The delivery rate is defined as the number of packets successfully received divided by the number of packets transmitted. The delivery rate results are shown in Figure 8, where the horizontal ordinates of Figure 8(a), (b), (c) and (d) represent the network load as a percentage of the maximum network capacity, the number of communication nodes, the average speed of the EVs and the average distance between a charging station and an EV, respectively. We can see that the delivery rates of the WiLD network with SDN, the cellular mobile telephone network (LTE) and the DSRC network are much higher than those of the traditional short-distance WiFi network. This is because the short-distance WiFi network needs more switch nodes to cover the same area as the WiLD network. Moreover, in the traditional short-distance WiFi network, there is no special roaming control mechanism designed for an environment with long distances and high-speed movement, so the transmission effect is poor. As the average distance between a charging station and an EV increases, the delivery rate of the DSRC network decreases more rapidly. This is because DSRC technology is more suitable for short-range communication. When used as the backhaul network in long-distance communication, the DSRC network requires too many hops, which causes its performance to degrade. We can see that the delivery rate of the WiLD

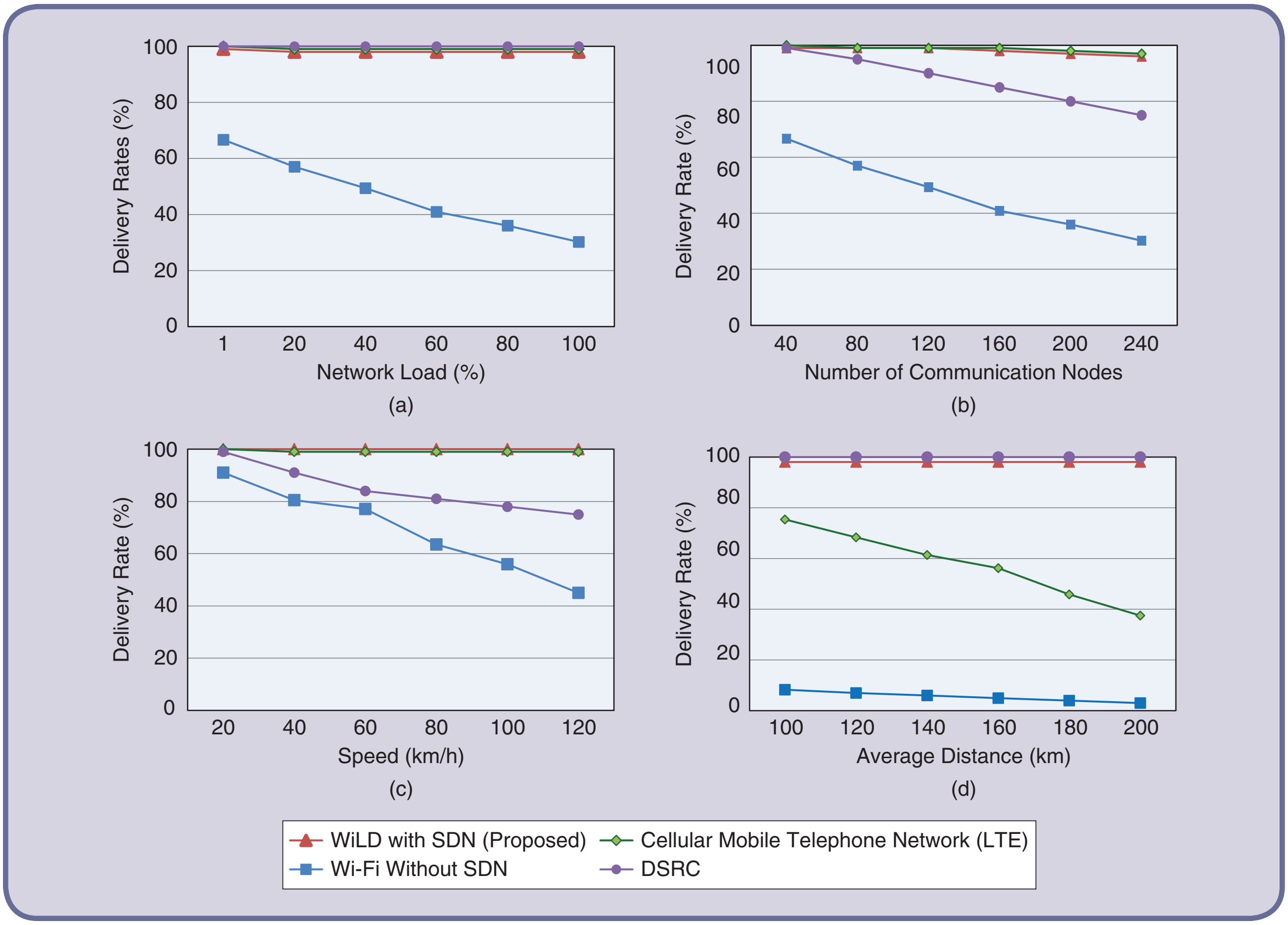

FIG 8 Variations in the traffic delivery rates with different (a) network load, (b) number of communication nodes, (c) average speed of EVs, (d) average distance between a charging station and an EV.

network with SDN is just a fraction less than that of the cellular mobile telephone network (LTE) and can be as high as 99.9% at all times. (Because of measures such as package reordering, overtime and error retransmission in our simulated network, it can effectively guarantee the delivery rate.)

V2G technology is a new type of technology for realizing a two-way exchange of data and energy between the power grid and electric vehicles.

2. Real-Time Performance Experiment

The simulation platform for software-defined Wi-V2G uses centralized management, and its network controller can modify the behavior of the network switches in a timely manner. With the two-stage flow table mechanism and double roaming mechanism we proposed, it can provide fast access and seamless roaming for EVs. In this experiment, we measured the end-to-end delays of the traffic from a charging station to EVs with different influential factors, as shown in Figure 9. The horizontal ordinates of Figure 9(a), (b), (c) and (d) represent the network load as a percentage of the maximum network capacity, the number of communication nodes, the average speed of the EVs and the average distance between the charging station and an EV, respectively. Because of the use of the two-stage flow table mechanism and the double roaming mechanism, the mean end-to-end delay of the WiLD network with SDN is much lower than that of the traditional WiFi network. Likewise, it is still just a fraction higher than the end-to-end delay of the cellular mobile telephone network (LTE). As the number of communication nodes increases,

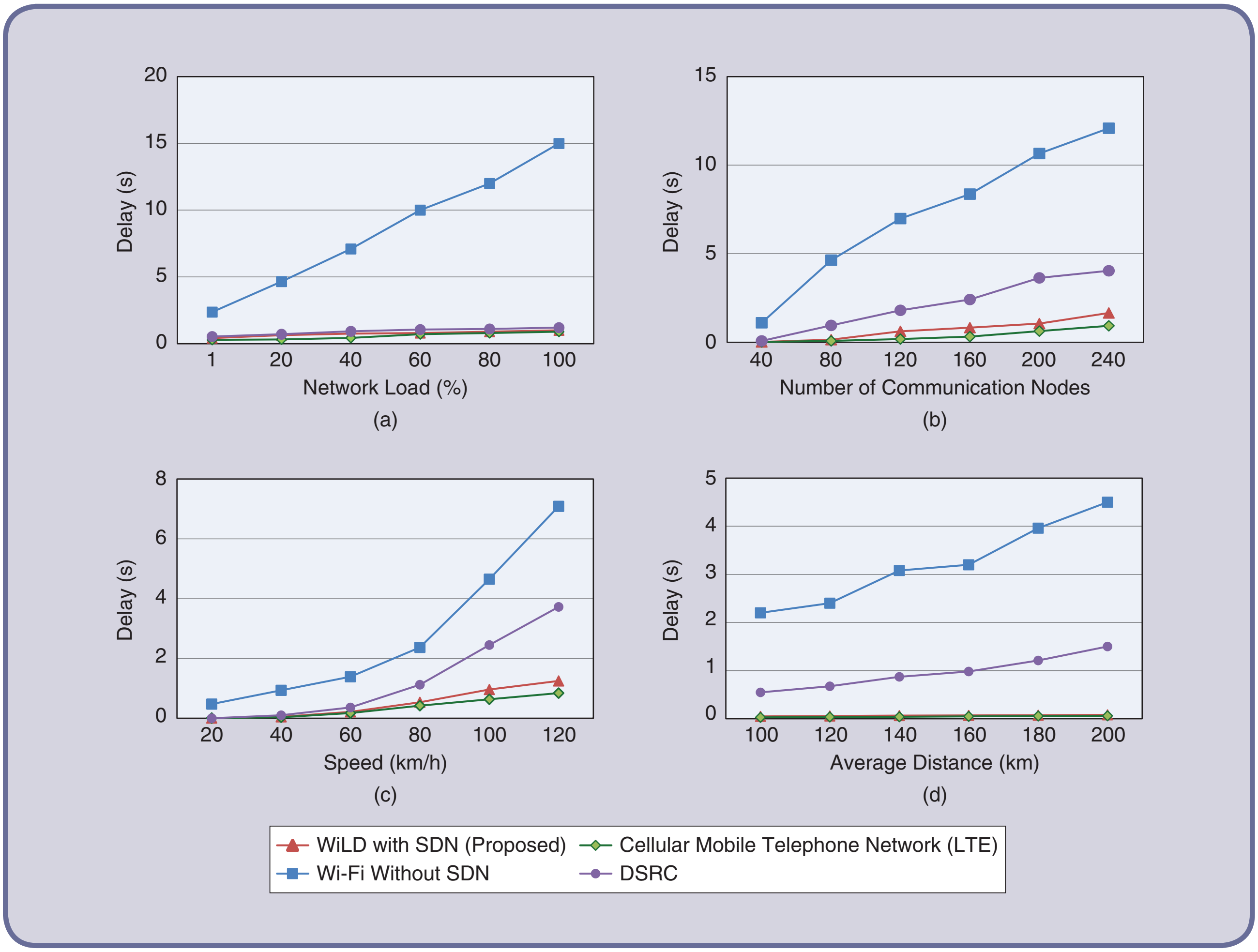

FIG 9 Variations in the end-to-end traffic delays with different (a) network load, (b) number of communication nodes, (c) average speed of EVs, (d) average distance between a charging station and an EV.

the end-to-end delay of the DSRC network grows more rapidly because a greater number of nodes results in more severe interference. By contrast, in the WiLD network, which uses directional antennas and the 2P-MAC protocol, the interference can be considerably reduced. Although the delay increases with increasing EV speed, the end-to-end delay of the WiLD network with SDN is still on the order of milliseconds and thus can satisfy the roaming demand (milliseconds). Meanwhile, the WiLD network with SDN has the advantage of not relying on third-party facilities, unlike the cellular mobile telephone network (LTE), and has a lower cost in the long run.

In conclusion, the experimental results show that the proposed software-defined Wi-V2G network can satisfy the necessary demands in terms of reliability and real-time communication.

VI. Previous Related Works

Governments in several countries have issued EV development strategies as well as national plans to promote the industrialization of electric vehicles. The Electric Power Research Institute (EPRI) predicts that by 2050, plugin hybrid electric vehicles (PHEVs) and pure electric vehicles (PEVs) will account for 62% of all transport [8]. In November 2008, the German government proposed expanding the number of PEVs and PHEVs over the next 10 years by 1 million vehicles. They announced that the implementation of this plan marks the entry of Germany into the era of electric vehicles [9].

With the increasing number of electric vehicles, such vehicles are having a growing influence on the power grid. V2G networks have become a hot topic of research. In research on related technology, a basic problem of V2G networks, capacity calculation and benefits, was studied and the considerable economic value and engineering principles of V2G networks were noted. The study presented in [10] focused on the effects of V2G technology in mobile energy storage and showed that V2G systems can replace static energy storage systems with load cycles from one second to one day. In [11], the author proposed a method of scheduling charging and discharging for electric vehicles that minimized the influence on the power grid. The quality of service (QoS) degradation problem caused by the competition among EVs for charging resources was studied in [12]. The authors proposed a hierarchical operational scheme to optimize the QoS while ensuring grid stability.

Several studies on WiLD networks have also been published in recent years. Various protocols based on the 2 P-MAC protocol have been proposed for WiLD networks, such as WiLDNet [13], JazzyMAC [14] and JaldiMAC [15]. Zhao et al. [16] proposed a traffic scheduling protocol based on the 2P-MAC protocol that provides a cross-layer admission control mechanism. Hussain proposed a QoS-aware multipath routing protocol for WiLD networks in [17]. These studies demonstrate that WiLD networks are suitable for long-distance transmission.

In studies of wireless network architectures based on SDN, several network models have been proposed, such as OpenRoads [18], OpenRadio [19], Odin [20] and LiveSec [21]. However, all of these studies have focused only on either V2G networks or SDN networks individually, and to our knowledge, there has been little research on the design of network architectures that combine these two technologies.

VII. Conclusion

V2G technology is a new type of technology for realizing a two-way exchange of data and energy between the power grid and electric vehicles. The use of an SDN architecture, with its characteristics of centralized control and separation between forwarding and control, can improve V2G network performance. WiLD networks also have many beneficial characteristics, including simple implementation, low-cost equipment, and wide-area coverage. Therefore, in this article, on the basis of the SDN approach and the use of WiLD nodes both to replace some RSUs and as the backhaul network, we propose a new type of V2G network architecture. To cope with the mobility problem, we propose a two-stage flow table mechanism to meet the high mobility demands of V2G network terminals. At the same time, taking advantage of the wide-area coverage offered by the WiLD nodes, we propose a double roaming mechanism to guarantee network access and rapid data transmission. Finally, we analyze the operation modes of the network and propose a rapid data transmission scheme based on a combination of multicasting and broadcasting. The state information of the charging stations is multicast to the corresponding WiLD nodes in one or more VLANs. Then, the state information is broadcast to the EVs, with the WiLD nodes acting as edge switches. Finally, the EVs can decide whether it is necessary to charge or discharge according to their needs.

Acknowledgment

The authors would like to thank the financial support of the National Nature Science Foundation of China under Grant No. 61502474, 61501447 and 61233007, and the Youth Innovation Promotion Association of the Chinese Academy of Sciences.

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