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Controlling WiFi Direct Group Formation for Non-Critical Applications in C-V2X Network

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ABSTRACT The fifth-generation (5G) networks are expected to meet various communication requirements for vehicles. C-V2X, introduced in LTE V2X in Release 14, is designed to provide ultra-high reliability and ultra-low latency performance required by the most demanding V2X applications. In the literature, research interests are primarily focused on safety-critical applications in a dynamic environment. Therefore, in most communication models, both safety and non-safety critical applications operate through the same radio access technology. This is the case of both C-V2X Direct Communication and IEEE 802.11p. However, in an urban environment characterized by high traffic density, the availability of resources can be problematic. In that case, it would be best to propose new communication strategies because different use cases will have different sets of requirements. In this paper, we propose to increase the capacity of C-V2X Direct Communication by introducing WiFi Direct as a second connection alternative. Indeed, several works have shown that WiFi offloading can alleviate the congestion of cellular networks. Thus, an SDN-based P2P Group Formation is proposed by extending OpenFlow to manage the WiFi Direct control plane. This solution also allows establishing multi-hop communication, something that is not possible in the standard version of WiFi Direct. The performance evaluation of the P2P Group Formation procedure is proposed via simulations in an urban environment. The results show that our proposed procedure performs better compared to those proposed in the literature. To demonstrate the implementation feasibility of the proposed solution in real hardware, we also performed prototyping.

INDEX TERMS C-V2X, connected vehicles, software defined networking, WiFi direct.

I. INTRODUCTION

The emergence of new ITS (Intelligent Transportation Systems) services suggests growing connectivity needs. Services such as creating a high-resolution video stream between two vehicles for real-time information sharing require high-speed, low-latency connectivity. In this scenario, the 3GPP has developed Cellular-V2X (C-V2X) to enable short-range communications. C-V2X can achieve the V2X (Vehicle-to-Everything) requirements and pave most efficiently the way to connected and automated driving [1]–[5]. However, the exponential rise of cellular data traffic, especially with the deployment of the Internet of Things, poses a significant problem for mobile operators. Therefore, simply using cellular infrastructure for vehicular communication may worsen the overload problem [5], [6]. C-V2X enables new ser-

vices and features to be created. Applications can be classified either into safety-critical or non-safety critical [2], [7]–[9]. Safety-critical applications mainly involve cooperation among vehicles and require direct communication (Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Vehicle-to-Pedestrians). To address the constraints of vehicular communication (low latency, high reliability, high mobility, high density), the 3GPP Release 14 proposes C-V2X Direct Communications over the LTE PC5 interface [4], [5]. There are also non-safety critical applications that are mostly related to Vehicle-to-Network (V2N) communication over the LTE Uu interface [3]. This mode of communication can handle V2N use cases like infotainment and latency-tolerant safety messages. However, several scenarios may also involve cooperation among vehicles and require direct communication. This is the case in particular for Vehicular Cloud (VC) [10], [11] which concern vehicles which are still and at rest in parking lots, or dynamic v-cloud composed of moving

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vehicles. Social Internet of Vehicles (SIOV) [12], [13] is another scenario that needs direct communication. The discovery of vehicle-related services like the gas-filling station, electric vehicle charging station, public transport information can also be handled via cooperative communication. Common to all these scenarios is there is no need for ultra-low latency or high reliable communication. Therefore, using of LTE PC5 interface in such situations is not the right solution, as it could make resource allocation more difficult [9]. In addition, the implementation of traffic prioritization schemes remains complex and will not fully resolve overload issues. Several works [7], [14]–[16] propose hybrid schemes based on C-V2X and IEEE 802.11p communication. However, 802.11p is only optimized for day 1 safety applications [17]. So applications such as VC, SIOV... cannot be correctly handled by 802.11p, especially in dense traffic scenarios [5], [18].

The 3GPP proposes, via different releases, several methods to offload cellular traffic. WiFi offloading is a commonly used technique for reducing the traffic load in mobile networks [19], [20]. WiFi offloading process is typically infrastructure-based (via AP, Access Point). However, in the D2D (Device-to-Device) communication scenario, WiFi Direct has emerged as a potential candidate [21]–[23]. Offloading traffic to the D2D network enables low computational complexity at the base station besides increasing the network capacity [21]. In [6], the authors discuss the challenges and solutions for vehicular WiFi offloading. The highly dynamic topology of vehicles and intermittent connections constitute the major challenge for WiFi offloading in vehicular communication. However, in an urban environment, cars generally travel at slow speed with frequent stops and sometimes are in quasi-stationary mode during traffic jams. In such scenarios, WiFi Direct may well be suitable for direct communication [24]–[26].

WiFi-Direct, formally known as WiFi P2P, is a popular technology released by WiFi Alliance [27] aimed at enhancing direct D2D communications without connecting to an AP. WiFi Direct is built on the infrastructure mode of IEEE 802.11 and operates in 2.4 GHz and 5 GHz bands. P2P Device can operate concurrently with a traditional WiFi network by utilizing multiple physical or virtual MAC entities. P2P Group Formation (P2P GF) consists of determining which P2P Device will be the P2P Group Owner (P2P GO), the equivalent of AP. The choice of P2P GO is essential for the stability of the P2P Group. In literature, several works [28]–[30] propose to enhance WiFi Direct Group Formation. However, the proposed schemes do not take into account the constraints of vehicular communication. In contrast, some papers [24]–[26], [31], [32] discuss the use of WiFi Direct for data communication in VANET (Vehicular Ad Hoc Network). However, their work uses the standard P2P GF, or limited details are provided in their proposed procedure. Multi-hop communication is essential for vehicular networks. By default, WiFi Direct does not support intergroup communication. Thus, some works [33]–[35]

propose multi-hop communication schemes for WiFi Direct. The fact is, however, that their work focused on the feasibility of their solution on Android devices without taking into account the mobility of the P2P Devices and did not provide the selection criteria of relay nodes. The idea of leveraging Software Defined Networking (SDN) in vehicular networks has emerged as essential in literature [36]. SDN is designed to make the network more flexible and agile by decoupling control and data plane. Thus, the whole network intelligence is placed in the control plane and managed by a central entity named Controller. In [19], SDN-based WiFi offloading using D2D communication is proposed. However, WiFi Direct is not used because the authors consider it unsuitable for D2D-based WiFi offloading.

Based on the remarks raised, this paper proposes an SDN-based P2P Group Formation to offload Direct Communication in C-V2X network. The main contribution is the proposition of an extension of OpenFlow for managing the WiFi Direct control plane. We also proposed a novel P2P Group Formation procedure that takes into account the vehicular communication constraints and features such as multi-hop communication. The novelty of the proposed Group Formation procedure is the introduction of the stability factor for the selection of GOs. This factor allows the P2P WiFi network to react more effectively to vehicle dynamics. Load balancing is also taken into account by dividing the network into small areas and by setting a limit number of P2P Devices per Group. We have implemented and evaluated the proposed architecture in a simulation. We also showed that the proposed solution could be implemented with real hardware by proposing a prototype.

The rest of the paper is structured as follows. Section II presents the background of C-V2X and WiFi Direct. Section III provides the literature review on the use of WiFi Direct for vehicular communication. Our proposed solution is presented in section IV, followed by performance evaluation based on simulation and prototyping, respectively, in section V and section VI. Finally, section VII concludes the paper.

II. BACKGROUND

A. CELLULAR V2X

Cellular V2X (C-V2X) [3]–[5], introduced in LTE V2X in Release 14, has two complementary communication modes:

1) DIRECT COMMUNICATION

It is a short-range communication (< 1 kilometer) between vehicles (V2V), between vehicle to pedestrians (V2P), and vehicle to infrastructure (V2I). This mode, based on D2D communications, is implemented over LTE PC5 interface and operating in ITS 5.9 GHz bands independent of cellular networks.

2) NETWORK COMMUNICATION

It is a long-range communication (> 1 kilometer) between vehicle to network (V2N). This mode is implemented over

the LTE Uu interface and operates in a traditional mobile broadband licensed spectrum.

The 3GPP Release 14 focused on specifically supporting V2V communications by adding two new modes:

3) MODE 3 (SCHEDULED)

The network infrastructure provides centralized collision-free resource allocation (Semi-Persistent Scheduling, SPS) for each V2V transmission over the PC5 interface. eNodeBs assist vehicular UE via control signaling over the Uu interface.

4) MODE 4 (AUTONOMOUS)

Vehicular UE does not require support from the cellular infrastructure. V2V resource scheduling and interference management over the PC5 interface are supported in a distributed way.

B. WIFI DIRECT

In WiFi Direct, the role of each P2P Device is dynamically negotiated in the P2P Group, an equivalent of BSS (Basic Service Set). P2P Group Owner (GO) is a P2P Group creator, acts like an AP that provides BSS functionality and services for P2P Client. Legacy Client (LC), is a WiFi STA that sees the P2P GO as a traditional AP. P2P Discovery enables P2P Devices to find each other and create P2P Group quickly. P2P Discovery is composed of different phases.

1) DEVICE DISCOVERY

Consists of the detection of other P2P Devices by scanning (passive scan) in social channels (channels 1, 6, and 11 of 2.4 GHz band). The delay of such a procedure can be relatively high if several devices are simultaneously performing Device Discovery [37].

2) SERVICE DISCOVERY

It is an optional feature that allows a P2P Device to seek information about the services available in the group prior to joining it.

3) GROUP FORMATION

Consists of determining which P2P Device will be the GO. Three Group Formation modes are proposed in the WiFi Direct specification. In standard Group Formation, the GO is selected during the GO Negotiation phase. This is done by exchanging a GO Intent value (from 0 to 15) with the device sending higher intent becoming GO. In autonomous Group Formation, the role of GO is not negotiated. A P2P Device autonomously creates a P2P Group and starts sending beacons. In persistent Group Formation, P2P Devices can use the Invitation Procedure to quickly re-instantiate the group. The next phase is the establishment of secure communication by employing WPA2-Personal security, and finally, a DHCP exchange for setting up the IP configuration.

III. RELATED WORK

To study the suitability of WiFi Direct technology for VANETs, performance analysis of WiFi Direct for VANET is proposed in [24]. The simulation results show that WiFi Direct can be considered as a potential wireless technology for VANET. In [25], the authors propose to adapt the WiFi Direct protocol by taking into account vehicular communication constraints. Thus, a broadcast mechanism between the GO and the clients is proposed to reduce transmission delays in WiFi Direct. Performance analysis is based on both analytical and simulation results. In [26], a V2X communication system based on WiFi Direct and cellular technologies is proposed. Smartphones are used as communication devices. The Device Discovery and WiFi Direct Group Formation procedure are managed by a server that receives the status (MAC address, position, velocity) of each vehicle via the cellular network. When conditions (distance between vehicles $< 250\text{m}$) for Group Formation are reached, the server sends a message to the concerned vehicles to form a WiFi Direct Group. The evaluation of this system is performed in a real environment and consists of measuring discovery delay and 4G data usage in different scenarios. In [31], a smartphone integrated driving safety application based on WiFi Direct is proposed. When the vehicle faces unusual condition, V2V communication through WiFi Direct is used to report this incident to the neighbor vehicles. WiFi Direct secure location-aided routing protocols for VANET are proposed in [32]. A modified Diffie-Hellman key exchange protocol is used to establish secure communication links between vehicles.

Several works propose to enhance the WiFi Direct Group Formation procedure. In [28], the WD2 algorithm is proposed and consists of computing the intent value based on RSSI. The device with the highest intent value is selected as GO. Compared to the default WiFi Direct protocol, WD2 increases throughput and reduces Group Formation delay. An optimized version of WD2 is proposed in [29]. The procedure consists first of determining the weight of each device based on RSSI and then mapping the weight with a valid intent value. The bit rate at each client device is evaluated based on SNR (Signal-to-Noise Ratio). GO that leads to near-optimal bit rate performance is selected from the list of preselected GO. In [30], a Seamless Group Reformation scheme is proposed to maintain connectivity even when the GO disappears without notice. A Dormant Backend Links mechanism is also proposed to reduce the disruption time. In [38], a redundant GO scheme is proposed to minimize the packet loss and network discontinuity-time in the response of unforeseen GO failures.

By default, WiFi Direct follows the client-server architecture; therefore, it does not support multi-hop or intergroup communication. Intra and intergroup bidirectional communication schemes are introduced in [32] by letting a device have two virtual P2P network interfaces. Thus, the device can connect simultaneously between two groups by combining standard WiFi and WiFi Direct functionalities, and building a

communication bridge between two groups. Some solutions are proposed in [34] to allow multi-hop communication in WiFi Direct multi-group network. In the first solution, a time-sharing mechanism in which the gateway node switches between two groups are proposed. The second solution is based on simultaneous connections, as in [32]. Performance evaluation shows that the simultaneous connections mechanism best performs. In [35], bidirectional intergroup communication, also based on simultaneous connections, is proposed with the introduction of relay nodes.

Very few papers [22], [23], [39] discuss LTE offloading onto WiFi Direct. In [22], performance gains for WiFi Direct offloading are studied. The cellular network assists P2P Devices to create WD Group. Their studies reveal that network-assisted D2D offloading provides significant gains in capacity and energy efficiency. A protocol for supporting D2D communications in cellular networks using WiFi Direct and LTE is proposed in [39]. This protocol allows the deployment of the D2D paradigm on top of the LTE cellular infrastructure. In [23], the same authors propose an extension of their previous work [39] by providing an analytical model for their proposed system. The cluster head, i.e., GO, is selected based on the device with the highest SNR with the eNB. The rest of the Group Formation procedure is identical to that of standard WiFi Direct. In [19], SDN-based WiFi offloading using D2D communication is proposed. Devices periodically send updated control information to the SDN controller using their cellular network interfaces. Based on this information, the controller can instruct devices to perform WiFi D2D communication when they are within the signal coverage range.

IV. SDN-BASED WIFI DIRECT GROUP FORMATION

In this section, we present the proposed SDN-based architecture for C-V2X Direct Communication over WiFi Direct. We suppose that vehicles move in an urban environment where cellular coverage is always present. The goal is to increase the capacity of C-V2X Direct Communication by introducing WiFi Direct as a second connection alternative for non-critical applications (VC, SIOV, or advanced vehicle-related services).

A. SYSTEM MODEL

The system consists of vehicles, UTRAN (Universal Terrestrial Radio Access Network), and SDN WiFi-P2P Controller, as shown in Fig. 1a. Each vehicle is equipped with C-V2X interfaces (PC5 and LTE-Uu) and two WiFi interfaces; one for scanning and the other for communication via WiFi Direct (WD). The SDN WiFi-P2P Controller manages the WD Group Formation based on the WD devices' status represented by vehicles. The WD control plane is transmitted from vehicles to the controller over LTE-Uu interfaces. For V2V communication, i.e., WD data plane, WD interfaces are used. During communication, vehicles form a group where one of them is the Group Owner (GO), and all the others are considered Group Members (GM). For intergroup

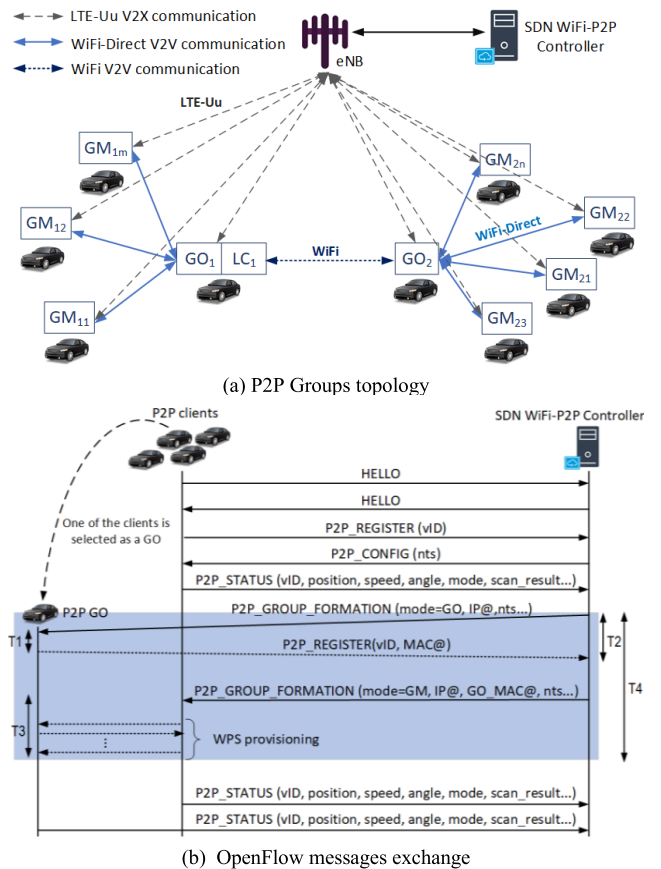


FIGURE 1. Architecture of SDN-based C-V2X Direct Communication over WiFi Direct.

communication, one of the GOs also acts as a GM in LC mode to communicate with the other P2P Group. The SDN WiFi-P2P Controller is a fog device [40], i.e., located near the eNB. This geographical proximity to vehicles allows rapid transmission and processing of the WD control plane.

An extension of the OpenFlow protocol is used to define new features for transporting the WD control plane. Thus, the proposed new OpenFlow messages are preceded by the P2P_ prefix, as shown in Fig. 1b. After exchanging HELLO messages, vehicles must register to the SDN WiFi-P2P Controller using the P2P_REGISTER message. This message contains the vehicle identifier (vID). The controller responds by sending a P2P_CONFIG message that indicates the next time to scan (nts). Once this moment arrives, each vehicle performs a scan with a second WiFi interface to find WD devices, i.e., neighbor vehicles. After that, vehicles send P2P_STATUS messages to the controller. These messages are crucial because they contain all the information (position, speed, angle, scan result...), allowing the controller to perform Group Formation procedure. After this procedure, the controller selects a set of vehicles that will be set in GO mode and send them a P2P_GROUP_FORMATION message containing its role or mode=GO, the assigned IP address, and the next time to scan. When receiving this message, each vehicle selected as GO starts a P2P Group by creating

a P2P interface and send a *P2P_REGISTER* message to the controller to indicate the MAC address of the created P2P interface (GO MAC address). This message is important because it is a confirmation of the creation of the P2P Group. Thus, by receiving this message, the controller is able to send to vehicles considered as GM a *P2P_GROUP_FORMATION* message containing the mode=GM, the assigned IP address, the GO MAC address, and next time to scan. When a GM receives this message, it connects the GO via WPS provisioning and starts a P2P Group session. For inter-group communication, the controller also sends the same *P2P_GROUP_FORMATION* message to the GO considered as GM with the difference that the role becomes mode=LC.

By default, the GO is also required to run a DHCP server to provide P2P Clients (GM and LC) with IP addresses. However, this is not a viable option in vehicular communication because multiple GO will be used in addition to the recurrent handovers of P2P Clients. In the proposed architecture, the SDN WiFi-P2P Controller is responsible for IP addresses management. Therefore DHCP server is no longer needed. The advantage is that the P2P Clients quickly establish a connection with the GO and keep their IP addresses during a handover. In addition, the communication is interrupted only during the T3 or T4 period (see Fig. 1b).

B. GROUP FORMATION PROCEDURE

After receiving vehicles (P2P Devices) status, i.e., *position, speed, angle, p2p rule* and *scan result*, the SDN WiFi-P2P Controller starts the Group Formation procedure consisting of the following steps:

1. Discovery data consist of a set of scan results, noted $scan_{V_i}$, sent by each vehicle V_i .

$$scan_{V_i} = \{RSSI_{V1,i}, RSSI_{V2,i}, \dots, RSSI_{V_j,i}, \dots\} \quad (1)$$

where $RSSI_{V_j,i}$ is the RSSI of the P2P Device of a vehicle V_j measured by V_i .

2. Vehicle stability factor S_{V_i} depends on the intent value IV_{V_i} , the difference in speed Δv_{V_i} and in angle $\Delta\theta_{V_i}$, and the cost C_{V_i} for Group Formation.

(a) IV_{V_i} is a numerical value between 0 and 15. It is determined based on the method proposed in [29]. First, the P2P Device weight w_{V_i} is determined as follows:

$$w_{V_i} = \frac{\sum_{j=1}^n RSSI_{V_j,i}}{n} \quad (2)$$

where n is the total number of discovered P2P Devices. Then:

$$IV_{V_i} = \frac{15}{RSSI_{max} - RSSI_{min}} w_{V_i} + s \quad (3)$$

s is a constant whose value is chosen so that when $w_{V_i} = RSSI_{max}$ then $IV_{V_i} = 15$.

(b) The difference in vehicle speed is normalized as follows:

$$\Delta v_{V_i} = \frac{\sum_{j=1}^n |v_{V_i} - v_{V_j}| - \delta v_{min}}{\delta v_{max} - \delta v_{min}} \quad (4)$$

where $\delta v = |v_{V_i} - v_{V_j}|$, v_{V_i} and v_{V_j} are the speeds of vehicles V_i and V_j respectively.

(c) The difference in vehicle angle (direction) is normalized as follows:

$$\Delta\theta_{V_i} = \frac{\sum_{j=1}^n |\theta_{V_i} - \theta_{V_j}| - \delta\theta_{min}}{\delta\theta_{max} - \delta\theta_{min}} \quad (5)$$

where $\delta\theta = |\theta_{V_i} - \theta_{V_j}|$, θ_{V_i} and θ_{V_j} are the angles of vehicles V_i and V_j respectively.

(d) If V_i is already GO, a Group Reformation is no longer needed.

$$C_{V_i} = \begin{cases} 1 & \text{if } V_i \text{ is already a GO} \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Finally, the vehicle stability factor S_{V_i} is determined as follows:

$$S_{V_i} = \alpha_1 \frac{IV_{V_i}}{15} - \alpha_2 \Delta v_{V_i} - \alpha_3 \Delta\theta_{V_i} + \alpha_4 C_{V_i} \quad (7)$$

where $\alpha_1, \alpha_2, \alpha_3$ and α_4 are weighting factors.

(e) S_{V_i} is used to rank vehicles in ascending order. In other words, vehicles with the highest stability factor are selected to be GO.

3. Divide the network into small areas, i.e., $Z = \{Z_1, Z_2, \dots, Z_i, \dots\}$. For each area $Z_i \in Z$, determine the number of K_i GO needed. $K_i = \frac{n_{VZ_i}}{n_{GM}}$ where n_{VZ_i} is the number of vehicles present in the zone Z_i and n_{GM} is the limit number of GM per GO. For each zone $Z_i \in Z$, create subareas $z = \{z_1, z_2, \dots, z_i, \dots\}$. The number of subareas depends on n_{VZ_i} , i.e., if $n_{VZ_i} \leq \lambda_i$ then the number of subdivisions on each edge of the area is (l_i, m_i) . Thus:

$$\{\lambda_i : (l_i, m_i)\} = \{2 : (1, 1), 8 : (2, 2), 16 : (3, 3), \dots, 64 : (5, 5)\}$$

The goal of subareas creation is to prevent all GOs from being in one place. Next, for each subarea $z_i \in Z$, determine the number of k_i GO needed. $k_i = \frac{n_{Vz_i}}{n_{GM}}$ where n_{Vz_i} is the number of vehicles present in the subarea z_i . If $n_{Vz_i} < 2$, no GO will be needed in this subarea.

4. Each vehicle V_{i,Z_i} present in z_i need to be associated with a GO in an optimized way. Thus, for each GO_i present in $scan_{V_i}$ during the discovery phase (see step1), determine:

$$IV_{GMGO_i} = \frac{15}{RSSI_{max} - RSSI_{min}} RSSI_{GO_i} + s \quad (8)$$

Then,

$$S_{GMGO_i} = \alpha_5 \frac{IV_{GMGO_i}}{15} - \alpha_6 \frac{|v_{GO_i} - v_{GM}|}{\max(v_{GO_i}, v_{GM})} + \alpha_7 C_{V_i,GM} \quad (9)$$

where α_5, α_6 and α_7 are weighting factors. S_{GMGO_i} is used to rank GO present in $scan_{V_i}$ in ascending order. The vehicle V_{i,Z_i} selects the GO from the top.

5. This step begins with the GO with the highest S_{Vi} (see step 2). The selection of candidates, i.e. GM, is based on the following rules:
 - (a) Reject all candidates that are moving in the opposite direction.
 - (b) Select the first n_{GM} candidates with the highest S_{GMGOi} values.
 - (c) If a candidate is not selected, it will have to select the next GO based on the ranking result (see step 4).
6. After step 5, if there is a candidate that is not yet associated with a GO, this candidate will be associated with the first GO (based on the ranking via step 4) that has not yet reached the limit number n_{GM} of GM. If all GOs have reached the limit number n_{GM} , then the GM is associated with the GO from the top.

After the Group Formation, the next step is the establishment of intergroup communication via the LC mode. Let:

$$GO_{i,neigh} = \{GO_1, GO_2 \dots\}$$
 the set of neighbors of a GO_i

7. First, identify all GOs with a single neighbor, i.e. $|GO_{i,neigh}| = 1$, then connect them to that neighbor.
8. For all GOs with multiple neighbors, i.e. $|GO_{i,neigh}| > 1$, identify all its neighbors, noted $G_{i,neigh}^*$, that have no connection with the rest of the neighbors in $GO_{i,neigh}$. Then, establish a connection with the most stable neighbor in $G_{i,neigh}^*$ based on the formula (9).
9. If there is a GO with no neighbor, i.e. $|GO_{i,neigh}| = 0$, then it is considered as isolated.

V. SIMULATION

A. SIMULATION DESCRIPTION

In this section, we assess the performance of the proposed Group Formation procedure. The simulation is carried out using the Python-TraCI Library for interfacing a python script with SUMO [41]. A segment of Dakar downtown is used to simulate an urban vehicular scenario, see Fig. 2. A complete scenario (Through Traffic Factor, Count, type of vehicles) is built using OpenStreetMap Web Wizard. We used the WiFi Direct channel model for VANET proposed in [25]. To improve GO selection procedures, two Group Formation strategies are proposed:

- *GF strategy 1*: the aim is to maintain a good quality signal, reduce latency and packet losses in P2P Group by assigning high values for ponderation factors relative to IV_{Vi} and C_{Vi} .
- *GF strategy 2*: the aim is to reduce connection losses by maintaining the same topology in the P2P Group. Thus, high values are assigned to ponderation factors relative to Δv_{Vi} and $\Delta \theta_{Vi}$.

To prove the validity of these two proposed strategies, we also implemented the approaches proposed by Jeong et al. [26], Zhang et al. [28], and Jahed et al. [29] for comparison purposes. The simulation key parameters are summarized in Table 1, and the following metrics are determined during the simulation:

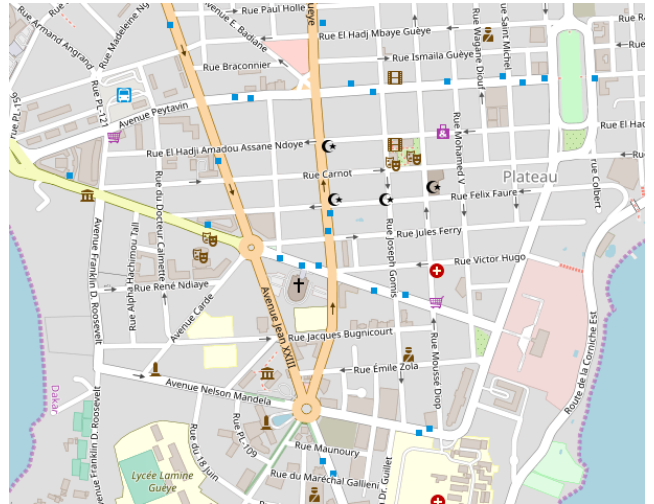


FIGURE 2. Map of downtown Dakar.

TABLE 1. Simulation parameters.

Simulation time	1200s
Simulation area	2887.67m × 3068.97m
n_{GM}	10
GF strategy 1	$\alpha_1=\alpha_5=10, \alpha_2=\alpha_6=2, \alpha_3=3$ and $\alpha_4=\alpha_7=5$
GF strategy 2	$\alpha_1=\alpha_5=3, \alpha_2=\alpha_6=10, \alpha_3=10$ and $\alpha_4=\alpha_7=3$

- *Connection losses*: percentage of GMs having lost connectivity with the GO before the next scheduled scan.
- *Control plane overhead*: total number of OpenFlow packets exchanged between P2P Devices (via LTE-UU interfaces) and SDN WiFi-P2P Controller.
- *Overloaded GOs*: percentage of GOs with number of GMs connected to them greater than n_{GM} .
- *Number of Group Formation*: the total number of Group Formation during the simulation.
- *Number of handovers*: the total number of times the GMs have switched from one GO to another.

B. RESULTS AND DISCUSSION

During the simulation, vehicles can enter or leave the area Z. Each point in the x-axis (Fig. 3) represents the total number of vehicles that crossed this area during the whole simulation period (1200s). The simulation is repeated with different values of OpenStreetMap parameters (Through Traffic Factor, Count) to obtain the values represented on the x-axis.

Fig. 3 shows the impact of the traffic density, scan interval, and GF strategies on some WiFi Direct key performance metrics. First, we are focused on the impact of the scan interval in connection losses, overhead and P2P Group size. Fig. 3a shows that only the scan interval affects the connection losses. Indeed, the connection losses decrease with decreasing scan intervals. This result is predictable because the topology of the vehicles does not change significantly over a short time interval. However, the use of short scan intervals induces a

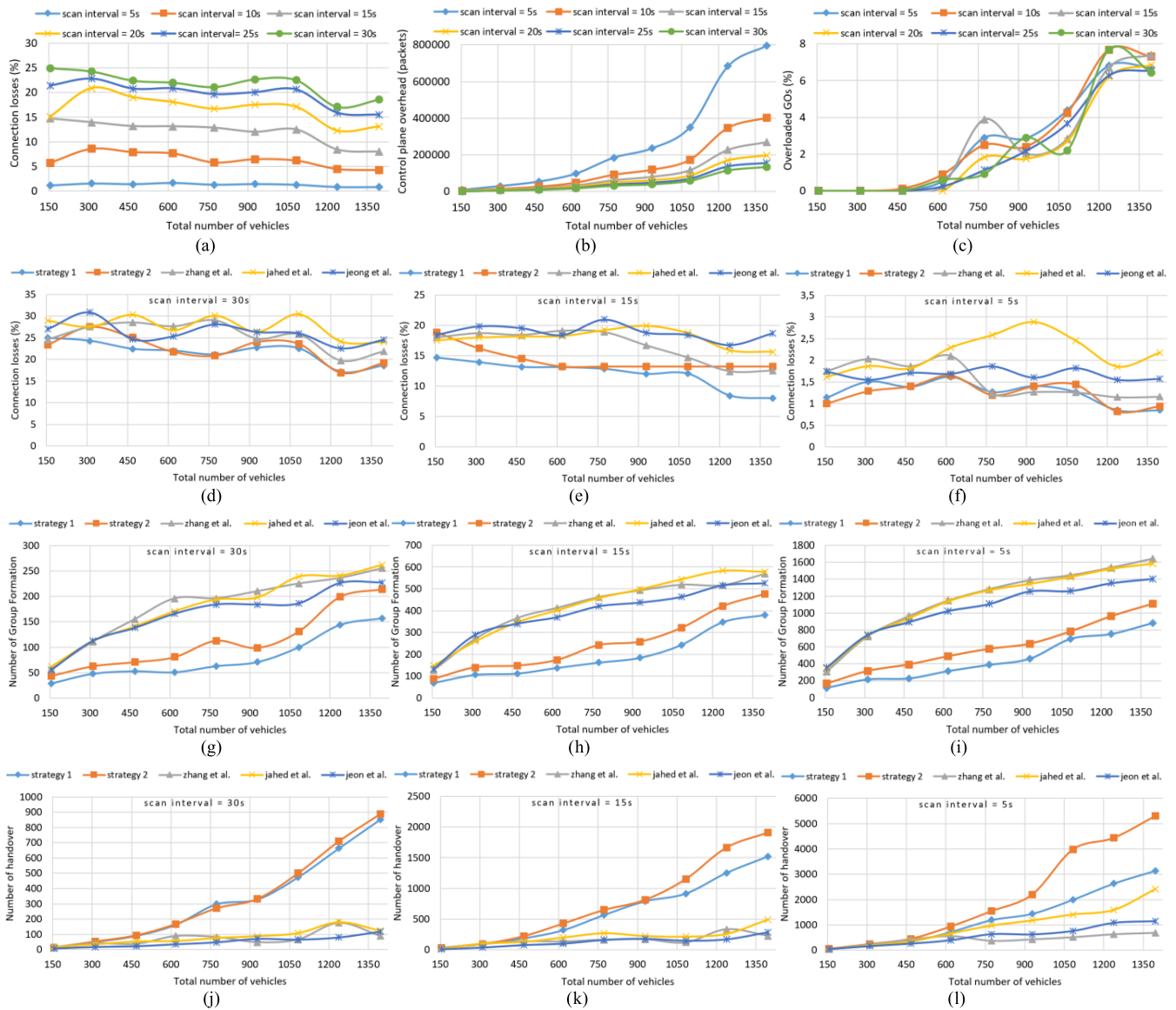


FIGURE 3. Simulation results.

high network overhead, as shown in Fig. 3b. Fig. 3c shows that the scan interval has no major influence on the size of the P2P Group, unlike traffic density. Indeed, when the number of vehicles increases, the number of overloaded GOs also increases. However, this percentage is relatively low thanks to the strategy of the division of the network into small areas and subareas described in step3 of Group Formation procedures. The observations mentioned above are not enough to decide how to set the P2P network. As a result, we also determined the impact of weighting factors in connection losses, the number of Group Formation and handover via the two proposed GF strategies, as shown in Fig. 3d-3l. The first observation is that the proposed strategies best perform compared with the strategies proposed by Jeong et al. [26], Zhang et al. [28], and Jahed et al. [29]. Indeed, Fig. 3d, 3e, and 3.f show that GF

strategy 1 and GF strategy 2 have fewer packet losses. This is due to the use of the vehicle stability factor (formula (7) and (9)) for the selection of GOs unlike the strategies based exclusively on RSSI (Zhang et al. and Jahed et al.) or distance (Jeong et al. [26]). Note also that for all of the strategies, the scan interval has a great impact on connection losses as predicted by Fig. 3a. Fig. 3g, 3h, and 3.i also show that GF strategy 1 and GF strategy 2 have the lowest number of Group Formation. This is mainly due to the consideration of C_{Vi} parameter (formula (6)) in the vehicle stability factor. In effect this parameter promotes the maintenance of already selected GOs. Consequently, fewer new GOs are created. In addition, traffic density and scan intervals have also an influence on the number of Group Formation. Indeed, short scan interval induces an increase in the number of Group Formation. This

TABLE 2. WiFi Direct network performances.

Performance metrics	Intra Group Communication			Inter Group Communication		
	GM ₁₁ -GO ₁	GM ₁₁ -GM ₁₂	GM ₁₁ -X during Group Formation	LC ₁ -GO ₂	GM ₁₁ -GO ₂	GM ₁₁ -GM ₂₁
Group Formation delay	–	–	T1 = 1.77s, T2 = 2.03s T3 = 2.24s, T4 = 4.36s	–	–	–
RTT (ms)	36.61	75.17	69.63	57.277	169.13	175.227
TCP Bandwidth (Mbps)	24.99	15.28	14.61	30.5	14.4	8.02
Packet Losses (ping)	2%	3%	9%	8%	13%	13%
Packet Losses UDP (1Mbps)	1.2%	9%	22%	3.8%	4.9%	8%
Packet Losses UDP (6Mbps)	0.51%	16%	28%	7.7%	13%	15%

situation is undesirable. Thus, the integration of GF strategies allows a much better reduction of Group Formation, especially with the *GF strategy 1*. The division of network into small area (step 3), especially with the introduction of the limit number of GM per GO (n_{GM}), has resulted in an increase in the number of handover for the *GF strategy 1* and *GF strategy 2* as shown in Fig. 3.j, 3.k and 3.l. Indeed, to prevent GO overloading, some GMs are forced to leave their current P2P Groups to join less overloaded P2P Groups. In an attempt to maintain the same topology in P2P Group, the parameters Δv_{Vi} and $\Delta \theta_{Vi}$ (formula (4) and (5)) also promote the handover of GMs especially for *GF strategy 2*. Note also that short scan interval and high traffic density lead the higher number of handovers.

In short, the performance evaluation shows that the proposed *GF strategy 1* is the most suitable for P2P Group Formation for vehicular communication. Indeed, this strategy has fewer connection losses and less Group Reformation. The reduction of Group Reformation is essential for good communication quality.

VI. PROTOTYPING

A. PROTOTYPING DETAILS

The deployment of the SDN-based WiFi-Direct network is based on Raspberry Pi 3 (Cortex-A 53 \times 64.1.2GHz, SRAM 1GB, WiFi 2.4GHz 802.11b/g/n, OS Raspbian Stretch Lite) that is used as a P2P Device. Huawei E8372 LTE USB modem is used as an LTE interface and Wi-Pi WLAN module as a WiFi second interface for scanning in monitor mode using *tcpdump*. An extension of Python Twink OpenFlow library is used to create OpenFlow-switch and OpenFlow-controller. The WiFi Direct implementation in *wpa_supplicant* is used to configure and to manage the P2P interface via Shell scripts. To synchronize SDN WiFi-P2P Controller and P2P Devices, *chrony* is used as an NTP (Network Time Protocol) server and client. For intergroup communication, GO (WiFi Direct), and LC (WiFi) interfaces must be bridged. A Layer 3 bridge [42] is used because simple Layer 2 bridging does not work with wireless ethernet client in STA mode. Thus, *parprouted* is used for transparent IP proxy ARP bridging. However, the first tests show that bridge connectivity is very unreliable

in Raspberry Pi. To solve this problem, we implemented an SDN-based proxy ARP in addition to *parprouted*. So, when a GO is select as a client, i.e., LC mode, the SDN WiFi-P2P Controller adds in the *P2P_GROUP_FORMATION* message the list of P2P Devices (MAC and IP addresses) located on both sides of the two interfaces (GO and LC). Based on this information, the concerned GO can sniff ARP Request packets and responds appropriately by generating ARP Reply packets using Scapy.

B. PERFORMANCE STUDY

For network performance study, *iperf* and *ping* tools are used to measure delay, bandwidth, and packet losses. Table 2 and Fig. 4 show the performances of intra and intergroup communication. The results demonstrate that network performance depends on the number of hops. Thus, one hop communication (GM11-GO1 and LC1-GO2) presents low delay, high bandwidth, and low packet losses, as shown in Table 2 and Fig. 4a, 4b, 4c and 4.d. For two hops communication, i.e., intra GM communication (GM11-GM12), network performance is relatively degraded compared to the one-hop performance; see Table 2 and Fig. 4e and 4f. Group Formation has a negative impact on network performance, as shown in Table 2 and Fig. 4i and 4j. Indeed, during Group Formation, the concerned P2P Devices need to create a new P2P interface, which causes their unavailability. The duration of the latter is measured via T4, see Fig. 1b and Table 2, which details the duration of the different stages (T1, T2, and T3) of Group Formation. Based on these results, P2P Devices' unavailability is T4=4.36s, and the negative consequences, i.e., high delay, low bandwidth, and very high packet losses are observed in Fig. 4i and 4j, exactly at t=40s. Concerning the intergroup communication (GM11-GO2 and GM11-GM21), we also observed the degradation of the network performance compared to intragroup communication. The degradation gets worse with the number of hops, i.e., three hops communication for GM11-GO2 (see Fig. 4.g and 4.h) and four hops communication for GM11-GO2 (see Fig. 4.k and 4.l). Another factor that may justify high latency, low bandwidth, and packet losses are the usage of L3 bridging for intergroup communication. Indeed, as mentioned above,

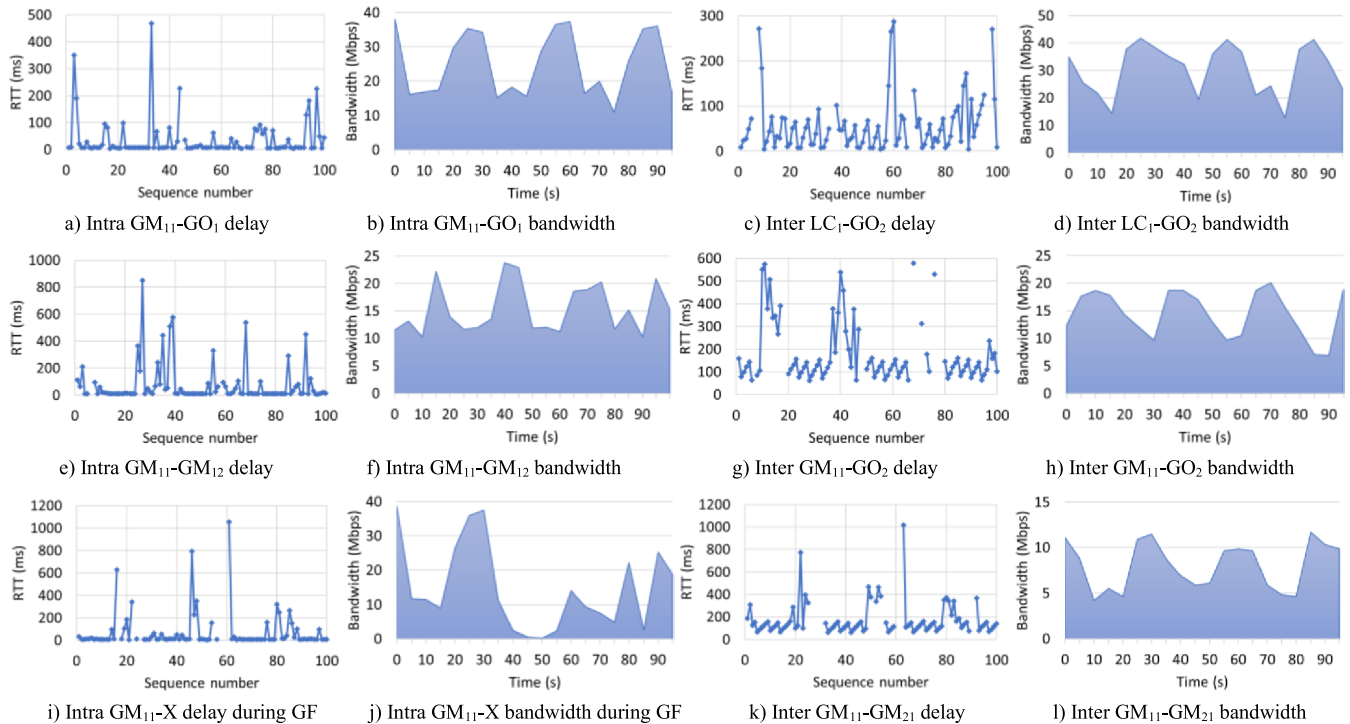


FIGURE 4. Evolution of the WiFi Direct network performances.

bridge connectivity is very unreliable on Raspberry Pi; in addition, ARP Request sniffing and ARP Reply generation using scapy (Python library executed in user-space) presents performance issues. Note that the network performance also depends on the hardware, especially the WiFi chipset and the CPU load.

VII. CONCLUSION

In this paper, we experienced the potential of WiFi-Direct to offload C-V2X Direct Communication (V2V, V2I, and V2P). An SDN-based Group Formation procedure adapted for vehicular communication is proposed. In addition to RSSI, other metrics such as vehicle speed, angle, and cost for Group Formation are used for GO selection. Simulation results show that two major factors affect the WiFi Direct network performance. The first is the scan interval that allows much better reducing connection losses. However, a high network overhead, a high number of Group Reformations, and handovers are caused by the usage of short scan intervals. The introduction of Group Formation strategies allows reducing the number of Group Reformations and handovers, especially where RSSI and maintaining the same GO in P2P Group are privileged during GOs ranking. The evaluation of performance results also shows that our proposed strategies best perform compared to other works in the literature. To prove the feasibility of our solution, we implemented the proposed architecture in real hardware. In the proposed Group Formation procedure, vehicle trajectory prediction is not taken into account. However, this parameter could be decisive for the reduction of connection losses.

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