Non-Orthogonal Multiple Access Vehicular Small Cell Networks: Architecture and Solution

Li Ping Qian, Yuan Wu, Haibo Zhou, and Xuemin (Sherman) Shen

ABSTRACT

Recently, the concept of 5G vehicular small-cell networking (V-SCN) has been proposed to meet the growing demand of mobile data services in vehicular communications. However, it is a great challenge to explore spectrum and energy efficiency due to the fast vehicle mobility and varying communication environment. In this article, we focus on critical issues, such as interference management and handover, when employing 5G V-SCNs. In order to solve these issues, the network architecture embedded with NOMA is deigned. Furthermore, we propose a hierarchical power control solution to perform the joint optimization of cell association and power control to improve the spectrum and energy efficiency in NOMA-enabled 5G V-SCNs. Numerical comparison results provide some guidelines for developing NOMA-enabled 5G V-SCNs in an economical and highly energy-efficient manner.

INTRODUCTION

Vehicular wireless networks are expected to deliver safety applications such as safety warning, traffic information, road obstacle warning, and intersection collision warning, real-time contents such as monitoring and multimedia streams, and non-real-time contents such as web browsing, images, messaging, and file transfers for vehicles [1]. The small cell networking (SCN) topology has been proposed as a promising and scalable solution to accommodate the unprecedented growth of wireless data traffic for future fifth-generation (5G) cellular networks [2, 3]. Driven by the ever denser deployment of small cells, vehicles can communicate with one another with the aid of small cell base stations (BSs) for a wide spectrum of safety and comfort applications. Therefore, the vehicular SCN (V-SCN) has been emerging as a promising vehicle-to-infrastructure (V2I) access technology to provide vehicles with better coverage and high-quality service experience while on the move [4, 5].

Although the SCN topology has been extensively studied in different contexts, the salient features of vehicular communications (e.g., varying road density, fast mobility, observable social patterns) mean that the application of V-SCNs poses new challenges. With the massive deployment of small cells, the V-SCN suffers from severe co-channel interference and unbalanced traffic load distribution among neighbor cells. Meanwhile, more frequent handover requests would be triggered easily due to fast vehicle mobility. With the growing demand for mobile data services, more spectral resources are required for V-SCNs. To meet these challenges, the 5G communication technologies, including non-orthogonal multiple access (NOMA), massive multiple-input multiple-output (MIMO) antenna technology, millimeter-wave communication technology and so on can be developed for V-SCNs to reduce handover frequency, improve spectrum efficiency, and balance traffic load as well as mitigate interference among cells.

NOMA has been validated as an essential enabling technology for 5G wireless networks to meet the heterogeneous demands for low latency, high reliability, massive connectivity, and high throughput [6]. As such, we propose 5G V-SCNs by introducing NOMA with successive interference cancellation (SIC). NOMA with SIC enables multiple simultaneous transmissions on the same frequency-time resource. Using NOMA with SIC, some of the co-channel interference can be eliminated by the SIC receiver equipped at the receiver side so that the capacity and resource utilization of V-SCNs can be effectively improved. Therefore, NOMA with SIC can be applied to 5G V-SCNs to provide multiple vehicles with efficient simultaneous transmissions of safety applications and real-time/non-real-time contents in the context of ever scarcer radio resource. Considering vehicle mobility, it is significant to dynamically allocate small cell BSs and transmit power to vehicles that perceive different channel gains to BSs. Such an operation can enhance the long-term system-wide performance and avoid excessive handovers. This leads us to the concept of joint optimization of cell association and power control, which is essentially the power-updating-based re-association/handover problem for NOMA-enabled 5G V-SCNs. In this context, this article proposes a solution of cell association and power control to improve the spectrum efficiency and energy efficiency of NOMA-enabled 5G V-SCN. More specifical, it intends to maximize the long-term station data rate related network-wide utility subject to the upper bound of small cell BSs' power consumption.

The remainder of this article is organized as follows. We first review the recent literature on 5G V-SCNs, and then discuss the challenges in NOMA-enabled 5G V-SCNs. After that, we describe the architecture of downlink NOMA-enabled 5G V-SCNs. We then propose a hierarchical

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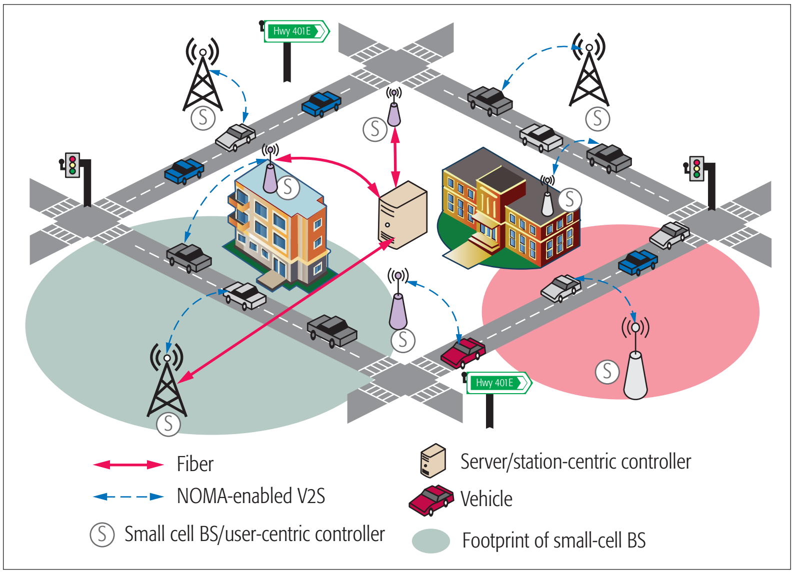

FIGURE 1. Architecture of downlink NOMA-enabled 5G V-SCN.

power control solution to perform the joint optimization of cell association and power control in this context. Finally, we verify the proposed solution using simulations, and close the article with conclusions and discussions on future research.

Related Work on 5G V-SCNs

Architecture Design

The widespread use of connected vehicles generates high volumes of mobile data services. To meet this growing demand, various potential communication technologies are emerging in 5G V-SCNs. Massive MIMO antenna technology is validated to improve the 10-20× spectrum efficiency over the same time and frequency range [7]. Due to the large bandwidth (usually more than 100 MHz frequency), millimeter-wave (mmWave) communication technology is explored to support gigabit wireless services in 5G networks. As illustrated in [8], mmWave can perform as a scalable solution for forwarding massive backhaul traffic originating from small cells into the core network. Full-duplex (FD) transmission has been emerging as a promising transmission mode in cellular networks [9], because it can potentially double the spectrum efficiency by allowing simultaneous downlink and uplink transmission within the same frequency band.

Apart from the aforementioned communication technologies, other networking technologies may also be imperative for the wireless evolution to 5G. Self-organizing networks (SONs) with the abilities of self-configuration, self-optimization, and self-healing have been explored to reduce both the network's operational and capital expenditures for 5G [10]. Cloud radio access networking (C-RAN) has been proposed to provide low-cost, high-resource-utilization, and energy-efficient wireless networks for 5G [11].

Technologies for Multiple Access

Orthogonal multiple access (OMA) techniques have been used for interference avoidance in 4G Long Term Evolution (LTE) and LTE-Advanced (LTE-A) networks, such as orthogonal frequency-division multiple access (OFDMA) for downlink and single-carrier FDMA (SC-FDMA) for uplink. The 5G V-SCN is expected to perform WITH high spectral efficiency, high energy efficiency, massive connectivity, low latency, and infrequent handovers. To address these challenges, NOMA has been actively investigated as a potential alternative to OFDMA and SC-FDMA for the 5G V-SCN [6].

Unlike conventional OMA schemes, the key idea of NOMA is to support multiple vehicles on the same frequency-time resource by non-orthogonal resource allocation. Since NOMA leads to a controllable amount of inter-user interference, it can be mitigated with the aid of sophisticated multi-user detectors at the cost of more complicated receiver design. Considering the superior benefits, various novel NOMA schemes have been extensively investigated for 5G in the literature, such as power-domain NOMA and code-domain NOMA, including low-density spreading multiple access, sparse code multiple access, lattice partition multiple access, multi-user shared access, as well as pattern division multiple access.

Mobility-Aware Cell Association

To enhance mobility resilience and spectrum efficiency, 5G V-SCNs have necessitated mobility-aware cell association mechanisms. The increased cell desification becomes the natural choice for 5G wireless networks. On the other hand, the handover performance experienced in LTE-A systems reveals that a cell association optimization technique can effectively reduce the handover rate [12].

Concerning optimization strategies, a survey [13] presents the main works addressing mobility-aware cell association. To reduce the handover complexity, dual connectivity, which allows vehicles to be simultaneously associated with macrocell BSs and small cell BSs, has been standardized as a remedy for supporting the fast vehicle mobility in small cell networks [14]. Dual connectivity enables vehicles to maintain the connection to the macrocell BS, and thus guarantees the long-term system-wide performance due to the wide footprint of macrocell BSs, although vehicles might hand over among small cell BSs frequently.

Challenges in NOMA-Enabled 5G V-SCNs

Driven by the superior benefits from NOMA, it has been proposed as a promising multiple access technique to apply to 5G V-SCNs. It is worth noting that the NOMA-enabled 5G V-SCN is not a simple upgrade of any exiting V2I networks by adopting a promising multiple access. It needs rethinking from the system and architecture levels down to the physical layer.

Network architecture: Due to the fast vehicle mobility and varying communication conditions, it is important to design a sophisticated network architecture to guarantee the low latency, high reliability, massive connectivity, and high throughput for moving vehicles. The key elements in the architecture include:
- A novel access layer to serve massive numbers of vehicles simultaneously in the NOMA manner
- Mobility-aware network intelligence to optimize limited network resource usage and planning

- An efficient data forwarding management layer to offload the data traffic requested by vehicles to associated small cell BSs adaptively.

Handover delay: A direct consequence of small cell densification could be more frequent handovers among cells due to the fast vehicle mobility. However, handovers trigger a whole host of complex procedures, which may result in undesirable handover delays. This delay can significantly degrade transmission reliability for vehicles. Therefore, characterizing the handover delay will be crucial in designing handover (or cell association) schemes for NOMA-enabled 5G V-SCNs.

Interference management: To support the exponentially increasing demand on mobile data services, massive small cells will be deployed in 5G V-SCNs. This necessitates denser spectrum reuse patterns for capacity boosting. Therefore, the 5G V-SCN is evolving toward in-band communication by adopting NOMA. As such, intelligent cell association and resource allocation strategies are imperative that can effectively mitigate interference from concurrent transmissions for NOMA-enabled 5G V-SCNs.

Backhaul: Due to the fast vehicle mobility and varying communication environment, the traffic load per small cell can be highly time-varying in NOMA-enabled 5G V-SCNs. Moreover, with the ultra dense deployment of small cells, forwarding massive backhaul traffic into the core network with satisfactory quality of service (QoS) is a challenging issue for NOMA-enabled 5G V-SCNs. Therefore, it is of practical importance to develop efficient and economical backhauling solutions that can adaptively account for the communication conditions and traffic loading conditions per small cell.

NETWORK ARCHITECTURE AND CELL ASSOCIATION

We consider that the downlink NOMA-enabled 5G V-SCN consists of multiple small cell BSs deployed along the roadsides and a set of vehicles moving on the road. All small cell BSs are connected to the server established by the mobile network operator via fiber. The architecture of a NOMA-enabled 5G V-SCN is shown in Fig. 1. The considered network employs NOMA with SIC as a multiple access scheme. In NOMA with SIC, every small cell BS adopts simultaneous multi-user transmission via superposition coding, and every vehicle adopts the SIC receiver to decode the signals from its associated small cell BS.

Considering the difference of smal cell BSs in service capacity due to the individual maximum transmit power, we formulate the load level of small cell BSs using the function $U_s(\bar{R}_s)$, which maps the long-term station data rate $\bar{R}_s$ into a utility value. Furthermore, we consider $U_s(\cdot)$ as an increasing, strictly concave, and continuously differentiable function. In our V-SCN, we therefore formulate the joint optimization of cell association and power control to maximize the network-wide aggregate utility across small cell BSs over a long-term station data rate region, that is,

$$\sum_{\forall s} U_s(\bar{R}_s).$$

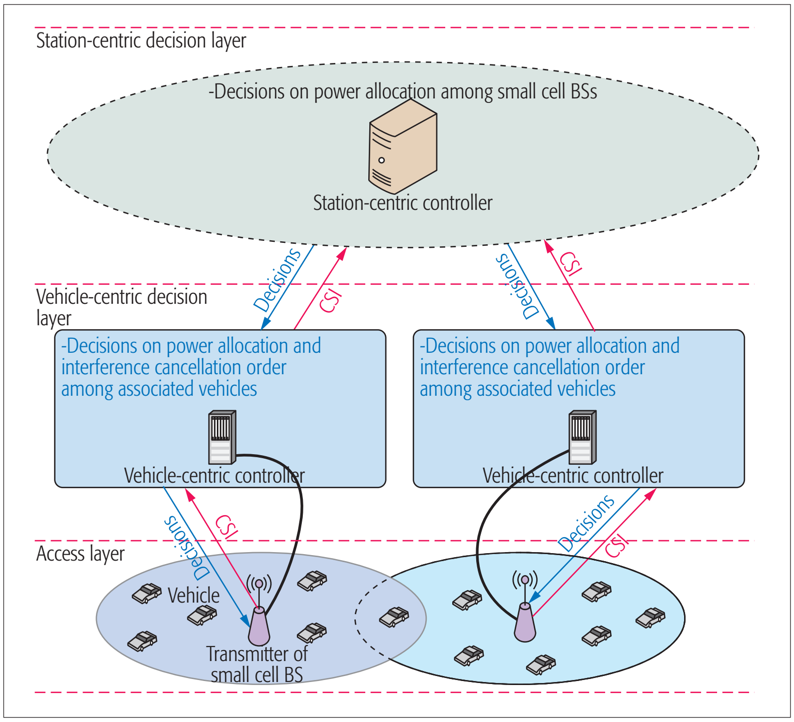

FIGURE 2. Hierarchical power control solution.

In this context, our proposed cell association can be summarized as follows:

- **Objective**: Maximize the long-term station data rate related network-wide aggregate utility across small cell BSs.
- **Constraints**:

1. The long-term station data rate R_s satisfies the sum date rate across vehicles associated with small cell BSs averaged over time.
2. The data rate of a vehicle associated with small cell BS s is obtained when the SIC receiver of a vehicle performs the SIC decoding while treating the signals from all other active smal cell BSs as interference.
3. The total transmit power across associated vehicles should be lower than or equal to the transmit power $P_{s,t}$ available at the small cell BS s in time t.
4. The available transmit power cannot exceed the upper bound of transmit power at a time.

SOLUTION: HIERARCHICAL POWER CONTROL

Naturally, if a small cell BS is off, its transmit power is equal to zero, and on otherwise. Moreover, the vehicle is associated with small cell BS s only when small cell BS s allocates positive transmit power to send its data stream. Therefore, the power control can integrate the on/off small cells strategy and the cell association strategy together. Furthermore, the optimal solution of maximizing the network-wide utility can be performed based on a standard gradient-based algorithm due to the convex nature of $U_s(\cdot)$ and $\bar{R}_s$. The obtained optimal solution corresponds to the optimal power control that maximizes the weighted sum rate across small cell BSs with weights being marginal utilities in each timeframe. Motivated by this, we develop a hierarchical power control solution to implement the joint optimization of cell

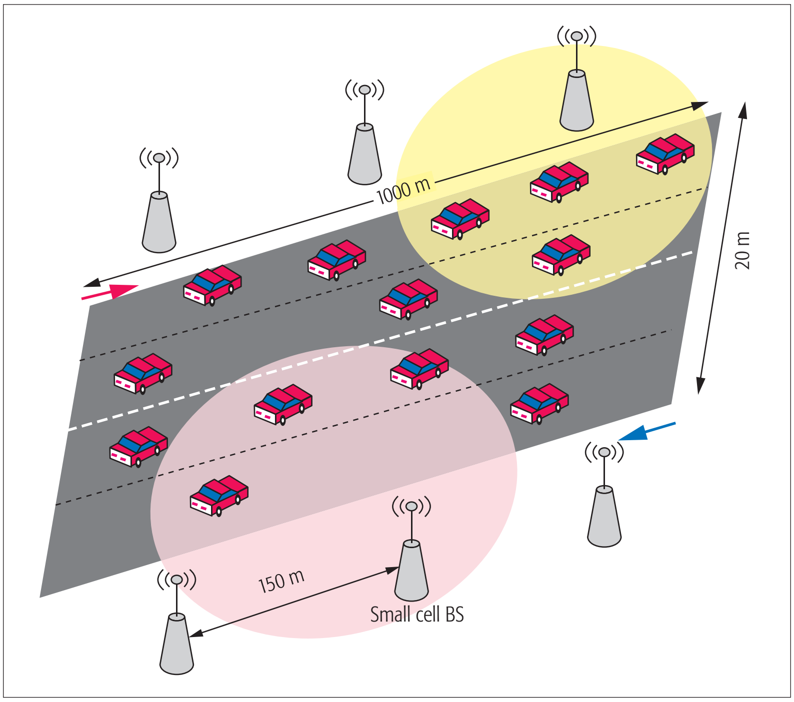

FIGURE 3. One NOMA-enabled 5G V-SCN topology.

Simulation parameters	Value choice
Carrier frequency	2000 MHz
Bandwidth	20 MHz
Path loss model	$(128.1 + 37.6\log_{10}(d))$dB ($d$ in km)
Fading model	Rayleigh fading
Noise power spectral density	–174 dBm/Hz
Range of maximum transmit power of small cell BSs	250 mW ~ 2 W
Small cell radius	100 m ~ 300 m
Maximum vehicle velocity	60 km/h
Timeframe length	1 ms

TABLE 1. Simulation parameters.

association and power control for the downlink NOMA-enabled 5G V-SCN through maximizing the weighted sum station rate in each timeframe.

Figure 2 shows the hierarchical power control solution. It covers two decision layers: the station-centric decision layer (SL) and the vehicle-centric decision layer (VL). The SL includes the station-centric controller, to which all small cell BSs are connected via fiber. The station-centric controller is in charge of determining the total amount of power to be transmitted by each small cell BS based on the channel state information (CSI). The VL is close to vehicles, and includes vehicle-centric controllers embedded with small cell BSs. The vehicle-centric controller allocates the determined total amount of power among the data streams to its associated vehicles and determines the interference cancellation order of each associated vehicle according to CSI. The resulting power allocation is used to configure the encoder at the transmitter of a small cell BS, and the resulting interference cancellation order facilitates the decoder at each associated vehicle.

In what follows, we first describe the power control, which is performed in the SL for the optimal power allocation among small cell BSs. After that, we describe the power control, which is done in the VL for allocating the transmit power previously assigned to small cell BS s among all its associated vehicles.

POWER CONTROL IN SL

For the downlink NOMA-enabled 5G V-SCN, the optimal power allocation among small cell BSs can be impractical in each timeframe, since it requires exponential computational complexity due to the complicated interference coupling between small cell BSs. Therefore, we develop a low-complexity near-optimal power allocation based on the idea of successive convex approximation. The station-centric controller performs three key ingredients at each iteration k as follows:

1. Form the k-th approximated problem of the weighted sum station data rate based on the successive convex approximation around the power allocation $\boldsymbol{P}_t^{(k-1)} = (P_{1,t}^{(k-1)}, \cdots, P_{s,t}^{(k-1)}, \cdots, P_{S,t}^{(k-1)})$ obtained at the $(k - 1)$-th iteration.
2. Solve the k-th approximated problem to obtain $\mathbf{P}_t^{(l)}$.
3. Increment k and go to step 1 until convergence to a stationary point.

POWER CONTROL IN VL

Every vehicle adopts the SIC receiver to decode the signals from its associated small cell BS. Therefore, the vehicle-centric controller performs the greedy power control to maximize the data rate for its served small cell BS. The main operations at the vehicle-centric controller include the following two parts. The first one finds the best vehicle with the maximum ratio between channel gain and out-of-cell interference among all vehicles in the footprint of a small cell BS. The second part transmits the data stream oriented to the best vehicle with the available transmit power of a small cell BS.

SIMULATION VERIFICATION

In this section, we evaluate the proposed scheme with two other baseline schemes: the maximum-power-based random association scheme (scheme 1 for simplification) and maximum-power-based best vehicle association scheme (scheme 2 for simplification). Scheme 1 assumes that in each timeframe, every small cell BS randomly serves one vehicle in its footprint with the maximum transmit power. Scheme 2 assumes that in each timeframe, every small cell BS serves the best vehicle in its footprint using the maximum transmit power.

The networking parameters were suggested in a Third Generation Partnership Project (3GPP) LTE document [15]. Table 1 presents all simulation parameters adopted. We use Clarke's model to generate the fading level, and the coherence time of channel fading is larger than 4 ms due to the fact that maximum vehicle velocity is 60 km/h. Suppose that the changes in the fading level occur relatively slowly during one timeframe, and thus we set the length of the timeframe to be 1 ms, which implies the station-centric controller and vehicle-centric controllers are allowed to dynamically update the vehicle association via power control per millisecond.

Figure 3 shows the NOMA-enabled 5G V-SCN topology used for performance evaluation. Twelve small cell BSs are uniformly distributed along with two sides of 1000 m linear road, in which the distance between any two neighboring small cell BSs at the same side is 150 m. A dynamic number of vehicles are moving on four two-way lanes for 100,000 timeframes (i.e., 100 s). The arriving model of vehicles is assumed to be a Poisson process with the arriving rate being one vehicle per second at each direction, and each arriving vehicle is assumed to uniformly select a lane.

Two types of network-wide utilities are considered in the simulation: the proportional fairness utility (i.e., $U_s(\bar{R}_s) = \log \bar{R}_s$ for all s) and the weighted sum-rate across small cell BSs (i.e., $U_s(\bar{R}_s) = w_s R_s$ for all s. The weight w_s is uniformly chosen in [0,1]. Three different analyses are performed to evaluate the performance of the proposed scheme:

- The obtained network-wide utility. This is the network-wide utility obtained up to time t.
- The total power consumption. This is the total power across small cell BSs consumed at time t.
- The service time. This is the total time that each vehicle is associated with one small cell BS, which is averaged on all vehicles up to time t. The service time can be used to evaluate the handover rate, and more service time implies lower handover rate.

Figure 4 shows the system performance obtained when the three schemes are applied to the NOMA-enabled 5G V-SCN in Fig. 3 for maximizing the proportional fairness. We can see from Fig. 4a that the proportional fairness obtained by the proposed scheme can approach that obtained by scheme 2 after a certain time (e.g., 70 s). Furthermore, the proposed scheme always outperforms the other two schemes in terms of total power consumption and service time. This implies that compared to the other two schemes, the proposed scheme can achieve higher energy efficiency and lower handover rate for the NOMA-enabled 5G V-SCN.

Figure 5 shows the system performance obtained when the three schemes are applied to the NOMA-enabled 5G V-SCN in Fig. 3 for maximizing the weighted sum-rate across small cell BSs, respectively. We can see that the proposed scheme always outperforms the other two schemes in terms of weighted sum-rate, total power consumption, and service time. Specifically, the proposed scheme can at least improve the weighted sum-rate by 16 percent, reduce the total power consumption by 10 W, and increase the service time by 17 percent in comparison with scheme 2. Therefore, the proposed scheme is preferable for spectrum and energy efficiency and infrequent handover of NOMA-enabled 5G V-SCNs.

CONCLUSION AND FUTURE WORK

We have introduced the NOMA-enabled 5G V-SCN to enhance the spectrum and energy efficiency in vehicular communications. Furthermore, a mobility-aware cell association solution has been proposed that can adapt to the traffic load conditions in the small cells and the fast vehicle mobility. The proposed solution addresses two challenges of NOMA-enabled 5G V-SCNs:

- Severe co-channel interference among concurrent transmissions
- Frequent handovers among small cells

For interference management, the NOMA scheme has been applied to the 5G V-SCN, with which some of the co-channel interference can

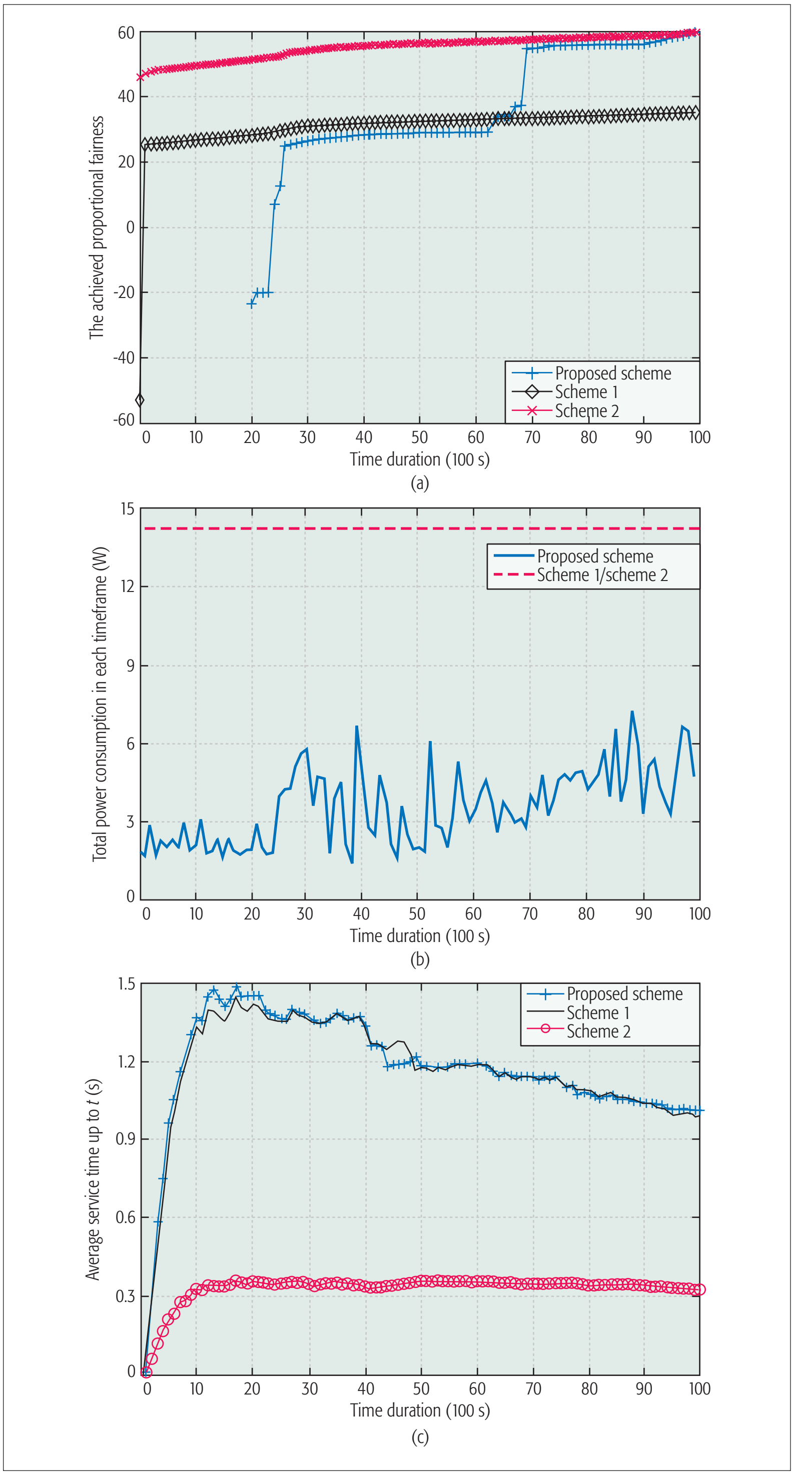

FIGURE 4. The system performance obtained when the proportional fairness utility is considered for the scenario in Fig. 3, where schemes 1 and 2 represent the maximum-power-based random association scheme and the maximum-power-based best vehicle association scheme, respectively.

be eliminated by the SIC receiver. To tackle the handover issue, the NOMA-enabled 5G V-SCN has employed a mobility-aware cell association mechanism that avoids excessive handovers by accounting for the long-term system-wide performance.

Although this article provides the initial step toward 5G V-SCNs, there are still many open issues that deserve in-depth investigations.

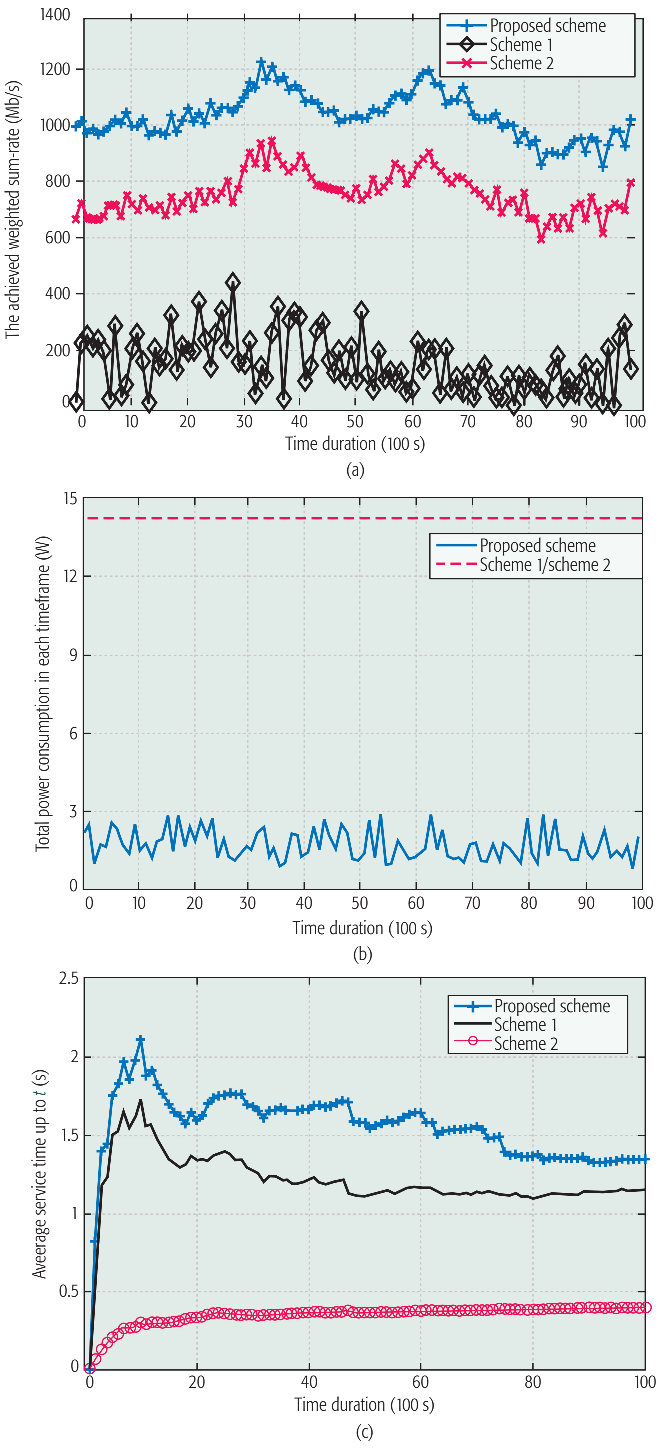

FIGURE 5. The system performance obtained when the weighted sum-rate utility is considered for the scenario in Fig. 3, where schemes 1 and 2 represent the maximum-power-based random association scheme and the maximum-power-based best vehicle association scheme, respectively.

Deployment of small cells: With the ultra dense deployment of small cells, moving vehicles are more likely to join vehicular wireless networks. However, more spectral resources and more frequent handovers are required to guarantee the QoS of individual vehicles due to the severe co-channel interference. Therefore, it is of practical meaning to take into account the deployment density of small cells for improving the spectrum efficiency and reducing the handover rate.

Cell association: Due to the emerging mobile data services in vehicular networks, the existing cell association schemes such as channel-aware, traffic-load-aware, and transmit-power-aware schemes may be highly suboptimal and require excessive handovers. New cell associations are therefore necessitated that perform cell handovers by accounting for the mobility issue, including handover frequency, handover delays, backhaul variations, and network dynamics in addition to traffic load and channel conditions.

Resource allocation: Adaptive resource allocation solutions should be developed to improve the spectrum efficiency and energy efficiency of NOMA-enabled 5G V-SCNs. 5G V-SCNs are much more dynamic than conventional small cell networks. From the operators' perspective, the resource allocation among small cells should be efficiently adjusted according to the vehicle locations, channel conditions, and traffic load per small cell. This will efficiently utilize resources, such as power, time slots, and frequency bands, while achieving satisfactory QoS requirements.

Multiple access: To serve multiple vehicles on the same frequency-time resource in the downlink V-SCN, new promising multiple access schemes are inevitable. From the operators' perspective, employing new multiple access technologies to serve massive vehicle applications using the same time-frequency resource could be more attractive than using multiple sets of channels due to the limited frequency-time resource. With such multiple access technologies, efficient interference cancellation techniques are necessitated to avoid the co-channel interference among concurrent applications. Correspondingly, more advanced receiver design and antenna systems should be further developed.

Backhaul solution: To support the massive backhaul transmission from small cell BSs or the core network, provisioning of efficient and economical backhauling solutions for NOMA-enabled 5G V-SCNs is imperative. The backhaul requirements in NOMA-enabled 5G V-SCNs may significantly vary depending on the locations of small cells, the cost of implementing backhaul connections, the traffic load intensity of small cells, the vehicle mobility, and the delay tolerance and target QoS requirement of vehicles. As such, backhaul solutions adaptive to the backhaul requirements aree critical to overcome the backhaul bottleneck in NOMA-enabled 5G V-SCNs.

NOMA for V2V communications: In addition to V2I communication, vehicle-to-vehicle (V2V) communication is another promising V2X communication technology in vehicular networks that enables vehicles to communicate with one another in an ad hoc manner. Usually, an ad hoc network based on 802.11p is exploited as the traditional solution for V2V communications. However, this leads to inefficient spectrum utilization due to massive co-channel collisions. Therefore, serving multiple V2V links on the same time-frequency resource is more attractive for enhancing spectrum efficiency. With NOMA for vehicles, it is very useful to explore the co-channel interference mitigation technology to accommodate more vehicles.

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