Energy-Efficient Subchannel Matching and Power Allocation in NOMA Autonomous Driving Vehicular Networks

Yupei Liu, Haijun Zhang, Keping Long, Arumugam Nallanathan, and Victor C. M. Leung

Abstract

Autonomous driving is the key technology to achieve "smart cars" and "intelligent traffic." The non-orthogonal multiple access (NOMA)-based autonomous driving vehicular (ADV) network is recognized as a promising application scenario in next generation mobile networks. It is also an inevitable trend in the future development of automobiles due to the use of large amounts of fuel and lane occupancy. We propose an architecture of NOMA-based ADV networks to satisfy the communication requirements. In this article, we discuss the challenges and resource allocation problem for NOMA-based ADV networks. In order to improve ADV networks' performance, this architecture also considers cross-layer interference, vehicle quality of service, and algorithm complexity. Therefore, we have investigated the subchannel and power allocation in the NOMA system. The optimization problem is formulated as a non-convex problem for the convenience of calculation, and the problem is transformed into a convex form by introducing an alternative direction algorithm of multipliers method. Simulation results prove the proposed scheme has good feasibility and reliability, and also verify that the proposed algorithm has better energy efficiency compared to the existing schemes.

Introduction

Autonomous driving technology has great practical significance and is a product of adapting to the development trend of the times. Autonomous driving will greatly improve vehicle safety, reduce traffic accidents, and greatly reduce traffic congestion. At the same time, the technology will also release a large amount of labor to promote industrial innovation. In the future society, the autonomous driving vehicle (ADV) will become a trend. On this basis, autonomous vehicles are designed based on the Internet of Vehicles technology. With the development of fifth generation (5G) technology, 5G communication technology can be applied to the vehicle network to achieve the optimization of the communication system of the current automatic driving technology, and improve the data transmission rate, transmission delay, and number of vehicles [1]. Due to the high energy consumption in vehicular network communication, how to achieve energy-efficient resource allocation is still a problem that cannot be ignored [2].

At present, there is an increasing demand for higher communication speed from vehicle network technology. The automatic driving technology requires good communication conditions. Although the automatic driving technology is more and more mature, according to the previous work, there are still some deficiencies. In [3], autonomous driving has been applied to highways, completing the tasks of parking and braking, but the application scenario is too simple, and it is not enough for complex driving tasks. In order to make autonomous driving safe, it is indispensable to establish a reliable communication network system. In [4], the authors proposed a short-range communication network, because the proposed network is mainly used for short-distance communication, which cannot solve long-distance communication problems and guarantee vehicle service quality. The researchers of [5, 6] found that Long Term Evolution networks had serious delay problems. But in autonomous driving, the occurrence of delay problems can affect the safety of the vehicle. The main reason for these problems is that there is no comprehensive consideration of autopilot multi-scene and good use of network resources. Thus, the next generation of vehicle networking combined with non-orthogonal multiple access (NOMA) technology can give the network high data rate and low latency.

NOMA technology can meet both mobile service rate requirements and improve spectrum efficiency of a system, and adopted by next generation mobile communication networks as a new technology [7]. This technology can improve the performance of the entire system, and attracts the attention of many scholars around the world. The basic idea of NOMA is to use non-orthogonal transmission at the transmitting end to actively introduce interference information and achieve correct demodulation at the receiving end through a serial interference cancellation (SIC) receiver. Although the complexity of the receiver using SIC technology is somewhat improved, it can achieve high spectral efficiency. In fact, the core idea of NOMA technology is to increase

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Digital Object Identifier: 10.1109/MWC.2019.1800515

the efficiency of the spectrum at the expense of receiver complexity [8]. Compared to code-division multiple access and orthogonal frequency-division multiple access (OFDMA), orthogonal transmission is used between NOMA subchannels. There will be no obvious near-far effect as in third generation mobile communications [9]. Since it can be independent of user feedback channel state information, after adopting power multiplexing technology, it is easier to respond to variable link states, even in a high-speed mobile environment, and it can provide good speed performance. Multiple users can be supported on one subchannel, in contrast to the fourth generation mobile communications, guaranteeing the transmission speed, which is the most important point to improve spectral efficiency [10].

Hence, we apply NOMA technology to the vehicle network and have designed a system architecture of NOMA ADV networks, which includes highway and intersection scenes. In different traffic scenarios, where we introduce vehicle-to-vehicle (V2V) communication technology, it can monitor the speed and position of other vehicles driving on the street; vehicle-to-infrastructure (V2I) communication, which not only saves the owner time, but also improves traffic conditions; and infrastructure-to-infrastructure (I2I) link communications, which belongs to device-to-device (D2D) technology [11]. In this network, we not only consider the cross-layer interference and the quality of service (QoS) of the vehicle, but also the low complexity constraints of the algorithm. Based on [12, 13], the fronthaul link and backhaul link are also considered. The data center can store, calculate, and fuse the information collected by the vehicle sensor through the fronthaul link, and the core network decides and plans the merged information through the routing protocol, finally sending the information to the vehicle through the backhaul link. In this way, the system can better provide good communication quality for the vehicle [14]. For the purpose of enhancing the performance of the entire system, a method of resource allocation is also proposed in this article, which solves the problem of subchannel allocation by subchannel matching, and also solves the power allocation problem by introducing the alternating direction method of multipliers (ADMM) algorithm [15]. ADMM is an optimization algorithm mainly used for constrained convex optimization problems.

We investigate the subchannel matching scheme and the power allocation scheme of ADMM to enhance the performance of the NOMA ADV network, and provide maximum energy efficiency based on NOMA ADV networks under cross-layer interference, QoS requirements, and low complexity of the algorithm. Hence, more detailed simulation results are discussed later. The main contributions of this article are summarized as:

- An innovative architecture of ADV networks based on NOMA is proposed, which consists of two scenarios of highway and intersection traffic, and the communication modes required by vehicles in different scenarios are analyzed. The architecture also takes into account constraints such as cross-layer interference and vehicle QoS that can effectively improve the traffic communication rate and wireless resource utilization.
- Based on the proposed NOMA ADV network architecture, we analyze the resource management in the network, which includes subchannel and power allocation, and transform the energy efficiency problem into a convex problem. An algorithm for subchannel matching is proposed, and the matching of the vehicle and the subchannel is optimized by continuous update iteration, which improves the utilization of the subchannel and the QoS of the vehicles.
- For enhancing the performance of NOMA ADV networks, based on the completion of subchannel allocation, we solve the power allocation problem by introducing the ADMM algorithm. Based on the channel allocation method mentioned above, the energy efficiency of the whole network should reach the local optimal solution, compared to existing schemes. The simulation results verify the feasibility of the proposed scheme, which has better performance according to energy efficiency.

The rest of the article is organized as follows. We describe the proposed system architecture for NOMA ADV networks. The application scenarios of autonomous driving are discussed, and the communication modes of vehicles in different scenarios are analyzed. To achieve the maximum energy efficiency of NOMA ADV networks, we propose a novel resource allocation scheme, a subchannel matching scheme, and ADMM-based power allocation. We analyze and evaluate the simulation results of the proposed algorithm. We then draw conclusions.

System Architecture for NOMA ADV Networks

Interactive data is required between the autonomous driving vehicles in ADV networks. With thousands of vehicles driving on different streets, achieving information exchange between all vehicles is difficult. Moreover, it also wastes communication resources. For example, first identify all surrounding environments and objects, signal information, distance, direction, and speed of close-range moving objects; then the system obtains its own position, road conditions, position of the surrounding objects, direction of motion, and speed, and next combines the known information with traffic rules (e.g., red light stopping, driving lane) to control vehicle advancement. Therefore, vehicles that are used for interacting with each other need to be organized into a small network to form a group of vehicles that depend on each other to form a mobile network. In addition, this article also considers parameters that can affect the energy efficiency of NOMA ADV networks, including cross-layer interference, QoS, and so on. Thus, we propose a novel NOMA-based architecture for ADV networks.

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As shown in Fig. 1, the ADV scenario infrastructure contains two frames of the upper and lower layers, which describe the two application scenarios of highways and intersections. The traffic flow under the highway scene is relatively stable, and there will be lane changes and overtaking. At the intersection, there are schools or buildings nearby. At this time, the traffic flow is relatively large, and the traffic is relatively congested. Not only will there be full lanes and overtaking, but the following situations will also occur. The distance between the front and rear vehicles is too close and exceeds the set safety distance. When there is a meeting with a vehicle from

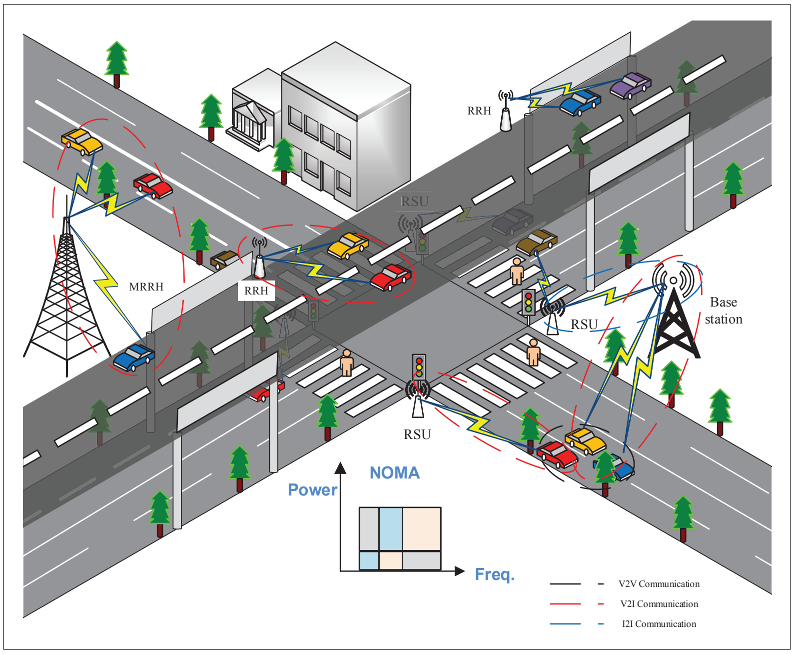

FIGURE 1. The model of NOMA ADV network architecture.

across the road, a signal is sent between the vehicles; or when an indicator light is encountered, the indicator light also signals the vehicle; once the vehicle receives the signal, it must take the corresponding measures.

To ensure the smoothness and fluency of the ADV network, whether on a highway or at an intersection, each traffic scene has a specific communication mode, and the cooperative communication between the vehicles is also different. In this article, we can see from Fig. 1 that when overtaking and lane change occur on a highway or at an intersection, communication is carried out through the V2I link. When encountering an indicator light at an intersection, the vehicle also communicates via V2I; thus, it can ensure that each vehicle can safely change lanes and drive at high speeds according to real-time commands. The vehicle receives the indicator light signal and needs to stop in time to avoid traffic accidents. When the vehicle is in a traffic condition in crowded traffic, and each vehicle is based on V2V direct communication, V2V communication can eliminate the network covered by the network operator and has high reliability. The communication between each base station and the wireless access point is through I2I communication, similar to the D2D communication technology, which ensures the QoS of the vehicle and reduces the interference between the communication links.

Combined with the characteristics of ADV networks, the NOMA-based ADV network is proposed in Fig. 2. The structure of this network includes base stations (BSs). For better communication, macro remote radio heads (mRRHs) are deployed on the roadside. Dense small RRHs (sRRHs) provide guarantee for the transmission of vehicle signals, and we use nearby roadside units (RSUs) to support more stable signals. Usually, the vehicle prefers to communicate with the RSUs; according to the communication service demand of the vehicle during the movement, it can be arbitrarily switched to other BSs that can meet the demand. Then the road condition information collected by the sensor installed on the vehicle is sent to the BSs. Next, the BSs upload the information to the data center through the fronthaul link. The data center stores, calculates, and integrates the received information. The core network decides on plans for the information that is fused. Finally, it is sent to the vehicle through the backhaul link, and the network unit ensures that the entire NOMA ADV network communication system is unblocked.

Energy-Efficient Resource Allocation in NOMA ADV Networks

In ADV networks, resource management has a vital role, improving utilization of resources in the vehicle network to achieve low latency, and stable and efficient vehicle communication based on the NOMA ADV networks architecture proposed in Fig. 2. We consider the NOMA-based downlink ADV networks, which is one of the innovations in this article. In contrast to the OFDMA system, the NOMA system can not only increase the number of vehicles accessed, but it can also increase the energy efficiency and spectrum utilization of the entire network. As for improving energy efficiency, how to allocate resources is the key problem. In this article, we divide it into two sub-problems of sub-channel matching and power allocation. Finally, we transform the non-convex form energy efficiency problem into a convex form optimization scheme. After iterations, we can get the energy efficiency of the NOMA ADV networks optimized by channel and power optimization.

Subchannel Matching Scheme

In this subsection, we study the subchannel allocation method in NOMA ADV networks considering energy efficiency. In order to dynamically match the vehicle and subchannel, we propose a subchannel matching method. The principle of the method is first to set two empty matrices that are used to record the number of vehicles allocated and not allocated; then the vehicle selects a subchannel with better conditions by CRNNs. When the number of vehicles on a channel is less than two, the vehicle can occupy the channel, at the same time the vehicle is removed from the matrix in the preset the unassigned vehicle. When the number of vehicles on a channel reaches two, once a new vehicle selects the channel, the channel compares the energy efficiency of the three vehicles, selecting two vehicles with higher energy efficiency; the unassigned vehicle continues to select the subchannel in the above method. The vehicle with the selected subchannel is recorded in the matrix of the assigned vehicle, and the unsuccessful vehicle is recorded in the unassigned vehicle. Finally, when all the vehicles are assigned to the subchannel (i.e., the unassigned vehicle matrix is an empty set), the dynamic matching iteration between the vehicle and the subchannel will stop. Compared to the random channel allocation method, matching the subchannel by this method can improve the subchannel utilization and improve the QoS of the vehicle.

Power Allocation Scheme By ADMM

As for further improving the energy efficiency of the ADV network's energy, the introduction of the ADMM algorithm provides a solution to the power allocation

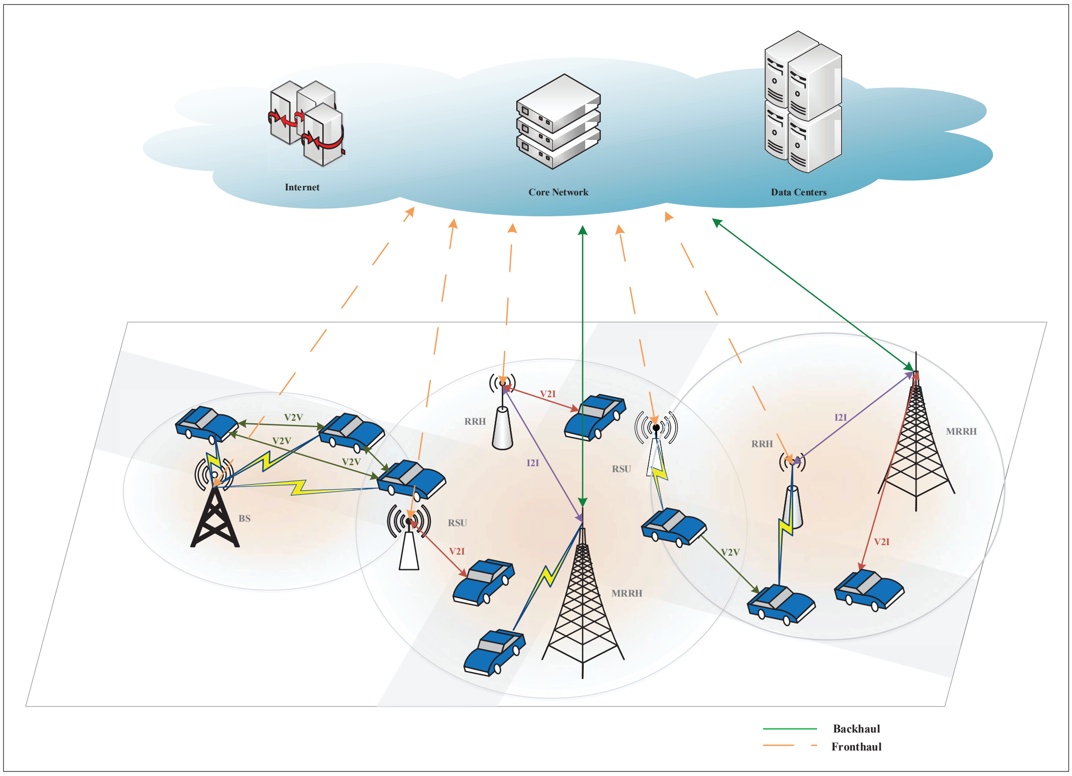

FIGURE 2. The NOMA ADV network system.

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problem in NOMA-based ADV networks. Here we first introduce the principle of the ADMM method.

The ADMM method is a widely used optimization method for solving constraints with minimization problems in machine learning. It integrates the advantages of the decomposition of the dual ascent algorithm and the convergence of the multipliers algorithm. In the mid-1970s, Gabay *et al.* first proposed the ADMM algorithm, and by the middle of the 1990s, the theoretical analysis of the algorithm had gradually improved. ADMM can decompose the original problem into two minimization problems of the objective function and then write it into a slightly simplified form by scaling the augmented Lagrangian function in the dual factor, and combine the linear term and the quadratic term about the equality constraint in the function. It is more convenient to alternate the target variables until the optimal solution is obtained. In this article, based on the fast convergence characteristics of the ADMM algorithm, we use it to achieve the best energy efficiency of the NOMA ADV network. Different from the traditional fixed power allocation method, by introducing the ADMM algorithm to solve the power allocation problem, the energy efficiency of the entire system can be improved.

Therefore, this article combines the characteristics of ADV networks; the subchannel and power are optimally allocated in the NOMA system. In the next section, simulation experiments are performed by changing different parameters, and the effects of parameter changes on system energy efficiency are discussed in detail.

Simulation Results

In this section, by changing the different parameters in the ADV network, the resource allocation scheme we have proposed is simulated in comparison with the existing scheme mentioned earlier, and a brief description of the existing schemes is provided below. We can see from the simulation results that the proposed solution has reliability and better performance. The system parameters are set as follows: taking a macrocell as an example, the mRRH is deployed at the center of the macrocell, and the radius of the mRRH is set to 500 m. It is assumed that the total bandwidth of the system is 1 MHz. The carrier frequency of the mRRH is 2 GHz. In the model of this article, all sRRHs are randomly distributed in the macrocell. We let the noise power spectral density be –174 dBm/Hz.

Fixed Power Allocation Scheme: Fixed power allocation means that the power of sRHHs and mRHHs is equally distributed to each vehicle so that each vehicle gets the same power resource. The subchannel allocation scheme applied here is the proposed subchannel matching scheme.

Random Subchannel Allocation Scheme: This subchannel allocation method randomly allocates vehicles to the channel without comparing channel conditions and allocates up to three vehicles on each channel, and each vehicle occupies at most four channels. The power allocation scheme here is ADMM.

It can be seen from Fig. 3 that the energy efficiency in the ADV network of the proposed scheme and the random subchannel allocation scheme corresponds to the relationship of the iterative index. When the number of iterations gradually increases, the energy efficiency of both algorithms increases gradually. Once the iteration index reaches 6, the energy efficiency tends to be stable. The proposed scheme converges to approximately 85 b/s/Hz/J, while the random subchannel matching scheme converges to 38

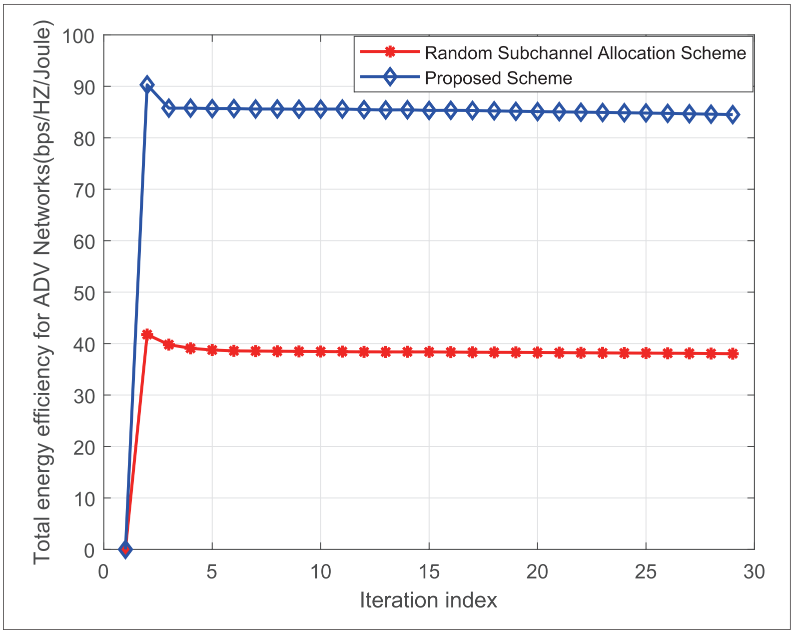

FIGURE 3. Energy efficiency vs. the iteration index.

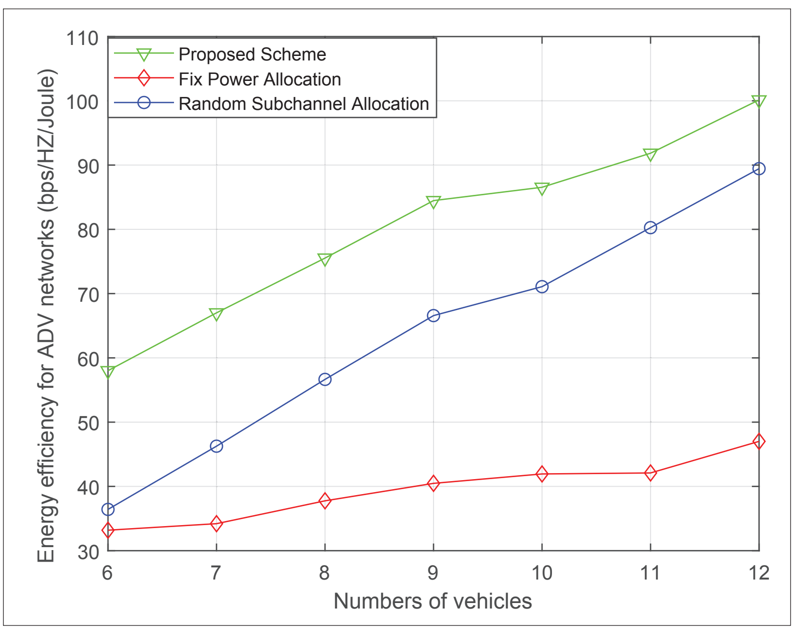

FIGURE 4. Energy efficiency vs. the number of vehicles.

b/s/Hz/J. It is obvious that the proposed algorithm is always higher than the energy efficiency of the random channel allocation scheme. It shows that the proposed algorithm is superior to other algorithms.

Figure 4 illustrates the corresponding change in the energy efficiency of the proposed algorithm and the existing algorithm of the ADV network, with the number of vehicles varying from 5 to 30. When the number of vehicles grows, the energy efficiency of all algorithms continues to rise, but when the vehicles exceed nine, the rate of energy efficiency growth begins to slow down. This phenomenon may be caused by the interference caused by the vehicle occupying the same channel, which affects the overall energy efficiency of the ADV network to some extent, and the performance of the random subchannel allocation scheme is not better than the fixed power allocation scheme. Compared to the other two schemes, Fig. 4 depicts the proposed scheme with higher energy efficiency than the random subchannel allocation scheme which is worse than the fixed power allocation scheme. Thus, the proposed scheme has better performance, and this proves that the proposed scheme promotes the performance of NOMA ADV networks.

Figure 5 depicts the energy efficiency of NOMA ADV networks vs. the number of sRRHs, which is varied from 5 to 30. It demonstrates that the more SRRHs are available, the better the performance of the ADV network. Owing to the number of SRHHs increases, the more use resources can be provided to the vehicles, at the same time, the whole energy efficiency of the ADV network has also increased. Due to the interference between the SRRHs, we can see that the energy efficiency of the ADV network is not a linear curve, since the SRRHs over 9, the rate of growth of the curve is slow, as expected, the performance of the proposed scheme is thoroughly outperforms other schemes.

Figure 6 shows the energy efficiency of NOMA ADV networks vs. the vehicle base station power, the vehicle BS power is varied from 5 dBm to 30 dBm. When the power of the vehicle BS increases, the proposed scheme and the energy efficiency curve of the random channel allocation scheme rise; however, the energy efficiency of the fixed power allocation method decreases, because when the power is a fixed value, the energy efficiency and the vehicle BS power are inversely proportional. As a result, compared to the random subchannel allocation scheme, the proposed scheme achieves higher energy efficiency and better performance.

Conclusion

In this article, we present the ADV network architecture based on NOMA. We investigate the traffic scenarios under two conditions of highways and intersections, analyze the specific traffic communication modes of vehicles in different scenarios, and present the problems and challenges. We consider the resource allocation problem for this problem in NOMA ADV networks. In order to achieve efficient resource utilization and improve system performance in ADV networks, in the proposed scheme, the subchannel matching scheme is used for optimizing channel utilization, using the ADMM algorithm to solve the problem of power allocation. Through the simulation results, we can see that the proposed scheme can have faster convergence characteristics compared to existing works and prove that the proposed scheme can obtain more energy efficiency and has better performance, and also can guarantee the QoS of vehicles in ADV networks.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (61771044), the Research Foundation of the Ministry of Education of China & China Mobile (MCM20170108), the Beijing Natural Science Foundation (L172025, L172049), the 111 Project (No. B170003), and the Fundamental Research Funds for the Central Universities (RC1631). The corresponding author is Haijun Zhang.

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Biographies

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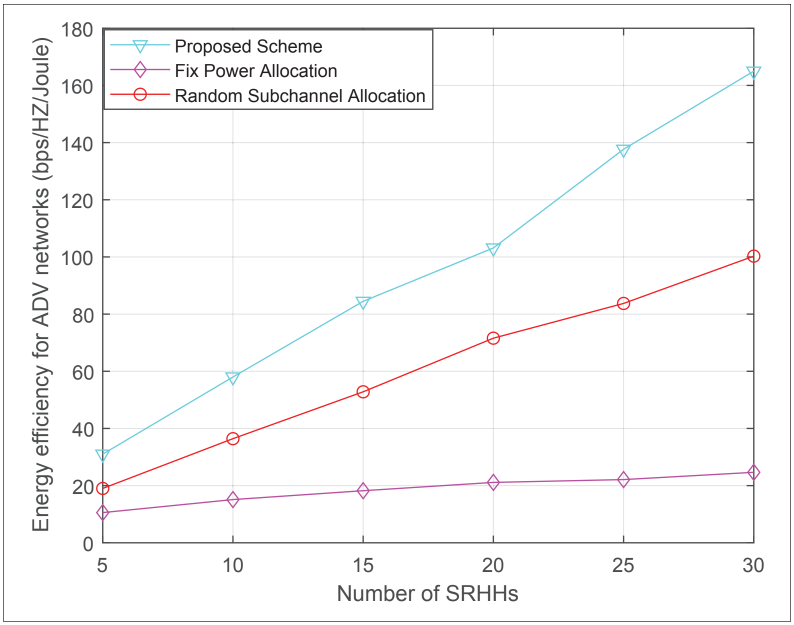

FIGURE 5. Energy efficiency vs. the number of sRRHs.

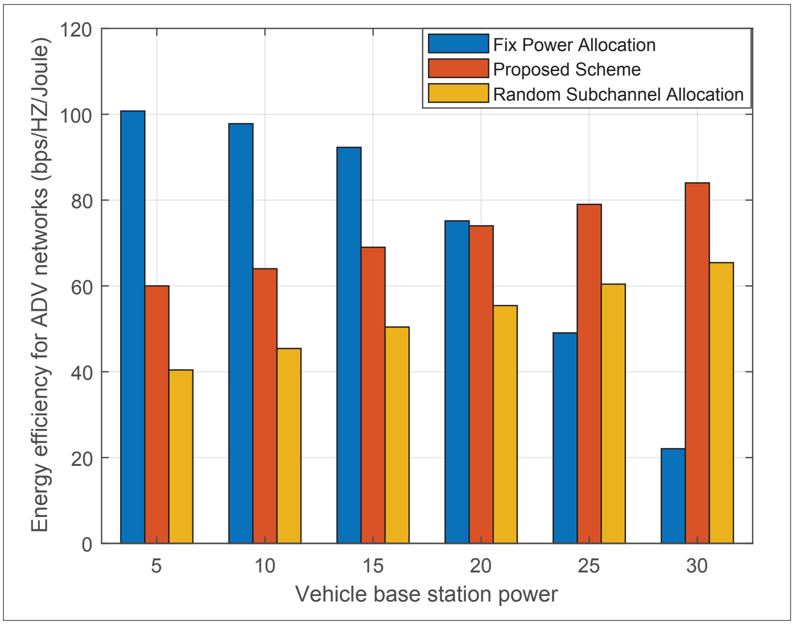

FIGURE 6. Energy efficiency vs. the vehicle base station power.