

Hybrid Multicast/Unicast Design in NOMA-based Vehicular Caching System

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Abstract—In this paper, we investigate a hybrid multi-cast/unicast scheme for a multiple-input single-output cache-aided non-orthogonal multiple access (NOMA) vehicular scenario in the face of rapidly fluctuating vehicular wireless channels. Considering a more practical situation, imperfect channel state information is taken into account. In this paper, we formulate an optimization problem to maximize the unicast sum rate under the constraints of the peak power, the peak backhaul, the minimum unicast rate, and the maximum multicast outage probability. To solve the formulated non-convex problem, a lower bound relaxation method is proposed, which enables a division of the original problem into two convex sub-problems. Computer simulations show that the proposed caching-aided NOMA is superior to the orthogonal multiple access counterpart.

Index Terms—Caching, non-orthogonal multiple access (NOMA), imperfect channel state information (CSI), vehicular communications.

I. INTRODUCTION

RECENTLY, multicast services have been gaining huge interest in cellular networks [1]. With the increasing demand of accessing to both multicast (e.g., proactive content pushing) and unicast services (e.g., targeted advertisements), the hybrid design of multicast and unicast services is a hot topic in the next-generation wireless communication studies [2]. According to the standards ratified by the 3rd generation partnership project (3GPP), multicast and unicast services need to be divided into different time slots or frequencies [3]. On the other hand, non-orthogonal multiple access (NOMA) is a recognized next-generation technology, which shows superior

spectral efficiency performance compared to conventional orthogonal multiple access (OMA) [4]. Unlike OMA, NOMA can distinguish users in the power domain by using successive interference cancellation (SIC) techniques. Compared to conventional cellular networks (e.g., LTE-multicast [3]), NOMA-based hybrid design can realize the requirements in the power-domain. Therefore, applying the NOMA technique to the design of a hybrid multicast/unicast system is envisioned to improve the efficiency of the system significantly [2].

The internet-of-vehicles ecosystem is another crucial technique in the future, in which vehicles need to exchange a massive amount of data with the cloud, resulting in substantial backhaul overhead [5], [6]. As a result, wireless edge caching technology is envisioned to resolve this challenge by storing contents at edge users or base stations in advance during off-peak time [7]. To further enhance system performance for vehicular communication, NOMA is applied [8]. Therefore, it is clearly that the combination of caching, NOMA, and vehicular system is feasible and promising. Nevertheless, to the best of our knowledge, only one work [9] investigates a two-user cache-aided NOMA vehicular network. However, the users' mobility and multiple receivers have not been taken into consideration.

In this context, we introduce a cache-aided NOMA vehicular scheme for a hybrid multicast/unicast system with a backhaul-capacity constraint in the face of rapidly fluctuating vehicular wireless channels. Without loss of generality, we consider one multicast user cluster and K unicast users with high mobility. Additionally, we consider the imperfect Gaussian-distributed channel state information (CSI). The main contributions of this paper are summarized below:

- We study a generalized and practical cache-aided NOMA vehicular system, where K high-speed unicast vehicular users and one multicast user cluster coexist. Moreover, we take the backhaul constraint and imperfect CSI (I-CSI) into consideration and study their impacts on the proposed schemes.
- We formulate an optimization problem for the joint design in order to find the maximum sum rate of unicast users. With the aid of a proposed lower bound relaxation method, we turn the non-convex problem into a convex problem. We achieve a feasible solution by dividing the formulated problem into two convex sub-problems.
- We compare the cache-aided NOMA scheme with the cache-aided OMA one. Results reveal that the NOMA scheme achieves a much higher unicast sum rate than the OMA scheme. In addition, it shows that the cache-aided

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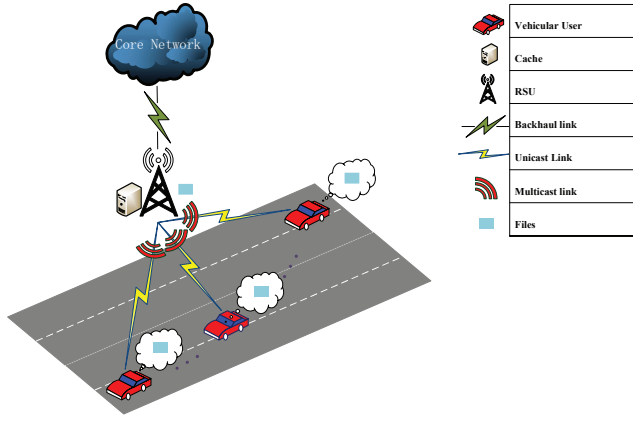


Fig. 1. System model.

system can alleviate the backhaul link.¹

II. SYSTEM MODEL

We consider a vehicular downlink single-input single-output (SISO) transmission system, where a roadside unit (RSU), configured with one transmit antenna, provides hybrid multicast and unicast services to K vehicular users (denoted by $U_i, i \in \{1, \dots, K\}$), equipped with a single antenna. As shown in Fig. 1, RSU is allocated with some cache resources, and the backhaul link of RSU is assumed to be capacity-limited. For simplicity of analysis, we study the case of a single one multicast group, i.e., $\{U_i\}$, while the case of multiple multicast groups will be extended in the future work.

A. Transmission Model

Let $x_M, x_i (i \in \{1, \dots, K\})$ be the data symbols corresponding to multicast and unicast transmissions, respectively. All the data symbols are assumed to have the same unit power, i.e., $E[|x_M|^2] = E[|x_i|^2] = 1$. It is assumed that RSU uses the NOMA protocol to send the superimposed signal to all users, which apply the SIC technique to decode the signal. To be realistic, we assume that the channel estimation processes are imperfect [10]. Hence, we have $h_i(t) = \sqrt{1 - \phi^2} \hat{h}_i(t) + \phi \epsilon_i(t)$, where h_i denotes the channel vector from RSU to U_i , $\hat{h}_i(t) \in \mathbb{C}^{N_t \times 1}$ denotes the estimated channel vector between the same nodes with variance Ω_i , and $\epsilon_i \in \mathbb{C}^{N_t \times 1}$ denotes the estimation error vector with variance $\Omega_{\epsilon,i}$. For convenience, $\Omega_{\epsilon,i}$ is assumed to be a constant Ω_ϵ . All the channels are characterized by Jakes' model [11] to measure users' mobility, i.e., $\phi = J_0(2\pi f_c v_i / c\tau)$, where J_0 is the zeroth-order Bessel function of the first kind, f_c denotes the carrier frequency, v_i indicates the moving velocity of U_i , c is the light speed, and τ represents the duration between two adjacent time slots. Without loss of generality, we sort the average power of RSU $- U_i$ links as $|h_1|^2 \geq \dots \geq |h_K|^2$. For the sake of fairness, a minimum rate limitation, namely r_{min} is set. The unicast rate of each user must satisfy $r_i^U \geq r_{min}$.

Considering any active time slot, RSU transmits a superimposed signal as $z = \sqrt{\beta_M P} x_M + \sum_{i=1}^K \sqrt{\beta_U P_i} x_i$,

¹Notation: $\mathcal{N}_c(\mu, \sigma_0^2)$ denotes complex Gaussian distribution with mean μ and variance σ_0^2 . $F_X(\cdot)$ denotes the cumulative distribution function (CDF) of random variable X .

where β_M and β_U denote the power allocation coefficients for multicast and unicast transmissions, respectively; P and $P_i (\sum_{i=1}^K P_i = P)$ denote the transmit power in multicast layer and for U_i in unicast layer, respectively. Let y_i be the received signal at U_i , which is given as: $y_i = \sqrt{\beta_M P} h_i x_M + \sum_{j=1}^K \sqrt{\beta_U P_j} h_i x_j + n_i$, where $n_i \sim \mathcal{N}_c(0, \Omega_0)$ is additive white Gaussian noise (AWGN). Because in the downlink system, multicast mode is more resource-efficient than unicast mode, multicast messages should have a higher priority [12]. Therefore, the multicast messages are assumed to be decoded and subtracted before decoding the unicast messages. Thus, the data rate of x_M at U_i can be obtained as

$$r_i^M = \log_2 \left(1 + \frac{\rho_M \lambda_i}{\rho_U \lambda_i + \Psi} \right), \quad (1)$$

where $\lambda_i = |\hat{h}_i(n)|^2$, $\rho_M = \beta_M P / \Omega_0$, $\rho_U = \beta_U P / \Omega_0$, $a = 1/(1 - \phi^2)$, $b = \phi^2/(1 - \phi^2) \Omega_\epsilon$, and $\Psi = (\rho_M + \rho_U)b + a$. Obviously, $\rho_M + \rho_U = \rho$, where $\rho = P / \Omega_0$. Similarly, the instantaneous rate of x_i observed at U_i can be derived as

$$r_i^U = \log_2 \left(1 + \rho_i \lambda_i / \left(\sum_{j=1}^{i-1} \rho_j \lambda_j + \sum_{j=1}^i \rho_j b + a \right) \right), \quad (2)$$

for $i \in \{1, \dots, K\}$, where $\rho_i = \beta_U P_i / \Omega_0$. The detailed derivations of (1) and (2) are shown in [13].

B. Cache Model

We assume that the ergodic rate of the backhaul link between RSU and the core network is subject to R bit/s/Hz. Besides, we assume that RSU is equipped with a finite capacity cache of size N . Let $\mathcal{F} = \{1, 2, \dots, F\}$ denote the content of F files, each with normalized size of 1. Obviously, not all users can ask for their unicast messages at a time slot. As adopted in most existing works [14], the popularity profile on \mathcal{F} is modeled by a Zipf distribution, with a skewness control parameter ζ . Specifically, the popularity of file f (denoted by $q_f, f \in \mathcal{F}$), is given by $q_f = f^{-\zeta} / \sum_{j=1}^F j^{-\zeta}$, which follows $\sum_{f=1}^F q_f = 1$. Let c_f represent the probability that RSU caches the file f , satisfying $0 \leq c_f \leq 1$. Due to cache capacity limit at RSU, we can obtain $\sum_{f=1}^F c_f \leq N$.

III. PROBLEM FORMULATION

Without loss of generality, the reception performance of multicast messages x_M should meet the users' quality of service (QoS) requirements, i.e., each user has a preset target rate R_M . As for unicast messages, they are assumed to be received opportunistically according to the user's channel condition [4]. Therefore, we use the outage probabilities and instantaneous achievable rates to measure the reception performance of multicast and unicast messages, respectively.

A. Outage Probability

Since the CDF of λ_i is $F_{\lambda_i}(x) = 1 - \exp(-x/\Omega_i)$, given the definition of the outage probability of x_M at U_i (denoted by P_i^M), namely, $P_i^M = \Pr\{r_i^M < R_M\}$, we have

$$P_i^M = 1 - \exp \left(- \frac{\Psi \theta_M}{(\rho_M - \theta_M \rho_U) \Omega_i} \right), \quad (3)$$

where $\theta_M = 2^{R_M} - 1$. Obviously, $P_i^M > 0$; in other words, we have $\rho_U < \rho/2^{R_M}$.²

B. Optimization Problem

Notably, our objective is to maximize the sum rate of unicast signals, and the optimization problem can be formulated as

$$P_0 : \quad \max_{c_f, \rho_U, \rho_i} \quad \sum_{i=1}^K r_i^U$$

$$s.t. \quad P_i^M < \delta, \quad (4a)$$

$$r_i^U \geq r_{min}, \quad (4b)$$

$$\sum_{i=1}^K \rho_i = \rho_U, \quad (4c)$$

$$\rho_M + \rho_U = \rho, \quad (4d)$$

$$\sum_{f=1}^F \sum_{i=1}^K q_f(1 - c_f)r_i^U \leq R, \quad (4e)$$

$$0 \leq c_f \leq 1, \quad (4f)$$

$$\sum_{f=1}^F c_f \leq N, \quad (4g)$$

where (4a) and (4b) indicate the QoS requirements for the multicast and the unicast messages, respectively; (4c) and (4d) denote transmit power relationships for different signals; (4e) indicates the backhaul capacity constraint; (4f) indicates the value range of cache probability; (4g) represents the cache capacity limit at the RSU. Without loss of generality, we have the outage requirement δ satisfying $0 < \delta < 1$, i.e., $\ln(1 - \delta) < 0$. Therefore, by substituting (3) and (4d) into (4a), for $\rho_U < \rho/2^{R_M}$, we can arrive at $\rho_U \leq \Psi\theta_M/(2^{R_M}\Omega_i \ln(1 - \delta)) + \rho/2^{R_M}$. Therefore, P_0 can be equivalently rewritten as

$$P_1 : \quad \max_{c_f, \rho_U, \rho_i} \quad \sum_{i=1}^K r_i^U$$

$$s.t. \quad \rho_U \leq \frac{\Psi\theta_M}{2^{R_M}\Omega_1 \ln(1 - \delta)} + \frac{\rho}{2^{R_M}}, \quad (5a)$$

$$(4b), (4c), (4e) - (4g).$$

IV. PROPOSED LOWER BOUND RELAXATION METHOD

Evidently, the objective function of P_1 is non-convex and hard to solve. Moreover, as shown in (2), $(\lambda_i + b)$ in the denominator makes r_i^U hardly be reformulated. Therefore, we use the *lower bound relaxation* method, which can be derived as

$$r_i^U = \log_2 \left(1 + \rho_i \lambda_i / \left(\sum_{j=1}^{i-1} \rho_j \lambda_j + \Psi \right) \right). \quad (6)$$

The detailed derivation of (6) is shown in [13]. Invoking [15], ρ_U can be split into two parts: ρ_{min} for r_{min} and $\Delta\rho$ for $\sum_{i=1}^K \Delta r_i^U$. The minimum transmit signal-to-noise

ratio (SNR) and the excess transmit SNR of U_i are denoted by $\rho_{i,min}$ and $\Delta\rho_i$, respectively.³ Apparently, we have $\rho_{min} = \sum_{i=1}^K \rho_{i,min}$ and $\Delta\rho = \sum_{i=1}^K \Delta\rho_i$. For convenience, we use ρ_{sum}^{min} to represent the sum of $\rho_{i,min}$, i.e., $\rho_{sum}^{min} = \sum_{i=1}^K \rho_{i,min}$. After several mathematical steps, we can obtain **Propositions 1** and **2**. See Appendix A for the proofs of them.

Proposition 1: With fixed r_{min} , we have

$$\rho_{sum}^{min} = (2^{r_{min}} - 1) \sum_{i=0}^{K-1} 2^{ir_{min}} / \lambda_{K-i}, \quad (7)$$

and

$$\sum_{i=1}^K r_i^U = Kr_{min} + \sum_{i=1}^K \Delta r_i^U. \quad (8)$$

For ease of representation, by defining

$$\rho_i^e = (\Delta\rho_i - (2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta\rho_j) 2^{(K-i)r_{min}}, \quad (9)$$

and $n_i^e = (\Psi/\lambda_i + \sum_{j=1}^i \rho_{j,min}) 2^{(K-i)r_{min}}$, we can arrive at $\Delta r_i^U = \log_2 \left(1 + \rho_i^e / (n_i^e + \sum_{j=1}^{i-1} \rho_j^e) \right)$.

Proposition 2: The more power we allocate to the users with stronger channel conditions, the higher the sum rate is. In other words, when all the excess power is allocated to U_1 , we have the optimal solution as $\sum_{i=1}^K \Delta r_i^U = \Delta r_1^U = \log_2(1 + (\rho_U - \rho_{sum}^{min})\lambda_1/(\Psi 2^{Kr_{min}}))$.

Occupying the **Propositions** above, P_1 can be derived as

$$P_2 : \quad \max_{c_f, \rho_U, \rho_i} \quad Kr_{min} + \sum_{i=1}^K \Delta r_i^U$$

$$s.t. \quad (4c), (4f), (4g), (5a),$$

$$Kr_{min} + \sum_{i=1}^K \Delta r_i^U \leq \frac{R}{\sum_{f=1}^F q_f(1 - c_f)}, \quad (10a)$$

$$\Delta r_i^U = \log_2 \left(1 + \frac{\rho_i^e}{n_i^e + \sum_{j=1}^{i-1} \rho_j^e} \right). \quad (10b)$$

Obviously, P_2 is still hard to solve due to (4c), (5a), and (10a). If we can fix ρ_i , P_2 will be facilitated. Therefore, our aim is to find a value of ρ_U which always satisfies (4c) and (5a), with any distribution of ρ_i . To elaborate a little further, first, we assume to allocate all excess power to U_1 as shown in **Proposition 2**. Obviously, this is the maximum value of the objective function which ρ_i can achieve in various distributions and also the strictest (10a) limitation. In this case, (10a) can be rewritten as $Kr_{min} + \Delta r_1^U \leq R/(\sum_{f=1}^F q_f(1 - c_f))$. Apparently, $\rho_U = 0$ is a feasible point, which leads to $\rho_{min} = 0$, $\Delta\rho = 0$, and $r_{min} = 0$. In this case, (5a) and (10a) are bound to be satisfied. Consequently, we can achieve P_3 as

$$P_3 : \quad \max_{c_f, \rho_U} \quad \text{obj} = Kr_{min} + \Delta r_1^U$$

$$s.t. \quad (4f), (4g), (5a), (10a),$$

²This condition ensures the quality of service of multicast signals, but may not hold when there exists interrupt.

³It is assumed that with $\rho_{i,min}$ ($i \in \{1, \dots, K\}$), U_i will achieve the same data rate r_{min} .

Algorithm 1 Algorithm for Solving The Problem

Initialization: System Parameters, $Converge=false$, iteration index $l = 1$, and tolerance δ .

Output: System sum rate.

```

1: while  $Converge=false$  do
2:    $l = l + 1$ ;
3:   Solve  $P_4$  for current  $\rho_U^{(l)}$ .
4:   With  $\rho_U^{(l)}$ , solve  $P_5$  for current  $c_f^{(l)}$ .
5:   Calculate  $obj^{(l)}$ .
6:   if  $|obj^{(l)} - obj^{(l-1)}| \leq \delta$  then
7:      $Converge=true$ ,  $obj^* = obj^{(l)}$ .
8:   end if
9: end while
10: return Optimal system sum rate  $obj^*$ .

```

$$\Delta r_1^U = \log_2 \left(1 + \frac{(\rho_U - \rho_{sum}^{min})\lambda_1}{\Psi 2^{Kr_{min}}} \right), \quad (11a)$$

$$\rho_{sum}^{min} = (2^{r_{min}} - 1) \sum_{i=0}^{K-1} \frac{2^{ir_{min}}}{\lambda_{K-i}}. \quad (11b)$$

However, P_3 is still non-convex. Hence, we divide it into two convex sub-problems to find its optimal solution. For given c_f , problem P_3 reduces to

$$P_4: \max_{\rho_U} \text{obj} \quad \text{s.t.} \quad (5a), (10a), (11a), (11b).$$

For given ρ_U , problem P_3 reduces to

$$P_5: \max_{c_f} \text{obj} \quad \text{s.t.} \quad (4f), (5a), (10a), (11b).$$

Based on P_4 and P_5 , we can obtain the *lower bound* of the optimal solution of P_3 in **Algorithm 1**.

Lemma 1. **Algorithm 1** guarantees convergence.

Proof. Cauchy's theorem proves that function with compact and continuous constraint set always converges. Besides, solving P_4 and P_5 alternatively guarantees the convergence [16].⁴ Therefore, proposed algorithm is convergent. \square

Lemma 2. The time complexity of **Algorithm 1** is $\mathcal{O}(\frac{1}{\delta^2})$.

Proof. The complexity of sub-linear rate, e.g., $f^{(l)} - f^* \leq \delta$ is $\mathcal{O}(\frac{1}{\delta^2})$. Therefore, the complexity of the proposed algorithm is obtained. \square

V. NUMERICAL RESULTS

In this section, we discuss the performance of the proposed cache-aided NOMA, and compare it with the cache-aided OMA systems. The transmit power at RSU is set as $P = 10$ W and the backhaul capacity constraint is set as $R = 5$ bit/s. We consider that RSU serves $K = 2$ and $K = 3$ vehicles respectively. For convenience, we set $(\Omega_1, \Omega_2) = (10, 5)$ for the scenario where $K = 2$, and $(\Omega_1, \Omega_2, \Omega_3) = (10, 5, 1)$ for the scenario where $K = 3$. In addition, the detailed settings of

⁴Since ρ_U and c_f are mutually decoupling, we can calculate them alternatively.

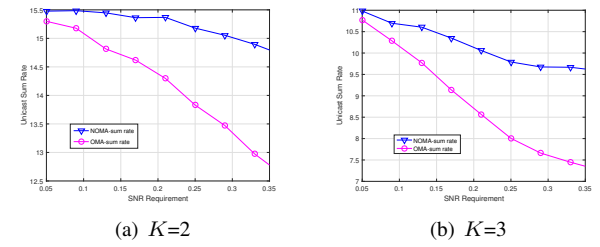


Fig. 2. Sum-rate versus minimum rate constraint with cache size $N = 2$.

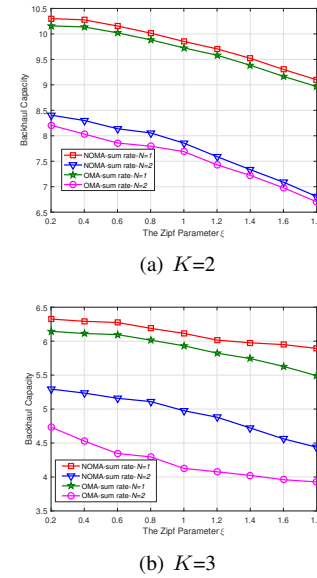


Fig. 3. Backhaul capacity versus cache size with minimum rate constraint $r_{min} = 0.2$.

the Jakes' model are shown as follows: $v_i = 150$ km/h, which is practical especially for a highway scenario; $f_c = 5.9$ GHz; $\tau = 10^{-6}$. The noise power is set as $\Omega_0 = 1$ W. As for the CSI estimation errors, we set $\Omega_e = 0.1$. The outage probability threshold for multicast service is set as $\delta = 0.1$.

In Fig. 2, we compare the unicast sum rate of cache-aided NOMA with that of the OMA counterpart under different minimum rate constraints. As expected, the NOMA scheme outperforms the OMA one in all cases. Obviously, the sum rates decrease when r_{min} increases, but the decrease is moderate. This is because Kr_{min} is linearly increased while Δr_1^U is exponentially decreased. Furthermore, compare Figs. 2(a) and 2(b), we can easily find that the systems with three users have lower unicast sum rate. This is because when the transmission power of the RSU is fixed, the increase of the user will also aggravate the interference, which leads to the decrease of the receiving performance, and finally affects the unicast rate.

Figure 3 shows the backhaul capacity versus the zipf parameter ξ for different cache size N . Obviously, as ξ increases, the backhaul capacity decreases, which comes from the fact that larger ξ represents the more concentrated request hotspots. In other words, the probabilities that the cached files at RSU are requested by users are larger, which reduces the backhaul overhead. Moreover, one can observe that the backhaul capacity of the NOMA scheme is always larger than that of the OMA one. This is because, compared to

OMA, NOMA shows a superior unicast rate performance and therefore requires a relatively higher amount of backhaul resources. Besides, we can find that an increasing number of users will decrease the backhaul capacity, whose cause is the same as that of the previous figure.

VI. CONCLUSIONS

In this paper, we have incorporated multicast and unicast services into a cache-aided SISO vehicular NOMA system with high mobility. We have formulated an optimization problem to maximize the unicast sum rate subject to the peak power, the backhaul capacity, the minimum unicast rate, and the maximum multicast outage probability constraints. The proposed non-convex problem has been appropriately solved by the proposed lower bound relaxation method. Simulation results have demonstrated that our proposed cache-aided NOMA scheme outperforms the OMA counterpart.

REFERENCES

- [1] M. Fallgren *et al.*, "Multicast and broadcast enablers for high-performing cellular V2X systems," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 454–463, Jun. 2019.
- [2] E. Chen, M. Tao, and Y. Liu, "Joint base station clustering and beamforming for non-orthogonal multicast and unicast transmission with backhaul constraints," *IEEE Trans. Wireless Commun.*, vol. 17, no. 9, pp. 6265–6279, Sept. 2018.
- [3] D. Lecompte and F. Gabin, "Evolved multimedia broadcast/multicast service (eMBMS) in LTE-advanced: overview and Rel-11 enhancements," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 68–74, Nov. 2012.
- [4] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Process. Lett.*, vol. 21, no. 12, pp. 1501–1505, Dec. 2014.
- [5] S. K. Datta, J. Haerri, C. Bonnet, and R. Ferreira Da Costa, "Vehicles as connected resources: Opportunities and challenges for the future," *IEEE Veh. Technol. Mag.*, vol. 12, no. 2, pp. 26–35, Jun. 2017.
- [6] X. Pei, H. Yu, X. Wang, Y. Chen, M. Wen, and Y. Wu, "NOMA-based pervasive edge computing: Secure power allocation for IoV," *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2020.3001955.
- [7] Z. Ding, P. Fan, G. K. Karagiannis, R. Schober, and H. V. Poor, "NOMA assisted wireless caching: Strategies and performance analysis," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4854–4876, Oct. 2018.
- [8] Y. Chen, L. Wang, Y. Ai, B. Jiao, and L. Hanzo, "Performance analysis of NOMA-SM in vehicle-to-vehicle massive MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2653–2666, Dec. 2017.
- [9] S. Gurugopinath, P. C. Sofotasios, Y. Al-Hammadi, and S. Muhaidat, "Cache-aided non-orthogonal multiple access for 5G-enabled vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 8359–8371, Sept. 2019.
- [10] K. S. Ahn and R. W. Heath, "Performance analysis of maximum ratio combining with imperfect channel estimation in the presence of cochannel interferences," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1080–1085, Mar. 2009.
- [11] Y. M. Khatibi and M. M. Matalgah, "Alamouti-OSTBC wireless cooperative networks with mobile nodes and imperfect CSI estimation," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3447–3456, Apr. 2018.
- [12] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: A survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 148–157, May 2013.
- [13] X. Pei, H. Yu, Y. Chen, M. Wen, and G. Chen, "Hybrid multicast/unicast design in NOMA-based vehicular caching system with supplementary material," *arXiv: 2011.03232*, 2020.
- [14] S. H. Chae and W. Choi, "Caching placement in stochastic wireless caching helper networks: Channel selection diversity via caching," *IEEE Trans. Wireless Commun.*, vol. 15, no. 10, pp. 6626–6637, Oct. 2016.
- [15] Z. Chen, Z. Ding, X. Dai, and R. Zhang, "An optimization perspective of the superiority of NOMA compared to conventional OMA," *IEEE Trans. Signal Process.*, vol. 65, no. 19, pp. 5191–5202, Oct. 2017.
- [16] S. Boyd and L. Vandenberghe, *Convex Optimization*, New York, NY, USA: Cambridge Univ. Press, 2004.

APPENDIX A

PROOFS OF *Propositions 1* AND *2*

Being allocated $\rho_{i,min}$, the unicast rate of U_i can achieve r_{min} , i.e.,

$$r_{min} = \log_2 \left(1 + \rho_{i,min} \lambda_i / \left(\sum_{j=1}^{i-1} \rho_{j,min} \lambda_i + \Psi \right) \right), \quad (\text{A.1})$$

which yields

$$2^{r_{min}} - 1 = \rho_{i,min} / \left(\sum_{j=1}^{i-1} \rho_{j,min} + \Psi / \lambda_i \right). \quad (\text{A.2})$$

Using partition ratio theorem, (A.2) can be formulated as

$$\begin{aligned} \frac{(2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^{i-1} \Delta \rho_j} &= \frac{\rho_{i,min}}{\sum_{j=1}^{i-1} \rho_{j,min} + \Psi / \lambda_i} \\ &= \frac{\rho_{i,min} + (2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^{i-1} \rho_{j,min} + \sum_{j=1}^{i-1} \Delta \rho_j + \Psi / \lambda_i}. \end{aligned} \quad (\text{A.3})$$

Substituting (A.3) into (A.1), we can obtain

$$r_{min} = \log_2 \left(1 + \frac{\rho_{i,min} + (2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^{i-1} \rho_j + \Psi / \lambda_i} \right). \quad (\text{A.4})$$

Therefore, Δr_i^U can be expressed as

$$\begin{aligned} \Delta r_i^U &= r_i^U - r_{min} \\ &= \log_2 \left(1 + \frac{\Delta \rho_i - (2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^i \rho_{j,min} + \frac{\Psi}{\lambda_i} + 2^{r_{min}} \sum_{j=1}^{i-1} \Delta \rho_j} \right) \\ &= \log_2 \left(1 + \frac{\mathcal{P}_i}{\mathcal{N}_i + \mathcal{Q}_i} \right), \end{aligned} \quad (\text{A.5})$$

where $\mathcal{P}_i = \Delta \rho_i - (2^{r_{min}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j$, $\mathcal{N}_i = \sum_{j=1}^i \rho_{j,min} + \frac{\Psi}{\lambda_i}$, and $\mathcal{Q}_i = 2^{r_{min}} \sum_{j=1}^{i-1} \Delta \rho_j$. Using the properties of *recurrence*, we have

$$\mathcal{Q}_i = 2^{r_{min}} \sum_{j=1}^{i-1} \Delta \rho_j = \sum_{j=1}^{i-1} (2^{r_{min}})^{i-j} \mathcal{P}_j. \quad (\text{A.6})$$

Let ρ_i^e denote $\mathcal{P}_i (2^{r_{min}})^{K-i}$. Then, we can rewrite (A.6) into $\mathcal{Q}_i (2^{r_{min}})^{K-i} = \sum_{j=1}^{i-1} (2^{r_{min}})^{K-j} \mathcal{P}_j = \sum_{j=1}^{i-1} \rho_j^e$. Therefore, we can derive

$$\Delta r_i^U = \log_2 \left(1 + \frac{\rho_i^e}{n_i^e + \sum_{j=1}^{i-1} \rho_j^e} \right), \quad (\text{A.7})$$

where $n_i^e = (\Psi / \lambda_i + \sum_{j=1}^i \rho_{j,min}) 2^{(K-i)r_{min}}$. On the other hand, (A.2) can be rewritten as $\rho_{i,min} = (2^{r_{min}} - 1) (\sum_{j=1}^{i-1} \rho_{j,min} + \Psi / \lambda_i)$. After the recurrence operation, we have

$$\rho_{i,min} = \frac{2^{r_{min}} - 1}{\lambda_i} + \frac{(2^{r_{min}} - 1)^2 2^{(i-j-1)r_{min}}}{\lambda_i}, \quad (\text{A.8})$$

which results in $\rho_{sum}^{min} = \sum_{i=1}^K \rho_{i,min} = (2^{r_{min}} - 1) \sum_{i=0}^{K-1} 2^{ir_{min}} / \lambda_{K-i}$. Because ρ_{sum}^{min} represents all the excess power, $\rho_i^e \leq \rho_{sum}^{min}$. Therefore, when $i = 1$, $\rho_i^e = \rho_{sum}^{min}$, (A.7) achieves its optimal value. The proofs complete.