Abstract—In this paper, we investigate a hybrid multicast/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 taking 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], [4]. 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) [5], [6]. 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 [7]), 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 [2]. 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 [8], [9]. To further enhance system performance for vehicular communication, NOMA is applied [10], [11]. 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 [12] 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 system can alleviate the backhaul link.

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Notation: $N_0(\mu, \sigma^2)$ denotes complex Gaussian distribution with mean $\mu$ and variance $\sigma^2$. $F_X(\cdot)$ denotes the cumulative distribution function (CDF) of random variable $X$. 

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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 $U_i$, $i \in \{1, ..., K\}$), 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 $x_M, x_i = (i \in \{1, ..., K\})$ 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., $\mathbb{E}[|x_M|^2] = \mathbb{E}[|x_i|^2] = 1$. 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\(^{\text{13}}\). Hence, we have $h_i(t) = \sqrt{1 - \varphi^2} h_i(t) + \phi x_i(t)$, where $h_i$ denotes the channel vector from RSU to $U_i$, $\hat{h}_i(t) \in \mathbb{C}^{N \times 1}$ denotes the estimated channel vector between the same nodes with variance $\Omega_i$, and $\phi \in \mathbb{C}^{N \times 1}$ denotes the estimation error vector with variance $\Omega_e$. For convenience, $\Omega_e$ is assumed to be a constant $\Omega$. All the channels are characterized by Jakes’ model\(^{\text{14}}\) 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 $\tau$ represents the duration between two adjacent time slots. Without loss of generality, we sort the average power of RSU – $U_i$ links as $|h_1|^2 \geq \cdots \geq |h_K|^2$. For the sake of fairness, a minimum rate limitation, namely $r_{min}$ is set. The unicast rate of each user must satisfy $r_i \geq r_{min}$.

Considering any active time slot, RSU transmits a superimposed signal as $z = \sqrt{\beta_M} x_M + \sum_{i=1}^{K} \sqrt{\beta_U} x_i$, where $\beta_M$ and $\beta_U$ denote the power allocation coefficients for multicast and unicast transmissions, respectively; $P$ and $P_i \left(\sum_{i=1}^{K} P_i = P\right)$ 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: $y_i = \sqrt{\beta_M} x_M + \sum_{j=1}^{K} \sqrt{\beta_U} h_j x_j + n_i$, where $n_i \sim \mathcal{C}(0, \Omega_0)$ 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\(^{\text{15}}\). 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

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

where $\lambda_i = |h_i|^2$, $\rho_M = \beta_M P / \Omega_0$, $\rho_U = \beta_U P / \Omega_0$, $a = 1 / (1 - \beta^2)$, $b = \beta^2 / (1 - \beta^2) \Omega_z$, 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

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

for $i \in \{1, ..., K\}$, where $\lambda_i = \beta_i P_i / \Omega_0$. The detailed derivations of (1) and (2) are shown in the end of this paper.

### 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 $\mathcal{F} = \{1, 2, \cdots, F\}$ 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\(^{16}\), the popularity profile on $\mathcal{F}$ is modeled by a Zipf distribution, with a skewness control parameter $\zeta$. 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\(^{\text{15}}\). 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 $\lambda_i$ 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

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

where $\theta_M = 2R_M - 1$. Obviously, $P_i^M > 0$; in other words, we have $\rho_U < \rho / 2R_M$\(^{\text{2}}\). This condition ensures the quality of service of multicast signals, but may not hold when there exists interrupt.
B. Optimization Problem

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

\[
P_0 : \quad \text{max} \quad \sum_{i=1}^{K} r_i^U
\]

\[
s.t. \quad P_i^M < \delta, \quad r_i^U \geq r_{\min}, \quad \sum_{i=1}^{K} \rho_i = \rho_U, \quad \rho_M + \rho_U = \rho, \quad \sum_{j=1}^{F} q_f (1 - c_f) r_i^U \leq R,
\]

\[
0 \leq c_f \leq 1, \quad \sum_{f=1}^{F} c_f \leq N,
\]

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 \(\delta\) satisfying \(0 < \delta < 1\), i.e., \(\ln(1-\delta) < 0\). Therefore, by substituting (3) and (4d) into (4a), for \(\rho_U < \rho/2R_M\), we can arrive at \(\rho_U \leq \Psi \theta_M / (2R_M \Omega, \ln (1-\delta)) + \rho/2R_M\). Therefore, \(P_0\) can be equivalently rewritten as

\[
P_1 : \quad \text{max} \quad \sum_{i=1}^{K} r_i^U
\]

\[
s.t. \quad P_i^M < \delta, \quad r_i^U \geq r_{\min}, \quad \rho_U \leq \Psi \theta_M / (2R_M \Omega, \ln (1-\delta)) + \rho/2R_M .
\]

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

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

The detailed derivation of (6) is shown in the end of this paper. Invoking (6), \(\rho_U\) can be split into two parts: \(\rho_{\min}\) 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.\(\rho_{i,\min}\) and \(\Delta \rho = \sum_{i=1}^{K} \Delta \rho_i\) for convenience, we use \(\rho_{\min}^{sum}\) to represent the sum of \(\rho_{i,\min}\), i.e., \(\rho_{\min}^{sum} = \sum_{i=1}^{K} \rho_{i,\min}\). After several mathematical steps, we can obtain Proposition 1 and 2. See Appendix A for the proofs of them.

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

\[
\rho_{\min}^{sum} = (2^{r_{\min} - 1} - 1) \sum_{i=0}^{K-1} 2^{r_{\min} / \lambda_{K-i}} , \tag{7}
\]

and

\[
\sum_{i=1}^{K} r_i^U = K r_{\min} + \sum_{i=1}^{K} \Delta r_i^U . \tag{8}
\]

For ease of representation, by defining

\[
\rho_i^* = (\Delta \rho_i - (2^{r_{\min} - 1} - 1) \sum_{j=1}^{i-1} \Delta \rho_j ) 2^{(K-i) r_{\min}} \tag{9}
\]

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

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 \(\sum_{i=1}^{K} \Delta r_i^U = \Delta r_1^U = \log_2 \left( 1 + (\rho_U - \rho_{\min}^{sum}) / \Psi 2^{K r_{\min}} \right)\).

Occupying the Propositions above, \(P_1\) can be derived as

\[
P_2 : \quad \text{max} \quad K r_{\min} + \sum_{i=1}^{K} \Delta r_i^U
\]

\[
s.t. \quad \rho_{\min}^{sum} \leq \sum_{f=1}^{R} q_f (1 - c_f), \quad \Delta r_i^U = \log_2 \left( 1 + \rho_i^* / \left( \sum_{j=1}^{i} \rho_j^* \right) \right) .
\]

Obviously, \(P_2\) is still hard to solve due to (4a), (5a), and (10a). If we can fix \(\rho_U\), \(P_2\) will be facilitated. Therefore, our aim is to find a value of \(\rho_U\) which always satisfies (4a) and (5a), with any distribution of \(\rho_i\). 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 \(\rho_i\) can achieve in various distributions and also the strictest (10a) limitation. In this case, (10a) can be rewritten as \(K r_{\min} + \sum_{i=1}^{K} \Delta r_i^U \leq R / (\sum_{f=1}^{R} q_f (1 - c_f))\).

Apparentely, \(\rho_U = 0\) 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

\[
P_3 : \quad \text{max} \quad \text{obj} = K r_{\min} + \sum_{i=1}^{K} \Delta r_i^U
\]

\[
s.t. \quad \Delta r_i^U = \log_2 \left( 1 + \rho_i^* / \left( \sum_{j=1}^{i} \rho_j^* \right) \right) .
\]

\[
\rho_{\min}^{sum} = (2^{r_{\min} - 1} - 1) \sum_{i=0}^{K-1} 2^{r_{\min} / \lambda_{K-i}} \tag{11b}
\]
Algorithm 1 Algorithm for Solving The Problem
Initialization: System Parameters, $Converge=false$, iteration index $l = 1$, and tolerance $\delta$.
Output: System sum rate.
1: while $Converge=false$ do
2: \hspace{0.5cm} $l = l + 1$; 
3: \hspace{0.5cm} Solve $P_4$ for current $\rho_U^{(l)}$.
4: \hspace{0.5cm} With $\rho_U^{(l)}$, solve $P_5$ for current $c_f^{(l)}$.
5: \hspace{0.5cm} Calculate $obj^{(l)}$.
6: \hspace{0.5cm} if $|obj^{(l)} - obj^{(l-1)}| \leq \delta$ then
7: \hspace{1.0cm} $Converge=true$, $obj^* = obj^{(l)}$.
8: \hspace{0.5cm} end if
9: \hspace{0.5cm} end while
10: return Optimal system sum rate $obj^*$.

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

$$P_3 : \max_{\rho_U} \ obj \ \ s.t. \ (1a), (10a), (11a), (11c).$$

For given $\rho_U$, problem $P_3$ reduces to

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

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. Therefore, proposed algorithm is convergent.

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

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

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 $P = 10w$ 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 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 $\Omega_0 = 1w$. As for the CSI estimation errors, we set $\Omega_e = 0.1$. The outage probability threshold for multicast service is set as $\delta = 0.1$.

Since $\rho_U$ and $c_f$ are mutually decoupling, we can calculate them alternatively.
NOMA scheme outperforms the OMA counterpart by the proposed lower bound relaxation method. Simulating the non-convex problem has been appropriately solved with high mobility. We have formulated an optimization problem to maximize the unicast sum rate subject to the peak rate constraint. The following figure shows the backhaul capacity versus cache size with minimum rate constraint.

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.

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APPENDIX A

PROOFS OF Propositions 1 and 2

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

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

which yields

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

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

$$\frac{(2^{r_{\text{min}}} - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^{i-1} \Delta \rho_j} = \frac{\rho_{i,\text{min}}}{\sum_{j=1}^{i-1} \rho_{j,\text{min}} + \Psi / \lambda_i}$$
\[ \Delta r_i^U = r_i^U - r_{\text{min}} \]
\[ = \log_2 \left( 1 + \frac{\rho_i - (2^m - 1) \sum_{j=1}^{i-1} \Delta \rho_j}{\sum_{j=1}^{i} \rho_j + \Psi / \lambda_i} \right) \]
\[ = \log_2 (1 + \frac{\rho_i}{n_i^e + \sum_{j=1}^{i-1} \rho_j^e}), \]
\[ \Delta r_i^U = \log_2 (1 + \frac{\rho_i}{n_i^e + \sum_{j=1}^{i-1} \rho_j^e}), \]

where \( n_i^e = \frac{\Psi / \lambda_i + \sum_{j=1}^{i} \rho_j}{\lambda_i} \) and \( \rho_i = \rho_i^e \) and \( \rho_i^e = \rho_i^{\text{min}} \). After the recurrence operation, we have
\[ \rho_i^{\text{min}} = (2^m - 1) \sum_{j=1}^{i} \rho_j^{\text{min}}, \]
\[ \rho_i = \rho_i^{\text{min}} \]

which results in \( \rho_i^{\text{min}} = \sum_{i=1}^{K} \rho_i^{\text{min}} \) represents all the excess power, \( \rho_i^e \leq \rho_i^{\text{min}} \). Therefore, when \( i = 1 \), \( \rho_i^e = \rho_i^{\text{min}} \), (A.7) achieves its optimal value. The proofs complete.

**B Supplementary Material**

**A. The Detailed Derivations of (1) and (2)**

As we know, the transmit signal at RSU is
\[ z = \sqrt{\beta_M P x_M} + \sum_{i=1}^{K} \sqrt{\beta_i P_i} x_i, \]
where \( E[|x_M|^2] = E[|x_i|^2] = 1 \). Then the received signal at user \( i \) can be derived as
\[ y_i = \sqrt{\beta_M P h_i x_M} + \sum_{j=1}^{i-1} \sqrt{\beta_j P_j h_i x_j} + n_i, \]
which can be rewritten as
\[ y_i = \sqrt{\beta_M P} \sqrt{1 - \phi_i^2} h_i x_M \]

Without loss of generality, multicast message always has a higher priority than the unicast one. Therefore, the receiver should first decode the multicast message \( x_M \) and subtract it from \( y_i \). In this way, the SINR of \( x_M \) at user \( i \) can be obtained by
\[ \gamma_i^M = \beta_M P (1 - \phi_i^2) |\hat{h}_i|^2 \]
\[ + \sum_{j=1}^{K} \sqrt{\beta_j P_j (1 - \phi_j^2)} |\hat{h}_j|^2 \]
\[ + \frac{\sum_{j=1}^{K} \beta_j P_j \phi_j^2 |\epsilon_j|^2 + \Omega_0}{\sum_{j=1}^{K} \beta_j P_j (1 - \phi_j^2) |\hat{h}_j|^2} \]

which equals to the SINR in (1). After decoding \( x_M \), user \( i \) aims to obtain \( x_i \) from the superposed signal
\[ y_i = \sum_{j=1}^{K} \sqrt{\beta_j P_j} h_i x_j + n_i. \]

Recall \( |h_i|^2 \geq \cdots \geq |h_K|^2 \), user \( i \) aims to decode the data symbols for the users with weaker channels, subtract them through SIC technique, and then decoding the data symbol for itself. Consequently, we can obtain
\[ y_i = \sqrt{\beta_i P_i} \sqrt{1 - \phi_i^2} h_i x_i \]
\[ + \sum_{j=1}^{i-1} \sqrt{\beta_j P_j (1 - \phi_j^2)} |\hat{h}_j|^2 \]
\[ + \frac{\sum_{j=1}^{K} \beta_j P_j \phi_j^2 |\epsilon_j|^2 + \Omega_0}{\sum_{j=1}^{K} \beta_j P_j (1 - \phi_j^2) |\hat{h}_j|^2} \]

(B.7)

In this way, we can finally derive (1) and (2).

**B. The Derivation of (6)**

Recall the instantaneous rate of \( x_i \) observed at \( U_i \), i.e.,
\[ r_i^U = \log_2 \left( 1 + \frac{\rho_i \lambda_i}{\sum_{j=1}^{i} \rho_j \lambda_j + \frac{\sum_{j=1}^{i} \rho_j b + a}{\Omega_0}} \right). \]

Since the last two parts in the denominator are hardly handled, we herein use the lower bound relaxation method and replace them by a constant, i.e.,
\[ \sum_{j=1}^{i} \rho_j b + a = \sum_{j=1}^{i} \beta_j P_j b + \rho \sum_{j=1}^{i} \rho_j b + a = \Psi. \]

In this way, we can derive (6).