Cooperative NOMA for Wireless Layered Multicast

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Abstract—This paper proposes a novel design of cooperative non-orthogonal multiple access (NOMA) for layered multicast, where the information is encoded into the messages of high-priority (HP) and low-priority (LP). Two types of multicast users coexist in the system: 1) regular users (RUs), which locate far away from the base-station (BS) and demand only the HP message; 2) advanced users (AUs), which locate close to the BS and demand both HP and LP messages. To improve the reliability of layered multicast, an opportunistic cooperative NOMA multicast strategy is proposed, in which one of successfully decoded AUs is selected to forward both HP and LP messages. For the proposed strategy, we derive the closed-form exact outage probabilities of AUs and RUs. By further carrying out the asymptotic analysis, the achieved diversity orders are shown to be no less than the number of AUs, indicating that the spatial diversity offered by AUs are fully exploited in the proposed strategy. Finally, numerical results are presented to verify the theoretical analysis and demonstrate the superiority of the proposed strategy.

I. INTRODUCTION

Compared with the conventional orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA) can provide better fairness and connectivity for the users with weak channel conditions, thus being viewed as a promising multiple access technique for the fifth generation (5G) mobile networks [11]–[6]. To improve the reliability/capacity of NOMA systems, cooperative relaying technique has been incorporated into NOMA, termed as cooperative NOMA, in which the user with strong channel conditions can decode its own message along with other users’ message, thus serving as a relay for other users [7]–[9]. However, the work in [7]–[9] has considered only wireless unicast, i.e., point-to-point information delivery. In practical wireless networks, some users may have the common interest in many scenarios, such as Internet protocol television (IPTV), video/audio multicast streaming, live sport streaming, video conferencing, etc. If only cooperative NOMA unicast is employed, the same data will be sent repeatedly, resulting in low spectrum/energy efficiency.

Thanks to the broadcast nature of wireless channels, wireless multicast can deliver the same information to multiple users simultaneously, thus being an efficient manner to serve the users with common interest [10]. When some users demand the same content in NOMA systems, integrating wireless multicast into cooperative NOMA, i.e., cooperative NOMA multicast, is expected to combine their advantages. Motivated by this idea, two opportunistic cooperative NOMA multicast strategies have been designed in most recent work [11] and [12], which opportunistically recruits a successfully decoded user to assist the other users. However, the work in [11] and [12] has focused on the non-layered multicast only, which does not consider the heterogeneity among multicast users. In fact, as multicast users own heterogeneous and time-varying channel conditions, the non-layered multicast, which employs fixed data-rate and coding scheme, can not best serve all multicast users simultaneously, especially in video multicast that requires seamless connectivity and low latency.

To cope with this problem, layered multicast is designed to deliver the same video content to multicast users with different video resolutions. In layered multicast, the original video information is split into a base-layer stream and several enhancement-layer streams, where the base-layer stream provides basic-quality video and each enhancement-layer stream can further refine video resolution. Consequently, each multicast user can adaptively decode its received layered streams, according to its reception quality of each layered stream. However, the current layered multicast mechanism is mainly performed over application layer without cooperative support at physical layer, thereby limiting the performance of layered multicast in heterogeneous wireless systems.

In this paper, we propose a novel cooperative NOMA strategy for layered multicast, which can significantly improve reliability of layered multicast by exploiting the spatial diversity. In the proposed strategy, the video information is encoded into data streams of high-priority (HP) and low-priority (LP), corresponding to the base-layer and enhancement-layer streams in the digital video broadcasting (DVB) [13]. Two types of multicast users coexist in the layered multicast system: 1) regular users (RUs), which locate far away from the base-station (BS) and demand only the HP data stream for basic quality-of-service (QoS), and 2) advanced users (AUs), which locate close to the BS and demand both the HP and LP data streams for better QoS. The main contributions of this work can be summarized as follows.

- To enhance reliability of layered multicast in NOMA systems, we propose an opportunistic cooperative NOMA (OC-NOMA) multicast strategy, in which one of successfully decoded AUs is selected to assist the layered multicast to unsuccessfully decoded AUs/RUs.
- For the proposed strategy, the outage probabilities are derived into closed form for AUs and RUs, and then further asymptotically analyzed in high signal-to-noise ratio (S-NR) regime. The derived theoretical results demonstrate that, the proposed OC-NOMA multicast strategy fully
exploits the spatial diversity offered by all AUs, namely, full diversity is achieved.

II. SYSTEM MODEL

Let us consider the layered multicast transmission from a BS denoted by $S$ to a group of AUs $A_1, ..., A_M$ ($M \geq 2$) and a group of RUs $R_1, ..., R_K$ ($K \geq 2$), as depicted in Fig. 1. The group of AUs are close to the BS and the group of RUs are far away from the BS. Let $x_H$ and $x_L$ denote the messages of HP and LP, corresponding to the multi-resolution DVB services [13]. By using NOMA, the BS superimposes both HP and LP messages and then send the superposition to AUs/RUs\(^1\). It is assumed that the RUs only decode HP message for basic QoS and the AUs decode both HP and LP messages for better QoS, as the channel conditions of AUs are better than those of RUs. Further, it is also assumed that more power is allocated to $x_H$ while the rest of power is allocated to $x_L$, since message $x_H$ is given high priority. Without loss of generality, we consider that the fixed power allocation is employed to superimpose the HP and LP messages. According to the principles of successive interference cancellation (SIC) [16], the information detection should be performed from the message with more power to the message with less power. As more power is allocated to HP message, each AU first detects HP message $x_H$ by treating LP message $x_L$ as interference. The target spectral efficiency for $x_H$ and $x_L$ are denoted as $r_H$ and $r_L$, respectively. Throughout this paper, we declare an AU is successful if it has correctly decoded both $x_H$ and $x_L$, and declare an RU is successful if it has correctly decoded $x_H$. Otherwise, the AU/RU is declared to be unsuccessful.

All nodes in this scenario are equipped with single antenna and operate in a half-duplex mode. Denote the channel coefficients pertaining to links $S - A_m$, $S - R_k$, $A_m - R_k$ and $A_m - A_m'$ as $f_{S,m}$, $f_{S,k}$, $h_{m,k}$ and $g_{m,m'}$, respectively. Assume that, all links experience independent but non-identically distributed Rayleigh fading, and thus, the channel coefficients follow circularly symmetric complex Gaussian distribution as $f_{S,m} \sim \mathcal{CN}(0, \Omega_{S,m}^f)$, $f_{S,k} \sim \mathcal{CN}(0, \Omega_{S,k}^f)$, $h_{m,k} \sim \mathcal{CN}(0, \Omega_{m,k}^h)$, $g_{m,m'} \sim \mathcal{CN}(0, \Omega_{m,m'}^g)$, where $\Omega_{S,m}^f \triangleq \mathbb{E}[|f_{S,m}|^2]$, $\Omega_{S,k}^f \triangleq \mathbb{E}[|f_{S,k}|^2]$, $\Omega_{m,k}^h \triangleq \mathbb{E}[|h_{m,k}|^2]$ and $\Omega_{m,m'}^g \triangleq \mathbb{E}[|g_{m,m'}|^2]$. Here, $\mathbb{E}[\cdot]$ represents the mathematical expectation. Block-fading model is also assumed, and thus, the channel coefficients keep unchanged within every transmission block, but vary independently among different transmission blocks. The duration of each transmission block is $T_0$. The noise at each user is modeled as additive white Gaussian noise (AWGN) with the identical variance $\sigma^2$.

III. OPPORTUNISTIC COOPERATIVE NOMA MULTICAST

A. Cooperation Strategy

The proposed OC-NOMA multicast strategy is performed within two phase. The duration of each phase is $T_0/2$. During the first phase, the BS sends superposed signals $\sqrt{P_S}x_H + \sqrt{P_S}x_L$ to all users, where $P_S$ is the transmit power of BS, $\alpha_H$ and $\alpha_L$ are the power allocation coefficients for messages $x_H$ and $x_L$ with $\alpha_H + \alpha_L = 1$ and $\alpha_H > \alpha_L$. Further, to ensure that NOMA can be realized, the power allocation coefficients should satisfy $\alpha_H - \alpha_L(2^{r_H} - 1) > 0$ [7].

Once receiving the superposed signals, all AUs successively detect messages $x_H$ and $x_L$ by using SIC. For AU $A_m$, its received signal can be expressed as

$$y_{S \rightarrow A_m} = \sqrt{P_S}x_H + \sqrt{P_S}x_L + n_{m},$$

where $n_{m}$ represents the AWGN at AU $A_m$. Defining $\rho \triangleq P_S/\sigma^2$ as the transmit SNR, the signal-to-interference-plus-noise ratio (SINR) for AU $A_m$ to decode $x_H$ can be expressed as

$$\gamma_{S \rightarrow A_m,H} = \frac{\alpha_H |f_{S,m}|^2}{\alpha_L |f_{S,m}|^2 + \rho^{-1}}.$$ (2)

If AU $A_m$ correctly decodes $x_H$, it performs SIC to remove $x_H$ from its observation, and then, decodes $x_L$ with the SNR being

$$\gamma_{S \rightarrow A_m,L} = \rho\alpha_L |f_{S,m}|^2.$$ (3)

Recalling that an AU is successful if it correctly decodes both messages $x_H$ and $x_L$, the condition for AU $A_m$ being successful is given by \( \{ \frac{1}{2}\log(1 + \gamma_{S \rightarrow A_m,H}) \geq r_H, \frac{1}{2}\log(1 + \gamma_{S \rightarrow A_m,L}) \geq r_L \} \). Thus, the indices set of successful AUs can be expressed as $S_A \triangleq \{ m | \gamma_{S \rightarrow A_m,H} \geq \tilde{r}_H \triangleq 2^{2r_H} - 1, \gamma_{S \rightarrow A_m,L} \geq \tilde{r}_L \triangleq 2^{2r_L} - 1 \}$. On the other hand, all RUs only decode message $x_H$ from their received signals. The received signal at RU $R_k$ can be expressed as

$$y_{S \rightarrow R_k} = \sqrt{P_S}x_H + \sqrt{P_S}x_L + n_k,$$ (4)

where $n_k$ represents the AWGN at RU $R_k$. By treating LP message $x_L$ as interference, RU $R_k$ decodes the HP message $x_H$ with the following SINR

$$\gamma_{S \rightarrow R_k,H} = \frac{\alpha_H |f_{S,k}|^2}{\alpha_L |f_{S,k}|^2 + \rho^{-1}}.$$ (5)

As the RUs only need to decode the message $x_H$, the condition for RU $R_k$ being successful is given by \( \{ \frac{1}{2}\log(1 + \gamma_{S \rightarrow R_k,H}) \geq r_H \} \). Accordingly, the indices set of successful RUs are given by $S_R \triangleq \{ k | \gamma_{S \rightarrow R_k,H} \geq \tilde{r}_H \}$.
If all users have been successful after the first phase, the second phase will be cancelled and the BS will proceed to transmit new messages. Otherwise, the cooperative transmission will be performed in the second phase. Prior to the second phase, a relay selection procedure is performed to select the best successful AU serving as a relay. The detailed selection scheme will be presented in the next subsection.

Without loss of generality, we here assume that a successful RU $A_m$ is selected to serve as a relay. Thus, the selected AU $A_m$ sends superposed signals $\sqrt{P_A}g_{A,m}x_H + \sqrt{P_A}g_{A,L,m}x_L$ during the second phase, where $P_A$ is the transmit power at each AU with $P_A = \mu P_S$ ($\mu > 0$). As a result, the observed signals at unsuccessful AU $A_{m'} (m' \in \{1, \ldots, M\} \setminus S_A)$ is

$$y_{A_m \rightarrow A_{m'}} = \sqrt{P_A}g_{A,m}x_H + \sqrt{P_A}g_{A,L,m}x_L + n_{m'}.$$  

Accordingly, the SINR for AU $A_{m'}$ to decode $x_H$ is given by

$$\gamma_{A_m \rightarrow A_{m'}, H} = \frac{\alpha_H |g_{m,m'}|^2}{\alpha_L |g_{m,m'}|^2 + (\mu \rho)^{-1}}.$$  

Once $x_H$ being correctly decoded, unsuccessful AU $A_{m'}$ performs SIC and then decodes $x_L$ with SNR given by

$$\gamma_{A_m \rightarrow A_{m'}, L} = \mu \rho |g_{m,m'}|^2.$$  

Similarly, the received signals at unsuccessful RU $R_k (k \in \{1, \ldots, K\} \setminus S_R)$ is

$$y_{A_m \rightarrow R_k} = \sqrt{P_A}g_{A,H}h_{m,k}x_H + \sqrt{P_A}g_{A,L}h_{m,k}x_L + n_k,$$  

and the SINR for $R_k$ to decode $x_H$ is

$$\gamma_{A_m \rightarrow R_k, H} = \frac{\alpha_H |h_{m,k}|^2}{\alpha_L |h_{m,k}|^2 + (\mu \rho)^{-1}}.$$  

B. Two-Step Selection

From (7), (8) and (10) we know that, the reception quality of unsuccessful AUs/RUs is affected by which successful AU being selected. Therefore, the best successful AU should be properly selected in order to maximally enhance the reception quality of all unsuccessful AUs/RUs. To this end, we design a two-step relay selection scheme described as follows.

First, we preselect a number of successful AUs as potential relays. Here, a successful AU is eligible for being preselected as a potential relay if it can reliably forward information to unsuccessful AUs. If successful AU $A_m$ is selected, the condition that all unsuccessful AUs become successful after the second phase is $\bigcap_{m' \in \{1, \ldots, M\} \setminus S_A} \{\gamma_{A_m \rightarrow A_{m'}, H} \geq \bar{\gamma}_H, \gamma_{A_m \rightarrow A_{m'}, L} \geq \bar{\gamma}_L\},$ which can be equivalently expressed as $\min_{m' \in \{1, \ldots, M\} \setminus S_A} |g_{m,m'}|^2 \geq \frac{\max{\phi_1, \phi_2}}{\mu \rho}$, where $\phi_1 \triangleq (\alpha_H / \bar{\gamma}_H - \alpha_L)^{-1}$ and $\phi_2 \triangleq \bar{\gamma}_L / \alpha_L$. Therefore, the indices set of the preselected potential relays can be expressed as

$$\mathcal{R}_p = \left\{ m \mid \min_{m' \in \{1, \ldots, M\} \setminus S_A} |g_{m,m'}|^2 \geq \frac{\max{\phi_1, \phi_2}}{\mu \rho}, m \in S_A \right\}.$$  

Second, among all preselected potential relays, we select the best one to maximally improve the reliability of all unsuccessful RUs. As the reliability of multicast is limited by the user with worst reception quality, the best successful AU that maximally enhances the reliability of unsuccessful RUs should be selected as

$$m^* = \arg \max_{m \in \mathcal{R}_p} \left( \min_{k \in \{1, \ldots, M\} \setminus S_R} |h_{m,k}|^2 \right).$$  

IV. PERFORMANCE ANALYSIS

A. Outage Analysis

1) Decoding Results of the First Phase: Recall that the condition for $A_m$ being successful after the first phase is $\frac{1}{2} \log(1 + \gamma_{S \rightarrow A_m, H}) \geq r_H, \frac{1}{2} \log(1 + \gamma_{S \rightarrow A_m, L}) \geq r_L$. Thus, after the first phase, the probability that AU $A_m$ is successful can be expressed as

$$\Pr(m \in S_A) = \Pr(\gamma_{S \rightarrow A_m, H} \geq \bar{\gamma}_H, \gamma_{S \rightarrow A_m, L} \geq \bar{\gamma}_L) = \Pr(\{|f_{S,m}|^2 \geq \max{\phi_1, \phi_2}/\rho\} \cap \delta_{\bar{\gamma}_H}) \cap \delta_{\bar{\gamma}_L}.$$  

Since the channel gains are independently distributed, the probability for the condition $S_A = A$ can thus be expressed as

$$\Pr(S_A = A) = \prod_{m \in \mathcal{A}} \left( (1 - \theta_m) \right),$$  

where $\mathcal{A}$ is a subcollection of the set $\{1, \ldots, M\}$. On the other hand, as the condition for $R_k$ being successful after the first phase is $\frac{1}{2} \log(1 + \gamma_{S \rightarrow R_k, H}) \geq r_H$, the probability for RU $R_k$ being successful can be obtained as

$$\Pr(k \in S_R) = \Pr(\gamma_{S \rightarrow R_k, H} \geq \bar{\gamma}_H) = \Pr(\{|f_{S,k}|^2 \geq \phi_1/\rho\} \cap \delta_{\bar{\gamma}_H}).$$  

Let $B$ represent a subcollection of the set $\{1, \ldots, K\}$, the probability for $S_R = B$ is obtained based on independence among channel gains as

$$\Pr(S_R = B) = \prod_{k \in B} \left( (1 - \zeta_k) \right).$$  

Further, conditioned on AU $A_m$ being successful after the first phase, the probability that AU $A_m$ can further serve as a potential relay is obtained as

$$\Pr(m \in \mathcal{R}_p | m \in S_A) = \Pr(\min_{m' \in \{1, \ldots, M\} \setminus S_A} |g_{m,m'}|^2 \geq \frac{\max{\phi_1, \phi_2}}{\mu \rho}) = \frac{\max{\phi_1, \phi_2}}{\mu \rho} \frac{1}{\sum_{m' \in \{1, \ldots, M\} \setminus S_A} |g_{m,m'}|^2 \Omega_{\bar{\gamma}_H, \bar{\gamma}_L}}.$$  

Then, let $C$ be a subcollection of $\mathcal{A} \subset \{1, \ldots, M\}$, the probability for $\mathcal{R}_p = C$ conditioned on $S_A = A$ can be expressed as

$$\Pr(\mathcal{R}_p = C | S_A = A) = \prod_{m \in \mathcal{C}} \omega_m(A) \prod_{m \in \mathcal{A} \setminus \mathcal{C}} [1 - \omega_m(A)].$$  

2) Exact Outage Probability: Since each potential relay can guarantee the reliable reception at all unsuccessful AUs, the AUs experience an outage only when not all AUs are successful after the first phase and no potential relay exists, i.e.,
\(|S| < M, R_p = \emptyset\). Consequently, the outage probability of AUs can be expressed as

\[
P_{out}^{AU} = \Pr(|S| < M, R_p = \emptyset) = \sum_{i=0}^{M-1} \sum_{|A|=i} \Pr(S_A = A) \Pr(R_p = \emptyset | S_A = A).
\]

(19)

Using (14) and (18) with letting \(C = \emptyset\), a closed-form expression for \(P_{out}^{AU}\) is derived as

\[
P_{out}^{AU} = \sum_{i=0}^{M-1} \prod_{|A|=i} \theta_m(1 - \omega_m(A)) \prod_{m \in \{1, \ldots, M\} \setminus A} (1 - \theta_m).
\]

(20)

On the other hand, an outage is declared for RUs when one of the following outage event happens:

- Outage event \(D_1^{RU} \triangleq \{|S| < K, R_p = \emptyset\}\), which means not all RUs are successful after the first phase and no successful AU can be a potential relay.
- Outage event \(D_2^{RU} \triangleq \{|S| < K, R_p = \emptyset\} \land \{\sigma_{2,k} \neq \emptyset, \{\gamma_{A_j,t} = R_k, H < \hat{\tau}_H\}\}\), meaning that some RUs remain unsuccessful after receiving the forwarded signal from \(A_m\).

Upon the above analysis, the exact expressions for probabilities \(\Pr(D_1^{RU})\) and \(\Pr(D_2^{RU})\) are provided in the following lemma.

Lemma 1: In OC-NOMA multicast, the outage event \(D_1^{RU}\) happens with the probability being

\[
\Pr(D_1^{RU}) = \left(1 - \prod_{k=1}^{K} \zeta_k\right) \sum_{i=0}^{M} \sum_{|A|=i} \prod_{m \in A} \theta_m(1 - \omega_m(A)) \prod_{m \in \{1, \ldots, M\} \setminus A} (1 - \theta_m),
\]

(21)

while the outage event \(D_2^{RU}\) happens with the probability being

\[
\Pr(D_2^{RU}) = \sum_{i=1}^{M} \prod_{m \in \{1, \ldots, M\} \setminus A} \theta_m \prod_{m \in \{1, \ldots, M\} \setminus A} (1 - \theta_m)
\]

\[
\times \sum_{j=0}^{K-1} \sum_{|B|=j} \prod_{k \in \{1, \ldots, K\} \setminus B} (1 - \zeta_k) \prod_{m \in \{1, \ldots, M\} \setminus A} \prod_{m \in \{1, \ldots, M\} \setminus A} [1 - \omega_m(A)] \prod_{m \in \{1, \ldots, M\} \setminus A} \theta_m(1 - \omega_m(A)) [1 - \theta_m(B)],
\]

(22)

where \(\zeta_m(B) \triangleq e^{-\frac{d_k^h}{\Omega_m^h} \sum_{k \in \{1, \ldots, K\} \setminus B} 1/\Omega_{m,k}}\).

Proof: Please refer to Appendix A.

As the outage events \(D_1^{RU}\) and \(D_2^{RU}\) are mutually exclusive, the overall outage probability of RUs can be obtained as

\[
P_{out}^{RU} = \Pr(D_1^{RU}) + \Pr(D_2^{RU}).
\]

B. Asymptotic Analysis and Diversity Orders

Based on the series representation of exponential function \([17, eq. (1.211.1)]\), we have \(e^{-c/P} \approx 1 - c/P \rho\) holds for \(\rho \to \infty\), where \(c\) is a positive constant. Applying this fact into (20) and ignoring the high order infinitesimals, the high-SNR asymptotic outage probability for AUs can be obtained as

\[
P_{out}^{AU} \propto \rho^{-M} \Upsilon
\]

(23)

with

\[
\Upsilon \triangleq \left[ \max(\varphi_1, \varphi_2) \right]^{M-1} \sum_{i=0}^{M} \sum_{|A|=i} \frac{1}{\Omega_{m,m'}} \left( \prod_{m \in \{1, \ldots, M\} \setminus A} \frac{1}{\Omega_{s,m}} \right) \prod_{m \in A} \left( \sum_{m' \in \{1, \ldots, M\} \setminus A} \frac{1}{\Omega_{m,m'}} \right).
\]

(24)

It is observed that \(P_{out}^{RU} \propto \rho^{-(M+1)}\) for \(\rho \to \infty\), showing that the diversity orders of \(M\) are achieved by AUs.

Following the same rationale, the high-SNR asymptotic outage probability for RUs can be obtained based on (21) and (22) as

\[
P_{out}^{RU} \propto \rho^{-(M+1)} \Theta
\]

(25)

with

\[
\Theta \triangleq \left( \sum_{k=1}^{K} \varphi_k \right)^{M-1} \sum_{i=0}^{M} \sum_{|A|=i} \prod_{m \in A} \max(\varphi_1, \varphi_2) \prod_{m \in \{1, \ldots, M\} \setminus A} \max(\varphi_1, \varphi_2)
\]

\[
\times \left( \prod_{m \in A} \frac{1}{\Omega_{s,m}} \right) \sum_{k=1}^{K} \varphi_k \prod_{m \in \{1, \ldots, M\} \setminus A} \max(\varphi_1, \varphi_2)
\]

(26)

As observed from (25), \(P_{out}^{RU} \propto \rho^{-(M+1)}\) for \(\rho \to \infty\), indicating that the RUs achieve diversity orders of \(M + 1\).

It is noteworthy that, in the OC-NOMA multicast, the RUs achieve one order higher diversity than AUs. This observation can be intuitively explained as follows. When the retransmission to AUs is required, there exists at least one AU is unsuccessful, which means at most \(M - 1\) AUs can be eligible for serving as potential relays. However, when the RUs need retransmission, all AUs may be able to serve as potential relays, thus leading to the higher diversity orders.

V. Simulation Results

This section provides the numerical results to verify our theoretical analysis and demonstrate the performance of our proposed strategy. An independently but non-identically distributed Rayleigh fading scenario is considered in our simulation: 1) the BS locates at coordinate \([0, 0]\); 2) the locations of AUs are randomly generated within a circle centered at \([50, 0]\); 3) the locations of RUs are randomly generated within another circle centered at \([100, 0]\); 4) the radii of both circles are equal to 30; 5) the randomly generated locations of AUs and RUs keep unchanged over all numerical trials; 6) the small-scale fading varies independently over each numerical trial. Denoting the distance between nodes \(i\) and \(j\) as \(d_{ij}\) and the pathloss reference distance as \(d_0\), the pathloss attenuation between \(i\) and \(j\) is modelled as \((d_{ij}/d_0)\kappa\) for \(d_{ij} \geq d_0\) \([18, sec.2.6]\), where \(\kappa\) is the pathloss exponent. Moreover, if \(d_{ij} < d_0\), we assume there is no pathloss attenuation between \(i\) and \(j\). Following the standard values for urban cellular...
Outage probability of RUs.

Fig. 2. Outage probability of AUs.

Fig. 3. Outage probability of RUs.

networks [18], we set the pathloss reference distance \(d_0 = 20\) and pathloss exponent \(\kappa = 3\). Since the BS is expected to own higher transmit power than successful RUs, we set \(\mu = P_A/P_S = 0.1\) in the simulation. The other parameters used in simulations are \(\alpha_H = 0.95\), \(\alpha_L = 0.05\), \(r_H = 1\) bps/Hz, \(r_L = 0.2\) bps/Hz, \(\sigma^2 = 1\), \(M = 3\) and \(K = 6\).

For the purpose of comparison, the numerical results of the following three strategies are also included in our simulation. Note that, the first phase of each following strategy is the same with the proposed one. Thus, we here only describe the second phase of each strategy.

- **Strategy-1**: In this strategy, all successful AUs are recruited to simultaneously forward both HP and LP messages.

- **Strategy-2**: This strategy employs the best user selection scheme for fixed power allocation [12], termed as F-BUS scheme, which selects the successful AU that maximizes the normalized worst-reception quality among unsuccessful AUs and RUs, i.e.,

\[
m^* = \arg \max_{m \in \mathcal{S}_A} \min_{m \in \{1, \ldots, M\} \setminus \mathcal{S}_A} \left( \min_{j : |h_{m,j}|^2 \leq \min_{k \in \{1, \ldots, K\} \setminus \mathcal{S}_R} |h_{m,k}|^2} \right) \cdot \frac{1}{\varphi_1},
\]

(27)

- **Strategy-3**: This strategy employs the best average reception selection (BARS) scheme in [19], in which the multicast user with best average channel gain to BS is selected to forward information. In this paper, as the AUs are assumed to serve as relays, the BARS should be performed as

\[
m^* = \arg \max_{m \in \{1, \ldots, M\}} \Omega_{\mathcal{S}_A}^m,
\]

(28)

namely, the AU that owns the best average channel gain to BS is selected.

Here, we first discuss the simulation results of proposed OC-NOMA multicast strategy. As shown in Fig. 2 and Fig. 3, the derived outage probabilities of AUs and RUs perfectly match the simulated values, verifying the derived closed-form expressions for outage probabilities. Further, the derived outage probabilities of AUs and RUs are tightly upper bounded by their asymptotes in high-SNR regime (\(\rho \geq 40\) dB), which validates our asymptotic analysis. In Fig. 2, by comparing with the reference line \(5 \times 10^5 \times \rho^{-3}\), it is known that the outage probability of AUs decays with transmit SNR \(\rho\) at a rate \(\rho^{-3}\). Similarly, in Fig. 3, it can also be seen that the outage probability of RUs decreases with transmit SNR \(\rho\) at the rate same as the reference line \(1 \times 10^{11} \times \rho^{-4}\). Since the number of AUs is \(M = 3\) in our simulation, these observations demonstrate that diversity orders of \(M\) are achieved by AUs while diversity orders of \(M + 1\) are achieved by RUs.

Next, we compare the proposed OC-NOMA multicast strategy with Strategy 1–3. As seen from both figures, compared with Strategy-1 and Strategy-3, the proposed OC-NOMA multicast strategy provides much better outage performance for both AUs and RUs. Further, it is observed from Fig. 2 that the proposed OC-NOMA multicast strategy outperforms the strategy-2 in terms of outage probability of AUs. For the outage probability of RUs, the proposed OC-NOMA multicast strategy achieves the same performance with Strategy-2, as shown in Fig. 3. These observations can be explained as follows. Recall that the proposed cooperation strategy employs a two-step selection, which ensures the reliability of AUs in the first step, and then, improves the reception quality of RUs in the second step. On the other hand, by observing the selection criterion given in (27), it is known that the F-BUS scheme [12] employed in Strategy-2 targets at improving the reception quality of AUs and RUs simultaneously. Therefore, it is expected that the lower outage probability of AUs is achieved by the proposed OC-NOMA multicast strategy.

**VI. CONCLUSION**

In this paper, we have proposed a novel cooperative NOMA strategy for layered multicast. For the proposed strategy, we have theoretically derived the exact outage probabilities and diversity orders. It has been shown that the proposed cooperation strategy achieves diversity orders not less than the number of AUs, indicating the spatial diversity offered by all AUs are fully exploited. Finally, numerical results have been provided to validate the theoretical analysis and confirm the advantages of proposed cooperation strategy.

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Further, the probability $Pr(O)$ can be obtained.

By using (16) with letting $B = \{1, \ldots, K\}$ as

$$Pr(S_R = \{1, \ldots, K\}) = \prod_{k=1}^{K} \zeta_k. \quad (A.2)$$

Further, the probability $Pr(R_p = \emptyset)$ can be obtained as

$$Pr(R_p = \emptyset) = \sum_{i=0}^{M} \sum_{A \subseteq i} \prod_{m \in [1, \ldots, M] \setminus A} \theta_m \prod_{k \in [1, \ldots, K]} (1 - \theta_k),$$

where the second equality uses the results in (14) and (18). Combining (A.2) and (A.3) with the help of (A.1), (21) is obtained.

On the other hand, based on the Total Probability Theorem, the probability for $\Omega_2^{RU}$ happening can be expressed as

$$Pr(\Omega_2^{RU}) = Pr(S_R < K, R_p \neq \emptyset) = \sum_{k=1}^{K} \sum_{A \subseteq i} \prod_{m \in [1, \ldots, M] \setminus A} \theta_m \prod_{k \in [1, \ldots, K]} (1 - \theta_k),$$

where the probabilities $Pr(S_A = A)$, $Pr(S_R = B)$ and $Pr(R_p = C | S_A = A)$ have been derived in (14), (16), and (18), respectively. In the following, we focus on deriving the conditional probability $Pr(\bigcup_{k \in [1, \ldots, K]} S_R = B, R_p = C)$. As $\varphi_{2,k} = \{\gamma_{m,k} \rightarrow h_R,k < \tilde{T_H} = \{ |h_{m,k}|^2 < \frac{\varphi_1}{\mu P} \}$, the conditional probability can be derived as

$$Pr(\bigcup_{k \in [1, \ldots, K]} S_R = B, R_p = C) = \prod_{m \in C} \left( 1 - \prod_{k \in [1, \ldots, K]} Pr(|h_{m,k}|^2 < \frac{\varphi_1}{\mu P} \big| S_R = B, R_p = C) \right), \quad (A.5)$$

where the second equality comes from (12). Finally, substituting (A.5) into (A.4), and then combining the results with (14), (16) and (18), (22) is obtained. This completes the proof.

REFERENCES


