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Special Topic: Cohesive Clustered Satellites System for 5GA and 6G Networks

Joint semi-grant-free NOMA for dual-layer LEO cohesive clustered satellite systems

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Recently, with the rapid development of ultra-dense low earth orbit (LEO) satellite systems, cohesive clustered satellites (CCS) have garnered significant attention from researchers. CCS refers to a highly coordinated satellite system operating on specific orbital configurations, playing a crucial role in enhancing coverage performance and other capabilities [1]. Leveraging the highly coordinated characteristics of CCS, this study explores the utilization of a dual-layer LEO cohesive clustered satellite system to provide communication services for ground users, incorporating semi-grant-free (SGF) [2] random access technology into the communication process. Based on this, a joint semi-grant-free non-orthogonal multiple access (NOMA) technique is proposed, which can proactively estimate whether an outage in data transmission will occur and select the appropriate satellite for communication.

In satellite communications, the use of NOMA-assisted SGF technology can enhance communication performance and increase the number of users that can be accessed [3]. Since a single user may be covered by satellites in multiple orbital layers, the proposed scheme leverages a multi-layer LEO satellite architecture with NOMA-assisted SGF technology to enhance communication quality for ground users.

System model and scheme description. An uplink CCS composed of a two-layer LEO satellite network is considered, which collaboratively provides communication services to ground users, as illustrated in Figure 1(a). It is assumed that multiple satellites exist in both L1 and L2, ensuring seamless ground coverage. To mitigate the Doppler shift, the guard bandwidth is set to twice the Doppler shift [4]. The satellites in the L1 are positioned at 1200 km, while those in the L2 operate at 350 km [5]. Since the L1 layer is farther from the ground, it can provide users with a long-term stable connection. Therefore, enhanced mobile broadband (eMBB) users (EU) primarily connect to the L1 layer satellites. To meet the low latency requirements of mission-critical communications (MCC) users (CU), CUs primarily connect to L2 layer satellites. Meanwhile, massive machine-type communications (mMTC) users (MU) can connect to either layer based on specific needs.

The log-normal distribution is adopted to model the millimeter wave (mmWave) channel [6]. The probability density function (PDF) of the channel gain $|h_{\mathrm{UE}}|^2$ from the user equipment (UE) to the corresponding satellite is given by

$$f_{|h_{\mathrm{UE}}|^2}(x) = \frac{\varepsilon_{\mathrm{UE}}^{m_{\mathrm{UE}}}}{\Gamma(m_{\mathrm{UE}})} x^{m_{\mathrm{UE}}-1} \exp(-\varepsilon_{\mathrm{UE}} x), \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, $\varepsilon_{\mathrm{UE}} = m_{\mathrm{UE}}/\Omega_{\mathrm{UE}}$, $m_{\mathrm{UE}} = 1/(\exp(\sigma_{\mathrm{UE}}) - 1)$ is a measure of the fading severity, $\Omega_{\mathrm{UE}} = q_{\mathrm{UE}}\sqrt{(m_{\mathrm{UE}}+1)/m_{\mathrm{UE}}}$ represents the average power of each link, $q_{\mathrm{UE}} = \exp(\mu_{\mathrm{UE}})$ is the constant area average power, and μ_{UE} and σ_{UE} represent the log-normal location and scale parameters, respectively.

In the proposed joint semi-grant-free NOMA framework, users are categorized into grant-based users (GBUs) and grant-free users (GFUs). GBUs, including EUs and CUs, operate under a grant-based scheme, while GFUs, including MUs, follow a grant-free scheme. GBUs are decoded in the first stage, and GFUs are decoded in the second stage. Users accessing L1 layer satellites are referred to as HEUs, HCUs, and HMUs, while users accessing L2 layer satellites are referred to as LEUs, LCUs, and LMUs. Additionally, a threshold is set to limit the interference of GFU signals on the decoding of GBU signals as follows:

$$\tau_{\mathrm{GBU}} = \max\left\{\frac{\rho_{\mathrm{GBU}}|h_{\mathrm{GBU}}|^2}{\epsilon_{\mathrm{GBU}}} - 1, 0\right\}, \quad (2)$$

where $\rho_U = P_U l_U^2/\sigma^2$, U represents the user, including GBU and GFU. P_U and l_U represent the transmit power and the gain factor of U, respectively. $l_U = \sqrt{G_U \cdot G_S/F_U}$, G_U and G_S are the antenna gain at user and satellite, respectively, and $F_U = 92.4 + 20\log_2 f + 20\log_2 d_U$ is the free space path loss between U and S, where d_U is the user-satellite distance and f is the carrier frequency. Additive white Gaussian noise (AWGN) has zero mean and variance σ^2. $\epsilon_U = 2^{R_U^{\mathrm{th}}} - 1$ is the SINR threshold of U and R_U^{th} represents the target rate of U. In the system, it is assumed that there are M GFUs requiring data transmission. Distributed contention control

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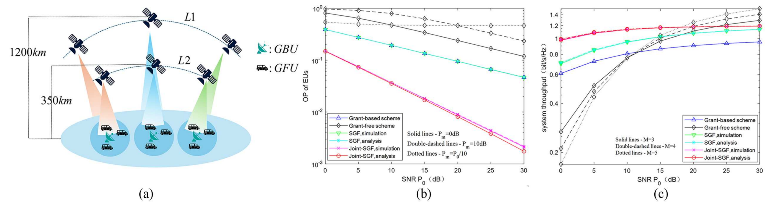

Figure 1 (Color online) System model and simulation results for the proposed scheme. (a) System model; (b) outage probability of EUs; (c) system throughput under different schemes.

is applied to those with a parameter $\rho_{\rm GFU}|h_{\rm GFU}|^2$ less than $\tau_{\rm GBU}$. From these, the GFU with the highest $\rho_{\rm GFU}|h_{\rm GFU}|^2$ is selected to superimpose its signal with that of the GBU using power-domin NOMA for transmission.

Unlike existing access technologies, the introduction of a threshold $\tau_{\rm GBU}$ ensures that the service quality experienced by the GBU is the same as that provided by orthogonal multiple access (OMA). Thus, upon receiving the random access response (RAR) from the satellite, GBUs calculate the estimated rate $\log_2(1+\rho_{\rm GBU}|h_{\rm GBU}|^2)$ and compare it with the target rate to predict the likelihood of an outage. If an outage is anticipated, GBUs can immediately switch to another satellite layer to reinitiate the handshake process. This allows for the detection of potential outages before they occur and enables preemptive measures to be taken.

Performance analysis. Since the access methods for CUs and EUs are similar, this study focuses solely on analyzing the performance of EUs and MUs. The outage probability (OP) for EUs is as follows:

$$\begin{aligned}P_{\rm EU} =&1-\Pr\left(\log_2\left(1+\gamma_{\rm HEU}\right)>R_{\rm EU}^{\rm th}\right)-\Pr\Big(\log_2\big(1\\&+\gamma_{\rm HEU}\big)<R_{\rm EU}^{\rm th}\Big)\Pr\left(\log_2\left(1+\gamma_{\rm LEU}\right)>R_{\rm EU}^{\rm th}\right)\\=&1-\frac{\Gamma(m_{\rm HEU},\frac{\varepsilon_{\rm HEU}\epsilon_{\rm EU}}{\rho_{\rm HEU}})}{\Gamma(m_{\rm HEU})}-\frac{\Gamma(m_{\rm LEU},\frac{\varepsilon_{\rm LEU}\epsilon_{\rm EU}}{\rho_{\rm LEU}})}{\Gamma(m_{\rm LEU})}\\&+\frac{\Gamma(m_{\rm HEU},\frac{\varepsilon_{\rm HEU}\epsilon_{\rm EU}}{\rho_{\rm HEU}})}{\Gamma(m_{\rm HEU})}\frac{\Gamma(m_{\rm LEU},\frac{\varepsilon_{\rm LEU}\epsilon_{\rm EU}}{\rho_{\rm LEU}})}{\Gamma(m_{\rm LEU})},\end{aligned}\tag{3}$$

where $\gamma_{\rm HEU}=\rho_{\rm EU}|h_{\rm HEU}|^2/(1+\rho_{\rm HMU}|h_{\rm HMU}|^2)$ and $\gamma_{\rm LEU}=\rho_{\rm EU}|h_{\rm LEU}|^2/(1+\rho_{\rm LMU}|h_{\rm LMU}|^2)$.

Assume that the channel gains of the existing M GFUs are ordered as $|h_1|^2<|h_2|^2<\cdots<|h_M|^2$, and the mth GFU is selected. The OP analysis for MUs is as follows:

$$\begin{aligned}&P_{\rm MU}\\&=\Pr\left(\log_2\left(1+\gamma_{\rm HEU}\right)>R_{\rm EU}^{\rm th}\right)\Pr\Big(\log_2\big(1+\rho_{\rm HMU}\\&\quad\times|h_{\rm HMU}|^2\big)<R_{\rm MU}^{\rm th}\Big)+\Pr\left(\log_2\left(1+\gamma_{\rm HEU}\right)<R_{\rm EU}^{\rm th}\right)\\&\quad\times\Pr\left(\log_2\left(1+\gamma_{\rm LEU}\right)>R_{\rm EU}^{\rm th}\right)\Pr\big(\log_2\big(1+\rho_{\rm LMU}\\&\quad\times|h_{\rm LMU}|^2\big)<R_{\rm MU}^{\rm th}\Big)+\Pr\left(\log_2\left(1+\gamma_{\rm HEU}\right)<R_{\rm EU}^{\rm th}\right)\\&\quad\times\Pr\left(\log_2\left(1+\gamma_{\rm LEU}\right)<R_{\rm EU}^{\rm th}\right)\\&=\theta(R_U,R_{\rm EU},\rho_{\rm HMU},\rho_{\rm HEU},dh,M)\\&\quad+\left(1-\frac{\Gamma(m_{\rm HEU},\frac{\varepsilon_{\rm HEU}\epsilon_{\rm EU}}{\rho_{\rm HEU}})}{\Gamma(m_{\rm HEU})}\right)\theta(R_{\rm MU},R_{\rm EU},\rho_{\rm LMU},\\&\quad\rho_{\rm LEU},dl,M)+\left(1-\frac{\Gamma(m_{\rm HEU},\frac{\varepsilon_{\rm HEU}\epsilon_{\rm EU}}{\rho_{\rm HEU}})}{\Gamma(m_{\rm HEU})}\right)\\&\quad\times\left(1-\frac{\Gamma(m_{\rm LEU},\frac{\varepsilon_{\rm LEU}\epsilon_{\rm EU}}{\rho_{\rm LEU}})}{\Gamma(m_{\rm LEU})}\right).\end{aligned}\tag{4}$$

Function θ and proof can be found in Appendix A.

Subsequently, the system throughput (ST) can be expressed as

$$T=R_{\rm EU}^{\rm th}(1-P_{\rm EU})+R_{\rm MU}^{\rm th}(1-P_{\rm MU}).\tag{5}$$

Simulation results. The relevant simulation parameters are included in Appendix B. From Figure 1(b), it is evident that the proposed scheme shows an improvement in OP over existing approaches, with a significant enhancement of approximately 76.1% compared with the SGF scheme. This is due to the SGF schemes limitation to a single satellite layer, while the proposed scheme allows users to estimate the data rate in advance and select the satellite layer. Figure 1(c) also shows a 15.6% increase in ST compared with the SGF scheme. Additionally, it is noted that changes in the parameters of GFUs have negligible impact on performance, indicating that for GBUs, GFUs are transparent and do not affect their performance.

Conclusion. Our proposed scheme utilizes a two-layer satellite architecture that collaboratively employs SGF technology to provide communication services to ground users. The expressions for the OP and ST under this scheme are derived, and simulation results are provided to validate the effectiveness and superiority of the proposed approach. Compared with the SGF scheme, the OP of GBUs is reduced by 76.1%, while the ST is improved by 15.6%.

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Supporting information Appendixes A–F. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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