SCIENCE CHINA
Information Sciences

• LETTER •

September 2024, Vol. 67, Iss. 9, 199301:1–199301:2
https://doi.org/10.1007/s11432-024-4106-5

Semantic-aware coordinated transmission in cohesive clustered satellites: utility of information perspective

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Received 27 May 2024/Revised 9 July 2024/Accepted 24 July 2024/Published online 9 August 2024

The cohesive clustered satellite (CCS) concept integrates diverse satellite payloads from different orbits, such as communication, remote sensing, and navigation satellites, into mobile, geometrically stable clusters for efficient collaborative networking [1]. By aggregating, reconstructing, and orchestrating heterogeneous satellite resources, such as computation, communication, and storage [2], the CCS enables resource ultra-sharing and provides information-centric and goal-oriented intelligent on-demand services [3] for a range of emerging Earth observation and deep space exploration missions [4]. For instance, satellites within these clusters, positioned at different latitudes and longitudes, can capture huge amounts of shared and exclusive information in image or video formats. This data is then transmitted to ground stations (GSs) to enhance ground stereo observations. Given the constraints of limited onboard resources, achieving efficient information-centric transmission within the CCS requires semantic-aware coordinated transmission techniques [5].

Unlike conventional bit-level coordinated transmission protocols that are semantic-agnostic and focus solely on optimizing data-oriented performance metrics such as access failure probability, transmission delay, and throughput, semantic-aware approaches prioritize the utility of information (UoI) and the correlation of semantic information between user equipment. Traditional methods often result in the delivery of redundant or valueless information, which is inefficient for resource-constrained satellite clusters. Moreover, traditional semantic-agnostic transmission scheduling approaches fail to support distributed semantic-aware decision-making in dynamic wireless environments with time-varying information relativity [6].

This study proposes a novel semantic-aware coordinated transmission (SCT) scheme for CCS. To maximize UoI per unit energy consumption within a limited connection window, this study introduces a multi-agent double and dueling deep Q-learning (MAD3QL) algorithm. This algorithm allows each satellite to make autonomous decisions based on its own observations in a distributed manner. Simulation results show that the SCT scheme significantly outperforms semantic-agnostic transmission methods, achieving higher average UoI per unit energy consumption within the constrained connection window.

System model and problem formulation. We consider a slotted downlink CCS consisting of M satellites S_m, $m \in \mathbb{M} = \{1, 2, \ldots, M\}$, cooperatively to perform observation tasks and transmit their data to the GS via scheduled beams to achieve stereo observation, as shown in Figure 1(a). To reduce redundant transmissions, semantic features are extracted from the observed source data using AI technologies. Each task-related semantic feature is formatted into block semantic information (BSI) for cooperative transmission. Given the cooperative nature of the observations, there exists shared and exclusive BSI among the M satellites. We define $\mathscr{B} = \{1, \ldots, B\}$ as the set of BSI. At each time slot, each satellite captures only a subset of $\mathscr{B}$. The BSI captured by the satellite cluster at time slot t can be represented by $\mathcal{V}_t = [v_t^{i,b}]_{M\times B}$, where $v_t^{i,b}$ indicates whether satellite S_i captures BSI b ($v_t^{i,b} = 1$) or not ($v_t^{i,b} = 0$). The satellite clusters compete for access to $\mathscr{C}$ wireless channels to deliver their captured BSI to the GS. For cooperative access, each satellite S_i needs to decide which channel to use for transmission and whether to transmit the captured BSI b to the GS, incurring an energy cost δ.

From the UoI perspective, receiving multiple copies of the same BSI does not yield additional value of information but rather results in additional energy consumption and network congestion, thereby reducing UoI. In practical semantic communications, the UoI of BSI can be quantified by the normalized semantic similarity loss (measured by metrics such as BLEU for text transmission and PSNR for visual data) after semantic decoding at the GS. If the GS perfectly recovers the semantic information of BSI b, then the UoI of b is equal to 1. In the SCT scheme, we define the UoI $U(t)$ as follows:

$$U(t) = \sum_{b=1}^{B}\sum_{j=1}^{\mathscr{C}} \lambda_b \max_{i\in\mathbb{M}}\{v_t^{i,b} \cdot a_{t,j}^{i,b} \cdot (1 - p_{t,j}^{i,b}) \cdot \mathcal{F}_{t,j}^{i,b}\}, \quad (1)$$

where λ_b denotes the importance weight of BSI b, $a_{t,j}^{i,b}$ represents whether satellite S_i chooses to transmit b-th BSI ($a_{t,j}^{i,b} = 1$) or remains idle ($a_{t,j}^{i,b} = 0$) in channel j, and $\mathcal{F}_{t,j}^{i,b}$ is the semantic similarity loss of b-th BSI in channel j. $p_{t,j}^{i,b}$ indicates the block error rate of BSI b for S_i in a shadowed Rician fading channel [7].

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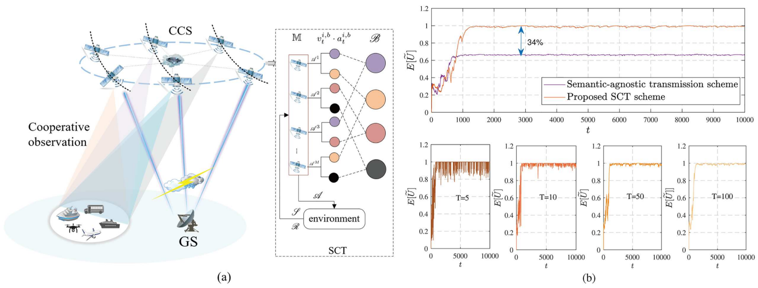

Figure 1 (Color online) Semantic-empowered cooperative LEO satellite communication system model and simulation results for the proposed scheme. (a) System model; (b) simulation results.

Further, we define the UoI per unit energy consumption, denoted by $\widetilde{U}(t)$ as follows:

$$\widetilde{U}(t)=\frac{\sum_{b=1}^{B}\sum_{j=1}^{\mathscr{C}}\lambda_b \max_{i\in\mathbb{M}}\{v_t^{i,b}\cdot a_{t,j}^{i,b}\cdot(1-p_{t,j}^{i,b})\cdot\mathcal{F}_{t,j}^{i,b}\}}{\delta\sum_{i=1}^{M}\sum_{b=1}^{B}a_t^{i,b}}. \tag{2}$$

Considering that the satellite clusters have limited connection windows, we aim to optimize the average sum of UoI within a sliding time window of length T, denoted by $E[\widetilde{U}]$. Then we can formulate the optimization problem as follows:

$$\max_{\mathcal{A}} E[\widetilde{U}]:\frac{1}{T}\sum_{t=0}^{T-1}\widetilde{U}(t),$$
$$\text{s.t.}\quad\begin{cases}\text{C1}:\sum_{j=1}^{\mathscr{C}}a_{t,j}^{i,b}\leqslant 1,\\ \text{C2}:I_t^{i,b}=\sum_{j=1}^{\mathscr{C}}v_t^{i,b}a_{t,j}^{i,b}\cdot\prod_{u\neq i}(1-a_{t,j}^{i,*}),\forall t,i,b,\\ \text{C3}:a_{t,j}^{i,b}=0,\forall v_t^{i,b}=0,\end{cases} \tag{3}$$

where $\mathcal{A}$ represents the transmission policy that determines which BSI is sent over time. $I_t^{i,b}$ denotes whether satellite S_i successfully transmits the b-th BSI at t without collision. C1 ensures that each satellite can choose at most one channel to transmit BSI at t. C2 guarantees that $I_t^{i,b}=1$ if satellite S_i chooses a channel to transmit the b-th BSI and no other satellite chooses the same channel to transmit any BSI. C3 specifies the captured BSI constraint.

Solution and simulation results. In a practical CCS system, solving the above nonlinear maximization problem of UoI is challenging. Specifically, as the number of satellites within the cluster increases or under poor channel conditions, satellite S_i fails to be aware of other satellites' history state information (e.g., action, channel state, or the interdependency of BSI). Consequently, S_i needs to make decisions to maximize $E[\widetilde{U}]$ in a distributed manner. Motivated by this, we utilize the semantic-aware MAD3QL algorithm. The design of the reward function, state, and action spaces in the proposed algorithm can be summarized as follows:

- Action space. At time slot t, the action of S_i can be expressed as $\mathscr{A}_t^i=(j,a_t^i)$, where $j\in\{1,\ldots,\mathscr{C}\}$, $a_t^i=[a_t^{i,1},\ldots,a_t^{i,B}]$.
- State space. The state space can be expressed as $\Omega_t=\{q_t^i:\{(\mathscr{A}_t^i,\boldsymbol{u}_t^{i,s},\boldsymbol{u}_t^{i,e})\}|i\in\mathbb{M},\forall t\}$, where $\boldsymbol{u}_t^{i,s}$ is the UoI vector that S_i obtains by sending its own BSI and $\boldsymbol{u}_t^{i,e}$ is the implicit UoI vector that S_i obtains under the coordination of other satellites.
- Reward function. The reward function at t is defined as $\mathcal{R}_t=E[\gamma_t^i/\sum_{b=1}^{B}\delta a_t^{i,b}]$ with $\gamma_t^i=\|\boldsymbol{u}_t^{i,s}\oplus\boldsymbol{u}_t^{i,e}\|_1$, where $\|\|_1$ is the L1 norm and $\oplus$ is the OR operation.

The simulation parameters of the SCT scheme are detailed in Appendix A. As illustrated in Figure 1(b), our proposed SCT scheme achieves about 34% higher UoI per unit energy consumption compared to the semantic-agnostic transmission scheme under the same simulation settings. This significant improvement verifies the effectiveness of the proposed SCT scheme in providing information-centric transmission services, which are crucial for future goal-oriented and energy-efficient satellite communication scenarios. Moreover, these results highlight the importance of periodically updating and disseminating policies within the CCS to improve the robustness of the SCT scheme, especially given the constraints of limited connection windows. The training procedure and additional simulation results can be found in Appendix B.

Conclusion and future work. Our proposed SCT scheme for CCS enables distributed semantic-aware coordinated transmission, outperforming traditional semantic-agnostic transmission schemes in terms of average UoI per unit energy consumption within a limited connection window. In future work, we aim to explore the design of semantic-aware coordinated superimposed transmission to further prolong the lifetime of resource-constrained CCS systems.

Acknowledgements This work was supported in part by National Natural Science Foundation of China (Grant Nos. 62071141, 62027802), Shenzhen Science and Technology Program (Grant Nos. JSGG20220831110801003, GXWD20231127123203001), Fundamental Research Funds for the Central Universities (Grant No. HIT.OCEF.2024046), and Major Key Project of PCL (Grant No. PCL2024A01).

Supporting information Appendixes A and B. 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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