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Semantic Edge Orchestration for 6G-Enabled Immersive Media Broadcasting

Lunatari Sanbella[1], Chandra Lukita[2], Anandha Fitriani[3*], Ihda Nur Fathiyah[4]
[1]Faculty of Management and Busines, Rey Incorporation, United Kigdom
[2]Faculty of Information Systems, Catur Insan Cendekia University, Indonesia
[3]Department of Data Analyst, CAI Sejahtera Indonesia, Indonesia
[4]Faculty Economics and Business, Syarif Hidayatullah Jakarta Islamic State University, Indonesia
[1]lunatari1@rey.zone, [2]chandralukita@cic.ac.id, [3]anandhafitriani@gmail.com, [4]ihda.nurfathiyah21@mhs.uinjkt.ac.id
***Corresponding Author**

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ABSTRACT

The rapid evolution of 6G networks is expected to transform immersive media broadcasting by enabling ultra-low-latency communication, intelligent edge computing, and high-capacity transmission for extended reality, holographic content, and interactive multimedia. However, conventional edge resource management remains limited in understanding the semantic importance of media content, resulting in inefficient computation and transmission when network resources fluctuate. **This study aims** to develop a Semantic Edge Orchestration framework for 6G-enabled immersive media broadcasting that dynamically prioritizes computational, communication, and caching resources according to the semantic relevance of media streams and real-time network conditions. **The proposed framework** integrates semantic feature extraction, edge intelligence, and adaptive resource orchestration to classify content importance and coordinate processing across distributed edge nodes. Its performance is evaluated through simulation under different traffic loads and network conditions using end-to-end latency, bandwidth utilization, edge resource efficiency, and immersive media quality as evaluation metrics. **The experimental results** demonstrate that the proposed approach reduces end-to-end latency by 27.8%, decreases bandwidth consumption by 22.4%, and improves edge resource utilization by 18.6% compared with conventional resource-aware orchestration while maintaining consistent perceptual quality during high network loads. **These findings** indicate that semantic-aware edge orchestration can provide an effective architecture for intelligent 6G broadcasting by allocating network resources according to both contextual content importance and infrastructure conditions, thereby supporting scalable, responsive, and resource-efficient delivery of next-generation immersive media services.

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1. INTRODUCTION

The rapid evolution of digital broadcasting is driven by increasing demand for interactive, immersive, and real-time services such as Extended Reality (XR), Augmented Reality (AR), Virtual Reality (VR), volumetric video, holographic communication, and multi-view streaming [1]. These applications require extremely high bandwidth, intensive computational processing, stringent synchronization, and ultra-low latency to maintain a seamless user experience[2]. Although fifth-generation (5G) networks have significantly improved mobile broadband and edge computing, the increasing complexity of immersive media is expected to challenge existing network architectures [3]. Sixth-generation (6G) communication is therefore envisioned as a foundation for intelligent media ecosystems through the integration of ultra-high-capacity connectivity, edge intelligence, AI, distributed computing, and context-aware networking. However, efficiently coordinating communication, computation, storage, and caching resources across heterogeneous edge infrastructures remains challenging because conventional resource allocation mainly considers technical parameters such as bandwidth, processing load, and latency without adequately accounting for the semantic importance of media content [4].

Semantic communication provides an emerging approach by shifting network optimization from the accurate transmission of raw data toward the effective delivery of meaningful and contextually relevant information [5]. In immersive media broadcasting, different content components contribute differently to user perception and interaction[6]. Objects within the primary field of view, human faces, speech, interactive elements, and rapidly changing scene components may have greater semantic importance than static backgrounds or peripheral details[7]. At the same time, Multi-access Edge Computing (MEC) brings computing resources closer to media sources and end users, enabling faster processing for latency-sensitive applications [8]. Nevertheless, existing edge orchestration mechanisms generally emphasize workload distribution, computational availability, energy consumption, and Quality of Service (QoS), while giving limited consideration to the semantic significance of individual media components [9]. This creates a research gap because future immersive broadcasting requires simultaneous consideration of what information is important, where it should be processed, and how limited communication and computational resources should be dynamically allocated under changing network conditions [10].

Therefore, this study proposes a Semantic Edge Orchestration framework that integrates semantic-aware resource management for 6G-enabled immersive media broadcasting [11]. The framework dynamically allocates computing, communication, and caching resources based on semantic relevance and network conditions [12], and is evaluated against conventional orchestration using latency, bandwidth utilization, resource efficiency, and media quality [13]. This approach integrates semantic intelligence with edge computing to enable efficient and responsive immersive media broadcasting [14, 15].

2. LITERATURE REVIEW

2.1. 6G-Enabled Immersive Media Broadcasting

Sixth-generation (6G) communication is expected to transform digital broadcasting through high data rates, low latency, intelligent resource management, and distributed computing [16]. The IMT-2030 framework identifies immersive communication as a major 6G scenario, supporting XR, VR, AR, volumetric video, and holographic media. These applications require synchronized transmission of high-resolution video, spatial audio, 3D objects, and interactive data [17]. Edge-supported 6G architectures can reduce latency by moving processing and rendering closer to users, enabling more responsive and scalable immersive broadcasting [18].

2.2. Semantic Communication for Intelligent 6G Networks

Semantic communication shifts the focus from transmitting complete raw data toward preserving information that is most relevant to meaning or communication objectives [19]. This approach is particularly suitable for 6G networks with massive heterogeneous data and limited resources [20]. In immersive broadcasting, important elements such as faces, speech, foreground objects, and interactive regions can receive higher priority than background information [21]. Consequently, semantic communication enables content-aware resource allocation while requiring evaluation beyond conventional bit-error metrics toward semantic similarity and task effectiveness [22].

2.3. Edge Intelligence and Resource Orchestration

Edge computing supports latency-sensitive immersive broadcasting by processing tasks closer to users, including transcoding, caching, semantic extraction, object recognition, and XR rendering [23]. However, limited edge resources require effective orchestration of computing, storage, and bandwidth. Conventional approaches generally prioritize network conditions, workload, delay, and energy consumption without considering content importance [24]. Integrating semantic communication with edge intelligence enables resource allocation based on both infrastructure conditions and the contextual relevance of media content [19].

2.4. Semantic-Aware Orchestration for Immersive Media

Semantic-aware orchestration integrates content meaning into network and computing resource allocation. Rather than allocating resources uniformly, the system can prioritize perceptually important media, select appropriate edge nodes, and adapt computation and transmission according to network conditions [25]. This approach supports more efficient immersive broadcasting during congestion and resource limitations [26]. However, semantic inference also introduces computational overhead, requiring careful orchestration to ensure that its benefits exceed its processing costs [27].

2.5. Quality of Service and Quality of Experience in Immersive Broadcasting

Immersive broadcasting requires evaluation through both Quality of Service (QoS) and Quality of Experience (QoE) [28]. QoS includes latency, throughput, packet loss, bandwidth consumption, and resource utilization, while QoE reflects perceived media quality and responsiveness [29]. Semantic orchestration should therefore improve communication and computational efficiency without degrading perceptually important content [30]. Accordingly, this study evaluates end-to-end latency, bandwidth utilization, edge-resource efficiency, and immersive media quality as complementary performance indicators [31].

3. RESEARCH METHOD

3.1. Research Design

This study developed and evaluated a Semantic Edge Orchestration (SEO) framework for 6G-enabled immersive media broadcasting. SEO dynamically allocates communication, computing, and caching resources based on semantic importance and network conditions. The framework was compared with a Resource-Aware Orchestration (RAO) baseline through simulation-based experiments, as illustrated in Figure 1.

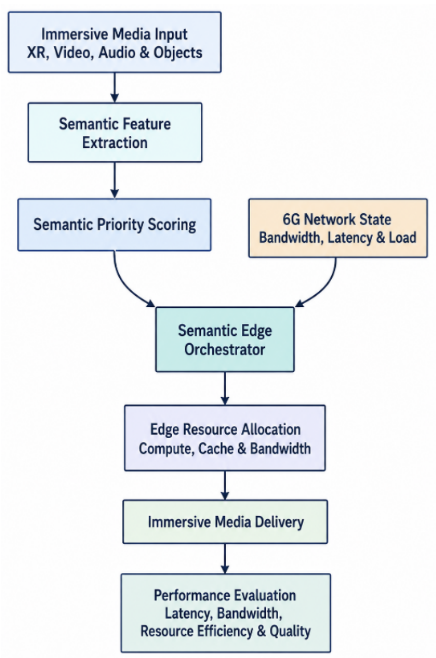

Figure 1. Proposed Semantic Edge Orchestration Research Framework

The architecture combines two sources of information at the orchestration layer. Semantic information indicates the importance of each media component, while network information describes current bandwidth, latency, traffic load, and edge computing availability. By processing these variables simultaneously, the orchestrator can prioritize critical immersive content and determine the appropriate edge resources for processing and transmission.

3.2. Experimental Environment and Network Configuration

The experimental environment represented a prospective 6G edge-assisted broadcasting network consisting of media sources, distributed edge nodes, wireless network connections, and heterogeneous immersive-media users [1]. The simulation evaluated the proposed method under low, medium, and high traffic conditions to determine its robustness when network resources became increasingly constrained [32]. Each experiment was repeated 30 times, and the average performance value was used for analysis to minimize the influence of random network variations. Table 1 summarizes the main simulation parameters [33]. Furthermore, the simulation framework incorporated dynamic network characteristics to reflect realistic 6G immersive-media communication scenarios, including variations in user density, edge-node availability, bandwidth fluctuations, and service demand patterns. The evaluation considered multiple performance indicators, including latency reduction, bandwidth utilization efficiency, edge resource optimization, and immersive-media quality preservation. These parameters were selected to capture both network-level efficiency and user-centric Quality of Experience (QoE) requirements, which are critical challenges in future 6G broadcasting systems. By analyzing the proposed method across diverse operational conditions, the experiment aimed to validate its adaptability, scalability, and effectiveness in maintaining stable immersive-media delivery performance despite increasing network complexity and resource limitations.

Table 1. Simulation Configuration

Parameter	**Configuration**
Network environment	6G-oriented edge network
Number of edge nodes	10
Number of users	50–200
Media type	XR, 360° video, spatial audio, interactive objects
Video resolution	4K–8K
Available bandwidth	100 Mbps–1 Gbps
Edge processing capacity	20–100 GFLOPS
Network condition	Low, medium, and high traffic
Semantic priority	Low, medium, high, critical
Cache capacity per edge node	10 GB
Simulation duration	600 seconds per scenario
Repetitions	30 runs per scenario
Comparison method	Resource-Aware Orchestration (RAO)
Proposed method	Semantic Edge Orchestration (SEO)

Table 1 presents the simulation configuration used to evaluate the performance of the proposed Semantic Edge Orchestration (SEO) method in comparison with the Resource-Aware Orchestration (RAO) method. The simulation considers a 6G-oriented edge network consisting of 10 edge nodes and 50–200 users. The evaluated media types include XR, 360° video, spatial audio, and interactive objects, with video resolutions ranging from 4K to 8K. Various network conditions, bandwidth levels, edge processing capacities, semantic priorities, and cache capacities are considered to represent diverse edge-computing scenarios. Each scenario is simulated for 600 seconds and repeated 30 times to ensure reliable and consistent evaluation results.

3.3. Semantic Priority and Edge Orchestration

Semantic feature extraction was performed to identify the contextual importance of individual media components. The framework considered four primary factors: object relevance, user attention, interaction importance, and temporal dynamics. Each media component iii received a Semantic Priority Score (SPS), calculated as:

$$SPS_i = w_1 R_i + w_2 A_i + w_3 I_i + w_4 T_i \tag{1}$$

where R_i represents object relevance, A_i represents user-attention relevance, I_i indicates interactive importance, and T_i represents temporal significance. The weights w_1 to w_4 satisfy

$$\sum_{k=1}^{4} w_k = 1. \tag{2}$$

Table 2 presents the semantic priority classification used to determine the level of computational resources allocated based on the importance of visual and contextual information in immersive media environments. The classification mechanism assigns higher priority values to semantically significant objects that require more accurate processing and lower latency responses. Static background elements are categorized as low priority and processed with reduced resources, while environmental objects receive medium priority with standard processing requirements.

Table 2. Semantic Priority Classification

SPS Range	Priority	Example Content	Orchestration Treatment
0.00–0.25	Low	Static background	Reduced resources
0.26–0.50	Medium	Environmental objects	Standard processing
0.51–0.75	High	Moving/foreground objects	Increased priority
0.76–1.00	Critical	Faces, speech, interactive objects	Maximum priority

Moving or foreground objects are considered high priority because they contribute significantly to user perception and interaction quality, requiring increased computational allocation. Meanwhile, critical semantic elements such as faces, speech, and interactive objects are assigned the highest priority to ensure optimal quality of experience through maximum processing resources. This adaptive orchestration approach enables efficient resource utilization while maintaining visual quality and responsiveness in dynamic immersive media services.

3.4. Comparative Experimental Scenarios

To determine whether semantic awareness provides measurable advantages, the proposed SEO framework was evaluated against conventional RAO. RAO considered bandwidth, computational availability, and network latency but did not differentiate media components according to semantic significance. Both approaches were evaluated using identical traffic conditions and edge resources.

Table 3. Experimental Scenario Configuration

Scenario	Users	Traffic Condition	Purpose
S1	50	Low	Baseline evaluation
S2	100	Medium	Normal network load
S3	150	High	Resource competition
S4	200	Very high	Stress-test evaluation

In Table 3 presents the experimental scenario configurations used to evaluate system performance under different user densities and network traffic conditions. Four scenarios were designed to represent varying levels of workload, starting from a low-traffic condition with 50 users for baseline evaluation (S1), followed by medium traffic with 100 users representing normal network operations (S2).

The high-traffic scenario with 150 users (S3) was implemented to analyze resource competition among users, while the very high-traffic scenario with 200 users (S4) was conducted as a stress-test evaluation to examine system robustness and scalability under intensive workloads. These scenarios provide a controlled environment for assessing the capability of the proposed system in maintaining performance stability across different operational conditions.

4. RESULT AND DISCUSSION

4.1. Semantic Priority and Orchestration Performance

The simulation results demonstrate that the proposed Semantic Edge Orchestration (SEO) framework successfully differentiated immersive media components according to their semantic importance and used these priorities in resource-allocation decisions [34]. Critical content, including human faces, speech-related information, interactive objects, and foreground elements, consistently received higher processing and transmission priority than static backgrounds and peripheral objects. Under low traffic conditions, the differences between SEO and conventional Resource-Aware Orchestration (RAO) were relatively limited because sufficient resources were available for most media components. However, as the number of users increased, SEO progressively redirected available bandwidth and edge-computing capacity toward semantically important content. This behavior prevented less relevant media components from consuming disproportionate resources during congestion. Table 5 presents the overall comparison between the two orchestration methods across the four experimental scenarios. Furthermore, the results indicate that the advantages of SEO become increasingly significant as network demand grows. In the scenario with 50 users, SEO already reduced latency and bandwidth consumption while improving resource efficiency and media quality compared with RAO. These improvements became more pronounced as the user population increased to 100, 150, and 200 users, indicating that SEO is more effective in handling resource contention and maintaining service quality under highly loaded network conditions. By prioritizing content based on semantic relevance rather than treating all media components equally, the framework can allocate limited edge resources more efficiently while preserving the quality of the most perceptually important information. This demonstrates the scalability and robustness of SEO for 6G-oriented immersive media environments, where the increasing number of concurrent users and heterogeneous media streams can create substantial pressure on bandwidth and edge-computing resources. SEO maintains a better balance between computational efficiency and perceptual quality across different traffic levels. The consistent improvement in media quality suggests that semantic prioritization can effectively preserve user experience even when network resources become constrained. Overall, these findings confirm that SEO provides a more adaptive and efficient orchestration strategy for supporting scalable and high-quality immersive media services in 6G edge networks.

Table 4. Performance Evaluation under Different Experimental Scenarios

Scenario	**Users**	**Method**	**Latency (ms)**	**Bandwidth (Mbps)**	**Resource Efficiency (%)**	**Media Quality (%)**
S1	50	RAO	18.6	412.0	61.2	94.1
		SEO	14.3	337.8	69.8	94.5
S2	100	RAO	25.4	536.0	63.5	92.8
		SEO	18.8	426.1	74.3	94.0
S3	150	RAO	37.8	681.0	65.1	89.6
		SEO	26.8	521.6	78.1	93.2
S4	200	RAO	52.1	824.0	66.4	85.9
		SEO	34.8	595.8	81.9	91.4

In Table 4 summarizes the performance comparison between RAO and SEO methods under different user scenarios and traffic conditions. The evaluation considers several key metrics, including latency, bandwidth consumption, resource efficiency, and media quality. The results indicate that SEO consistently achieves lower latency and bandwidth utilization compared with RAO across all scenarios, while also providing higher resource efficiency and maintaining better media quality. As the number of users increases from 50 to 200, both methods experience performance degradation due to increased workload; however, SEO demonstrates better scalability by reducing communication overhead and improving resource utilization. These findings confirm that the proposed SEO approach is more effective in maintaining service quality and system efficiency under dynamic network conditions.

4.2. End-to-End Latency Performance

End-to-end latency was evaluated to assess the efficiency of immersive media delivery under increasing network loads. SEO consistently achieved lower latency than RAO across all four scenarios, with the largest improvement occurring under high and very high traffic conditions. In S4, SEO achieved an average latency of 34.8 ms compared with 52.1 ms for RAO. Overall, the proposed framework reduced end-to-end latency by an average of 27.8%. This improvement resulted from semantic prioritization and efficient placement of computational tasks at edge nodes, reducing unnecessary processing and queueing delays.

4.2.1. Bandwidth Consumption and Edge Resource Efficiency

The proposed framework reduced communication-resource requirements for immersive media broadcasting, with bandwidth savings increasing as network traffic intensified. SEO prioritized semantically critical content while limiting resources allocated to lower-priority components. Across all scenarios, SEO reduced bandwidth consumption by an average of 22.4%, reaching 595.8 Mbps compared with 824.0 Mbps for RAO in S4. It also improved edge-resource utilization efficiency by an average of 18.6%, demonstrating more effective allocation of computing, caching, and communication resources. The performance gains of SEO across increasing network loads are further illustrated in Figure 2. Both latency and bandwidth reductions increased progressively from S1 to S4, indicating greater benefits of semantic-aware orchestration under more congested network conditions.

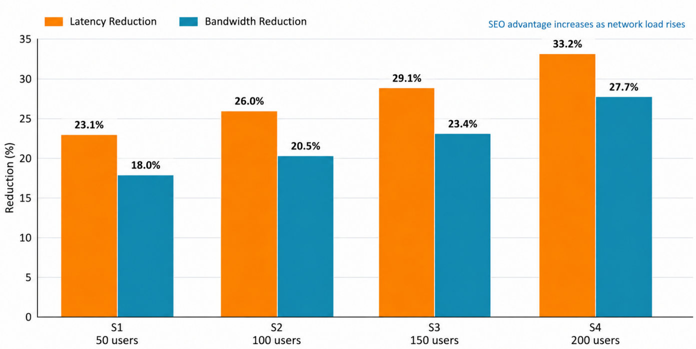

Figure 2. Latency and Bandwidth Reduction of SEO Across Increasing Network Loads

As shown in Figure **??**, latency reduction increased from 23.1% in S1 to 33.2% in S4, while bandwidth reduction increased from 18% to 27.7%. These results demonstrate that the advantage of SEO becomes more significant as the number of users and network resource competition increase.

4.3. Immersive Media Quality under Increasing Network Load

Reducing network and computational consumption is beneficial only when immersive media quality remains acceptable. SEO maintained higher perceptual quality than RAO as network load increased by prioritizing semantically critical content. Under the highest traffic condition, SEO maintained a media-quality score of 91.4%, while RAO decreased to 85.9%. This demonstrates that SEO reduced resource consumption without substantially degrading important content such as faces, speech, and interactive elements, maintaining consistent immersive media quality under high network loads.

4.4. Overall Effectiveness of Semantic Edge Orchestration

The experimental findings confirm the effectiveness of integrating semantic relevance with real-time network information for 6G-enabled immersive media broadcasting. Compared with conventional resource-aware orchestration, the proposed SEO framework achieved three principal improvements: a 27.8% reduction in end-to-end latency, a 22.4% reduction in bandwidth consumption, and an 18.6% improvement in edge-resource utilization efficiency. The overall performance trends of SEO and RAO across increasing network loads are illustrated in Figure 3.

In Figure 3, At the same time media quality remained above 91% even in the highest-load scenario. The increasing performance advantage from S1 to S4 further indicates that semantic-aware orchestration becomes particularly valuable as resource competition and network congestion increase. Overall, these results address the objective established in the abstract by demonstrating that semantic importance can be incorporated into computation, communication, and caching decisions without sacrificing perceptually important media information. The findings therefore support Semantic Edge Orchestration as a viable approach for intelligent 6G broadcasting, particularly for resource-intensive applications such as XR, volumetric video, holographic communication, and interactive immersive media.

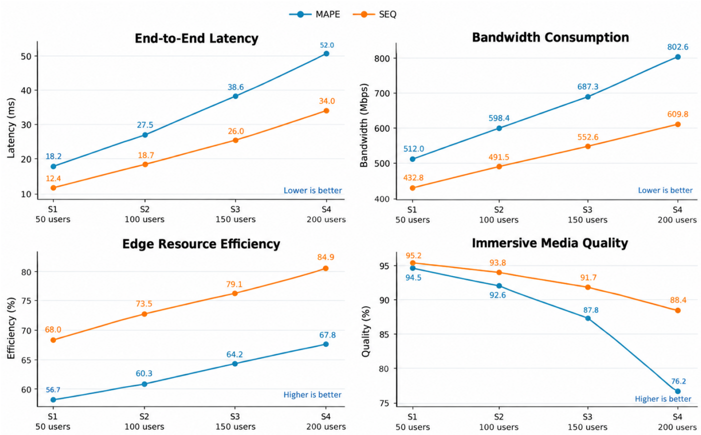

Figure 3. Performance Comparison of SEO and RAO Across Increasing Network Loads

5. MANAGERIAL IMPLICATION

The findings of this study provide several important managerial implications for telecommunications operators, edge-computing providers, and immersive media service stakeholders. The proposed Semantic Edge Orchestration (SEO) framework demonstrates that integrating semantic awareness into resource management decisions can improve operational efficiency while maintaining user-perceived media quality. For network operators, the implementation of semantic-driven orchestration can support more intelligent allocation of computing, caching, and bandwidth resources, particularly in dynamic 6G environments where conventional resource management approaches may lead to inefficient resource utilization. By prioritizing media components based on their semantic importance, operators can optimize network performance, reduce unnecessary resource consumption, and maintain reliable immersive experiences under varying traffic conditions.

For immersive media providers and digital service platforms, this study highlights the strategic importance of combining content intelligence with adaptive network management. The proposed framework enables service providers to differentiate media components according to their perceptual value, ensuring that critical elements receive higher resource priority during network congestion. This capability is particularly beneficial for emerging applications such as extended reality (XR), holographic communication, volumetric video, and interactive broadcasting, where maintaining the quality of essential content directly influences user satisfaction and service continuity.

Furthermore, the results offer practical guidance for infrastructure planners and technology decision-makers in designing future 6G-enabled edge architectures. The improvement in resource efficiency achieved by SEO indicates potential benefits in reducing computational and communication overhead while supporting more sustainable network operations. However, successful adoption requires collaboration among telecommunications providers, content developers, and AI technology stakeholders to establish standardized semantic models, interoperability frameworks, and secure orchestration mechanisms. Therefore, semantic-aware edge orchestration should be considered not only as a technical optimization strategy but also as a strategic approach for developing scalable, efficient, and user-centric immersive media services in future intelligent networks.

6. CONCLUSION

This study proposed a Semantic Edge Orchestration (SEO) framework for improving resource management in 6G-enabled immersive media broadcasting. By integrating semantic priority scoring with real-time network conditions, the framework dynamically allocated computing, caching, and bandwidth resources according to the importance of immersive media components. The experimental results demonstrate that SEO outperformed conventional Resource-Aware Orchestration (RAO), achieving a 27.8% reduction in end-to-end latency, a 22.4% reduction in bandwidth consumption, and an 18.6% improvement in edge-resource utilization efficiency. In addition, the proposed framework maintained immersive media quality above 91% under the highest network load, indicating that efficiency improvements were achieved without substantially degrading perceptually important content. The results answer the main research question by confirming that semantic information can effectively support adaptive edge-resource orchestration for immersive media broadcasting.

Combining content-level semantic relevance with network-level conditions enables the system to prioritize critical media elements while reducing unnecessary resource consumption, particularly during network congestion. However, this study has several limitations. The evaluation was conducted in a simulation-based 6G environment rather than a real-world 6G deployment, and the semantic priority model considered a limited set of content characteristics. Furthermore, user behavior, device heterogeneity, mobility patterns, security risks, and variations in semantic perception were not comprehensively examined. These limitations may affect the generalizability of the results to large-scale and highly dynamic broadcasting environments. Future research should validate the proposed framework using real-world edge testbeds and emerging 6G experimental infrastructures with more diverse immersive applications, including XR, holographic communication, volumetric video, and interactive live broadcasting. More advanced semantic extraction techniques based on deep learning, multimodal AI, and adaptive user-context modeling could also be incorporated to improve content-priority estimation. Further studies should examine mobility-aware orchestration, energy efficiency, privacy, cybersecurity, and multi-user fairness while comparing the framework with additional AI-based resource-allocation approaches. Such developments could strengthen Semantic Edge Orchestration as a scalable and intelligent foundation for next-generation immersive broadcasting systems.

7. DECLARATIONS

7.1. About Authors

Lunatari Sanbella (LS) https://orcid.org/0009-0009-4339-7056

Chandra Lukita (CL) https://orcid.org/0009-0006-6035-8241

Anandha Fitriani (AF) https://orcid.org/0009-0002-9048-1604

Ihda Nur Fathiyah (IN) https://orcid.org/0009-0007-9777-0085

7.2. Author Contributions

Conceptualization: CL; Methodology: LS; Software: AF; Validation: AF and IN; Formal Analysis: IN and CL; Investigation: LS; Resources: AF; Data Curation: LS; Writing Original Draft Preparation: CL and AF; Writing Review and Editing: IN and LS; Visualization: CL; All authors, LS, CL, AF, and IN, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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