Preserving Narrative Integrity in Distributed Immersive Storytelling through Coherence-Aware Adaptation

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Abstract

Immersive storytelling increasingly relies on distributed architectures to enable collaborative co-creation across remote participants, but network impairments such as delay and burst latency can introduce inconsistencies in shared object states, avatar gestures, and spatial audio cues that disrupt narrative coherence. While prior work has examined the perceptual impact of de-synchronization, existing approaches do not formally characterize the structural conditions under which such inconsistencies break narrative coherence and, consequently, narrative integrity. In this paper, we introduce Narrative Interaction Coherence (NIC), a system-level metric that captures causal event ordering violations, temporal misalignment, and state divergence in distributed immersive environments. We develop a simulation framework for collaborative storytelling under controlled network impairments and compare latency-based and QoE-inspired adaptation strategies with a coherence-aware approach. Results show that coherence-aware adaptation substantially reduces narrative break events and incoherence duration, maintaining high coherence even under adverse conditions. These findings highlight the importance of explicitly modeling structural narrative coherence as a design objective in immersive media systems and provide a foundation for future validation in real multi-user XR environments.

Keywords

immersive storytelling, narrative coherence, distributed XR, multimodal interaction, synchronization

ACM Reference Format:
Syed Safi Uddin Qadri and Gabriel-Miro Muntean. 2026. Preserving Narrative Integrity in Distributed Immersive Storytelling through Coherence-Aware Adaptation. In *Proceedings of ACM International Conference on Interactive Media Experiences (IMX) (IMX '26).* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 Introduction

Immersive media experiences are evolving from passive consumption to interactive and collaborative storytelling, where remote participants jointly create narrative moments through shared objects, avatar gestures, and spatial audio cues. These experiences rely on distributed architectures (edge–cloud, client–server, and hybrid) to meet latency and scalability constraints [8, 10]. However, under realistic network impairments (e.g., delay, jitter, and burst latency), the replicated state of a shared scene may diverge across users. Even when average latency is acceptable, inconsistencies such as out-of-order events, misaligned interactions, or premature audio cues can disrupt narrative flow and degrade engagement [8].

Prior work has shown that network-induced de-synchronization affects user perception and interaction behavior. However, most approaches model synchronization using subjective QoE metrics or latency-based measures, without capturing the *structural* conditions under which inconsistencies become story-breaking events. As a result, existing adaptation mechanisms may reduce delay while still allowing causal inversions and prolonged incoherence.

We argue that preserving immersive storytelling requires explicitly modeling these structural disruptions. In this paper, we introduce *Narrative Interaction Coherence (NIC)*, a system-level metric that captures (i) causal ordering violations, (ii) temporal misalignment between dependent events, and (iii) divergence of replicated interaction state. NIC enables coherence to be quantified and optimized independently of subjective perception, bridging distributed system behavior and narrative integrity.

Here, narrative integrity denotes preservation of the intended story structure and progression, not cryptographic integrity or tamper protection. We operationalize it through narrative coherence, captured by causal ordering, temporal alignment, and replicated state consistency.

We develop a simulation framework that models collaborative storytelling as a causally constrained event graph under controlled network impairments, and compare latency-based and QoE-inspired baselines with a coherence-aware adaptation strategy that prioritizes causally critical updates. Results show that coherence-aware adaptation substantially reduces narrative break events and incoherence duration, maintaining high coherence under adverse conditions.

Our contributions are threefold: (1) formalizing narrative integrity via NIC, capturing coherence breakdowns beyond latency metrics; (2) proposing a simulation methodology for evaluating narrative coherence under delay and burst-latency conditions; and (3) demonstrating that coherence-aware adaptation outperforms latency- and QoE-driven approaches in preserving narrative continuity.

2 Related Work

Distributed immersive environments rely on state replication and event synchronization to maintain a consistent shared experience. Previous work has explored latency compensation, prediction, and state reconciliation techniques to mitigate delay and jitter in collaborative VR [1, 8]. These approaches typically optimize network-centric metrics such as latency or packet loss, aiming to reduce motion-to-photon delay or minimize divergence in shared object states, but do not explicitly capture experience-level structural coherence [2, 9].

Research on perception and Quality of Experience (QoE) has shown that network-induced desynchronization can significantly affect user perception and even physiological responses [6, 7]. QoE models capture subjective satisfaction under varying delay conditions, but they do not formalize the structural conditions under which distributed inconsistencies translate into narrative breakdowns.

Adaptive orchestration strategies for distributed XR systems dynamically allocate resources or adjust rendering and streaming parameters based on network conditions. While such approaches improve responsiveness, they primarily optimize latency or QoE indicators [4] and do not consider causal dependencies or interaction-level coherence as optimization objectives.

In immersive storytelling, narrative integrity depends on temporal alignment, causal progression, and multimodal consistency. Disruptions such as out-of-order events or prolonged state divergence can break narrative flow even when average latency remains acceptable. Prior work in computational storytelling has addressed narrative coherence at the content and semantic level (e.g., symbolic planning or inconsistency detection in generated stories), but these approaches focus on centralized or text-based systems rather than distributed interaction execution.

In contrast, our work models coherence at the level of distributed interaction, where network-induced delay, jitter, and synchronization errors can disrupt the causal structure of multimodal events. We formalize Narrative Interaction Coherence (NIC) as a system-level metric capturing causal ordering, temporal alignment, and state consistency, and evaluate adaptation strategies based on their ability to preserve structural narrative continuity under adverse network conditions.

3 Narrative Interaction Coherence Model

We model collaborative immersive interaction as a causally constrained event graph, where narrative progression emerges from dependent events across distributed participants. Inspired by dependency-aware scheduling models (DAGs), we interpret dependencies as narrative constraints, where violations correspond to breakdowns in story continuity. This enables reasoning about narrative integrity as a system-level property under network impairments.

Participants observe and manipulate a shared narrative state that evolves through discrete events (e.g., object reveal, handover, gesture response, spatial audio trigger) subject to causal and temporal constraints.

Figure 1 illustrates the overall system architecture of the proposed coherence-aware adaptation framework for distributed immersive storytelling.

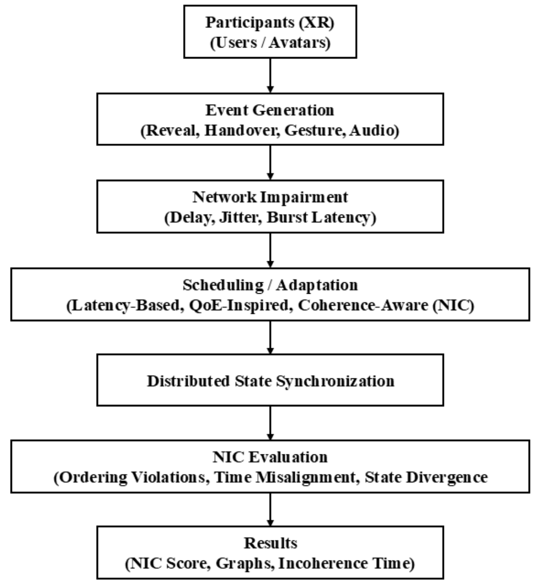

Figure 1: System architecture of the coherence-aware adaptation framework. Events are transmitted under network impairments and scheduled using latency-based, QoE-inspired, and coherence-aware strategies, followed by state synchronization and NIC evaluation.

3.1 Event and Dependency Model

Let $\mathcal{E} = \{e_1, e_2, \dots, e_n\}$ denote the set of narrative interaction events during a session. Each event e_i is associated with:

- A logical timestamp t_i
- A participant or source node
- A state update Δs_i

Narrative structure is represented as a directed acyclic graph $G = (\mathcal{E}, \mathcal{D})$, where $\mathcal{D}$ denotes causal dependencies. A directed edge $(e_i \rightarrow e_j)$ indicates that event e_j must occur after e_i for the narrative to remain coherent (e.g., *object reveal* $\rightarrow$ *reaction gesture*).

In the simulation, event types and dependencies are scenario-defined. In real deployments, they could be obtained from interaction scripts, scene graphs, authoring tools, or runtime semantic annotations. Each event may include metadata such as source participant, target object, interaction type, and narrative role, allowing the system to distinguish a gesture responding to a specific object reveal from unrelated gestures by other participants.

3.2 Causal Ordering Violations

Under network delay or jitter, events may be observed in an order that violates narrative causality. For each dependency $(e_i \rightarrow e_j)$, we define an ordering violation indicator:

$$V_{order}(e_i, e_j) = \begin{cases} 1 & \text{if } t_j^{obs} < t_i^{obs} \\ 0 & \text{otherwise} \end{cases}$$

where t^{obs} denotes the observed reception time at a participant. The total ordering violation count over a session is:

$$V_{order}^{total} = \sum_{(e_i \rightarrow e_j) \in \mathcal{D}} V_{order}(e_i, e_j)$$

3.3 Temporal Misalignment

Even when ordering is preserved, excessive delay between dependent events can disrupt narrative flow. For each dependency, we define temporal misalignment as:

Table 1: Feature-gap comparison of related work and the proposed NIC framework.

Work	Primary Focus	Optimization	Multi-user	Causal Dep.	Temporal Const.	State Div.	Coherence Metric	Coherence-Aware Adapt.
Van Damme et al. [8]	QoE/performance	Latency/QoE	Yes	No	Partial	No	No	No
Becher et al. [1]	Latency impact	Latency	Yes	No	No	No	No	No
Yousefdeh & Oyelere [12]	Co-presence/collaboration	User perception	Yes	No	No	No	No	No
Fowler & Souihi [4]	QoE optimization	QoE maximization	Yes	No	No	No	No	No
Wang et al. [10]	Edge scheduling	Delay minimization	Yes	Yes	No	No	No	No
Dantas & Baquero [3]	State synchronization	Eventual consistency	Yes	No	No	Yes	No	No
Yi et al. [11]; Nishigori & Takeda [5]	Narrative coherence (text)	Story consistency	No	Yes	Partial	No	Yes	No
This Work (NIC)	**Narrative coherence in XR**	**Structural coherence**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

$$M_{time}(e_i, e_j) = \max(0,\ (t_j^{obs} - t_i^{obs}) - \tau_{ij})$$

where τ_{ij} is the acceptable narrative latency threshold for the event pair. This threshold varies depending on the interaction type (e.g., gesture reaction vs. ambient audio update) and is defined in the evaluation setup.

3.4 State Divergence

Let $s^{(k)}(t)$ denote the replicated narrative state observed by participant k at time t. State divergence between two participants k and l is defined as:

$$D_{state}^{(k,l)}(t) = \|s^{(k)}(t) - s^{(l)}(t)\|$$

In practice, this distance is computed as a weighted combination of modality-specific differences (e.g., spatial position, animation phase, and audio synchronization), normalized to a common scale.

The aggregate state divergence across all participants is:

$$D_{state}(t) = \frac{1}{|\mathcal{P}|} \sum_{k,l \in \mathcal{P}, k<l} D_{state}^{(k,l)}(t)$$

where $\mathcal{P}$ denotes the participant set.

3.5 Narrative Interaction Coherence

We define Narrative Interaction Coherence as a composite metric capturing structural narrative integrity:

$$NIC = 1 - \left(\alpha \cdot \frac{V_{order}^{total}}{|\mathcal{D}|} + \beta \cdot \overline{M_{time}} + \gamma \cdot \overline{D_{state}}\right)$$

where:

- $\overline{M_{time}}$ is the normalized average temporal misalignment,
- $\overline{D_{state}}$ is the normalized average state divergence,
- α, β, γ are weighting coefficients,
- $0 \leq NIC \leq 1$ (higher values indicate better coherence).

In our evaluation, we set $\alpha = 0.5$, $\beta = 0.3$, and $\gamma = 0.2$, reflecting the relative importance of causal ordering, temporal alignment, and state consistency. Ordering violations are weighted highest as they directly break narrative causality, while temporal misalignment and state divergence have progressively lower impact.

We assign higher weight to ordering violations as they directly break causal structure (e.g., reaction preceding action), which is typically more disruptive than gradual temporal drift. However, the sensitivity analysis (Figure 5) demonstrates that the relative performance of coherence-aware adaptation remains consistent across different weighting configurations, indicating that the proposed approach is not dependent on a specific parameter choice.

Temporal misalignment is normalized as:

$$\overline{M_{time}} = \frac{1}{|\mathcal{D}|} \sum_{(e_i \to e_j)} \frac{M_{time}(e_i, e_j)}{\tau_{ij}}$$

State divergence is normalized over time:

$$\overline{D_{state}} = \frac{1}{T} \int_0^T \frac{D_{state}(t)}{D_{max}}\, dt$$

where D_{max} denotes the maximum allowable divergence and T is the session duration.

Unlike latency or QoE metrics, NIC explicitly penalizes structural violations of narrative causality and prolonged state divergence, enabling adaptation strategies to prioritize coherence-critical updates rather than minimizing delay alone.

NIC currently targets discrete interaction events and state updates. Continuous media streams could be represented through synchronization checkpoints, segment-level events, or stream-state descriptors. The approach is intended as a sidecar or middleware-layer mechanism that assigns coherence-aware priorities above existing transport or delivery protocols.

4 Coherence-Aware Adaptation

To evaluate the practical utility of NIC, we design an adaptation strategy that explicitly prioritizes updates contributing most to restoring structural narrative integrity. We compare this approach against two representative baselines that optimize latency and QoE-related objectives.

4.1 Baseline Strategies

Latency-Based Adaptation. This baseline prioritizes events with the smallest transmission delay and minimizes average end-to-end latency. Events are scheduled using earliest-deadline-first (EDF) or minimum-delay-first policies. While effective in reducing mean delay, this strategy does not differentiate between coherence-critical and non-critical events.

QoE-Inspired Adaptation. This baseline reflects common QoE-driven approaches that prioritize perceptually salient updates such as visual consistency and interaction responsiveness. Events are weighted according to their media type (e.g., visual updates over ambient audio) and delay sensitivity. Although this improves perceived smoothness, it does not explicitly consider causal dependencies or structural ordering constraints.

4.2 Coherence-Aware Scheduling Policy

In contrast, our proposed strategy dynamically prioritizes events based on their expected contribution to NIC improvement.

For each pending event e_i, we define a coherence impact score:

$$C(e_i) = \alpha \cdot \Delta V_{order}(e_i) + \beta \cdot \Delta M_{time}(e_i) + \gamma \cdot \Delta D_{state}(e_i)$$

where:

- $\Delta V_{order}(e_i)$ estimates the reduction in ordering violations,
- $\Delta M_{time}(e_i)$ estimates the reduction in temporal misalignment,
- $\Delta D_{state}(e_i)$ estimates the reduction in state divergence,
- α, β, γ are NIC weighting parameters.

These quantities are estimated using local predictions derived from the event dependency graph and current system state. In our implementation, these estimates are derived from local dependency tracking: events whose predecessors have already been delivered are assigned higher ordering impact, while events with delayed dependencies contribute more strongly to temporal and state-related terms. This lightweight heuristic enables efficient online scheduling without requiring global state knowledge.

Events are inserted into a priority queue ordered by decreasing $C(e_i)$ and transmitted accordingly, effectively treating coherence restoration as an explicit scheduling objective.

4.3 Adaptive Resource Allocation

Under bandwidth constraints or burst latency, the scheduler:

(1) Identifies coherence-critical dependencies in the event graph,
(2) Prioritizes events whose delay would introduce ordering violations or significant temporal misalignment,
(3) Temporarily deprioritizes non-critical background updates (e.g., ambient animation or low-impact audio),
(4) Allocates transmission opportunities to events that restore causal alignment and reduce divergence.

This results in controlled degradation of low-impact updates while preserving narrative continuity (e.g., ensuring object handover precedes reaction).

4.4 Expected Behavior Under Network Impairment

Under burst delay or jitter, latency-based scheduling may reduce average delay but still allow causal inversions. QoE-inspired policies may smooth perceptual disruption yet fail to prevent prolonged incoherence between dependent events.

By contrast, coherence-aware adaptation minimizes:

- The frequency of ordering violations,
- The duration of incoherent narrative states,
- The magnitude of replicated state divergence.

As a result, the system prioritizes structural narrative correctness over uniform delay reduction, enabling more stable and interpretable interaction sequences under adverse network conditions.

5 Simulation Setup and Evaluation

5.1 Scenario Description

We simulate a distributed collaborative immersive storytelling session involving three remote participants jointly enacting a structured narrative sequence. The scenario consists of recurring interaction chains of the form:

object reveal → *handover* → *reaction gesture* → *spatial audio cue*

Each chain is modeled as a causally constrained subgraph within the global event graph defined in Section 3. Background events (e.g., ambient animation updates) are also generated to emulate realistic scene activity but are not critical to narrative progression.

Events are timestamped at generation time and transmitted through a simulated network layer. The framework models event generation, dependency tracking, delay injection, scheduling, state synchronization, and NIC computation for three participants. Each condition is evaluated over 10 independent trials.

5.2 Network Impairment Model

Network delay is modeled as:

$$d = d_{base} + d_{jitter}$$

where d_{base} is a constant propagation delay and d_{jitter} is drawn from a bounded uniform distribution. To emulate adverse conditions, burst latency episodes are introduced, during which delay temporarily increases by a fixed offset for a limited duration.

This controlled stress-test model combines baseline delay, jitter, and burst episodes to isolate delay variability effects on causal event delivery, consistent with prior multi-user VR latency studies [8]. Trace-driven conditions are left for future work.

We evaluate three network conditions:

- **Stable**: low jitter, no burst events,
- **Moderate**: increased jitter,
- **Adverse**: burst latency episodes.

5.3 Compared Adaptation Strategies

We compare:

(1) Latency-based scheduling (minimum-delay-first),
(2) QoE-inspired weighted scheduling,
(3) Proposed coherence-aware scheduling.

All strategies operate under identical bandwidth constraints and event generation patterns.

5.4 Evaluation Metrics

We report:

- Total ordering violations V_{order}^{total},
- Average temporal misalignment $\overline{M_{time}}$,
- Mean state divergence $\overline{D_{state}}$,
- Overall NIC.

Additionally, we measure *incoherence duration*, defined as the cumulative time during which NIC falls below a threshold $\theta = 0.8$.

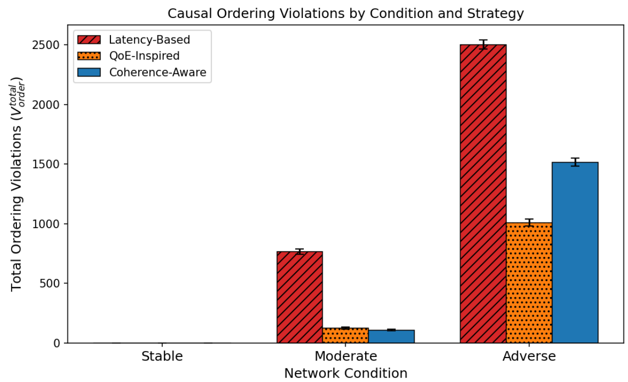

Figure 2: Total causal ordering violations across network conditions and adaptation strategies.

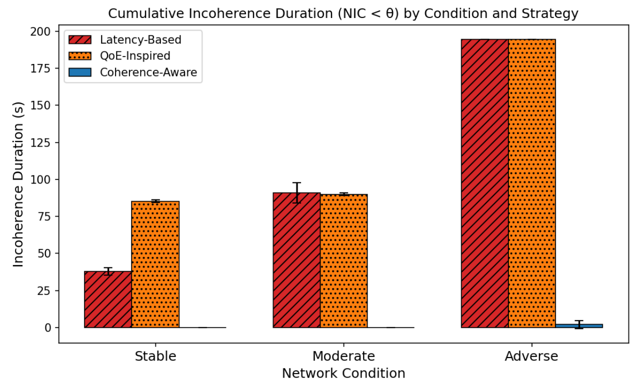

Figure 4: Cumulative incoherence duration ($NIC < 0.8$) across conditions.

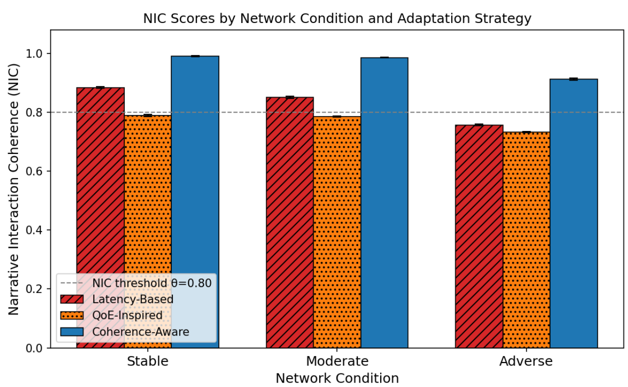

Figure 3: NIC scores across network conditions. The dashed line indicates the coherence threshold ($NIC = 0.8$).

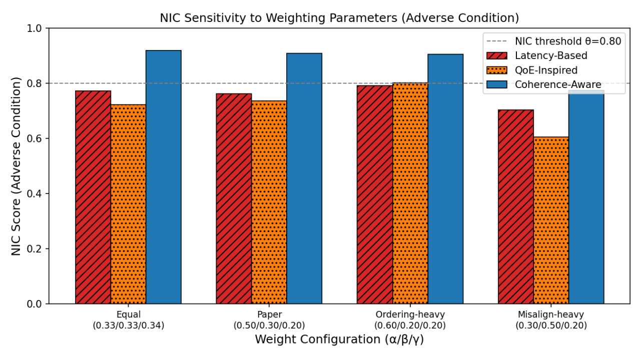

Figure 5: NIC sensitivity to weighting parameters under adverse conditions.

5.5 Results

All reported results correspond to mean values across multiple independent trials.

Causal Ordering Violations. Figure 2 shows the total number of ordering violations. The latency-based strategy produces the highest number of violations, particularly under adverse conditions where burst latency leads to frequent event inversions. The QoE-inspired baseline reduces violations but still exhibits substantial causal inconsistencies.

In contrast, the coherence-aware strategy substantially reduces ordering violations compared with latency-based scheduling and achieves the best overall NIC across all conditions. Under adverse conditions, QoE-inspired scheduling produces fewer ordering violations, but the coherence-aware strategy better controls the combined effects of ordering, temporal misalignment, and state divergence, resulting in higher overall coherence.

Narrative Interaction Coherence. Figure 3 presents NIC scores across conditions. Under stable conditions, all strategies maintain high coherence. However, under moderate and adverse conditions, both latency-based and QoE-inspired strategies exhibit significant degradation, often falling below the coherence threshold.

The coherence-aware strategy maintains consistently higher NIC values and remains above the threshold even under adverse conditions, demonstrating improved preservation of narrative integrity.

Incoherence Duration. Figure 4 shows the cumulative duration during which NIC falls below the coherence threshold. Latency-based scheduling results in prolonged incoherent periods, while QoE-inspired adaptation reduces but does not eliminate such disruptions.

The coherence-aware strategy significantly reduces incoherence duration, indicating faster recovery from network-induced inconsistencies and more stable narrative progression. In several scenarios (e.g., stable and moderate conditions), incoherence duration drops to zero, indicating that the system maintains narrative coherence above the threshold throughout the session. This reflects the ability of the coherence-aware strategy to completely prevent narrative breakdowns under moderate impairment levels.

Sensitivity Analysis. Figure 5 evaluates NIC under different weighting configurations. The coherence-aware strategy consistently outperforms both baselines across all configurations, demonstrating robustness to parameter selection.

Under adverse conditions, coherence-aware scheduling increases NIC from 0.758 (latency-based) and 0.733 (QoE-inspired) to 0.913, improving coherence by 20.4% and 24.6%, respectively. Although QoE-inspired scheduling has fewer ordering violations under adverse conditions, it does not adequately control temporal misalignment and state divergence, resulting in lower overall coherence.

Under moderate conditions, coherence-aware adaptation reduces ordering violations from 765.2 to 107.3, an 86.0% reduction over latency-based scheduling, and achieves the highest NIC score of 0.986. Under stable conditions, it also achieves the highest NIC (0.99), showing that it preserves structural narrative integrity even in low-impairment scenarios.

Table 2: Performance comparison across network conditions, averaged over 10 trials.

Condition	Strategy	V_{order}	NIC	Incoherence Duration (s)
Adverse	Latency	2503.6	0.758	194.57
Adverse	QoE	1009.6	0.733	194.43
Adverse	Coherence	1515.5	**0.913**	**2.04**
Moderate	Latency	765.2	0.851	90.90
Moderate	QoE	124.2	0.786	90.02
Moderate	Coherence	107.3	**0.986**	**0.00**
Stable	Latency	0	0.885	37.83
Stable	QoE	0	0.790	85.22
Stable	Coherence	0	**0.990**	**0.00**

6 Discussion and Implications

Traditional synchronization in distributed XR mainly optimizes latency or QoE, but our results show that preserving narrative integrity also requires causal structure, temporal alignment, and consistent shared state between dependent events.

In collaborative immersive environments, participants act as co-creators of narrative content. Coherence-aware adaptation can operate as a middleware layer that prioritizes causally critical updates to preserve shared narrative context under fluctuating network conditions. Although NIC is independent of subjective perception, it complements QoE-driven approaches and may improve perceived engagement, which requires user-study validation.

This work uses predefined dependency graphs and simplified impairments. Packet loss, retransmissions, heterogeneous devices, and variable wireless conditions are not explicitly modeled. Likewise, automatic event classification in complex multi-user XR may require semantic scene understanding, intent recognition, or authoring-tool support. Thus, the results validate NIC scheduling under controlled dependency structures, while future work will consider trace-driven networks, real XR deployments, dynamic dependency inference, and larger groups.

7 Conclusion

Distributed immersive storytelling enables remote collaborative co-creation, yet latency- or QoE-driven approaches do not explicitly capture the structural conditions under which synchronization failures disrupt story continuity. We introduced NIC, a system-level metric that operationalizes narrative integrity through causal ordering, temporal alignment, and state divergence. We also proposed a coherence-aware adaptation strategy that prioritizes updates critical to narrative alignment and evaluated it under controlled network impairments. Results show that optimizing for coherence reduces narrative break events and incoherence duration, maintaining high coherence even under adverse conditions. Future work will validate NIC in real multi-user XR environments.

Acknowledgments

This publication has emanated from research jointly funded by Taighde Éireann – Research Ireland via grant 13/RC/2094_2 for Lero Research Centre for Software, and co-funded by the European Union under the Systems, Methods, Context (SyMeCo) programme via grant 101081459. The views and opinions expressed are those of the authors only.

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