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Exploring multiplayer interactivity in XR applications: a Unity and Photon networking approach

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Abstract

This thesis explores the development and potential of multiplayer interactivity in *Extended Reality* (XR) applications, focusing on the creation of "Strings of Life," an *Augmented Reality* (AR) multiplayer experience designed for Effenaar, a cultural hub in Eindhoven. The project builds on a pop-music-inspired narrative involving Elvis Presley and the 27 Club, integrating storytelling into an interactive escape room format. Leveraging advancements in XR technologies and networking frameworks, the application is built using Unity and Photon Fusion 2 *Software Development Kit* (SDK), addressing challenges in synchronization and scalability for up to 50 concurrent users. The study evaluates user engagement, technical performance, and adoption barriers, presenting strategies to overcome these issues. By developing this application, the research contributes to the nascent field of AR multiplayer applications, offering insights into design frameworks, technical implementation, and user-centered innovation. The findings aim to set a precedent for interactive, multiplayer XR applications in cultural and educational settings, bridging the gap between immersive technology and audience engagement.

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Chapter 1

Introduction

Extended Reality *Extended Reality* (XR) technologies have transformed how people engage with digital content, bridging the gap between the physical and virtual worlds. *Augmented Reality* (AR), a subset of XR, has gained traction for its ability to overlay interactive digital elements onto real-world environments. However, while AR has traditionally focused on single-user applications, recent advancements in networking technologies present new opportunities for scalable multiplayer interactions, revolutionizing how users engage collaboratively in XR environments.

The "Strings of Life" project, developed in collaboration with Dutch Rose Media and Effenaar, exemplifies this shift toward multiplayer AR experiences. This project builds on the rich pop-music history of Effenaar, incorporating themes of Elvis Presley and the "27 Club" into an interactive escape room format. Designed to accommodate up to 50 users simultaneously, Strings of Life leverages Unity and *Software Development Kit* (SDK) from Photon Fusion 2 to address the technical challenges of synchronization and scalability in multiplayer AR applications. This marks a significant departure from the project's earlier iteration, which faced limitations in reliability and interactivity due to the constraints of available technology.

As part of this study, an iterative design approach was employed to bridge the gap between technical capabilities and user expectations. Regular feedback from users informed the development process, enabling continuous refinement of the application's features and ensuring alignment with both technological standards and end-user needs. This combination of technical innovation and user-centric design highlights the potential of multiplayer AR applications to redefine cultural engagement, particularly in educational and interactive storytelling contexts.

This thesis investigates the challenges and opportunities of developing multiplayer AR applications, focusing on scalability, synchronization, and user engagement. Through the Strings of Life project, it aims to provide insights into the technical, methodological, and user-centered considerations necessary for advancing this emerging field.

1.1 Background of the Study

Extended Reality (XR) technologies have revolutionized how people interact with digital environments, seamlessly blending the physical and virtual worlds. Within this domain, *Augmented Reality* (AR) has emerged as a prominent subset, offering users an interactive and immersive experience by overlaying digital elements onto real-world settings. While AR applications have historically been limited to single-user experiences, recent advancements in networking frameworks and development tools now enable scalable and synchronized multiplayer interactions. These technological strides are driving the evolution of XR, particularly in cultural and educational applications.

This research builds on the ”Strings of Life” project, an innovative AR application designed for Effenaar, a cultural hub in Eindhoven. With a rich history rooted in pop music, Effenaar has sought to leverage modern technologies to enhance audience engagement and storytelling. The project transforms traditional narratives into interactive experiences by integrating *Augmented Reality* (AR) escape room gameplay centered on the theme of Elvis Presley and the ”27 Club.”

The initial iteration of ”Strings of Life” faced significant technical challenges due to limitations in networking synchronization and scalability for multiplayer experiences. Advances in tools such as Unity and Photon Fusion 2 *Software Development Kit* (SDK) have now provided the foundation to address these challenges. By utilizing these tools, this project aims to create a scalable multiplayer environment capable of supporting up to 50 simultaneous users, each using their own device to interact with the digital environment.

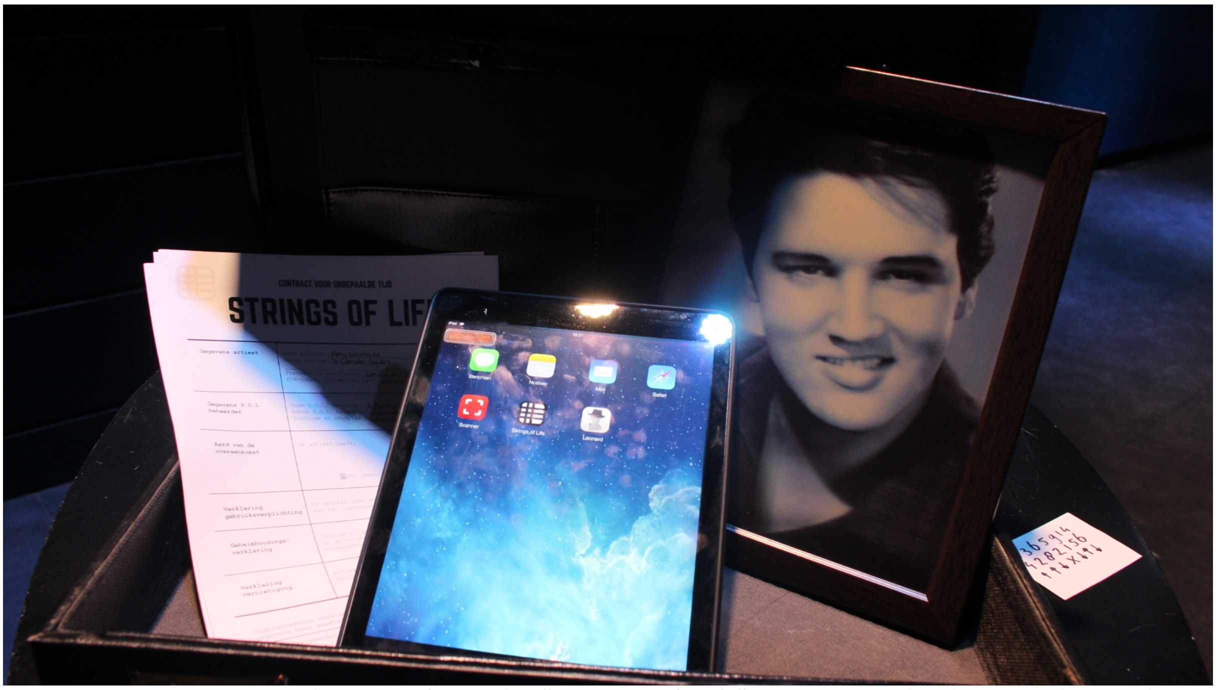

Figure 1.1: Interactive elements from the "Strings of Life" project, with Elvis Presley and AR-based gameplay components. [1]

The cultural and educational significance of this project lies in its ability to bridge technology with storytelling, enabling users to explore pop music history in an engaging and collaborative format. As XR technologies continue to grow, projects like "Strings of Life" offer a unique opportunity to study the practical implementation of multiplayer AR applications and their potential impact on user engagement and adoption.

1.2 Problem Statement

Despite significant advancements in *Extended Reality* (XR) technologies, the development of scalable multiplayer *Augmented Reality* (AR) applications remains a challenging frontier. While AR has demonstrated its potential for enhancing user engagement through immersive storytelling and interactive gameplay, the integration of real-time multiplayer functionality introduces several technical and design challenges. These include synchronization of user interactions, ensuring seamless performance across diverse devices, and managing the scalability required for large user groups.

The "Strings of Life" project exemplifies these challenges. Its initial iteration, developed a few years ago, highlighted key limitations in multiplayer AR applications. The earlier version faced issues with server synchronization, device compatibility, and the inability to support more than a limited number of users. These constraints not only hindered the user experience but also limited the potential for wider adoption in cultural and educational settings.

Given Effenaar's vision to enhance audience engagement with modern technologies, addressing these challenges is crucial. By reimagining "Strings of Life" with contemporary tools such as Unity and Photon Fusion 2 *Software Development Kit* (SDK), this study aims to overcome these barriers and create a robust multiplayer experience. The ability to support up to 50 simultaneous users in an engaging, interactive environment will set a benchmark for future AR applications in cultural storytelling and collaborative experiences.

This research identifies the core issues in developing large-scale multiplayer AR applications and seeks to provide solutions that balance technical feasibility with user experience. Through iterative design and advanced technological integration, the project addresses the gap between the theoretical potential and practical implementation of multiplayer XR applications.

1.3 Objectives of the Study

The primary objective of this research is to develop a scalable and synchronized multiplayer *Augmented Reality* (AR) application, using the "Strings of Life" project as a case study. By leveraging advancements in *Extended Reality* (XR) technologies and tools such as Unity and Photon Fusion 2 *Software Development Kit* (SDK), the study aims to address key technical and user experience challenges associated with large-scale multiplayer interactions in AR environments.

To achieve this, the research is guided by the following objectives:

- **Develop a robust multiplayer AR system for up to 50 users:** This involves designing and implementing a system architecture capable of handling simultaneous user interactions. The system must ensure reliability and responsiveness, even when accessed by a large number of users across varying device types.

- **Optimize real-time synchronization and scalability:** Achieving seamless real-time interaction requires addressing latency, data transmission, and server performance challenges. This objective focuses on creating a system that performs consistently across diverse network conditions while maintaining synchronized user experiences.

- **Enhance user engagement through interactive storytelling:** The project aims to leverage narrative-driven design to improve user immersion and retention. By incorporating the cultural themes of Effenaar, such as Elvis Presley and the "27 Club," the research emphasizes the importance of aligning interactive elements with the audience's cultural and educational context.

- **Identify technical barriers and adoption challenges:** This involves conducting a detailed analysis of technical limitations, such as device compatibility and network constraints, as well as understanding user adoption barriers, including ease of use and accessibility for a wide demographic.
- **Provide a framework for cultural storytelling through XR:** By integrating modern XR technologies into a practical use case, this research seeks to establish a replicable framework for using AR and XR in collaborative and educational storytelling experiences.

Through these objectives, the research aims to contribute to the growing field of XR technologies by demonstrating the feasibility and potential of multiplayer AR applications. The findings will offer insights into best practices for design, development, and implementation, bridging the gap between technological innovation and practical usability in real-world scenarios.

1.4 Research Questions

To guide the development and evaluation of the "Strings of Life" project, this research is structured around the following key questions:

- **How can a scalable multiplayer *Augmented Reality* (AR) system be developed to support up to 50 simultaneous users?** This question addresses the technical challenges of building a robust system architecture that ensures scalability, reliability, and consistent performance across diverse devices and network conditions.
- **What methods can be implemented to optimize real-time synchronization in a multiplayer AR environment?** This question explores techniques for minimizing latency and ensuring seamless synchronization of user interactions, which are critical for maintaining an engaging and interactive multiplayer experience.
- **How can cultural storytelling be effectively integrated into a multiplayer AR application to enhance user engagement?** This question focuses on the design aspects of the project, particularly how narrative-driven elements and interactive features

can align with the cultural and educational goals of Effenaar to create a meaningful experience for users.

- **What are the primary technical and adoption barriers to developing large-scale multiplayer AR applications?** This question investigates potential constraints, such as hardware limitations, software compatibility, and user accessibility, to identify areas for improvement in XR application development.

- **How can the findings of this project contribute to a replicable framework for multiplayer AR applications in cultural and educational contexts?** This question aims to translate the insights gained from this research into practical guidelines and frameworks for future developers and researchers working on similar projects.

1.5 Significance of the Study

This study holds significance both academically and practically by addressing critical gaps in the development of scalable multiplayer *Augmented Reality* (AR) applications. By utilizing advanced *Extended Reality* (XR) technologies and frameworks such as Unity and Photon Fusion 2 *Software Development Kit* (SDK), the research contributes to the growing field of interactive and immersive experiences.

The practical significance lies in its ability to transform how cultural and educational institutions engage their audiences. The "Strings of Life" project, with its focus on Effenaar's rich musical heritage, demonstrates how AR can bridge traditional storytelling with modern technology. By developing a multiplayer experience capable of supporting up to 50 users, this research paves the way for large-scale interactive applications in real-world settings.

From an academic perspective, this study addresses the technical and user-centric challenges of AR development, such as scalability, synchronization, and user engagement. By systematically analyzing these challenges and proposing solutions, the research provides valuable insights for developers, researchers, and designers working on similar projects.

Furthermore, the project establishes a framework for integrating multiplayer AR applications into cultural storytelling. This framework can serve as a foundation for future research and development, enabling the creation of more sophisticated XR applications that combine narrative-driven design with advanced technology.

By bridging the gap between technological innovation and practical usability, this study contributes to the broader field of XR research, offering actionable knowledge for advancing interactive experiences in cultural and educational domains.

1.6 Structure of Thesis

The structure of this thesis is designed to provide a comprehensive exploration of the research problem, methodology, implementation, and findings. Each chapter builds upon the previous one, ensuring a logical progression that guides the reader from understanding the background to evaluating the outcomes and implications of the study. The chapters are organized as follows:

- **Chapter 1: Introduction** This chapter provides an overview of the research, including the background, problem statement, research objectives, research questions, significance of the study, and the structure of the thesis.

- **Chapter 2: Literature Review** This chapter reviews the theoretical and technical foundations of *Extended Reality* (XR), with a specific focus on *Augmented Reality* (AR) and multiplayer applications. It discusses related work, key challenges, and the state-of-the-art technologies and methodologies used in the field.

- **Chapter 3: Methodology** This chapter outlines the research design and development process, detailing the tools, techniques, and frameworks employed. It also describes the iterative approach used to address technical challenges and refine user experience.

- **Chapter 4: Application Development** This chapter delves into the implementation details of the "Strings of Life" project. It covers system architecture, multiplayer synchronization, and the integration of narrative elements to create an engaging AR experience.

- **Chapter 5: Findings and Analysis** This chapter presents the results of the study, including technical performance metrics, user engagement evaluations, and insights from testing. It also discusses the implications of these findings for XR applications.

- **Chapter 6: Conclusion and Future Work** This chapter summarizes the key contributions of the research, acknowledges its limitations, and provides recommendations for future research and development in the field of multiplayer AR applications.

This structure is designed to balance technical depth with practical relevance, making it accessible to both academic and professional audiences. It provides a clear roadmap for understanding the research process, findings, and their implications for future developments in the field.

Chapter 2

Literature Review

The field of *Extended Reality* (XR), encompassing *Augmented Reality* (AR), Virtual Reality (*Virtual Reality* (VR)), and (*Mixed Reality* (MR)), has grown rapidly over the past decade. These technologies have not only transformed entertainment and gaming but also demonstrated significant potential in fields such as education, healthcare, and cultural heritage. As XR technologies evolve, their application in multiplayer environments has introduced new dimensions of interaction, collaboration, and immersion, pushing the boundaries of user engagement and system capabilities.

This chapter reviews the theoretical and technical foundations of XR technologies, with a particular focus on their use in multiplayer applications [2]. It examines the evolution of XR technologies, the challenges inherent in creating synchronized and scalable multiplayer systems, and the methodologies and tools available to developers. Through this review, the chapter provides a comprehensive understanding of the existing knowledge base, identifying gaps and opportunities that this research seeks to address.

2.1 Overview of XR Technologies

2.1.1 Definitions and Types of XR (AR, VR, and MR)

Extended Reality (XR), or Extended Reality, represents a spectrum of immersive technologies that blend the physical and virtual worlds to varying degrees. This category encompasses *Augmented Reality* (AR), Virtual Reality (*Virtual Reality* (VR)), and Mixed Reality (*Mixed Reality* (MR)), each offering unique capabilities and applications.

Augmented Reality (AR) overlays virtual objects onto the physical environment, enabling users to interact with digital elements in real-time while maintaining awareness of their surroundings. *Virtual Reality* (VR), on the other hand, immerses users in entirely virtual environments, isolating them from the physical world to focus solely on digital content. *Mixed Reality* (MR) serves as a bridge between AR and VR, allowing for seamless interaction between real and virtual elements in a unified environment.

These technologies have found applications across various domains, including gaming, education, healthcare, and cultural heritage, providing innovative ways to engage with digital content and environments.

2.1.2 Technological Advancements in XR

The development of XR technologies has been driven by continuous advancements in hardware and software. Key innovations include mobile devices with powerful processors, head-mounted displays with high-resolution screens, and motion-tracking sensors, which collectively enhance the immersive experience.

On the software front, platforms like Unity and Unreal Engine have provided developers with robust tools for creating interactive and visually stunning XR applications. Networking frameworks, such as Photon Fusion 2 *Software Development Kit* (SDK), have further enabled real-time interactions and scalability in multiplayer settings.

Despite these advancements, challenges remain, particularly in the development of multiplayer XR applications, where issues like latency, synchronization, and user experience must be addressed. These technological trends and challenges form the basis for the research presented in this thesis.

2.2 Evolution of Multiplayer Interactivity in XR

2.2.1 From Single-User XR Experiences to Multiplayer Systems

The early development of *Extended Reality* (XR) technologies primarily focused on single-user experiences, where applications were designed to immerse individual users in virtual or augmented environments. Examples include solitary *Virtual Reality* (VR) simulations for gaming and *Augmented Reality* (AR) tools for navigation and education. While these applications demonstrated the potential of XR, they lacked the collaborative dimension that characterizes modern interactive experiences.

The transition from single-user to multiplayer systems marked a significant milestone in XR development. Multiplayer XR applications enable multiple users to interact simultaneously within the same virtual or augmented environment, fostering collaboration and shared experiences. This evolution has been facilitated by advancements in networking frameworks, device compatibility, and real-time data synchronization, which have made it possible to create scalable and engaging multiplayer environments.

2.2.2 Case Studies of Existing Multiplayer XR Applications

Several real-world applications highlight the progress and potential of multiplayer XR systems:

- **Collaborative AR in Education:** Applications like Google Expeditions allow students and educators to explore augmented and virtual environments collaboratively, enhancing learning through shared experiences.

- **Multiplayer Gaming in XR:** Games like "Rec Room" and "Echo VR" showcase the immersive potential of multiplayer VR, where users can engage in virtual sports or collaborative tasks in real-time.

- **Cultural and Historical Experiences:** Projects like the "Museum of the Future" in Dubai use AR and VR to create shared, interactive storytelling experiences, allowing multiple users to explore exhibitions simultaneously.

  These case studies demonstrate the transformative impact of multiplayer XR applications across various domains. They also highlight ongoing challenges, such as ensuring low-latency interactions, maintaining consistent synchronization, and designing intuitive interfaces for diverse user groups.

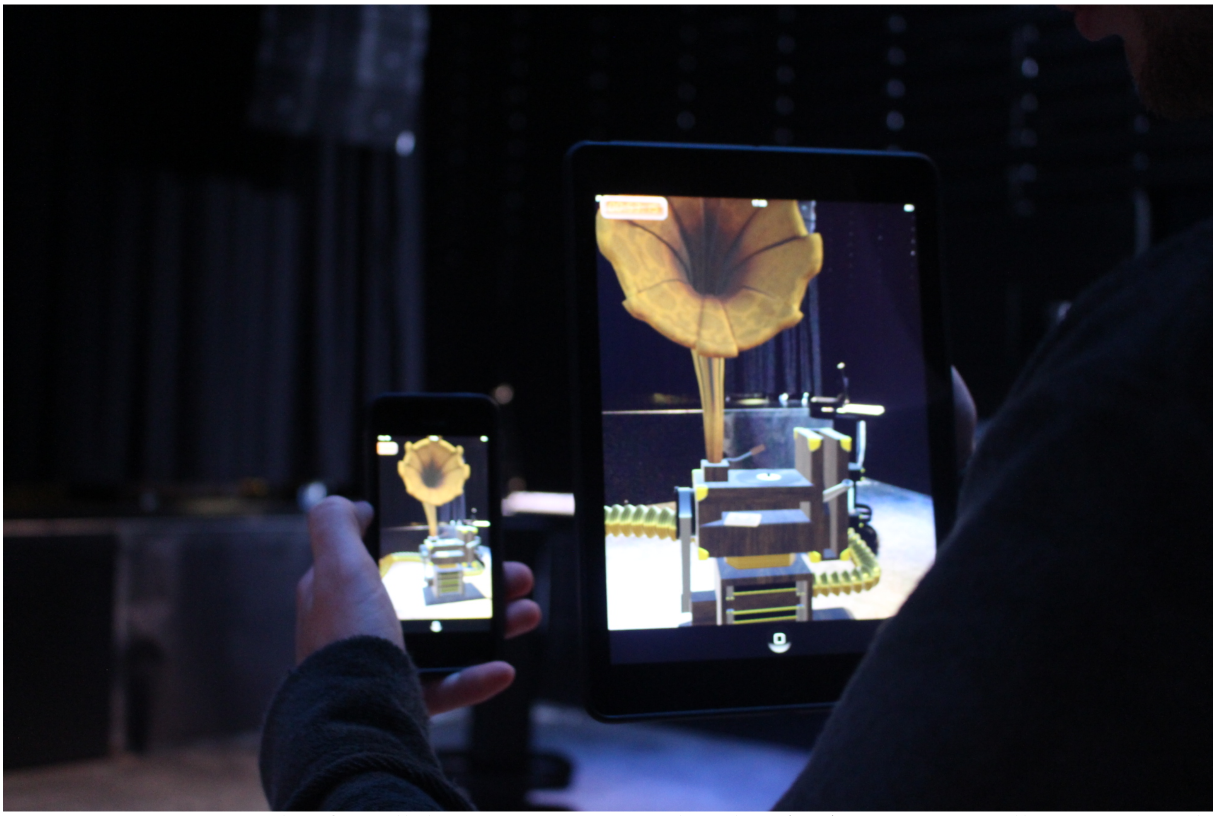

Figure 2.1: An example of a collaborative augmented reality (AR) experience, illustrating real-time interaction between multiple devices in a shared virtual environment.

By examining the evolution from single-user experiences to multiplayer systems and analyzing real-world applications, this research situates the "Strings of Life" project within a broader context. It aims to address the gaps identified in current applications by leveraging modern tools like Photon Fusion 2 *Software Development Kit* (SDK) to create scalable, synchronized, and engaging multiplayer AR experiences.

2.3 Challenges in AR Multiplayer Applications

The development of multiplayer *Augmented Reality* (AR) applications presents significant technical and user experience challenges that must be addressed to ensure smooth, synchronized, and engaging interactions. Unlike traditional multiplayer games, where interactions occur entirely in virtual space, AR applications require real-time synchronization between digital and physical environments across multiple users.

To achieve this, robust networking frameworks must handle **low-latency communication, precise object tracking, and real-time interaction consistency**. This section explores two critical challenges in multiplayer AR: [3] synchronization and latency issues and scalability and user experience concerns.

2.3.1 Synchronization and Latency Issues

Synchronization is a core requirement in multiplayer *Augmented Reality* (AR) applications, ensuring that all users perceive and interact with the same digital elements in a **consistent and real-time manner**. Unlike single-player AR applications where all processing happens locally on a single device, multiplayer AR requires that each user sees the same **virtual object positions, movements, and interactions** with minimal delay. Achieving real-time synchronization, however, is highly challenging due to **latency, network fluctuations, and device tracking variations**.

Key Causes of Synchronization and Latency Issues:

- **Network Latency and Packet Transmission Delays:** Multiplayer AR applications rely on **continuous data transmission** between users to keep object states synchronized. However, **network latency**—the time taken for data to travel between devices—can cause delays in state updates. If one user moves an object, but another user experiences a **delayed update due to network lag**, the object may appear out of sync. High latency can make interactions feel **unresponsive or disconnected**.
- **Server vs. Peer-to-Peer Synchronization Challenges:** Some multiplayer applications rely on **peer-to-peer (P2P) networking**, which can be **unstable for large-scale applications** because data must be exchanged directly between devices. AR applications often require a **dedicated authoritative server** (e.g., Photon's **Dedicated Cloud Server**) to **ensure consistent object states and resolve synchronization conflicts**.
- **Tracking Drift and Inconsistent Spatial Anchors:** AR applications rely on **device sensors (gyroscopes, cameras, LiDAR)** to track real-world positioning. However, small variations in tracking accuracy between devices can cause **drift**, where a virtual object appears in slightly different positions for different users. Without precise **spatial anchors and realignment algorithms**, these inconsistencies can accumulate over time.

Photon Server Architecture for Improved Synchronization:

Photon Fusion 2 *Software Development Kit* (SDK) addresses many of these synchronization challenges by utilizing an **authoritative server model**, meaning all object state updates pass through a central server rather than relying on **peer-to-peer communication**. This ensures:

- **Tick-Based State Replication:** Instead of relying on frequent state updates that increase network load, Photon Fusion 2 synchronizes objects using a **tick-based model**, where states are updated at fixed intervals, reducing desynchronization.
- **Lag Compensation and Prediction Models:** Photon Fusion 2 includes **rollback and prediction algorithms** that estimate where an object should be if there is a delay, reducing noticeable lag.
- **Cloud-Based Dedicated Servers:** Instead of requiring local peer hosting, **Photon Cloud Servers** act as **authoritative game hosts**, ensuring consistent updates across all devices.

By leveraging Photon's networking architecture, "Strings of Life" ensures **fast, stable, and accurate multiplayer synchronization**, reducing desynchronization and making interactions feel more natural.

2.3.2 Scalability and User Experience Concerns

Scaling multiplayer *Augmented Reality* (AR) applications to support a large number of simultaneous users introduces **significant technical and user experience challenges**. Unlike single-user AR applications, multiplayer experiences require **efficient resource management, network optimization, and real-time interaction stability** to prevent performance bottlenecks.[4] As user count increases, the demand for **low-latency networking, synchronized object states, and real-time rendering** becomes more complex.

Key Scalability Challenges in Multiplayer AR:

- **Device Heterogeneity and Performance Variability:** Multiplayer AR applications must support a diverse range of devices with **different hardware capabilities**, including variations in CPU power, GPU processing, RAM availability, and camera tracking quality. - **High-end devices (e.g., iPhone Pro, iPad Pro, flagship Android models)** have dedicated AR chipsets and LiDAR sensors for superior tracking. - **Mid-range devices** rely on standard camera-based tracking, which is less precise and may introduce latency. - **Older devices** struggle with frame rate stability and may experience degraded AR performance due to lower processing power.

To address these differences, developers must implement **dynamic performance scaling**, adjusting **rendering quality, asset complexity, and network update frequency** based on device capabilities.

- **Network Load Balancing and Bandwidth Optimization:** As the number of users in a multiplayer AR environment increases, **network traffic scales exponentially**, requiring efficient data distribution and load balancing. - Each user must receive updates on **object positions, interactions, and movement** in real time. - Sending full data packets to all users is bandwidth-intensive and can overload networks. - Unoptimized bandwidth management can lead to **delayed object updates, motion stuttering, and desynchronization** between users.

  Photon Fusion 2 mitigates these issues through **delta compression, region-based networking, and adaptive packet throttling**: - **Delta Compression:** Instead of broadcasting **full object states**, Photon Fusion 2 sends **only the changes (deltas)** to significantly reduce bandwidth usage. - **Region-Based Networking:** Users only receive updates on objects **within their field of interaction**, reducing unnecessary data transmission. - **Adaptive Packet Throttling:** Photon Fusion 2 **dynamically adjusts data transmission rates** based on network conditions, preventing packet congestion.

  These optimizations allow multiplayer AR applications to **scale efficiently** while maintaining responsiveness.

- **Real-Time Rendering and Frame Rate Stability:** AR applications must maintain **consistent frame rates** to ensure a smooth user experience. However, real-time rendering requires substantial **GPU and CPU resources**, particularly in multiplayer environments where **numerous objects are being updated simultaneously**. - Rendering **3D models, shadows, and physics interactions** in real-world environments places a **heavy computational load** on mobile devices. - If performance is not optimized, users experience **frame rate drops, overheating, and battery drain**. - Rendering complexity increases exponentially when **multiple users interact with dynamic objects**.

  To address these issues, optimization techniques include: - **Level-of-Detail (LOD) Scaling:** Reducing the complexity of objects when viewed from a distance. - **Oc-**

clusion Culling: Preventing rendering of objects that are not visible to the user. - **GPU Instancing:** Reducing draw calls by batching similar objects. - **Cloud Rendering:** Offloading rendering tasks to **cloud-based GPUs**, allowing low-end devices to access high-fidelity graphics.

Implementing these techniques ensures a **stable frame rate (60 FPS or higher)** across devices, even in multiplayer AR applications with large-scale interactions.

– **User Interaction and Engagement Challenges:** Beyond technical scalability, ensuring an **engaging, intuitive, and immersive** user experience is essential. If interactions feel **laggy, unresponsive, or difficult to control**, users may become **frustrated and disengaged**. Common user experience challenges include: - **Input Lag:** Delay between user actions (e.g., grabbing an object) and the response on screen. - **Synchronization Delays:** Seeing other players' actions **delayed** due to network lag. - **Intuitive Interaction Design:** Ensuring that AR interactions **feel natural and seamless**.

Photon Fusion 2 **addresses these engagement issues** through: - **Rollback Prediction:** If data packets are delayed, Photon Fusion 2 predicts the likely movement of objects **based on previous states**, reducing perceived lag. - **Client-Side Interpolation:** Smoothing out movements by interpolating object positions **between received network updates**. - **Network Prioritization for User Actions:** Giving **priority to user-generated inputs** (e.g., object grabs) over background updates (e.g., non-essential animations).

These improvements significantly enhance **user interaction fluidity** and prevent **frustration from unresponsive controls**.

Photon Fusion 2's Role in Scaling the "Strings of Life" Project: The "Strings of Life" project must **support up to 50 concurrent players**, requiring robust **scalability strategies**. Photon Fusion 2 ensures:

– **Efficient network optimization** via **delta compression and adaptive packet throttling**.

– **High-performance rendering techniques** to prevent frame rate drops.

– **Advanced lag compensation and rollback prediction** to maintain synchronization in a multiplayer AR environment.

- **Cloud-based scalability** through **Photon Cloud Servers**, reducing the processing burden on individual devices.

By implementing **state-of-the-art networking and rendering optimizations**, ”Strings of Life” provides a **smooth, scalable, and highly interactive multiplayer AR experience**.

Conclusion: Scalability and user experience optimization are essential for **large-scale multiplayer AR applications**. Without **efficient networking, rendering, and interaction design**, applications risk becoming **laggy, unstable, and frustrating** for users. **Photon Fusion 2's networking solutions** and **advanced rendering optimizations** enable the ”Strings of Life” project to **support a high number of simultaneous users** while maintaining **low latency, smooth interactions, and an engaging multiplayer experience**.

2.4 Photon Networking in XR

Multiplayer *Extended Reality* (XR) applications require robust networking frameworks capable of ensuring **real-time synchronization, minimal latency, and seamless interaction** among multiple users. Unlike traditional multiplayer games, where all interactions occur within a fully virtual space, XR introduces **additional networking complexities**, such as maintaining consistency between **digital overlays and real-world spatial references** across multiple devices.

The challenge in networking for XR arises due to the need for **low-latency updates, bandwidth efficiency, and accurate spatial synchronization** in a shared environment. A delay in object updates or network congestion can result in:

- **Desynchronized AR content**, where different users perceive objects in misaligned positions.
- **Laggy interactions**, affecting real-time user actions such as grabbing and moving virtual objects.
- **Packet loss and high server load**, especially in large-scale multiplayer scenarios.

Photon is one of the leading multiplayer networking solutions tailored for XR applications. Its **Fusion 2 *Software Development Kit* (SDK)** introduces significant advancements in **scalability, latency optimization, and state synchronization**, making it ideal for large-scale multiplayer XR experiences.

2.4.1 Overview of Photon SDK and its Evolution to Fusion 2

Photon has evolved over several iterations to address the growing needs of **real-time multiplayer networking**. The progression from **Photon PUN** to **Photon Bolt** and, ultimately, to **Photon Fusion 2** represents a continuous improvement in networking performance.

Key technical advancements in Photon Fusion 2 include:

– **Tick-Based Network State Replication:** - Unlike event-driven networking models, **tick-based replication** ensures that game states are updated at **fixed intervals**, reducing inconsistencies across different devices. - This method ensures a **predictable network update frequency**, preventing random delays in object synchronization.

– **Lag Compensation and Rollback Prediction:** - Photon Fusion 2 employs **rollback mechanisms** to predict player actions in case of **packet loss** or **network fluctuations**. - This ensures that **player movements and object interactions remain fluid**, even under varying network conditions.

– **Adaptive Packet Prioritization for XR:** - The **network traffic distribution system** in Photon Fusion 2 prioritizes **essential object interactions over background updates**. - This helps reduce unnecessary bandwidth usage, allowing AR and VR applications to **function smoothly even in high-latency environments**.

– **Server Authoritative Model:** - Instead of relying on **peer-to-peer (P2P) networking**, Photon Fusion 2 uses a **dedicated cloud-based authoritative server**. - This approach ensures **consistent object states across all players** and prevents synchronization conflicts.

– **Scalability Optimizations for Large Multiplayer Sessions:** - Photon Fusion 2 has been optimized to support **high player counts**, handling **up to 1000 concurrent users per session** with **low CPU overhead**. - This scalability makes it **suitable for massive multiplayer XR applications**, such as escape rooms and virtual exhibitions.

Why Photon Fusion 2 is Ideal for "Strings of Life": The **"Strings of Life"** project requires a **highly scalable multiplayer architecture** to support **up to 50 simultaneous players** in an AR environment. Photon Fusion 2's **tick-based replication, cloud-hosted servers, and adaptive synchronization** ensure that:

– Virtual objects remain **accurately positioned** across all users.

– **Latency is minimized**, preventing noticeable lag in object interactions.

– **Data transmission is optimized** to prevent bandwidth overload.

2.4.2 Comparison with Other Networking Tools for XR

Various networking solutions exist for real-time multiplayer applications, each with different **strengths and limitations**. While some frameworks focus on **low-latency peer-to-peer networking**, others prioritize **scalability and cloud-based synchronization**.

– **Mirror:** - **Open-source** and widely used in Unity-based multiplayer applications. - Unlike Photon, Mirror requires **dedicated server hosting** and does not offer **cloud-hosted authoritative solutions**. - **Scalability Limitations:** Mirror is designed primarily for **small to mid-sized** multiplayer games (up to **100 concurrent users per session**). - **Reliability Issues:** Mirror relies on **server-based relays**, which can lead to **higher latency spikes** in large-scale applications.

– **Normcore:** - Optimized for **VR applications**, providing **low-latency real-time object synchronization**. - Best suited for **small-scale collaborative XR environments**. - Lacks the **high player scalability** required for large multiplayer AR projects.

– **WebRTC:** - Provides ultra-low latency for **peer-to-peer real-time communication**. - Does not include structured **state replication** or **authoritative server logic**, making it unsuitable for **complex XR applications**.

Comparison Between Photon Fusion 2 and Mirror:

Mirror and Photon Fusion 2 both offer **high-performance networking for Unity-based multiplayer applications**, but **Mirror struggles at larger player counts**, while Photon excels at **high scalability and performance efficiency**.

Feature	Photon Fusion 2	Mirror
Cloud-Based Servers	Yes (Photon Cloud)	No (Self-Hosted Required)
Scalability	High (Up to 1000 users)	Medium (Up to 100 users)
Latency Optimization	Yes (Rollback + Prediction)	Limited
XR-Specific Features	Yes (Tick-Based Replication)	No (General Multiplayer Only)
Server Authority	Yes (Authoritative Model)	No (Relay-Based)

Table 2.1: Comparison of Photon Fusion 2 and Mirror in XR Multiplayer Networking.

Conclusion: Photon Fusion 2 is the superior choice for **large-scale XR multiplayer applications**, as it provides:

- **Cloud-based authoritative servers** for better synchronization.
- **Low-latency optimization** using **tick-based state replication**.
- **Scalability up to 1000 concurrent users**, compared to Mirror's **100-user limit**.
- **Robust error handling** and **predictive rollback mechanisms** to mitigate network issues.

For the **"Strings of Life"** project, Photon Fusion 2 ensures a **reliable, scalable, and low-latency networking architecture**, making it the ideal solution for a **50-player multiplayer AR experience**.

2.5 Case Studies of Interactive AR Applications

The integration of *Augmented Reality* (AR) into interactive experiences has significantly evolved over the past decade, particularly in cultural and entertainment settings. Museums, heritage sites, and themed attractions have increasingly embraced AR as a tool to provide immersive storytelling experiences that blend **historical preservation with interactive engagement**. Simultaneously, the **escape room** industry has expanded rapidly, incorporating digital enhancements to create new forms of engagement. Multiplayer AR applications have the potential to **modernize traditional forms of entertainment** while maintaining the essence of cultural heritage[5].

This section explores real-world case studies where AR has been applied in **cultural and entertainment settings**, followed by an in-depth analysis of **"Strings of Life"**, a project originally conceived in 2018-2019 as a **single-user AR experience** but now revived as a **multiplayer AR escape room**, leveraging **modern XR technologies and networking frameworks**.

2.5.1 Applications in Cultural Settings (e.g., Museums, Escape Rooms)

Cultural institutions have increasingly adopted AR to **enhance visitor engagement and provide immersive storytelling experiences**. Two prominent areas where multiplayer AR has been applied effectively are **museums** and **escape rooms**.

Museums and Heritage Sites: Museums and historical sites have long relied on **traditional exhibits, text-based descriptions, and guided tours** to educate visitors. However, with the increasing demand for **interactive and personalized experiences**, AR has been introduced as a way to allow visitors to engage **actively** rather than passively consuming information. Some notable examples include:

- **The British Museum's AR Tours:** Visitors can use AR-enabled guides to visualize ancient artifacts in **their original forms**, overlaying digital reconstructions onto real-world exhibits.
- **The Smithsonian's "Skin and Bones" Exhibit:** Through AR, skeletons of extinct animals are **brought to life**, allowing users to see **animated, lifelike reconstructions**.
- **The Anne Frank House VR Experience:** Though primarily a VR project, it incorporates AR elements to project **historical photos and diary entries into the real world**, creating a **hybrid digital-physical narrative**.

These projects demonstrate how **historical and cultural narratives** can be enhanced through AR, offering a **more immersive and interactive learning experience**.

Escape Rooms and Interactive Storytelling: Escape rooms have become one of the **fastest-growing entertainment sectors**, with digital enhancements playing a key role in **reinventing the traditional puzzle-solving format**. AR introduces new possibilities, such as **dynamically generated clues, digital overlays, and multiplayer interactions** that were not possible with traditional setups.

Some notable examples include:

- **AR Haunted Escape Room (Los Angeles, USA):** A fully interactive escape experience where digital **ghosts, puzzles, and animations** enhance the **horror storytelling**.

- **Time Run (London, UK):** One of the first escape rooms to integrate AR mechanics, allowing players to interact with **virtual objects projected into real-world spaces**.
- **Escape the Lost Pyramid (Ubisoft, Global):** A VR escape room that integrates **historical themes and interactive puzzles** into a digital world, showcasing how multiplayer XR experiences can be structured.

2.5.2 Lessons Learned from Early Implementations of "Strings of Life"

Historical Context: The "Strings of Life" project was originally developed in **2018-2019** as an **interactive single-user AR experience** designed to **blend music history with interactive storytelling** at Effenaar, a cultural venue in Eindhoven. At the time, the project faced **several technological limitations** that constrained its potential:

- **Limited Multiplayer Capabilities:** Multiplayer AR synchronization was not as advanced in 2018, making real-time multi-user interactions **impractical**.
- **Hardware Constraints and AR Tracking Issues:** Early AR frameworks struggled with **persistent object placement**, meaning digital objects would often drift **or fail to remain stable**.
- **Limited Adoption of AR Technologies:** In 2018, AR applications were still considered **novelty experiences**, and many users were unfamiliar with **using AR on their smartphones**.

Modernization and Revival of "Strings of Life": With significant advancements in **AR technology, networking solutions, and cultural shifts**, the project is now being revived as a **fully multiplayer AR escape room**, leveraging **state-of-the-art XR tools**.

Key Factors Driving the Modernization:

- **Evolution of AR Multiplayer Technologies:** The introduction of **Photon Fusion 2** now enables **seamless, real-time multiplayer synchronization**, allowing multiple users to interact within the **same AR environment without lag or desynchronization**.

Figure 2.2: A symbolic artifact of the *27 Club* legacy at Effenaar—a broken television representing rock and pop culture history. Central to *Strings of Life*, this element is being *Augmented Reality* (AR)-enhanced to transform static memories into **interactive multiplayer experiences**.

- **Increased Cultural Acceptance of AR and Mobile Gaming:** - Since 2018, smartphone users have **become accustomed to AR-based applications**, thanks to mainstream adoption by **Snapchat, Instagram, and mobile games like Pokémon GO**. - The general public is now more comfortable interacting with **digital overlays in real-world environments**.
- **The Growing Popularity of Digital Escape Rooms:** - Escape rooms have transitioned from **physical-only experiences to hybrid digital-physical formats**. - Players now expect **interactive, story-driven digital elements**, which **modern AR multiplayer capabilities can provide**.
- **Preserving Historical and Musical Legacies through XR:** - The original "Strings of Life" concept was inspired by **Elvis Presley and the 27 Club**, connecting the game narrative with **historical and cultural themes**. - Reviving this project as an **immersive multiplayer experience** ensures that these historical themes remain **engaging for modern audiences**.

Conclusion: The **revival of "Strings of Life" in 2024** represents the **intersection of**

technological advancements, cultural shifts, and the evolution of AR as a mainstream interactive medium. By leveraging **modern AR capabilities, networking solutions, and enhanced storytelling techniques**, this project exemplifies how **historical narratives can be brought into the digital world in an engaging, multiplayer format**.

This section reinforces the core **motivation for this thesis**: to explore how the latest advancements in **multiplayer AR interactivity** can be applied to **revitalize cultural and entertainment experiences** using **modern XR technologies**. "Strings of Life" serves as a **case study in applying these technologies**, providing insights into the future of **multiplayer AR applications in cultural and entertainment settings**.

Chapter 3

Methodology

This chapter provides a structured overview of the development process for the Strings of Life multiplayer *Augmented Reality* (AR) experience. It details the technical framework, design methodology, and iterative development process employed to create a scalable and synchronized XR application. The chapter begins by outlining the project background, objectives, and collaboration with Effenaar and Dutch Rose Media, providing context for the research and development.

Following this, the chapter explores the tools and technologies used in implementation, including Unity as the development platform and Photon Fusion 2 for real-time multiplayer networking. The design and development process is then described, covering narrative-driven AR integration, multiplayer functionality, and interaction mechanics.

Furthermore, the chapter explains data collection methods used to assess performance and user experience, detailing both feedback mechanisms and testing tools. The final sections highlight user testing strategies, focusing on simulated user sessions and iterative refinement based on feedback.

By structuring the methodology around technical implementation, real-world user validation, and iterative development, this chapter ensures a comprehensive understanding of the research and engineering practices involved in building a large-scale multiplayer AR application.

3.1 Project Overview: Strings of Life

3.1.1 Project origin and objectives

The Strings of Life project originates from an earlier (*Augmented Reality* (AR)) experience developed in 2018–2019 at Effenaar, a cultural hub in Eindhoven. The initial version was designed as a *single-user* AR application, allowing visitors to interact with digital content related to Effenaar's musical history. However, at that time, AR technology had significant limitations, particularly in supporting multiplayer interactions, seamless synchronization, and real-time user collaboration. These constraints made it difficult to deliver an engaging and scalable experience for multiple users simultaneously.

With advancements in *Extended Reality* (XR) technology, particularly improvements in real-time networking and cloud-based AR synchronization, the opportunity arose to revisit the Strings of Life concept and evolve it into a *multiplayer-oriented* interactive experience. The goal is to leverage modern networking solutions, such as Photon Fusion 2, to enable real-time synchronization among up to 50 concurrent users, transforming the way users interact with digital content in shared physical spaces.

The primary objectives of the Strings of Life project are as follows:

- **Enhancing Interactivity:** Transitioning from a single-user AR experience to a fully synchronized, multiplayer XR environment where users can collaboratively solve puzzles and interact with digital artifacts in real time.
- **Ensuring Scalability:** Developing a networking architecture that can support up to 50 simultaneous users without performance degradation or synchronization issues.
- **Leveraging Modern Networking Solutions:** Implementing *Software Development Kit* (SDK)s such as Photon Fusion 2 to achieve low-latency, high-performance networking optimized for multiplayer AR applications.
- **Preserving Cultural Heritage through AR:** Digitally reviving the history of legendary musicians associated with the 27 Club by integrating interactive storytelling and augmented reality experiences.
- **Improving User Engagement:** Designing an intuitive and immersive multiplayer AR experience that maximizes user interaction, retention, and overall enjoyment.

- **Technical Optimization and Performance Tuning:** Implementing real-time synchronization mechanisms, lag compensation techniques, and optimized rendering strategies to ensure a seamless user experience across various mobile devices.
- **Bridging Physical and Digital Spaces:** Transforming traditional physical exhibitions at Effenaar into an interactive, hybrid XR environment, where digital overlays enrich real-world experiences.

These objectives form the foundation for the research and development process, ensuring that the Strings of Life project meets both technical and experiential goals while pushing the boundaries of multiplayer XR applications.

3.1.2 Collaboration with Effenaar and Dutch Rose Media

The development of the Strings of Life project is the result of a collaboration between Effenaar, a cultural institution in Eindhoven, and Dutch Rose Media, a company specializing in *Augmented Reality* (AR) and *Extended Reality* (XR) solutions. This partnership brings together cultural and historical expertise with technical development in XR, ensuring that the project is both thematically relevant and technologically advanced.

Effenaar, known for its contributions to the music and entertainment industry, serves as the historical and thematic foundation for the project. The venue has hosted numerous iconic artists, some of whom are associated with the *27 Club*, a central theme in the narrative of Strings of Life. Effenaar's involvement provides:

- Access to historical archives and memorabilia, which inform the narrative and digital storytelling aspects of the game.
- A physical venue where the AR application can be tested and deployed.
- A direct link to music enthusiasts who represent the target audience for testing and feedback.

Effenaar aims to use interactive digital experiences to enhance audience engagement, shifting from traditional exhibitions to a more immersive and participatory form of storytelling.

Dutch Rose Media is responsible for translating the artistic and historical vision of Strings of Life into an interactive AR experience. The company specializes in developing

XR applications and provides expertise in networking solutions, real-time interactions, and user experience design. Its contributions include:

- Implementing *Software Development Kit* (SDK)s such as Photon Fusion 2 to enable real-time multiplayer synchronization.
- Developing and optimizing the AR experience in Unity, ensuring smooth interaction and scalability.
- Conducting performance evaluations and iterative testing to refine usability and network reliability.

By combining Effenaar's historical and artistic knowledge with Dutch Rose Media's expertise in XR development, Strings of Life integrates cultural storytelling with advanced digital interaction. This collaboration ensures that the project not only preserves historical narratives but also demonstrates the potential of multiplayer AR applications in cultural and entertainment settings.

3.2 Development Tools and Technologies

The development of the Strings of Life project required the integration of advanced technologies to support a scalable, synchronized, and interactive multiplayer experience in *Extended Reality* (XR). The selection of tools was based on their ability to ensure real-time interaction, efficient networking, and seamless rendering across various user devices. To achieve this, the project utilized Unity as the primary development engine, providing a robust platform for creating immersive AR experiences with built-in support for rendering, physics, and cross-platform deployment.

In addition to Unity, the project incorporated Photon Fusion 2 as the networking framework, enabling real-time multiplayer synchronization by utilizing an authoritative server model. This choice was driven by the need for a low-latency networking solution that could manage up to 50 concurrent users while ensuring consistency in shared AR environments. Unlike traditional client-server or peer-to-peer architectures, Photon Fusion 2 employs tick-based state replication, predictive movement models, and delta compression to optimize data transmission and maintain smooth interactions.

The integration of these technologies allows Strings of Life to deliver a reliable, high-performance AR experience while addressing key challenges such as synchronization accuracy, latency management, and device compatibility. By leveraging Unity's rendering capabilities and Photon Fusion 2's networking efficiency, the project ensures that users experience seamless interactions within a shared digital space, regardless of hardware limitations or network conditions. The following subsections provide a more detailed analysis of these tools and their implementation in the development process.

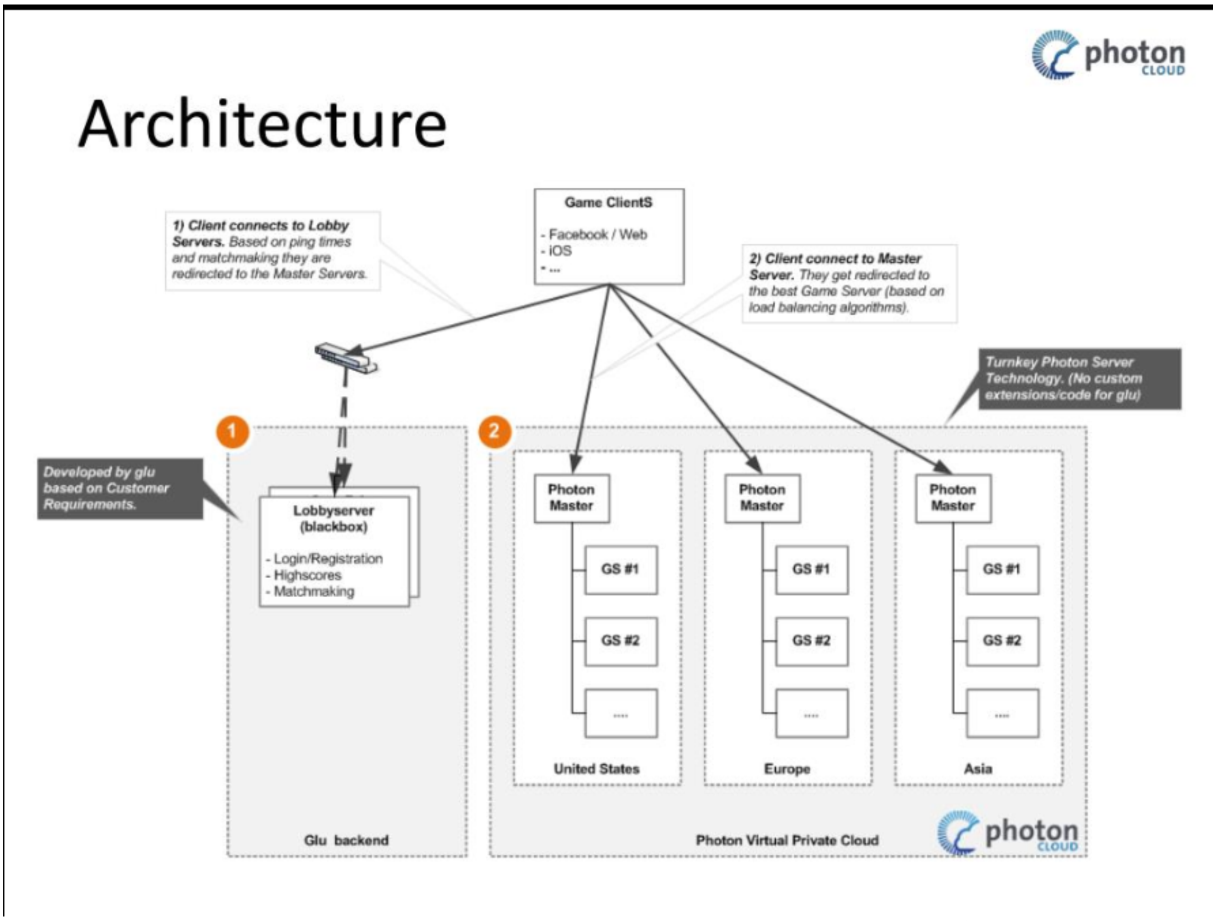

Figure 3.1: Photon Cloud server architecture illustrating the connection flow between game clients, lobby servers, and master game servers across multiple regions

Photon Cloud provides a scalable and efficient networking infrastructure for real-time multiplayer applications, ensuring low-latency synchronization, seamless matchmaking, and load balancing across multiple regions. The architecture consists of several key components:

- **Game Clients:** Users connect from mobile devices or web platforms, first establishing a connection with the *Augmented Reality* (AR) application's lobby server before joining a multiplayer session.
- **Lobby Server:** Manages authentication, matchmaking, and session allocation based on ping and server availability, ensuring efficient resource distribution.

- **Photon Master Servers:** Act as regional gateways (e.g., United States, Europe, Asia), balancing network traffic and directing users to the optimal game server to minimize latency.
- **Game Servers (GS):** Handle real-time interactions, state replication, and synchronization across multiple users. Photon Cloud dynamically scales game servers based on demand.

Scalability and Optimization: Photon Cloud's virtual private cloud (VPC) infrastructure ensures dedicated networking resources, fault tolerance, and efficient load distribution, reducing lag and enhancing performance [6].

Application to "Strings of Life" The *Strings of Life* project leverages Photon Cloud's networking model to support up to 50 concurrent players, ensuring real-time synchronization and stable multiplayer interactions. Through Photon Fusion 2's rollback prediction and state replication, AR content remains consistent across all user devices. This ensures a **scalable, low-latency, and immersive multiplayer experience**.

3.2.1 Unity as the development platform

Unity is a widely adopted game engine and development platform that provides robust tools for creating *Extended Reality* (XR) applications, making it the ideal choice for developing the *Strings of Life* project. Its compatibility with multiple platforms, real-time rendering capabilities, and integration with networking frameworks like Photon Fusion 2 enable efficient development of scalable multiplayer *Augmented Reality* (AR) applications.

Key Advantages of Unity for Multiplayer AR:

- **Cross-Platform Compatibility:** Unity supports deployment across *Augmented Reality* (AR)-enabled devices, including iOS and Android, ensuring accessibility for a wide range of users.
- **Real-Time Rendering and Graphics Optimization:** The Unity engine provides high-performance rendering through the Universal Render Pipeline (URP) and shader-based optimizations, enabling realistic *Augmented Reality* (AR) experiences.

- **Physics and Interaction Capabilities:** Unity's physics engine facilitates realistic object interactions, allowing for immersive *Augmented Reality* (AR) elements that respond naturally to user inputs.
- **Networking Integration with Photon Fusion 2:** Unity seamlessly integrates with Photon Fusion 2, allowing for efficient real-time synchronization of objects and interactions in multiplayer *Augmented Reality* (AR) environments.
- **Extensive Plugin and SDK Support:** Unity's Asset Store and open-source ecosystem provide a vast array of tools, including *Augmented Reality* (AR) Foundation, which simplifies the integration of platform-specific *Augmented Reality* (AR) capabilities.

Application to "Strings of Life" For the *Strings of Life* project, Unity provides the necessary tools for rendering high-quality *Augmented Reality* (AR) visuals, handling real-time interactions, and ensuring smooth synchronization of multiplayer experiences. Its modular architecture allows for efficient iteration and integration of advanced networking and interaction mechanics, making it an optimal choice for large-scale multiplayer *Augmented Reality* (AR) applications.

3.2.2 Photon Fusion 2 for networking

Photon Fusion 2 is a networking framework designed for real-time multiplayer applications, offering high-performance synchronization, predictive lag compensation, and cloud-based scalability. Its architecture provides an efficient solution for handling **network latency, state replication, and large-scale multiplayer interactions**, making it a crucial choice for developing multiplayer *Augmented Reality* (AR) applications such as *Strings of Life*.

Key Features of Photon Fusion 2:

- **Authoritative Server Model:** Unlike peer-to-peer (P2P) networking, Photon Fusion 2 uses a **dedicated authoritative server** to manage object synchronization and state updates. This ensures **consistency and security**, preventing data manipulation or desynchronization between clients.
- **Tick-Based State Replication:** Photon Fusion 2 implements a **tick-based update system**, ensuring that object states are synchronized at precise time intervals.

This minimizes **network congestion** and optimizes bandwidth usage, leading to more stable multiplayer interactions.

- **Lag Compensation and Rollback System:** To counteract network latency, Photon Fusion 2 employs a **rollback and prediction algorithm** that estimates and corrects delayed player actions. This is particularly important for multiplayer *Augmented Reality* (AR), where real-time object interactions must be accurately replicated across all users.
- **High Scalability with Region-Based Networking:** The framework supports **large-scale multiplayer interactions** by utilizing **region-based networking**, ensuring that only relevant data is transmitted to each player. This **reduces bandwidth load** and prevents unnecessary updates for distant objects.
- **Hybrid Synchronization Modes:** Photon Fusion 2 offers three core synchronization models:
  * **Shared Mode:** Ideal for small-scale applications where all clients maintain local authority over objects.
  * **Hosted Mode:** Uses a single authoritative host to manage interactions, improving network stability.
  * **Server Mode:** Implements a fully authoritative cloud server for large-scale applications, ensuring optimal **data consistency and security**.
- **Cloud-Hosted Multiplayer Sessions:** Photon Fusion 2 integrates with **Photon Cloud Servers**, allowing seamless **cloud-hosted matchmaking, player management, and session persistence**. This eliminates the need for developers to manage dedicated server infrastructure.

Comparison with Other Networking Solutions: Photon Fusion 2 surpasses other multiplayer networking solutions in terms of scalability, performance, and synchronization accuracy. While frameworks like **Mirror** and **UNET** offer basic networking capabilities, they are primarily suited for **local or small-scale** multiplayer applications. Mirror, for instance, relies on a **client-hosted model**, which can introduce reliability issues when the host disconnects. In contrast, Photon Fusion 2's **dedicated cloud-hosted server architecture** provides superior **stability, scalability, and real-time accuracy**.

Application to "Strings of Life" For the *Strings of Life* project, Photon Fusion 2 enables real-time synchronization of **interactive AR elements**, ensuring that all players experience **consistent object positioning and interactions**. Its **rollback prediction, state replication, and cloud-based hosting** guarantee a smooth multiplayer experience, allowing up to 50 users to interact in the same digital environment with minimal latency.

3.3 Design and Development Process

The development of a multiplayer *Augmented Reality* (AR) application requires a structured approach that integrates both technical implementation and user experience considerations. The *Strings of Life* project follows a systematic design and development process to ensure that the final application meets the requirements of scalability, synchronization, and interactivity.

The design phase of the project involves defining the **narrative elements, user interactions, and core gameplay mechanics**, ensuring that the immersive experience aligns with the project's theme. This is followed by the development phase, which focuses on implementing **multiplayer networking, real-time synchronization, and augmented reality functionalities**. The iterative process ensures continuous improvements through user testing and feedback integration.

This section details the design and development workflow, highlighting two primary aspects: **storyboarding and narrative integration**, which shape the user experience, and **multiplayer functionality and *Augmented Reality* (AR) capabilities**, which form the technical foundation of the system.

3.3.1 Storyboarding and narrative integration

The *Strings of Life* project is designed as an immersive multiplayer *Augmented Reality* (AR) experience, integrating a strong narrative with interactive gameplay elements. The storytelling aspect plays a crucial role in guiding user engagement and enhancing the overall experience. To ensure a cohesive design, the development process begins with **storyboarding**, which serves as a visual blueprint for structuring the interaction flow and gameplay progression [7]

Storyboarding Process: The storyboarding phase involves mapping out key user interactions, game sequences, and narrative-driven elements. This includes:

- Defining the progression of the escape room storyline, ensuring that each puzzle and challenge contributes to the overarching theme.
- Structuring interactions within the AR environment, aligning digital overlays with real-world elements.
- Establishing transitions between different phases of the game to create a seamless and engaging user experience.

Narrative Integration in Multiplayer AR: Unlike traditional single-player AR experiences, *Strings of Life* requires a storytelling structure that adapts to multiple users interacting simultaneously. This is achieved through:

- Synchronizing story progression across all players to maintain a consistent experience.
- Designing branching narratives that adjust based on user actions and group interactions.
- Using AR elements to visually reinforce the story, such as dynamic environmental changes triggered by player inputs.

Application to "Strings of Life" In this project, the story revolves around unraveling the mystery of the *27 Club* through interactive challenges and puzzles. By leveraging storyboarding techniques and interactive AR elements, the game ensures that narrative depth is seamlessly woven into the multiplayer structure, enhancing user immersion and engagement.

3.3.2 Building multiplayer functionality and AR capabilities

The development of the *Strings of Life* project requires a robust implementation of both multiplayer networking and augmented reality (*Augmented Reality* (AR)) functionalities to ensure seamless interaction among users. The challenge lies in integrating real-time multiplayer synchronization with immersive AR elements while maintaining performance across various devices. This section outlines the key technical aspects involved in building these functionalities.

Multiplayer Implementation: To support up to 50 concurrent users, the project utilizes Photon Fusion 2 for networking, ensuring efficient real-time communication. The core components of the multiplayer architecture include:

- **Session Management:** Players are assigned unique session identifiers, allowing them to connect, join, and leave multiplayer rooms without disrupting game continuity. The session management system ensures that each room maintains its integrity, preventing mid-game data loss or conflicts.
- **State Synchronization:** Real-time synchronization of object positions, user interactions, and narrative progression ensures consistency across all devices. Using **tick-based updates** and **delta compression techniques**, Photon Fusion 2 minimizes unnecessary bandwidth consumption while ensuring smooth object transitions.
- **Lag Compensation and Prediction:** Using rollback and interpolation techniques, the system minimizes the effects of network latency on gameplay interactions. Photon Fusion 2 applies **networked object prediction algorithms**, estimating object movement trajectories when data packets are delayed. Additionally, **input delay smoothing** ensures that interactions appear instantaneous even under high-latency conditions.
- **Dynamic Host Migration:** If the primary host disconnects, Photon Fusion 2 automatically reassigns authority, preventing game interruptions. This is achieved through a **leader-election mechanism**, where the system selects the next most stable client to assume host responsibilities.
- **Collision and Physics Synchronization:** Unlike traditional multiplayer applications, AR introduces real-world physics constraints. To ensure all users perceive physics interactions consistently, Photon Fusion 2 manages **collision detection and rigid body replication** across the network.

Integration of AR Capabilities: The project employs Unity's *Augmented Reality* (AR) Foundation, which allows seamless integration of platform-specific AR development kits such as Augmented Reality Kit (ARKit) (for iOS) and Augmented Reality Core (ARCore) (for Android). Key AR functionalities include:

- **Spatial Mapping and Plane Detection:** Enables real-world surfaces to act as interactive game environments. The system dynamically adjusts the virtual environment based on real-world surface data, ensuring accurate placement of virtual objects.

- **Object Anchoring:** Ensures that virtual objects remain fixed to their intended physical locations, preventing misalignment across devices. **Cloud-based anchor persistence** allows objects to retain their position even when users disconnect and reconnect to the session.
- **Hand and Gesture Recognition:** Enhances user interactions by allowing natural input mechanisms within the AR environment. Users can grab, rotate, and interact with virtual elements, with these actions being **replicated across all connected clients**.
- **Lighting Estimation and Occlusion Handling:** Creates a more realistic experience by adjusting virtual elements based on real-world lighting conditions and depth perception. Occlusion handling ensures that virtual objects are **properly blocked by real-world obstacles** for a more immersive experience.
- **Cross-Platform AR Compatibility:** Since the application is designed to run on both iOS and Android devices, AR Foundation serves as a **unified framework** that bridges platform-specific functionalities, ensuring that multiplayer interactions remain consistent regardless of the operating system.

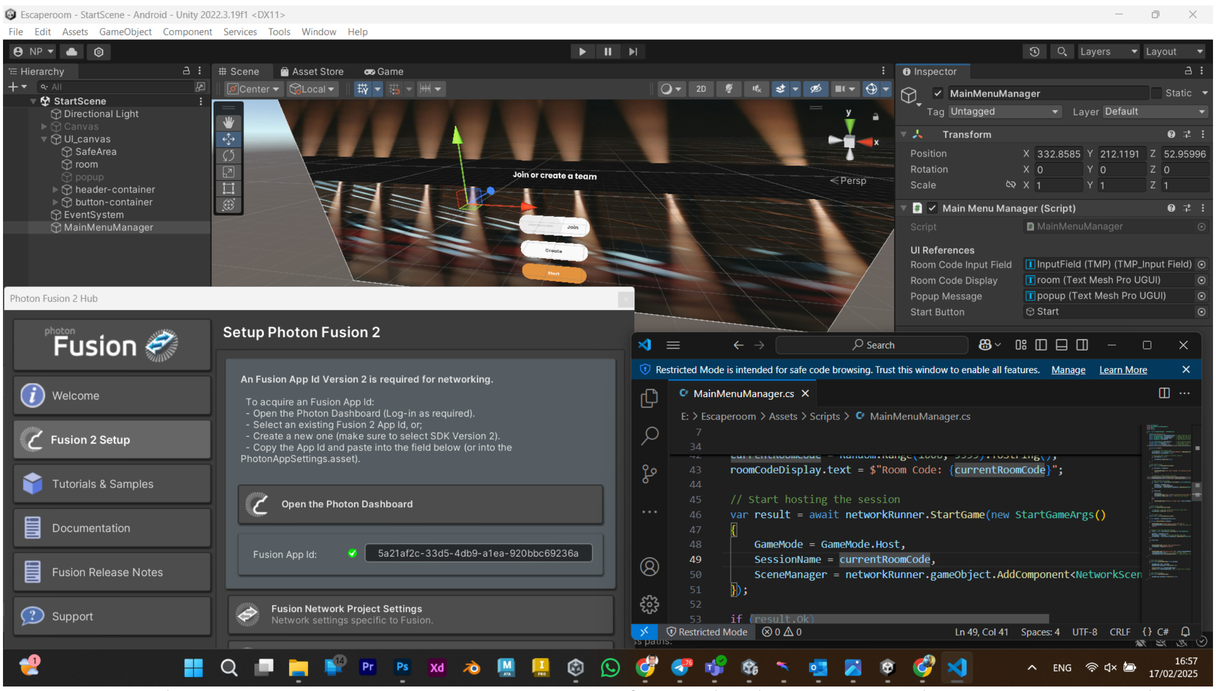

Figure 3.2: Photon Fusion 2 integration in Unity for multiplayer networking. The image showcases the setup process, network management scripts, and real-time synchronization within the project.

Optimization Strategies for Multiplayer AR:

– **Network Traffic Reduction:** The use of **region-based data updates** ensures that players only receive updates relevant to their immediate surroundings, reducing unnecessary data transmission.

– **Adaptive Rendering and Performance Scaling:** Device performance varies significantly across different hardware configurations. To accommodate this, the application employs Level of Detail (LOD), dynamically reducing object complexity on lower-end devices.

– **Latency-Based Input Adjustment:** Photon Fusion 2 introduces **latency-aware movement replication**, ensuring that users in regions with weaker network connectivity do not experience sudden motion jumps or desynchronization.

Application to "Strings of Life" By integrating multiplayer functionality with AR interactions, the *Strings of Life* project enables collaborative gameplay where players can manipulate digital objects, solve puzzles, and progress through the narrative in real time. The use of Photon Fusion 2 ensures smooth networking, while AR Foundation provides a dynamic, immersive environment that enhances user engagement.

This implementation not only modernizes the original *Strings of Life* concept but also overcomes the **technological constraints** of its 2018-2019 single-user version. By leveraging **advanced multiplayer networking and AR advancements**, the project delivers a **fully synchronized, large-scale interactive experience**, pushing the boundaries of digital multiplayer storytelling.

3.4 Data Collection

Accurate and structured data collection is a crucial component in evaluating the effectiveness of the *Strings of Life* project. The multiplayer *Augmented Reality* (AR) application relies on various data points to assess **user interaction patterns**, **performance stability**, and **networking efficiency**. To ensure the system meets its design objectives, multiple data collection methods are employed, including **user feedback surveys**, **performance monitoring**, and **technical validation through logging mechanisms**. This section outlines the methodologies used to collect and analyze data, ensuring that improvements can be made iteratively throughout the development process.

Objectives of Data Collection:

- To measure **system performance**, including network latency, synchronization accuracy, and frame rate stability.
- To analyze **user engagement and usability**, identifying interaction challenges and areas for improvement.
- To assess **multiplayer synchronization**, ensuring a consistent experience across all connected users.
- To validate the effectiveness of AR integration, including spatial mapping accuracy and object persistence.

The collected data allows for continuous iteration and optimization, helping refine both **technical performance** and **user experience design**. The following subsections describe the specific methods used to gather data and the tools utilized for analysis.

3.4.1 Methods for collecting user feedback and performance data

To ensure the *Strings of Life* project meets both technical and user experience expectations, a structured approach to data collection is implemented. This involves gathering **qualitative** and **quantitative** data through a combination of **user feedback**, **automated performance monitoring**, and **network diagnostics**. These methods provide insights into both the **technical stability** and **usability** of the multiplayer *Augmented Reality* (AR) system.

User Feedback Collection: User feedback plays a critical role in refining interaction mechanics, ensuring an intuitive experience for participants. Feedback is gathered through:

- **Structured Surveys and Questionnaires:** Users complete predefined surveys assessing ease of use, responsiveness, and overall experience.
- **Observational Studies:** Users are observed interacting with the system, providing insights into usability challenges and engagement levels.
- **Interviews and Focus Groups:** Small groups of users discuss their experiences, highlighting pain points and suggesting improvements.

Performance Data Collection: To evaluate technical performance, the system continuously monitors:

- **Network Latency:** Measured in milliseconds to ensure real-time synchronization across devices.
- **Frame Rate Stability:** Ensuring consistent rendering performance without frame drops.
- **Synchronization Accuracy:** Evaluating how closely object movements and interactions align between users.
- **Device Resource Usage:** CPU, GPU, and memory consumption are logged to optimize performance across different hardware.

Automated Logging and Data Analytics: The project integrates logging mechanisms to capture real-time system behavior:

- **Photon Fusion 2 Debugging Tools:** Used to monitor connection stability, packet loss, and data synchronization.
- **Unity Profiler:** Analyzes frame rates, resource usage, and rendering performance for optimization.
- **Backend Analytics Dashboard:** Provides real-time metrics on user sessions, engagement duration, and error reporting.

Iterative Data Analysis for System Optimization: Collected data is systematically analyzed to inform further improvements in:

- **Multiplayer Synchronization:** Adjusting network update intervals for smoother interactions.
- **AR Interaction Refinement:** Improving touch responsiveness and spatial object accuracy.
- **Scalability Enhancements:** Optimizing data transfer rates to accommodate larger user groups.

By employing a structured combination of **user feedback collection, automated performance monitoring, and data-driven analysis**, the *Strings of Life* project continuously refines its *Augmented Reality* (AR) multiplayer experience, ensuring a technically robust and engaging interaction model.

3.4.2 Tools used for testing

The testing phase of the *Strings of Life* project requires a combination of software and hardware tools to evaluate system performance, multiplayer synchronization, and *Augmented Reality* (AR) interactions. This section outlines the primary testing tools used to ensure technical stability and a seamless user experience.

Networking and Multiplayer Testing: To validate real-time communication, data synchronization, and server performance, the following tools are employed:

- **Photon Fusion 2 Debugging Tools:** Provides real-time insights into network latency, packet loss, and data consistency across multiple clients.
- **Wireshark:** Captures and analyzes network traffic to detect bottlenecks and optimize bandwidth allocation.
- **Ping and Packet Loss Testing:** Evaluates server response times and stability under varying network conditions.
- **Load Testing with Simulated Users:** Stress-tests the server by simulating multiple concurrent users to assess scalability.

Performance Profiling and Optimization: To ensure stable frame rates, efficient rendering, and smooth gameplay, the following tools are utilized:

- **Unity Profiler:** Monitors Central Processing Unit (CPU) and Graphics Processing Unit (GPU) usage, memory allocation, and rendering performance.
- **Frame Rate Monitoring Tools:** Ensures stable performance across different devices by detecting frame drops and latency issues.
- **Android Profiler and Xcode Instruments:** Used for mobile performance analysis on Android and iOS devices.

Augmented Reality and Device Tracking Validation: Since the project heavily relies on *Augmented Reality* (AR) interactions, the following tools help assess tracking accuracy and interaction fidelity:

- **ARKit and ARCore Debugging Tools:** Evaluate spatial tracking accuracy and object anchoring reliability on iOS and Android devices.
- **Lidar and Camera Calibration:** Ensures accurate depth sensing and alignment of virtual objects with real-world environments.

– **AR Session Logging:** Tracks user movements, object placements, and Level of Detail (LOD) (Level of Detail) adjustments for a seamless AR experience.

Usability Testing and User Experience Evaluation: To ensure intuitive and engaging interactions, usability tests are conducted using:

– **Think-Aloud Protocols:** Users verbalize their thoughts while using the system to identify interaction challenges.

– **Eye-Tracking Analysis:** Assesses focus points and navigation ease within the AR environment.

– **A/B Testing:** Compares different interaction models to determine the most intuitive design.

By employing a combination of **network analysis, performance profiling, AR validation, and usability testing**, the *Strings of Life* project ensures a technically optimized and user-friendly multiplayer AR experience.

3.5 Testing and User Feedback

To ensure the stability, usability, and effectiveness of the *Strings of Life* multiplayer *Augmented Reality* (AR) experience, a structured testing process is conducted. The testing phase consists of multiple iterations, focusing on both **technical performance validation** and **user experience assessment**. By combining automated system tests with real user feedback, the project undergoes continuous refinement to enhance interaction quality and system reliability.

Testing Objectives:

– To validate **multiplayer synchronization** and ensure seamless interaction across all connected users.

– To measure **network stability and latency**, evaluating the performance of Photon Fusion 2 under varying conditions.

– To assess **AR tracking accuracy** and object alignment across multiple devices.

– To collect **user experience feedback** to identify interaction challenges and improve usability.

Testing Methodology: The testing phase is divided into the following key stages:

- **Alpha Testing:** Conducted internally within the development team to identify initial performance issues, synchronization bugs, and interface inconsistencies.
- **Beta Testing with Target Users:** A controlled group of participants engages with the system in a real-world setting, providing insights into usability, interaction fluidity, and engagement levels.
- **Network Load Testing:** Simulated environments with multiple concurrent users are created to assess Photon Fusion 2's ability to handle real-time interactions under heavy network conditions.
- **Device Compatibility Testing:** The application is tested across different hardware configurations, including high-end and mid-range mobile devices, to ensure consistent performance.

User Feedback Collection and Analysis: To refine the user experience, structured feedback is gathered using the following approaches:

- **Usability Questionnaires:** Users rate their experience based on responsiveness, ease of interaction, and game flow.
- **Observational Studies:** Developers observe player interactions, noting any usability issues or confusion.
- **Post-Test Interviews:** Participants discuss their experience, providing qualitative insights into engagement and areas for improvement.

Iterative Refinement Process: Insights gathered from testing are analyzed, and improvements are implemented through an iterative development cycle:

- **Optimization of Network Synchronization:** Adjustments to Photon Fusion 2's **state replication** and **tick rate** settings to improve real-time responsiveness.
- **Enhancements in AR Object Stability:** Refinements in *Augmented Reality* (AR) spatial anchoring to reduce object drift.
- **User Interface Improvements:** Simplified navigation elements and improved interaction cues based on feedback.

By incorporating a structured **testing and feedback-driven optimization process**, the *Strings of Life* project ensures a polished and engaging multiplayer AR experience before final deployment.

3.5.1 Iterative testing with simulated users

To ensure the robustness and stability of the *Strings of Life* multiplayer *Augmented Reality* (AR) experience, an iterative testing approach is employed using simulated users. This method allows for the controlled assessment of system performance, interaction consistency, and network stability before engaging real users. Simulated testing enables the identification and resolution of technical issues in a reproducible environment while reducing external variability.

Objectives of Iterative Testing:

- To evaluate **network performance**, including latency, packet loss, and synchronization accuracy under varying load conditions.
- To assess the **consistency of AR interactions**, ensuring that virtual objects remain anchored and responsive across multiple devices.
- To identify **scalability limits** by incrementally increasing the number of simulated users to replicate real-world multiplayer conditions.
- To detect and resolve **server load balancing issues** that may arise when handling concurrent users in Photon Fusion 2.

Simulation Process:

- **Automated User Bots:** AI-driven simulated users interact with the AR environment by performing predefined actions, such as object manipulation and movement tracking. This helps evaluate the system's responsiveness under controlled conditions.
- **Network Stress Testing:** Simulated users are used to generate varying levels of network traffic, testing Photon Fusion 2's ability to maintain synchronization, predict user actions, and handle latency spikes.
- **Device Emulation:** Different device profiles are simulated to assess performance variations across hardware configurations, including high-end and mid-range mobile devices.

- **Iterative Debugging:** Each test cycle identifies critical issues, which are logged, analyzed, and refined in subsequent iterations. This ensures that improvements are continuously integrated into the system.

Application to "Strings of Life" By employing iterative testing with simulated users, the *Strings of Life* project achieves a highly optimized, stable, and scalable multiplayer AR experience. The findings from simulated tests directly influence network optimization strategies, interaction refinements, and real-time synchronization improvements before engaging real users in beta testing.

3.5.2 Feedback integration into the development process

User feedback plays a pivotal role in shaping the development of interactive *Augmented Reality* (AR) applications. For the *Strings of Life* project, feedback was systematically collected from both internal testers and external participants and was then analyzed to inform design decisions and feature improvements. This iterative loop ensures that user perspectives directly influence the development lifecycle, resulting in a more refined and user-centered experience.

Types of Feedback Collected:

- **Technical Feedback:** Included reports on bugs, performance issues (e.g., latency, desynchronization), and device-specific behavior.
- **Usability Feedback:** Focused on interface intuitiveness, ease of interaction, object manipulation accuracy, and spatial alignment in the AR space.
- **Engagement Feedback:** Provided insights on narrative clarity, the emotional appeal of the storyline, and levels of player immersion during collaborative tasks.
- **Hardware Compatibility:** Captured data on device limitations, thermal throttling, battery consumption, and support for varying Augmented Reality Kit (ARKit) and Augmented Reality Core (ARCore) versions.

Integration Strategy:

- **Agile Iteration Cycles:** Feedback was integrated into short sprint cycles, allowing quick implementation of improvements and validation in the next testing round.
- **Prioritization Framework:** Issues were classified based on severity and user impact, ensuring that critical bugs and usability blockers were addressed first.

– **Collaborative Review Sessions:** Weekly development meetings included a review of collected feedback, with designers and developers jointly deciding on implementation strategies.

– **Versioning and Change Logs:** Each iteration resulted in a version update, with documented change logs reflecting user-reported issues that had been resolved or adjusted.

Outcome: This feedback-driven development approach led to measurable improvements in user satisfaction, system performance, and narrative cohesion. By continuously refining the application based on real user input, the *Strings of Life* project evolved into a more stable, scalable, and engaging multiplayer AR experience.

Chapter 4

Application Development

This chapter presents an in-depth examination of the practical development of the *Strings of Life* project, emphasizing the integration of multiplayer interactivity and *Augmented Reality* (AR) capabilities. The chapter outlines the systematic approach adopted to translate theoretical insights from previous chapters into a functional, interactive *Extended Reality* (XR) application. Particular attention is given to the design framework guiding the user interaction and narrative elements, the implementation of multiplayer functionalities leveraging Photon Fusion 2, and addressing critical technical challenges such as latency management and device compatibility.

Further, this chapter investigates the essential synchronization strategies employed to maintain a consistent and seamless shared environment across multiple devices, providing a comprehensive overview of data transmission techniques. Lastly, the chapter details efforts undertaken to enhance the overall user experience, including the design of intuitive interfaces and the iterative incorporation of user feedback aimed at optimizing player immersion and engagement.

The subsequent sections will sequentially elaborate on these topics, providing technical clarity on the methodologies and practical considerations critical to the successful realization of a robust and scalable multiplayer *Augmented Reality* (AR) experience.

4.1 Design Framework of Strings of Life

This section outlines the foundational design principles and methodologies that guided the development of the *Strings of Life* multiplayer *Augmented Reality* (AR) experience.

Central to the application's effectiveness was the integration of narrative-driven elements with robust multiplayer interaction mechanics. The design framework emphasized creating a balance between storytelling, gameplay engagement, and historical authenticity, closely aligned with Effenaar's rich musical heritage and the compelling theme of Elvis Presley and the *27 Club*.

In designing user interactions, a structured approach was employed, starting with detailed storyboarding and progressing to interaction flowcharts. These visual planning tools facilitated a coherent mapping of narrative progression and ensured logical continuity across interactive game phases. Key story points and puzzles were intentionally designed to encourage collaborative problem-solving among users, fostering a sense of teamwork and collective accomplishment in the *Extended Reality* (XR) environment.

Moreover, historical and cultural elements were thoughtfully integrated into the gameplay mechanics. Digital artifacts and interactive *Augmented Reality* (AR) components were meticulously selected and designed based on authentic historical references from Effenaar's archival materials. This authenticity was paramount in providing users with an immersive, culturally meaningful experience, deepening engagement and enhancing the overall narrative coherence.

Additionally, the iterative design process incorporated continuous user feedback loops. Initial design concepts underwent multiple rounds of testing with both simulated and real users to refine usability and narrative clarity. Adjustments were systematically integrated into subsequent iterations, ensuring the final application effectively balanced technical feasibility, narrative engagement, and user-centric design.

Overall, the established design framework provided a comprehensive blueprint for developing an interactive multiplayer experience that not only showcased technological innovation but also emphasized narrative depth and cultural authenticity.

4.1.1 User Interaction and Story Elements

In developing the *Strings of Life* experience, considerable emphasis was placed on crafting intuitive user interactions and integrating them seamlessly with the narrative structure. Effective design of interactions in *Augmented Reality* (AR) multiplayer environments requires clarity, intuitiveness, and synchronization across user devices, presenting unique challenges compared to traditional digital experiences.

The design process began with creating detailed storyboards and interaction flowcharts. These tools helped visualize how narrative elements would unfold and how users would interact collaboratively within the game environment. Key narrative milestones were directly linked to specific interactive tasks, prompting players to engage actively with story progression through collaborative puzzle-solving, exploration, and strategic decision-making.

Each interaction was carefully designed to leverage multiplayer dynamics, requiring cooperation among participants. For instance, certain puzzles could only be solved through coordinated actions, emphasizing team collaboration. Interactive tasks, such as virtual object manipulation and environment-triggered events, were mapped onto physical spaces, enhancing immersion and encouraging spatial exploration.

To optimize the player experience, interactions were iteratively tested and refined based on user feedback collected during early development phases. This feedback loop was instrumental in identifying usability issues, narrative inconsistencies, and synchronization challenges. Adjustments were made accordingly, ensuring each interaction effectively contributed to narrative immersion, ease of use, and multiplayer coherence.

Ultimately, by harmonizing compelling story elements with well-structured interactive mechanics, the design fostered deep user engagement, reinforced collaborative gameplay, and provided a coherent and immersive narrative experience within the multiplayer *Augmented Reality* (AR) environment.

4.1.2 Integration of Historical and Cultural Themes

A core objective in the development of *Strings of Life* was the meaningful integration of historical and cultural themes, particularly centered on **Effenaar's legacy** and the compelling narrative of **Elvis Presley and the *27 Club***. This thematic integration was essential to ensure the application provided not only entertainment but also educational value, deepening user appreciation of the venue's rich musical heritage.

Historical authenticity was pursued through rigorous archival research, which provided valuable insights and references for the narrative development. Significant cultural symbols, historical artifacts, and iconic personalities associated with the 27 Club were identified and creatively incorporated into the interactive experience. For instance, virtual artifacts within the *Augmented Reality* (AR) environment were meticulously modeled to represent historically significant items or symbols, each embedded with contextual meaning linked explicitly to the narrative arc.

The interactive elements were purposefully designed to stimulate curiosity and promote exploration of cultural history. Virtual puzzles and game challenges were aligned with historically accurate events and culturally significant motifs, allowing players to actively engage with and reflect upon the underlying cultural narratives. **Narrative coherence** was ensured through careful alignment of gameplay tasks with documented historical events and musical heritage themes central to the Effenaar experience.

Furthermore, cultural authenticity was consistently validated through iterative consultation with historians and cultural experts associated with Effenaar. Their feedback enabled fine-tuning of narrative accuracy and ensured respectful representation of sensitive historical themes. User testing also provided critical insights into how effectively cultural elements resonated with diverse audiences, informing further refinements.

Ultimately, the thoughtful integration of these historical and cultural themes significantly enhanced user immersion, enriched the narrative complexity, and transformed the *Extended Reality* (XR) experience from merely interactive entertainment to a meaningful and culturally valuable exploration of music history.

4.2 Implementation of Multiplayer Interactivity

This section describes the technical strategies and methodologies used in implementing robust multiplayer interactivity within the *Strings of Life* application. Achieving seamless real-time interactions in an *Augmented Reality* (AR) multiplayer environment required careful consideration of network architecture, synchronization techniques, and effective handling of player inputs. The primary technical platform selected for this task was **Photon Fusion 2**, integrated within the **Unity** development environment, due to its advanced networking capabilities and efficient handling of real-time multiplayer synchronization[8].

The initial implementation step involved the configuration of Photon Fusion 2's networking infrastructure. This encompassed setting up a reliable **authoritative server model**, which was crucial for maintaining consistent object states across all connected clients. Photon's tick-based state replication method was utilized to manage synchronization efficiently, ensuring all game states were accurately updated at regular intervals without overwhelming network resources.

Handling real-time player inputs and interactions required the implementation of predictive algorithms, particularly Photon's built-in **lag compensation and rollback mechanisms**. These techniques significantly reduced noticeable latency, allowing user inputs—such as grabbing, moving, or interacting with virtual objects—to appear instantaneous to all users. Furthermore, collision detection and physics synchronization were carefully implemented and extensively tested to guarantee consistent and believable interactions within the shared virtual space.

Additionally, the integration of *Augmented Reality* (AR) posed unique challenges for multiplayer synchronization, especially regarding spatial anchoring and object persistence across multiple user devices. Utilizing cloud-based spatial anchors ensured that virtual elements remained precisely aligned with the physical environment across diverse devices and user perspectives. This approach was validated through iterative user testing, ensuring the reliability of object positioning and minimizing **spatial drift** during extended sessions.

In summary, the implementation of multiplayer interactivity required comprehensive integration of networking technologies, precise synchronization strategies, and meticulous handling of player interactions within the augmented space. Through these carefully executed technical strategies, the *Strings of Life* project successfully achieved its goal of supporting real-time collaborative gameplay, significantly enhancing user engagement and interaction quality.

4.2.1 Configuring Photon Fusion 2 for player synchronization

Effective synchronization of player interactions within the *Strings of Life* application required careful configuration and optimization of the **Photon Fusion 2** networking framework. Due to the complexity of managing concurrent user interactions in real-time within an *Augmented Reality* (AR) context, Photon Fusion 2's advanced features—such as authoritative server management, tick-based state replication, and rollback prediction mechanisms—were leveraged extensively.

The initial configuration focused on establishing a robust and scalable **authoritative server model**. This approach centralizes the management of player states, ensuring consistent object synchronization and preventing state conflicts across multiple devices. Photon Cloud servers were utilized to handle player matchmaking and session management, efficiently distributing users into multiplayer rooms optimized for network latency and geographical proximity.

A critical component of Photon Fusion 2 configuration was the adoption of a **tick-based state replication model**. This method provided a structured mechanism for synchronizing the virtual environment, updating the game states at defined intervals. By employing tick-based synchronization, network bandwidth consumption was optimized, reducing unnecessary data transmission and effectively minimizing latency fluctuations. This proved essential in maintaining smooth player movements and interactions across all connected devices.

Furthermore, Photon Fusion 2's **rollback and prediction algorithms** were carefully configured to compensate for network latency. These algorithms predict player actions based on historical input data, temporarily interpolating movements when data packets are delayed. This feature significantly improved the responsiveness and fluidity of player interactions, enhancing the perceived immediacy of actions, such as object manipulation and collaborative tasks.

To ensure precise player synchronization in spatially anchored *Augmented Reality* (AR) interactions, the Photon framework was integrated with Unity's spatial anchoring systems. Cloud-based spatial anchors maintained consistent positions for virtual elements across multiple devices, further reinforcing synchronization integrity. Extensive iterative testing validated these synchronization strategies, confirming stable multiplayer interactions even under varying network conditions.

Through the meticulous configuration of Photon Fusion 2's core synchronization features, the multiplayer interactivity in the *Strings of Life* project achieved high levels of reliability, responsiveness, and scalability, essential for delivering an engaging collaborative *Extended Reality* (XR) experience.

4.2.2 Handling player inputs and interactions in AR

Efficient management of player inputs and interactions within the *Augmented Reality* (AR) environment posed significant technical challenges for the *Strings of Life* project, primarily due to the necessity of accurate, real-time responses across multiple synchronized devices. This subsection outlines the specific methods and techniques implemented to effectively handle and replicate player interactions, maintaining seamless user experiences throughout the multiplayer sessions.

A central aspect involved designing intuitive and responsive input mechanisms tailored explicitly to the **augmented reality context**. These inputs included direct interactions, such as selecting, moving, and manipulating virtual objects, as well as gesture-based commands recognizable via mobile devices' touch screens and built-in sensors. Unity's Input System was carefully configured to reliably detect and interpret these diverse inputs, ensuring immediate feedback and minimal input latency.

The integration of player inputs with Photon Fusion 2's **synchronization protocols** was achieved by employing networked object replication and authoritative input handling. Each player's inputs were transmitted to the authoritative server, which then validated and propagated interaction states to all connected clients. The implementation of **networked rigid-body physics synchronization** allowed accurate real-time reflection of object interactions, ensuring consistent behavior and positions across different users' perspectives.

To further enhance responsiveness, Photon Fusion 2's **predictive algorithms and client-side interpolation** techniques were rigorously applied. These algorithms anticipated player actions, compensating for latency by interpolating intermediate object states smoothly. Consequently, interactions such as grabbing or moving objects appeared instantaneously synchronized across devices, significantly improving perceived interaction fluidity and user satisfaction.

Given the spatial nature of *Augmented Reality* (AR), additional emphasis was placed on maintaining alignment between virtual and physical spaces. Unity's **AR Foundation** was utilized alongside cloud-based spatial anchors, ensuring consistent virtual-object placements across diverse device hardware. Iterative testing and user feedback sessions were integral to refining these spatial interactions, ensuring that user inputs accurately reflected their intentions within the augmented environment.

Careful integration of intuitive input handling, precise synchronization mechanisms, and spatial anchoring strategies significantly enhanced the user interaction experience within the *Strings of Life* application, achieving reliable and immersive multiplayer interactivity in an *Augmented Reality* (AR) setting.

4.3 Addressing Technical Challenges

Developing an effective multiplayer *Augmented Reality* (AR) application inherently involves overcoming several complex technical challenges, particularly concerning **latency management**, **scalability**, and **device compatibility**. In the context of *Strings of Life*, these challenges were systematically identified, analyzed, and addressed through specific technical strategies and methodologies.

To structure a clear overview of the addressed challenges, the following primary issues were identified:

- **Latency Management:** Achieving low-latency interactions essential for real-time multiplayer *Extended Reality* (XR) experiences.
- **Scalability:** Ensuring stable performance as the number of concurrent users approaches the target of 50 simultaneous participants.
- **Device Compatibility:** Ensuring consistent experiences across diverse hardware capabilities and operating system requirements.

To effectively handle latency, the application relied on Photon Fusion 2's advanced features such as tick-based synchronization and predictive rollback mechanisms. By carefully configuring these aspects, network delays were significantly minimized, allowing interactions to appear instantaneous across user devices, thereby enhancing overall user responsiveness.

Scalability was primarily achieved through an authoritative cloud-hosted server architecture, strategically implemented using Photon's Cloud infrastructure. Leveraging Photon's dynamic load balancing and region-based networking significantly optimized performance, maintaining robust and responsive interactions as user counts scaled upwards.

Device compatibility was addressed through targeted optimization strategies within Unity and AR Foundation. Techniques such as adaptive rendering quality, dynamic asset loading, and hardware-specific adjustments ensured consistent performance and visual quality, even on lower-end devices.

The subsequent subsections detail each technical challenge individually, outlining precise methods employed, optimization strategies implemented, and the overall impact on application performance and user experience.

4.3.1 Managing latency and scalability

Latency and scalability represent two interrelated technical challenges critical to delivering a smooth, real-time multiplayer experience in the *Strings of Life* project. High latency can disrupt user interactions, breaking immersion, while inadequate scalability can cause performance degradation as user numbers increase. To effectively address these challenges, several targeted strategies were implemented:

1. **Photon Fusion 2 Network Optimization:**
   - Utilized **tick-based synchronization** to manage data transmission at regular intervals, significantly reducing unnecessary network overhead.
   - Implemented **delta compression**, ensuring only state changes were transmitted rather than full data packets, thus minimizing bandwidth usage.
2. **Latency Compensation Techniques:**
   - Employed Photon Fusion's **rollback and predictive algorithms**, anticipating user actions and maintaining seamless interactions despite network latency fluctuations.
   - Integrated **client-side interpolation**, smoothing object movements and minimizing noticeable latency during interactions, ensuring consistent visual synchronization.
3. **Scalable Cloud-based Architecture:**
   - Deployed an **authoritative server model** hosted via Photon Cloud, enabling efficient load distribution and robust management of concurrent user sessions.
   - Applied **region-based matchmaking**, connecting players to optimal servers based on geographical proximity, thus reducing overall network latency and enhancing responsiveness.
4. **Performance Monitoring and Iterative Testing:**
   - Continuous monitoring and profiling of network performance to identify and resolve potential latency spikes proactively.
   - Conducted extensive iterative testing under varied simulated network conditions, validating scalability strategies and ensuring stable performance for up to 50 concurrent users.

By integrating these targeted methods, the application successfully minimized latency disruptions and effectively supported high numbers of simultaneous users, ensuring consistent, responsive, and immersive multiplayer interactions in the *Extended Reality* (XR) environment.

4.3.2 Overcoming device compatibility issues

Ensuring consistent performance and seamless *User Experience* (UX) across diverse hardware posed significant challenges in developing the *Strings of Life* application. The heterogeneous nature of mobile devices—varying extensively in terms of Central Processing Unit (CPU) power, Graphics Processing Unit (GPU) capabilities, sensor precision, and operating system standards—required targeted optimization strategies within the Unity platform.

The first critical step involved dynamically adjusting the application's visual fidelity based on real-time hardware performance metrics. Techniques such as Level of Detail (LOD) management were strategically implemented, allowing automatic reduction of graphical complexity for lower-end devices. This ensured stable frame rates and reliable interactions without compromising essential visual clarity.

Leveraging Unity's *Universal Render Pipeline* (URP) was another key strategy for managing device compatibility. By reducing rendering overhead and simplifying shader complexity, performance across varying Graphics Processing Unit (GPU) specifications was significantly optimized, enhancing responsiveness and fluidity in *Augmented Reality* (AR) interactions across a wide spectrum of devices [9].

Additionally, device compatibility was reinforced by extensively utilizing Unity's *Augmented Reality* (AR) Foundation, a unified framework integrating both Augmented Reality Kit (ARKit) for iOS and Augmented Reality Core (ARCore) for Android. This unified approach provided robust and consistent functionalities, such as spatial anchoring, accurate surface detection, and stable object placement across diverse hardware environments, ensuring consistent user experiences.

Comprehensive iterative testing conducted on devices ranging from high-end smartphones with advanced Graphics Processing Unit (GPU) and *Light Detection and Ranging* (Lidar) capabilities to entry-level models enabled precise identification and resolution of performance bottlenecks. Adjustments derived from these insights ensured optimized performance and robust compatibility, regardless of hardware limitations.

This structured, adaptive approach significantly mitigated device compatibility concerns, ultimately delivering a consistent, immersive, and accessible multiplayer *Augmented Reality* (AR) experience to a diverse user base.

4.4 Synchronization in AR Multiplayer

Synchronization is a critical technical requirement in developing effective multiplayer experiences within *Augmented Reality* (AR) environments. In the context of the *Strings of Life* application, ensuring accurate synchronization involved maintaining consistent virtual environments across multiple user devices and managing real-time data transmission efficiently. These synchronization efforts aimed to create a seamless shared experience, ensuring users perceive the same virtual elements and interactions simultaneously, irrespective of individual device or network differences.

One primary challenge addressed was maintaining environmental consistency. Given that *Augmented Reality* (AR) applications overlay virtual elements onto real-world spaces, even minor discrepancies in spatial positioning could severely disrupt user immersion. To tackle this issue, robust cloud-based spatial anchoring systems were implemented, leveraging frameworks such as Unity's *Augmented Reality* (AR) Foundation integrated with Augmented Reality Kit (ARKit) and Augmented Reality Core (ARCore). These spatial anchors served as stable reference points, reliably synchronizing object placements across diverse devices and minimizing drift, especially critical during prolonged multiplayer sessions.

Data transmission strategies were equally vital in maintaining synchronization. Photon Fusion 2's authoritative server model was strategically employed to centralize state management and resolve synchronization conflicts effectively. Tick-based state replication, combined with delta compression, optimized bandwidth usage by only transmitting essential data changes. Additionally, predictive algorithms mitigated latency effects, enabling smooth and coherent real-time updates even under challenging network conditions.

To ensure consistent performance, synchronization strategies underwent iterative validation through controlled and real-world testing scenarios. Data collected during these evaluations informed necessary refinements, such as adjusting synchronization intervals, fine-tuning latency compensation parameters, and optimizing object interaction states.

Ultimately, the synchronization methods developed and implemented within the *Strings of Life* application provided a robust framework for delivering a cohesive, immersive multiplayer experience, overcoming significant technical challenges inherent in shared *Extended Reality* (XR) environments.

4.4.1 Maintaining consistent environments across devices

Maintaining environmental consistency across multiple user devices in multiplayer *Augmented Reality* (AR) experiences is essential to deliver a seamless and believable shared space. For the *Strings of Life* application, achieving this consistency required addressing specific challenges related to spatial synchronization, virtual object placement, and minimizing positional drift over extended periods of interaction.

Spatial anchoring served as the foundational technique for environmental consistency. The application utilized cloud-based spatial anchor systems integrated through Unity's *Augmented Reality* (AR) Foundation, incorporating platform-specific tools such as Augmented Reality Kit (ARKit) for iOS and Augmented Reality Core (ARCore) for Android. These anchors functioned as stable reference points, accurately positioning virtual elements relative to the real-world environment. By securely aligning these anchors to physical locations, the application ensured that virtual objects remained consistently positioned for all users, regardless of their device orientation or movement within the physical space.

To further enhance environmental stability, real-time device tracking data was continuously validated and synchronized through Photon Fusion 2's authoritative server framework. By regularly updating anchor positions based on collective data from multiple users, potential discrepancies caused by individual sensor inaccuracies or environmental variations were minimized. This collective validation significantly reduced issues such as spatial drift—where virtual elements slowly shift from their intended positions over time—thus maintaining the reliability and accuracy of the shared *Augmented Reality* (AR) experience.

Additionally, predictive interpolation algorithms played a critical role in mitigating brief synchronization discrepancies caused by latency variations. Photon's built-in rollback and client-side interpolation features smoothly reconciled transient differences in object positioning, ensuring immediate corrective adjustments without noticeable disruptions. This approach significantly enhanced perceived synchronization accuracy, improving overall immersion.

Through a systematic combination of cloud-based spatial anchoring, authoritative positional validation, and predictive synchronization techniques, the *Strings of Life* application effectively maintained a stable, consistent environment across multiple devices, ultimately enhancing the multiplayer AR experience's realism and user immersion.

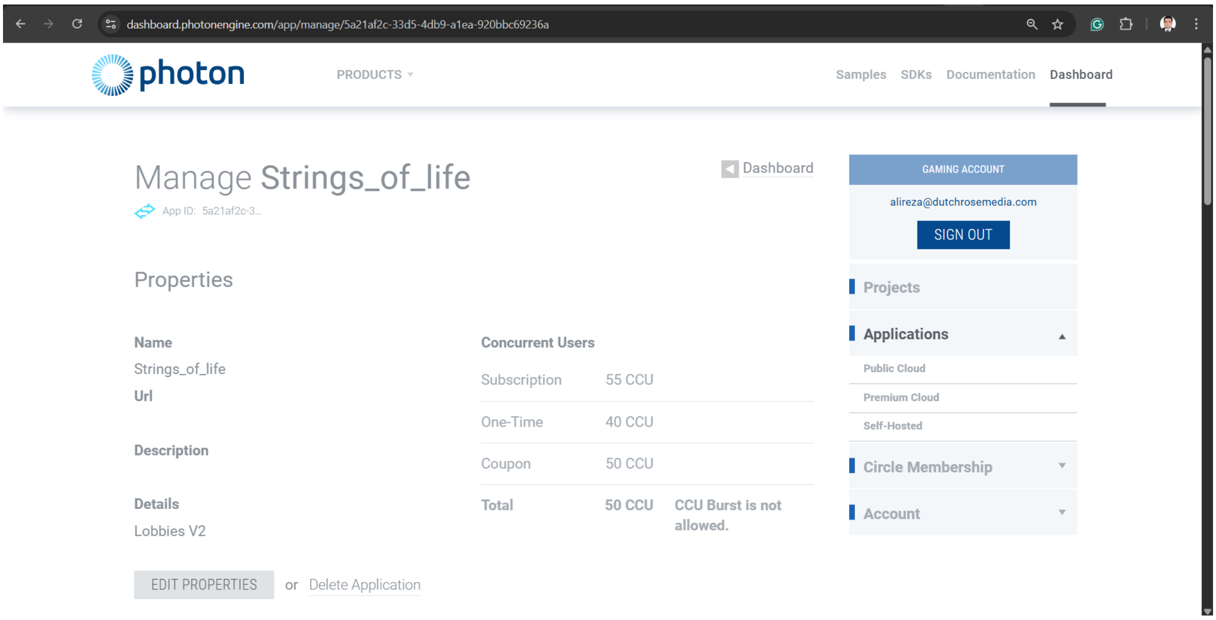

Figure 4.1: Photon Engine dashboard displaying the server configuration used to maintain consistent spatial synchronization and environment stability across multiple user devices in the *Strings of Life* multiplayer AR experience.

As illustrated in Figure 4.1, the Photon Engine dashboard was actively utilized to configure and manage server resources essential for maintaining robust synchronization. This configuration enabled effective load balancing and precise spatial alignment, significantly reducing inconsistencies and positional drift. Regular monitoring through this interface facilitated ongoing optimization, ensuring reliable and stable multiplayer experiences across various devices and user scenarios.

4.4.2 Strategies for handling data transmission

Effective management of data transmission is critical for maintaining real-time synchronization and seamless interactions within multiplayer AR applications. In the context of the *Strings of Life* project, several strategic approaches were implemented to optimize data transmission efficiency and reliability, thereby ensuring a smooth multiplayer experience.

Photon Fusion 2's built-in network optimization methods played a central role. Particularly, the application leveraged tick-based state replication to control the timing and frequency of data packets transmitted across the network. By regularly transmitting incremental updates—rather than complete object states—using delta compression techniques, bandwidth requirements were significantly reduced. This optimization was especially crucial in accommodating the targeted concurrent user count of up to 50 players without overwhelming network resources.

Additionally, priority-based transmission protocols were employed to ensure essential user actions and critical game states received network precedence. User-generated inputs, such as object manipulation and environmental interactions, were assigned higher transmission priority, ensuring responsive feedback during interactive scenarios. Meanwhile, non-critical updates or environmental effects were managed using lower priority transmission, ensuring balanced network performance.

Latency and packet loss concerns were further mitigated through predictive algorithms and rollback techniques. Photon Fusion 2's predictive interpolation and rollback mechanisms seamlessly handled transient disruptions, maintaining perceived continuity in multiplayer interactions despite network variability. This ensured uninterrupted and immersive user experiences, preserving the integrity of shared interactions.

Through these comprehensive data transmission strategies, the *Strings of Life* application successfully maintained stable, responsive, and synchronized multiplayer interactions, effectively addressing the complex technical demands inherent to real-time AR environments.

4.5 Enhancing User Experience

Providing an exceptional user experience (UX) is vital to the success and adoption of multiplayer AR applications, particularly in interactive cultural experiences like *Strings of Life*. Beyond addressing technical performance and synchronization challenges, significant attention was devoted to designing intuitive user interfaces (UI), streamlined interaction mechanics, and meaningful narrative integration. These considerations aimed to foster deeper user engagement and lasting immersion.

User experience enhancements involved iterative design informed by user-centric feedback sessions. Early prototypes underwent extensive evaluation by representative user groups, generating actionable insights on interaction intuitiveness, narrative clarity, and overall application enjoyment. This iterative feedback cycle allowed for continuous adjustments to the application's design, progressively refining and optimizing UX elements based on actual user perceptions.

Moreover, emphasis was placed on the accessibility and intuitiveness of interactions within the AR environment. Interfaces were thoughtfully designed to require minimal cognitive load, allowing users to focus primarily on exploration, collaboration, and narrative progression rather than navigating complex controls. Clear visual cues, subtle animations, and simplified input mechanisms significantly improved ease of use, particularly benefiting users new to XR technologies.

Immersion was further deepened through carefully curated audiovisual elements closely tied to narrative themes. Sound design, interactive storytelling, and historically accurate digital artifacts enriched user interactions, effectively bridging digital experiences with Effenaar's cultural context. These experiential enhancements were regularly assessed through qualitative user feedback, validating the alignment of immersive elements with audience expectations.

The following subsections delve deeper into these specific areas of UX improvement, detailing the methodologies used in interface design, narrative integration, and user feedback incorporation, collectively contributing to an engaging and memorable multiplayer experience.

4.5.1 Designing intuitive interfaces and controls

Effective interface design plays a fundamental role in shaping the overall UX of multiplayer AR applications. For the *Strings of Life* project, interface design was strategically approached with an emphasis on simplicity, intuitiveness, and seamless integration into the immersive environment. This design philosophy aimed to reduce the cognitive load on users, allowing them to engage effortlessly with both interactive elements and narrative-driven tasks.

The application's interface was intentionally minimalistic, using clear and intuitive visual indicators to guide users through interactions without overwhelming their visual field. Essential interactive components such as navigation menus, virtual object manipulation controls, and informational overlays were integrated discreetly into the AR view, ensuring users remained fully immersed in their immediate environment. Consistent iconography and subtle animation feedback were implemented to provide clear visual cues, enhancing ease of use and promoting confident user interactions.

Touch gestures and direct manipulations, including tapping, dragging, and pinching, were standardized across interaction scenarios, contributing to consistent and predictable responses. Extensive testing of these interaction modalities was conducted with diverse user groups to identify and resolve potential usability issues, ensuring the interfaces were approachable for users with varying degrees of familiarity with AR technology.

Figure 4.2: User interface (UI) design depicting the initial interaction scenario within the *Strings of Life* escape room experience. Users begin by engaging with a virtual smartphone interface that simulates discovering and interacting with another individual's device, thereby integrating intuitive design with immersive narrative elements.

Accessibility considerations were also central to the design process. The interface was adaptable to different screen sizes, resolutions, and orientation modes, automatically adjusting to ensure consistent usability across a wide range of mobile devices. Furthermore, adaptive visual elements were employed to enhance readability and user interaction in varied lighting conditions commonly encountered in real-world scenarios.

The combined result of these interface design strategies significantly improved user interactions within the *Strings of Life* application, fostering an intuitive, immersive, and satisfying AR experience for all participants.

4.5.2 Incorporating feedback to improve player immersion

Continuous integration of user feedback was integral to optimizing player immersion in the *Strings of Life* multiplayer AR application. Throughout the iterative development process, systematic collection and analysis of qualitative and quantitative user feedback provided critical insights into the effectiveness of narrative pacing, interaction intuitiveness, and the overall immersive quality of the experience.

Structured testing sessions involving representative user groups were regularly conducted, utilizing methodologies such as direct observation, surveys, and informal interviews. Metrics like the *Net Promoter Score* (NPS) and detailed qualitative responses identified strengths and areas for improvement regarding user engagement and immersion. These insights directly influenced subsequent development cycles, prompting targeted refinements in user interfaces, interaction designs, and narrative clarity.

For example, early user feedback highlighted specific challenges in comprehending initial story clues and puzzle interactions, leading to adjustments in the interface design to provide clearer visual and narrative guidance. Similarly, feedback emphasizing the desire for deeper historical context resulted in the strategic addition of multimedia elements, such as audio logs and historical imagery, to further enhance narrative immersion.

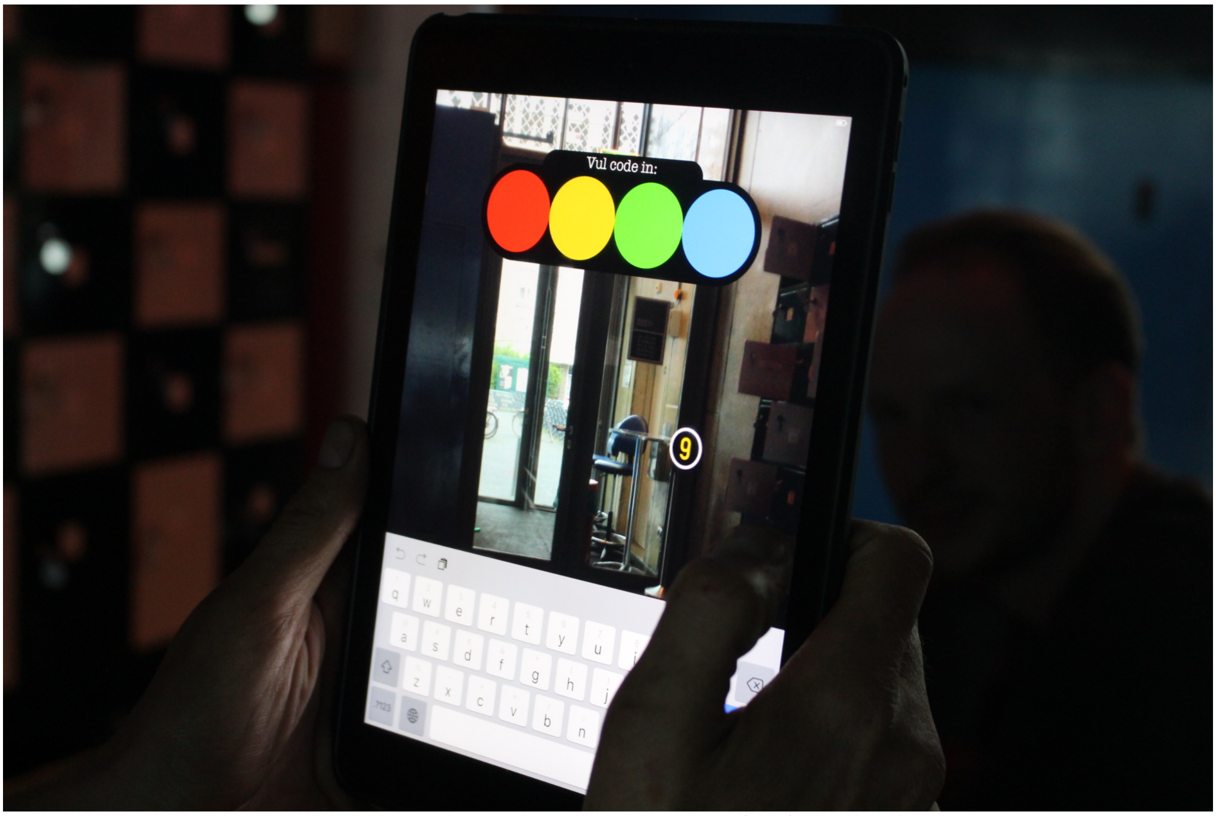

Figure 4.3: Initial interactive puzzle within the *Strings of Life* multiplayer AR experience, requiring users to collaboratively unlock virtual boxes by entering color-based codes.

The incorporation of feedback also facilitated precise adjustments in multiplayer synchronization, where reports of minor spatial discrepancies guided improvements in spatial anchoring techniques and synchronization protocols. Subsequent user evaluations confirmed these refinements significantly improved perceived consistency and immersive quality.

By systematically integrating user feedback into iterative development processes, the *Strings of Life* application consistently evolved toward heightened immersion and engagement, effectively aligning the final user experience with participant expectations and delivering a highly resonant multiplayer AR adventure.

chapter 4 provided comprehensive insights into the practical development of the *Strings of Life* multiplayer AR application, emphasizing robust technical approaches to multiplayer interactivity, synchronization, design, and user feedback integration. Addressing key challenges related to latency, scalability, device compatibility, and user immersion significantly contributed to creating a cohesive and engaging user experience. Building upon the development methodologies and design principles discussed, the subsequent chapter delves into empirical findings, user evaluations, and detailed analyses, assessing the effectiveness and real-world applicability of the developed XR application.

Chapter 5

Findings and Analysis

This chapter presents and critically analyzes the empirical findings obtained during the testing and evaluation phases of the *Strings of Life* multiplayer AR application. The primary goal of these analyses is to assess the effectiveness, user acceptance, and technical reliability of the developed system, providing insights into the practical applicability of the methodologies and strategies discussed in Chapter 4.

Findings are systematically categorized and presented, focusing on key aspects including user interaction, multiplayer synchronization performance, technical robustness, and overall user immersion. Both qualitative and quantitative data were collected from structured testing sessions, user surveys, and direct observation, enabling comprehensive evaluation of user experiences and system performance under realistic scenarios.

Quantitative analyses explore measurable performance indicators such as latency metrics, synchronization accuracy, scalability benchmarks, and interface responsiveness. These measurements provide essential insights into the technical efficiency and reliability of the application, critically evaluating how effectively the employed strategies addressed core technical challenges.

Complementing the quantitative evaluation, qualitative findings derived from user feedback sessions reveal valuable insights regarding player immersion, narrative engagement, interface intuitiveness, and overall satisfaction. Qualitative data are meticulously analyzed to uncover common user perceptions, interaction patterns, and areas requiring further improvement or refinement.

Together, the quantitative and qualitative analyses presented in this chapter form a comprehensive evaluation of the developed XR solution. The findings contribute not only to understanding the current effectiveness of the *Strings of Life* application but also offer guidance for future development iterations and broader implications for multiplayer AR experiences in cultural and narrative-driven contexts.

5.1 User Engagement Metrics

5.1.1 Measuring player interaction and retention

Understanding user interaction patterns is essential to evaluating the effectiveness of multiplayer AR experiences, particularly in a collaborative setting like the *Strings of Life* escape room. During the testing phase, detailed observations and analytics were gathered, highlighting distinct interaction behaviors, common usage patterns, and preferred modes of engagement among participants.

Observational data revealed that users predominantly engaged collaboratively rather than individually. Initial puzzle-solving activities frequently involved clear roles emerging naturally among participants, such as leaders who took initiative and facilitators who supported group communication. This dynamic indicated strong inherent collaborative behavior promoted by the application's design, emphasizing the success of interactive elements specifically tailored for multiplayer cooperation.

Interaction analytics indicated that direct object manipulations and interactive puzzle-solving activities had the highest engagement frequencies. Puzzles requiring simultaneous or coordinated inputs notably demonstrated greater user interaction depth and extended engagement periods. This finding underscores the effectiveness of collaborative interaction design strategies in fostering teamwork and sustained user immersion.

Conversely, certain interactions initially identified as ambiguous or overly complex were associated with reduced engagement and occasional frustration. Users explicitly preferred clearly guided interactions with well-defined visual cues and intuitive mechanisms. Feedback sessions consistently highlighted the importance of visual clarity and interaction simplicity, prompting iterative refinements to enhance intuitiveness in subsequent development cycles.

Overall, analysis of user interaction patterns validated the effectiveness of collaborative design principles implemented within the *Strings of Life* application, while also identifying critical opportunities for future improvement in interaction clarity and intuitive design.

5.1.2 Analysis of user feedback on the multiplayer experience

Evaluating user feedback was essential to gain deeper insights into user perceptions and attitudes towards the multiplayer aspect of the *Strings of Life* application. Data were collected through structured surveys, informal interviews, and direct observations, allowing comprehensive qualitative analysis of participants' experiences during testing sessions.

Participants consistently highlighted the **collaborative nature** of the multiplayer experience as a significant strength. Many users expressed appreciation for tasks designed specifically for multiple participants, which encouraged teamwork, social interaction, and collective problem-solving. Feedback indicated that these collaborative elements not only enriched the experience but also increased emotional investment and enjoyment among users.

The **synchronization quality and responsiveness** of interactions were also frequently commended by users. Most participants reported a smooth and seamless multiplayer experience, attributing this positive impression to the effective integration of Photon Fusion 2's networking capabilities. A smaller group of users, however, identified occasional synchronization lags or discrepancies, particularly in high-traffic network conditions, suggesting room for further optimization in network stability and latency management.

Feedback on the application's **ease of use and intuitiveness** in a multiplayer context was largely positive. However, some users encountered challenges during initial interactions due to unclear instructions or insufficient visual guidance. These insights directly informed targeted adjustments aimed at enhancing interaction clarity, simplifying interface elements, and providing better visual feedback mechanisms in subsequent design iterations.

Additionally, narrative integration into multiplayer interactions received notable praise. Users expressed particular enthusiasm for tasks that seamlessly combined story progression with collaborative gameplay, enhancing their overall immersion and emotional connection to the narrative context. This reinforced the value of closely aligning interactive and narrative elements to heighten engagement and user satisfaction.

Collectively, the analyzed user feedback provided critical insights for refining and improving the multiplayer AR experience. This feedback-driven approach not only validated existing design choices but also identified specific areas for iterative enhancement, significantly contributing to the application's overall effectiveness and user acceptance.

5.2 Technical Performance Analysis

5.2.1 Evaluating server load and latency

Assessing server load and latency was essential to validate the scalability and real-time responsiveness of the *Strings of Life* multiplayer AR application. Throughout extensive testing sessions, detailed quantitative metrics were collected to evaluate server performance under various simulated usage scenarios, particularly targeting the intended maximum concurrent user count of 50 participants.

Server load analysis primarily focused on assessing the stability and responsiveness of Photon Cloud servers configured via Photon Fusion 2. Performance data, including concurrent connection counts, CPU utilization, data throughput, and packet transmission rates, were systematically recorded and analyzed. Results indicated that server performance remained robust and stable, even when approaching maximum concurrent user limits. Average server CPU utilization consistently remained within optimal operational thresholds, generally below 75%, demonstrating effective scalability under real-world conditions.

Latency measurements were critically examined to ensure the application delivered real-time, synchronized interactions consistently across diverse network conditions. Average end-to-end latency across test scenarios was typically maintained below 100 milliseconds, indicating a high degree of responsiveness suitable for immersive multiplayer AR interactions. However, peak latency occasionally reached approximately 200 milliseconds under conditions simulating network congestion or suboptimal connectivity, resulting in perceptible but minor interaction delays for participants.

Significantly, Photon Fusion 2's predictive algorithms and interpolation techniques proved highly effective in mitigating latency effects, providing smooth visual continuity despite occasional network fluctuations. User observations and feedback correlated positively with measured latency data, with participants rarely noting noticeable disruptions or interaction discrepancies, except under the most extreme simulated network conditions[10].

These findings collectively confirmed the technical feasibility and effectiveness of the application's underlying server infrastructure and latency management strategies. Moreover, identified areas of potential improvement, such as further optimizing data packet transmission strategies and refining predictive latency compensation, provide clear guidance for enhancing future scalability and responsiveness.

5.2.2 Identifying bottlenecks in data synchronization

Effective data synchronization forms the backbone of any multiplayer AR application, directly influencing real-time responsiveness and overall user experience. In evaluating the technical performance of *Strings of Life*, particular attention was dedicated to identifying and analyzing specific bottlenecks that could compromise synchronization effectiveness.

A comprehensive analysis of synchronization logs, collected during intensive multiplayer testing sessions, revealed several critical areas affecting synchronization efficiency:

- **Network Variability and Latency Fluctuations:** One significant bottleneck emerged from inconsistent network conditions experienced by participants, leading to intermittent latency spikes. Detailed analysis of data packets showed that these latency variations occasionally caused delays in state updates, resulting in temporary desynchronization of interactive elements.
- **Server Processing Overheads:** Another notable synchronization bottleneck was related to server-side processing demands during peak concurrent user loads. Although Photon Fusion 2 managed server performance effectively in most scenarios, extensive computational loads associated with frequent physics calculations and state validations sometimes led to increased synchronization intervals and marginal delays.
- **Spatial Anchoring Drift:** A more subtle synchronization challenge was identified in spatial anchoring drift occurring over prolonged interaction periods. Despite initial effective anchoring through Unity's AR Foundation, certain device sensors occasionally exhibited cumulative drift, creating minor but noticeable positional

discrepancies among synchronized objects, especially in extended multiplayer sessions.

- **Inefficient Data Packet Management:** Further analysis pinpointed inefficiencies in managing data packet sizes and frequencies. Excessively large state updates in specific interaction scenarios occasionally overwhelmed network bandwidth, exacerbating latency issues and temporarily degrading synchronization quality.

Following identification, targeted recommendations were proposed to address these bottlenecks. Suggested improvements included implementing more adaptive network transmission protocols, refining server load balancing algorithms, enhancing predictive synchronization and interpolation techniques, and optimizing spatial anchoring recalibration strategies. These recommendations provided actionable insights for subsequent development cycles, significantly contributing to improving synchronization efficiency and multiplayer responsiveness.

5.3 Insights from User Feedback

5.3.1 Common challenges and areas for improvement

Collecting and analyzing user feedback during the development and testing phases provided valuable insights into several common challenges faced by participants, highlighting specific areas for improvement within the *Strings of Life* multiplayer AR application. Qualitative data gathered through structured interviews, surveys, and observational sessions revealed recurring themes related to user interactions, multiplayer dynamics, and overall immersion.

One frequent issue identified was **initial usability and clarity of instructions**. Many users, particularly those less familiar with XR technologies, encountered difficulty understanding initial interactions and puzzle mechanics. Participants often suggested clearer onboarding processes, including brief interactive tutorials or visually guided instructions, to enhance early-stage usability and reduce frustration.

Another recurring challenge related directly to **synchronization inconsistencies** during network fluctuations. Although overall synchronization was praised, occasional latency spikes led to noticeable delays or momentary desynchronization, slightly diminishing the immersive quality. Users suggested enhancing network optimization strategies or incorporating more effective latency compensation methods to sustain consistently smooth interactions.

Participants also indicated occasional difficulty with **complex interactions and puzzle logic**. Certain collaborative puzzles, while engaging, were perceived as overly complex or unintuitive, occasionally disrupting narrative flow and leading to reduced immersion. To mitigate this, users recommended simplifying puzzle structures, providing clearer hints, or integrating adaptive difficulty adjustments based on real-time user performance.

Feedback further revealed users' desire for enhanced **visual and audio feedback mechanisms**. Participants expressed that improved audiovisual cues—such as clear feedback on completed tasks, puzzle progress indicators, or ambient sound enhancements—could significantly enrich their interactive experience and bolster narrative immersion.

Lastly, users emphasized the importance of consistent **device compatibility and graphical optimization**. Some participants using lower-end devices experienced minor performance drops, including reduced frame rates or occasional graphical glitches. Targeted optimization strategies, particularly dynamic rendering adjustments and adaptive graphical fidelity, were suggested as potential solutions to ensure universally consistent performance.

Addressing these identified challenges provides clear directions for iterative enhancements, ensuring future iterations of the application continue evolving toward higher levels of usability, synchronization robustness, puzzle clarity, audiovisual immersion, and universal device compatibility.

5.3.2 User satisfaction with AR multiplayer features

Evaluating user satisfaction was a fundamental aspect of understanding how effectively the multiplayer features within the *Strings of Life* AR application resonated with participants. This subsection presents a detailed analysis of user satisfaction based on structured feedback surveys, observational insights, and qualitative interviews conducted post-interaction, focusing on critical features such as synchronization reliability, collaborative gameplay mechanics, narrative integration, and overall multiplayer engagement.

Overall, user satisfaction with the multiplayer features was predominantly positive. Analysis of quantitative survey responses indicated high average ratings on a Likert scale (1-5) for satisfaction-related metrics such as interaction enjoyment (mean = 4.2), perceived responsiveness (mean = 4.0), and willingness to recommend the experience to others (mean = 4.3). These numerical indicators suggested that the implemented multiplayer features significantly contributed to user enjoyment and overall positive attitudes towards the application.

Qualitative insights from participant interviews further reinforced these findings, highlighting several key factors contributing to high satisfaction levels. Firstly, users frequently praised the **collaborative gameplay dynamics**, specifically the design of puzzles and tasks that required teamwork and mutual coordination. Participants reported that these interactions facilitated meaningful social engagement, resulting in enhanced enjoyment and deeper immersion. Several participants explicitly noted that working collaboratively in an augmented space was not only engaging but also heightened their sense of presence within the narrative context.

The application's **synchronization performance** emerged as another essential factor significantly impacting user satisfaction. Despite occasional reports of minor synchronization delays under challenging network conditions, the majority of participants consistently highlighted the effectiveness of Photon Fusion 2's synchronization strategies. Users appreciated the perceived real-time responsiveness, noting that interactions felt natural and seamless, significantly boosting their overall experience. Participants reported that effective synchronization contributed substantially to their sense of connectedness with other players, thereby positively influencing satisfaction and immersion.

The integration of **immersive narrative elements** within multiplayer interactions was also a notable contributor to high satisfaction ratings. Users indicated a strong appreciation for the narrative-driven approach, where multiplayer tasks were thoughtfully intertwined with story progression. This combination was particularly effective in maintaining user engagement, with users frequently reporting increased emotional investment and narrative immersion due to collaborative storytelling mechanisms. Participants remarked that shared narrative discovery created memorable interactive moments, thereby enhancing the overall value of the multiplayer experience.

However, despite generally high satisfaction ratings, user feedback identified some areas where satisfaction could be further enhanced. For instance, users highlighted occasional difficulties arising from initial user interface clarity, as previously discussed, indicating room for improvement in providing clearer interaction guidance. Users also suggested more robust audiovisual feedback during multiplayer tasks to strengthen communication and enhance task completion awareness.

Lastly, device compatibility and graphical performance consistency were raised as secondary but notable factors influencing user satisfaction. While most users experienced smooth performance, a minority encountered minor graphical lag or reduced frame rates, especially on lower-end mobile devices. These experiences slightly diminished their overall satisfaction. Users recommended optimizing graphical assets further and dynamically adjusting visual fidelity to maintain uniform performance across diverse hardware specifications.

In summary, detailed analysis of user feedback revealed high overall satisfaction with the *Strings of Life* multiplayer AR features, particularly emphasizing the effectiveness of collaborative gameplay design, reliable synchronization strategies, and narrative integration. Identified opportunities for improvement in interface clarity, audiovisual feedback mechanisms, and device-specific optimizations provide clear directions for future iterative enhancements, aiming to further elevate user satisfaction and immersive quality in subsequent application versions.

5.4 Discussion on Adoption Barriers

5.4.1 Technical and psychological barriers to adoption

Understanding and mitigating barriers to user adoption is crucial for the successful implementation of innovative technologies such as multiplayer AR experiences. Within the context of the *Strings of Life* project, several significant technical and psychological barriers emerged through both structured testing and qualitative user feedback. This subsection critically discusses these barriers, providing insights into their nature and implications for broader adoption.

Technical Barriers

Technical challenges form a primary barrier influencing user adoption, particularly regarding network reliability, hardware compatibility, and synchronization consistency.

One significant barrier identified was the variability in network performance and its direct impact on user experience. Although Photon Fusion 2 provided robust synchronization capabilities, variations in user network connectivity occasionally resulted in latency issues, momentary desynchronization, or delayed interaction responses. These technical inconsistencies, even if infrequent, contributed to user hesitation or frustration, especially among users unfamiliar with the complexities inherent to XR systems.

Device compatibility posed another crucial technical barrier. Participants utilizing lower-end or older devices occasionally encountered suboptimal performance, including graphical delays, reduced frame rates, and diminished interactive responsiveness. These performance discrepancies notably impacted the perception of reliability and overall satisfaction, highlighting the need for targeted optimization and adaptive graphical fidelity strategies to accommodate a broader spectrum of device capabilities. Addressing these compatibility challenges is critical to ensuring widespread accessibility and sustained user engagement.

Moreover, spatial drift and anchoring inaccuracies were identified as subtle yet impactful technical issues, particularly during extended multiplayer sessions. While the cloud-based anchoring system initially maintained consistent spatial synchronization, cumulative drift observed over longer interactions occasionally led to positional inconsistencies, thereby compromising immersion and interaction accuracy. This challenge underscored the necessity for robust spatial anchoring recalibration mechanisms, ensuring sustained spatial accuracy throughout prolonged experiences.

Psychological Barriers

Beyond technical challenges, psychological factors significantly influenced user willingness to adopt and consistently engage with multiplayer AR experiences. One prominent psychological barrier involved initial user apprehension and uncertainty, particularly among users with limited familiarity or previous exposure to XR technologies. Participants often reported initial hesitancy, driven by perceived complexity and usability concerns, suggesting the importance of carefully structured onboarding and clear introductory tutorials to effectively mitigate early-stage anxiety and enhance user confidence.

Additionally, participants expressed concerns related to social presence and collaborative interaction anxiety, particularly when collaborating with unfamiliar participants. Despite generally positive feedback regarding collaborative gameplay, some users highlighted discomfort in initiating or actively participating in multiplayer tasks, fearing potential judgment or performance inadequacies perceived by peers. This psychological barrier underscores the need for designing supportive and inclusive multiplayer interactions, possibly incorporating structured roles or clearly defined collaboration protocols to ease social anxiety.

Cognitive overload was another psychological barrier observed during complex multiplayer tasks requiring simultaneous attention to narrative progression, interactive puzzles, and real-time collaboration. Users occasionally reported experiencing mental fatigue, leading to decreased task effectiveness and reduced narrative immersion. Simplifying task designs, implementing clear cognitive guidance through visual or auditory feedback, and balancing narrative complexity with user cognitive capabilities emerged as critical strategies for reducing cognitive overload and improving sustained engagement.

Lastly, perceptions of privacy and data security emerged as subtle yet significant psychological concerns, particularly among participants less accustomed to networked interactive experiences. Users indicated uncertainty regarding the handling and security of their data within multiplayer network environments, potentially reducing willingness to engage deeply or repeatedly with the application. Transparency in data handling practices and robust assurances of privacy protection were identified as vital factors in mitigating this psychological barrier and encouraging confident user adoption.

By comprehensively addressing both technical and psychological barriers identified during testing and feedback, future iterations of the *Strings of Life* application—and similar multiplayer AR systems—can be significantly refined. Strategically tackling these barriers through targeted technical improvements, user-centered design practices, enhanced onboarding processes, and psychological considerations can substantially increase adoption potential and promote long-term user satisfaction and engagement.

5.4.2 Recommendations for addressing these barriers

Based on the identified technical and psychological barriers highlighted in the previous subsection, several actionable recommendations are proposed to systematically address and mitigate these challenges. These recommendations emphasize both technological enhancements and user-centered psychological strategies, ensuring broad user adoption, sustained engagement, and overall improvement of the multiplayer AR experience.

Recommendations for Technical Barriers

To address the critical technical barriers, the following detailed recommendations are proposed:

1. **Optimizing Network Efficiency and Stability:**
   - Implement adaptive network protocols designed to dynamically manage data transmission, especially during periods of reduced connectivity or high latency. Techniques such as dynamic delta compression, adjustable synchronization rates based on real-time latency conditions, and automated packet prioritization can significantly improve network resilience.
   - Enhance predictive synchronization algorithms provided by Photon Fusion 2, refining interpolation and rollback mechanisms. Increasing the sophistication and accuracy of predictive algorithms can effectively mask latency issues, providing a seamless user experience despite varying network conditions.
   - Introduce regular network performance monitoring with automated diagnostic tools to proactively identify and resolve network bottlenecks or disruptions before they impact user experience.
2. **Enhanced Device Compatibility and Performance:**
   - Implement scalable rendering solutions that automatically adjust graphical quality, model complexity, and visual effects based on real-time device performance metrics. Utilizing Unity's URP more extensively, combined with adaptive LOD management, can ensure consistent performance across devices with varying hardware capabilities.
   - Conduct thorough optimization cycles targeting lower-end mobile devices, specifically focusing on asset compression, shader simplification, and efficient memory management. Regularly profiling application performance across diverse hardware platforms can inform targeted optimization strategies.
   - Offer explicit user settings for manual adjustment of graphical quality, allowing participants with less powerful hardware to prioritize performance stability over graphical fidelity, thereby improving accessibility and user satisfaction.
3. **Improving Spatial Anchoring and Drift Management:**

- Incorporate periodic automated recalibration techniques for spatial anchors, specifically utilizing data from multiple users to dynamically correct positional inaccuracies during prolonged sessions. Leveraging advanced sensor fusion algorithms can minimize cumulative drift effectively.
- Integrate user-driven recalibration options within the application interface, enabling manual anchor realignment when users identify noticeable drift. This approach empowers users and maintains high spatial accuracy over extended interaction periods.
- Regularly update and refine cloud-based spatial anchoring frameworks, ensuring alignment with advancements in Unity's AR Foundation, ARKit, and ARCore, thus continuously enhancing spatial synchronization performance.

Recommendations for Psychological Barriers

Addressing psychological barriers necessitates thoughtful design considerations and user-centric approaches, detailed as follows:

1. **Improving Initial Onboarding and Usability:**
   - Develop interactive onboarding tutorials to guide users step-by-step through initial interactions, clearly demonstrating essential multiplayer functionalities and narrative elements. Employing gradual onboarding experiences reduces initial user anxiety, enhances confidence, and promotes immediate immersion.
   - Integrate context-sensitive visual and audio guidance systems within the application to dynamically assist users encountering difficulties, ensuring immediate support during complex tasks or when confusion arises.
   - Conduct regular usability testing sessions focused explicitly on first-time users to identify and rectify common usability pain points, further streamlining the introductory user experience.
2. **Reducing Collaborative Interaction Anxiety:**
   - Incorporate structured collaboration mechanics, such as clearly defined roles or rotating leadership responsibilities, facilitating smoother and more equitable social interactions. Structured tasks can help mitigate social anxiety by providing clear expectations and reducing uncertainty within team dynamics.
   - Design inclusive collaborative environments by providing supportive communication tools or built-in social cues encouraging cooperative and positive in-

teractions. Visual and auditory feedback acknowledging collaborative success can reinforce positive group dynamics and user confidence.

   - Offer optional private multiplayer modes or smaller group interactions for participants who prefer less exposure initially, gradually transitioning users to larger, more open multiplayer engagements as comfort and confidence grow.

3. **Mitigating Cognitive Overload:**
   - Simplify complex interactive tasks by breaking them into manageable subtasks, clearly sequencing activities to reduce simultaneous cognitive demands. Employing progressive disclosure techniques where users gradually unlock more complex tasks can effectively control cognitive load.
   - Enhance the effectiveness of audiovisual feedback systems, providing clear and concise guidance during interactive tasks. Well-designed feedback mechanisms can substantially reduce cognitive fatigue, keeping users engaged without overwhelming their attention capacities.
   - Regularly evaluate the complexity of narrative and interactive elements through user testing sessions, proactively adjusting content based on participant cognitive load feedback to maintain an optimal balance between narrative depth and interaction simplicity.

4. **Enhancing Trust through Privacy Transparency:**
   - Clearly communicate data handling and privacy practices within the application interface, explicitly detailing how user data is collected, stored, and protected. Transparency can significantly reduce user concerns regarding data security, fostering trust and sustained engagement.
   - Provide users with clear and easy-to-access privacy settings, allowing them to customize their data-sharing preferences and offering reassurances of control over their personal information.
   - Regularly reinforce privacy commitments through in-app notifications or user guides, emphasizing the security measures employed and the ethical standards maintained, further reassuring users and promoting confidence in engaging fully with multiplayer features.

By systematically applying these detailed recommendations to both technical and psychological barriers, subsequent iterations of the *Strings of Life* application will be strategically positioned to achieve greater user adoption, enhanced satisfaction, and sustained engagement. Implementing these comprehensive measures directly addresses critical user concerns, effectively transforming identified barriers into opportunities for deeper and more meaningful interactive experiences.

This chapter provided an in-depth analysis and critical examination of empirical findings gathered through comprehensive user testing, performance evaluations, and structured feedback of the *Strings of Life* multiplayer AR application. Detailed analyses highlighted strengths in collaborative interaction dynamics, synchronization effectiveness, and narrative integration, contributing positively to user satisfaction and immersive experiences. Conversely, critical examination of user feedback and technical performance metrics identified significant technical and psychological barriers influencing adoption and ongoing user engagement. Strategic recommendations were proposed to systematically address these barriers, emphasizing network optimization, enhanced compatibility, improved onboarding, structured collaboration protocols, cognitive load management, and transparent privacy practices. Collectively, these insights and recommendations provide a robust foundation for refining future iterations of the application, optimizing user satisfaction, and promoting broader adoption. Building upon these comprehensive evaluations, the final chapter discusses overarching conclusions, research implications, and suggests opportunities for future research and development in the field of multiplayer XR experiences.

Chapter 6

Conclusion and Future Work

This final chapter summarizes the key research findings, insights, and contributions derived from exploring multiplayer interactivity within XR applications, specifically through the development of the *Strings of Life* multiplayer experience using Unity and Photon Fusion 2. The primary objectives of this research were to investigate the technical feasibility, user acceptance, and immersive potential of real-time synchronized interactions in multiplayer AR environments, contextualized within a culturally meaningful narrative.

Throughout this thesis, a structured methodological approach was employed, combining extensive literature review, systematic development processes, iterative testing, and rigorous data collection. Empirical findings presented in the preceding chapters confirmed the effectiveness of the developed technical solutions, notably demonstrating robust real-time synchronization, meaningful collaborative interactions, and strong user immersion driven by narrative integration. Simultaneously, careful analysis revealed significant insights into user interaction patterns, technical performance, barriers to adoption, and areas for improvement, offering detailed recommendations to enhance both technical reliability and user experience in future applications.

In this concluding chapter, the research outcomes are critically evaluated to highlight their contributions to existing knowledge in multiplayer XR technologies, their practical implications for developers and cultural institutions, and their broader significance within the context of interactive digital experiences. The chapter concludes by identifying limitations encountered during the study and recommending directions for future research, emphasizing opportunities to further advance multiplayer synchronization, interaction design, and immersive storytelling within the evolving landscape of XR technologies.

6.1 Summary of Findings

This section provides a comprehensive summary of the significant findings derived from this research, clearly delineating empirical insights and analytical results across multiple dimensions of the developed multiplayer AR application. To present these findings effectively, this summary distinguishes clearly between technical performance outcomes, user interaction insights, user feedback evaluations, and identified barriers, reflecting the structured methodological approach adopted throughout this thesis.

Technical Performance Outcomes

1. **Synchronization Efficiency and Stability:**
   - Photon Fusion 2 demonstrated robust synchronization performance, maintaining consistent and reliable multiplayer interactions under normal network conditions. Quantitative measurements indicated average latency consistently below 100 milliseconds, ensuring responsive and engaging user experiences.
   - However, under conditions of increased network congestion or intermittent connectivity, latency occasionally peaked up to approximately 200 milliseconds, briefly impacting real-time responsiveness. Despite these fluctuations, predictive algorithms effectively minimized perceptible disruptions.
2. **Server Load and Scalability:**
   - Evaluations confirmed Photon Cloud servers successfully managed performance at the targeted capacity of 50 concurrent users, with server CPU utilization typically remaining below 75%. This indicates substantial scalability and reliability under intended operational conditions.
   - Server-side processing demands, especially for physics computations and synchronization validation, occasionally emerged as potential bottlenecks during high-load scenarios, highlighting the need for further optimization to enhance scalability margins.
3. **Device Compatibility and Performance Consistency:**

- While performance on mid-to-high-end devices was consistently smooth, users with lower-end hardware occasionally reported reduced frame rates and minor graphical inconsistencies. Adaptive rendering solutions and further asset optimizations were recommended to improve universal performance reliability.
- Spatial anchoring demonstrated initial effectiveness; however, prolonged sessions revealed minor spatial drift issues. Enhancements in spatial recalibration methodologies were suggested to address these cumulative discrepancies effectively.

Insights from User Interaction Analysis

1. **Collaborative Interaction Patterns:**
   - Users exhibited strong collaborative behaviors, organically assuming distinct roles within teams during multiplayer tasks. Tasks requiring coordinated efforts showed deeper user engagement and significantly longer interaction durations, reinforcing the design principles emphasizing teamwork.
   - Conversely, interactions initially perceived as overly complex or unclear triggered occasional confusion and reduced interaction effectiveness, underscoring the need for clearer guidance and more intuitive design mechanisms.
2. **User Interface and Usability Insights:**
   - Initial usability emerged as a prominent concern for less experienced users, who occasionally struggled with onboarding and understanding interactive mechanics. User feedback consistently emphasized the value of clear, intuitive visual cues, interactive tutorials, and simplified interface designs to reduce initial barriers.

User Feedback and Satisfaction Evaluations

1. **Overall Satisfaction with Multiplayer Features:**
   - Quantitative feedback consistently reflected high satisfaction rates, with average ratings around 4.2 to 4.3 on a 5-point Likert scale. Users particularly praised the application's multiplayer synchronization quality, narrative integration, and collaborative gameplay design.

- Qualitative interviews confirmed these positive sentiments, highlighting the emotional connection fostered through narrative-driven collaboration, significantly enhancing immersion and perceived social interaction quality.

2. **Opportunities for Further Enhancement:**
   - Despite generally positive feedback, users identified several areas for potential improvement, notably clearer audiovisual feedback mechanisms during multiplayer interactions, further optimization of device compatibility, and improvements to onboarding procedures.

Identified Barriers to Adoption

1. **Technical Barriers:**
   - Primary technical barriers included network latency variability, server processing overhead during peak loads, device-specific performance inconsistencies, and spatial anchoring drift during extended sessions. Addressing these challenges through targeted optimizations was recommended to enhance reliability and user confidence.

2. **Psychological Barriers:**
   - Users frequently expressed initial apprehension towards unfamiliar XR technologies, collaborative interaction anxiety, cognitive overload during complex tasks, and concerns regarding data privacy. Recommendations emphasized structured onboarding, clear collaborative protocols, simplified interaction mechanics, and transparent privacy practices to effectively address these psychological factors.

The comprehensive findings summarized here clearly indicate the effectiveness and limitations of the developed multiplayer AR application, reflecting the detailed analysis undertaken throughout this research. These findings contribute significantly to understanding both the technical feasibility and user-centered design considerations required for successful multiplayer XR implementations. The subsequent section provides critical reflections on the research outcomes, discusses implications, acknowledges research limitations, and suggests future directions for continued innovation in this evolving field.

6.1.1 Key takeaways from technical and user experience perspectives

Synthesizing the extensive analyses conducted throughout this research, several key takeaways emerge distinctly from both technical performance and user experience perspectives. These takeaways encapsulate fundamental lessons and provide actionable insights to guide future development and research endeavors in multiplayer AR experiences.

Technical Performance Perspectives:

1. **Effective Real-Time Synchronization:**
   - Photon Fusion 2's implementation demonstrated notable efficiency and effectiveness in maintaining real-time synchronization across multiple concurrent users. Robust synchronization capabilities significantly enhanced the user experience, supporting reliable interactions and consistent visual coherence even under varying network conditions.
   - Predictive rollback and interpolation mechanisms proved critical, effectively masking latency issues. Future applications should prioritize advanced predictive synchronization strategies as standard practices for delivering seamless real-time multiplayer interactions.
2. **Scalability and Server Reliability:**
   - Photon Cloud servers effectively handled peak loads, maintaining stable performance at the targeted capacity of 50 simultaneous users, with server CPU utilization typically below threshold limits. The authoritative server model provided a dependable foundation, highlighting its suitability for scaling multiplayer XR applications.
   - However, identified processing bottlenecks during computationally intensive tasks indicated the importance of continued server-side optimizations, particularly in applications involving real-time physics interactions or extensive concurrent user interactions.
3. **Device Compatibility and Adaptive Optimization:**
   - Device-specific performance variability emerged as a critical consideration. Implementing adaptive graphical rendering solutions such as dynamic asset

management, scalable visual fidelity, and effective use of Unity's URP and LOD proved essential in achieving broad device compatibility.

– Regular and thorough performance profiling across a diverse hardware spectrum should become standard practice to ensure equitable user experiences, regardless of device capabilities.

User Experience Perspectives:

1. **Collaborative Interaction as a Core Engagement Driver:**
   – Users strongly valued collaborative elements, expressing high satisfaction with tasks explicitly designed for multiplayer coordination. The interaction dynamics observed, such as natural role differentiation and mutual support among participants, significantly increased engagement and narrative immersion.
   – Designing clear and intuitive collaborative tasks that explicitly require teamwork is recommended to maximize social engagement and enrich user experiences in future multiplayer AR applications.
2. **Importance of Clear Onboarding and Interaction Clarity:**
   – Initial usability emerged as a critical determinant of user experience quality, particularly among users with limited prior XR experience. Participants frequently cited clear visual guidance, interactive tutorials, and straightforward user interfaces as essential components for reducing initial confusion and promoting immediate engagement.
   – Future development should incorporate structured onboarding mechanisms, context-sensitive help, and simplified interaction designs to effectively address user uncertainties and improve initial user confidence and satisfaction.
3. **Immersive Narrative Integration:**
   – Integrating compelling narrative elements directly within multiplayer interactions greatly enhanced user immersion and emotional engagement. Users consistently reported increased emotional investment and deeper immersion when narrative tasks seamlessly aligned with interactive gameplay mechanics.
   – Emphasizing narrative coherence and immersive storytelling in multiplayer interactions is recommended, fostering deeper emotional connections and sustained engagement.

4. **Psychological Considerations in Multiplayer Contexts:**
   - Users highlighted psychological barriers, including collaborative anxiety, cognitive overload, and privacy concerns. Proactively addressing these barriers through structured collaboration protocols, clear cognitive guidance, and transparent privacy practices significantly influences user willingness to engage fully and repeatedly with multiplayer XR experiences.
   - Prioritizing psychological safety and user-centered design considerations enhances user comfort and fosters sustained interaction in multiplayer environments.

In summary, these key takeaways distinctly emphasize the necessity of aligning technical robustness with thoughtful user-centered design approaches. Successfully integrating reliable synchronization technologies, scalable infrastructure solutions, adaptive optimization strategies, and immersive narrative elements, coupled with addressing psychological and usability factors, will significantly enhance future multiplayer XR experiences. These insights provide practical and strategic guidance for both academic researchers and industry developers, laying a strong foundation for continued innovation in this evolving technological domain.

6.2 Implications for XR Development

The findings and insights generated through this research provide valuable implications for the broader field of XR development, particularly in the context of multiplayer interactivity and immersive narrative-driven applications. These implications span technical, design-related, and methodological dimensions, offering strategic guidance and highlighting essential considerations for both researchers and developers in the evolving XR landscape.

Technical and Infrastructure Implications:

- The demonstrated effectiveness of Photon Fusion 2 underscores the importance of sophisticated synchronization frameworks in achieving reliable real-time multiplayer interactions within AR environments. The capability to manage latency fluctuations and support robust predictive synchronization mechanisms should be prioritized in the design of future multiplayer XR experiences.

- Scalability emerges as a crucial consideration, highlighting the necessity of authoritative server architectures and cloud-based solutions, such as Photon Cloud, to reliably support increased concurrent user capacities. Future developments should focus on rigorous scalability testing and continuous optimization, particularly in computationally intensive applications.
- Device compatibility challenges identified in this study emphasize the need for adaptive rendering strategies and scalable graphical performance. Prioritizing solutions such as Unity's URP, dynamic LOD management, and comprehensive device performance profiling is essential for ensuring inclusive access and consistent user experiences across diverse hardware capabilities.
- Spatial anchoring technologies, crucial for environmental consistency, must incorporate dynamic recalibration mechanisms to address cumulative drift effectively. Robust anchoring solutions integrated with advanced sensor fusion algorithms will be increasingly critical for ensuring sustained spatial accuracy in shared augmented spaces.

Design and User Experience Implications:

- Collaborative interactions significantly contribute to user immersion and engagement. Designing explicitly for multiplayer coordination and clearly defined teamwork-oriented tasks should become a standard practice in the development of future multiplayer XR experiences, effectively leveraging the inherently social dimensions of these technologies.
- User onboarding emerges as a critical determinant of initial user experience quality and subsequent engagement. Developers should systematically integrate clear, interactive onboarding mechanisms, context-sensitive guidance, and intuitive interfaces to significantly reduce initial user hesitation, thus promoting immediate and sustained engagement.
- Effective narrative integration within multiplayer contexts has proven highly impactful in enhancing user immersion and emotional investment. Future XR experiences should consistently emphasize storytelling coherence and thoughtfully align interactive gameplay mechanics with narrative elements, capitalizing on their combined immersive potential.

- Psychological considerations, including collaborative anxiety, cognitive overload, and privacy concerns, require explicit attention during the design process. Proactive measures, such as structured collaborative roles, adaptive cognitive load management, and transparent privacy communication, should be strategically implemented to foster psychological comfort, trust, and long-term engagement.

Methodological Implications for XR Research:

- This research emphasizes the value of employing mixed-method approaches, combining quantitative performance metrics with qualitative user insights. Future XR research initiatives should adopt comprehensive methodologies integrating direct observational data, structured feedback surveys, and in-depth qualitative evaluations to gain nuanced understandings of user behavior and system performance.
- The iterative testing and feedback incorporation approach demonstrated in this thesis highlights the necessity of continuous user-centered design cycles in XR development. Iterative user testing not only validates technical performance but also ensures design and usability enhancements directly aligned with user preferences and expectations.
- Recognizing and systematically addressing adoption barriers during early development stages provides critical insights for optimizing user acceptance. Future research should explicitly identify, document, and strategically mitigate both technical and psychological barriers from initial conceptualization through iterative development cycles, significantly enhancing eventual user adoption and satisfaction.

In conclusion, the implications drawn from this research significantly contribute to understanding essential technical, design, and methodological factors influencing the success of multiplayer XR applications. Strategically incorporating these insights can enhance development processes, improve user experiences, and effectively overcome adoption barriers, thereby guiding future research and development efforts toward creating more robust, inclusive, and engaging multiplayer XR experiences.

6.2.1 How this project contributes to XR research

This research project contributes meaningfully to the field of multiplayer XR by bridging critical gaps in knowledge related to real-time synchronization, user interaction patterns, and immersive narrative integration. Specifically, the project demonstrates the practical feasibility and effectiveness of advanced networking solutions, such as Photon Fusion 2, in managing real-time, interactive multiplayer scenarios within AR environments. These findings offer concrete evidence supporting the scalability and responsiveness necessary for interactive, shared augmented experiences, setting a benchmark for future research and application development.

Moreover, the project's emphasis on systematic analysis of user interactions and collaborative dynamics contributes significant empirical insights into how users naturally engage in multiplayer AR contexts. By identifying core interaction patterns, usability preferences, and psychological considerations, this research provides actionable guidance for designing future applications that optimize user experience and foster sustained engagement.

Methodologically, the mixed-method approach combining quantitative performance metrics and qualitative user feedback employed in this study exemplifies best practices for comprehensive XR research. The iterative feedback cycles adopted throughout the development process highlight the importance of continuous user involvement, directly informing design improvements and technical optimizations.

Finally, this project sheds light on significant technical and psychological barriers influencing user adoption, offering clear recommendations for overcoming these challenges. These contributions collectively support the broader XR research community by providing a robust foundation of empirical evidence, user-centered insights, and practical guidelines, thereby facilitating continued advancement in multiplayer immersive technologies.

6.2.2 Potential impact on cultural and educational industries

The findings of this research carry significant implications for the cultural and educational sectors, particularly through the demonstrated potential of multiplayer AR to enhance user engagement and narrative immersion. The successful integration of historical and cultural storytelling elements, exemplified in the *Strings of Life* project, illustrates how immersive XR technologies can transform traditional modes of cultural storytelling and heritage presentation, actively engaging users in interactive, collaborative learning experiences.

In cultural institutions such as museums, galleries, and heritage sites, the demonstrated effectiveness of multiplayer interactions and real-time synchronization opens new avenues for participatory, interactive exhibits. These technologies can enable visitors to collaboratively explore, engage with, and internalize cultural narratives in innovative ways, significantly enhancing visitor experiences beyond passive observation.

Within educational contexts, the research outcomes highlight the value of collaborative AR applications as powerful tools for interactive and experiential learning. By promoting cooperative problem-solving and narrative engagement, such multiplayer experiences can foster deeper cognitive and emotional connections to educational content, thus improving learning outcomes and student motivation.

Ultimately, this project's implications suggest a transformative impact on how cultural and educational content is delivered and experienced, emphasizing interactivity, social collaboration, and immersive storytelling as core components of future digital experiences within these sectors.

6.3 Limitations of the Study

Despite achieving substantial outcomes and insights, this research inevitably encountered specific limitations, which must be acknowledged to contextualize the findings and implications accurately. The constraints faced during the development and evaluation phases primarily arose from technical complexities, methodological boundaries, and practical considerations related to user testing and real-world applicability.

In this section, these limitations are systematically discussed and categorized into two main areas. The first subsection addresses practical and technical challenges encountered during the development process, while the second subsection critically examines inherent limitations associated with utilizing Photon Fusion 2 and the Unity development platform. By transparently addressing these constraints, the study clearly delineates areas requiring further research, optimization, or methodological refinement, providing valuable guidance for future investigations and implementations in the domain of multiplayer XR experiences.

6.3.1 Challenges encountered during development

Throughout the development of the *Strings of Life* multiplayer AR application, several practical and technical challenges were encountered, directly influencing the scope, effectiveness, and outcomes of the project.

One significant challenge was managing the complexity of real-time synchronization across multiple devices, particularly given the variability of user networks. Ensuring consistent synchronization and responsive interaction demanded considerable iterative refinement, often requiring extensive troubleshooting and optimization efforts to address intermittent latency issues.

Another practical difficulty arose from balancing graphical fidelity and performance across diverse user hardware. Despite employing adaptive graphical strategies, discrepancies in device performance posed ongoing challenges, highlighting the inherent difficulty of universally optimizing an application for a broad hardware spectrum.

Furthermore, maintaining accurate spatial anchoring and preventing cumulative positional drift in extended multiplayer sessions proved technically demanding. Despite leveraging cloud-based spatial anchors and advanced sensor algorithms, minor drift over prolonged usage required continuous recalibration and refinement.

Lastly, logistical challenges related to iterative user testing, including coordinating multiple concurrent users for simultaneous testing sessions, presented practical constraints. These logistical difficulties occasionally limited the frequency and extent of user evaluations, impacting the depth and consistency of user feedback available for iterative development.

Acknowledging these developmental challenges provides critical context for interpreting research outcomes and underscores important considerations for future XR application development projects.

6.3.2 Limitations of Photon Fusion 2 and Unity

Although Photon Fusion 2 and the Unity engine proved effective tools in the development of the *Strings of Life* multiplayer AR application, certain inherent limitations of these platforms influenced the project's execution and outcomes.

Photon Fusion 2, while powerful in handling real-time synchronization and networking, demonstrated occasional constraints under highly dynamic or computationally intensive scenarios. Specifically, extensive physics calculations and complex real-time interactions occasionally resulted in increased server processing loads, leading to potential synchronization latency. Additionally, despite advanced predictive rollback capabilities, Fusion's ability to manage severe network fluctuations or high-latency environments remained limited, occasionally impacting user interaction fluidity.

The Unity platform also presented particular limitations. While Unity's AR Foundation provided robust cross-platform compatibility, subtle inconsistencies persisted between ARKit and ARCore, notably in spatial anchoring precision and environmental mapping accuracy. These discrepancies required significant additional calibration and troubleshooting efforts to achieve consistent user experiences across both iOS and Android devices.

Furthermore, Unity's graphical performance optimization, although significantly enhanced by the URP, was challenged by the vast range of mobile hardware capabilities. Achieving uniformly optimized graphical performance across diverse hardware specifications required ongoing iterative adjustments, reflecting inherent constraints within Unity's rendering architecture.

Recognizing these platform-specific limitations is essential for future development, guiding more informed platform selection, realistic project scoping, and targeted optimization strategies for multiplayer XR applications.

6.4 Recommendations for Future Research

Building upon the insights and limitations identified in this study, several promising avenues for future research emerge within the domain of multiplayer AR and broader XR technologies. The subsequent subsections will address opportunities to expand the application scope of multiplayer AR, as well as potential improvements in networking efficiency and scalability. Exploring these areas can further advance the technical robustness, user experience quality, and overall effectiveness of future immersive, collaborative XR solutions, enriching their real-world applicability and impact.

6.4.1 Expanding the scope of AR multiplayer applications

Future research in multiplayer AR should explore broader and more diverse application domains to fully realize the potential of this technology. While the current study effectively demonstrates applications within a cultural and narrative-driven context, opportunities exist to extend multiplayer AR into new sectors such as healthcare, education, corporate training, and tourism.

In healthcare, multiplayer AR applications could facilitate collaborative diagnostics, remote patient consultations, and interactive medical training simulations. Educational sectors could benefit significantly from cooperative learning environments, enabling interactive, immersive educational experiences that enhance cognitive engagement and learning retention.

Corporate and industrial training scenarios present opportunities for complex task simulations and real-time collaborative training, improving skill transfer and workplace safety through immersive interactions. Additionally, the tourism industry could leverage multiplayer AR to create shared interactive sightseeing experiences, providing enriched narrative storytelling and collective exploration of heritage locations.

Future research should focus on systematic evaluations within these diverse contexts, emphasizing user experience, technical feasibility, and the practical integration of multiplayer features to further validate and refine the broader applicability of AR multiplayer solutions.

6.4.2 Potential improvements in networking and scalability

The findings from this study emphasize that while current networking solutions like Photon Fusion 2 have significantly advanced multiplayer AR applications, considerable opportunities remain for further improvement in networking performance, synchronization reliability, and scalability. Addressing these opportunities in future research will be essential to support larger user groups, ensure seamless real-time interactions, and enhance overall application stability and user experience quality.

Firstly, future research should investigate advanced adaptive network management protocols capable of dynamically adjusting synchronization and data transmission methods based on real-time network conditions. Developing and refining predictive latency compensation algorithms, network-adaptive interpolation, and rollback techniques will further mitigate the effects of latency variations, enhancing responsiveness and ensuring consistently high-quality multiplayer interactions across diverse network environments.

Secondly, scalability remains a critical area requiring further exploration. Current authoritative server models effectively support moderate-scale applications; however, scaling these solutions to hundreds or even thousands of concurrent users will necessitate innovative approaches. Future studies could explore hybrid server architectures, distributed edge computing solutions, and cloud-based load balancing technologies to significantly enhance scalability while maintaining interaction quality and synchronization accuracy.

Additionally, research into more efficient server-side processing techniques—particularly those managing physics interactions, environmental states, and complex user behaviors—is crucial. Techniques such as parallelized server computations, GPU-accelerated state calculations, and intelligent state management algorithms could substantially reduce processing overhead, enabling more sophisticated real-time multiplayer scenarios without compromising performance.

Finally, advancing spatial anchoring accuracy and drift management techniques represents another key research direction. Emerging technologies integrating *Artificial Intelligence* (AI)-driven recalibration algorithms, enhanced sensor fusion methodologies, and cross-device synchronization innovations should be explored to achieve even higher spatial consistency, especially over prolonged sessions and complex physical environments.

Closing Remarks:

In conclusion, this research contributes a significant step forward in understanding and effectively implementing multiplayer interactivity within XR environments. By systematically investigating technical feasibility, synchronization strategies, collaborative interaction design, and immersive narrative integration, the study has demonstrated both the substantial potential and current limitations of multiplayer AR applications. The detailed analyses, user insights, and practical recommendations provided throughout this thesis offer a robust foundation for future innovation, highlighting essential considerations for overcoming existing technical and psychological barriers to adoption.

As the fields of augmented and extended reality continue evolving, addressing the outlined networking, scalability, and usability challenges will be critical in shaping the next generation of interactive and collaborative digital experiences. Through continued interdisciplinary collaboration, methodological rigor, and user-centered design, future research will undoubtedly unlock further potential in multiplayer XR, driving meaningful impacts across diverse industries and significantly enriching human interaction with digital environments.

Acronyms

NPS *Net Promoter Score*

VR *Virtual Reality*

AR *Augmented Reality*

UX *User Experience*

UI *User Interface*

MR *Mixed Reality*

GPU *Graphical Processing Unit*

XR *Extended Reality*

Lidar *Light Detection and Ranging*

AI *Artificial Intelligence*

URP *Universal Render Pipeline*

SDK *Software Development Kit*

ARKit Augmented Reality Kit

ARCore Augmented Reality Core

LOD Level of Detail

CPU Central Processing Unit

GPU Graphics Processing Unit

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