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Distributed Computing Paradigms for Optimization of Mixed Reality Applications in Digital Culture

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Abstract

Given the wide proliferation of immersive applications nowadays, such as Mixed Reality (MR), broad research is continuously being conducted on their applicability and impact on Digital Culture. Still, most of these applications are time-constrained, requiring heavy computation in order to keep track of the engaged users' navigation and orientation, and in parallel generate high-quality three-dimensional (3D) graphics that are perfectly mapped to their surroundings, a fact that is not easily attainable through standard mobile devices. These issues are exceedingly difficult to address when considering large-scale Cultural Heritage environments, where numerous users are present at any given moment, resulting in fluctuating network conditions and service demands. Motivated by the capabilities offered by the emerging Mobile Edge Computing paradigm, this paper shares insights regarding potential optimization approaches that can be adopted in order to speed up the complex user tracking, area mapping, and 3D rendering processes in Digital Culture. The main goal is to deliver scalable MR applications with constant Quality of Experience guarantees to the visitors, by exploiting existing and elastic infrastructure in close proximity to cultural landmarks within large-scale Cultural Heritage sites.

Keywords

Digital cultural heritage, distributed 3D rendering, edge server placement, mixed reality applications, mobile edge computing, quality of experience

1. Introduction

Back in the 2000s, when all media went digital, from text and imagery to audio and video, digital convergence transformed the domains of culture, art, and the humanities, bridging existing gaps and bringing them together under new digital contexts that envisioned new opportunities for cultural dissemination, preservation and promotion in museums and Cultural Heritage creative industries. With this gradual rise of digital convergence, the subject areas of information, communication, and computing, fields, which up until then had developed separately, became integral and inseparable, while inspiring emerging fields such as *Digital Culture* [1].

Digital Culture, nowadays, is used to describe the effect of digital technology on the entirety of cultural society, encompassing new functions, activities and methods for producing content, performing scientific research, communicating its results and findings, and enhancing cultural and environmental preservation and protection [2]. Given this shift towards Cultural Heritage

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digitization, this work focuses on one of its most prominent means of realization, which refers to *Mixed Reality* (MR) [3].

MR has been used as a broad label to identify situations in which synthetic elements coexist with real ones, offering immersive experiences where an admixture of the two can be envisaged [4]. That said, in the Digital Culture paradigm it liberates visitors from screen-bound experiences, by offering instinctual interactions with monuments, data and artifacts in the physical space around a cultural landmark.

In order to provide seamless MR applications, however, a number of *computational intensive services*, such as three-dimensional (3D) rendering or delay-efficient user navigation tracking and space mapping, must be performed in real-time [5]. These challenges are amplified when considering geographically dispersed landmarks in large-scale Cultural Heritage sites and the demand for personalized experiences [6]. In this direction, advents in Cloud Computing and its recent Mobile Edge Computing (MEC) counterpart have proven a valuable ally [7], enabling computational offloading to idle resources distributed at the network outskirts, that can be harvested to deliver latency-critical services to nearby users whose mobile devices are incapable of executing due to technical limitations [8].

In this paper, we formally introduce a computational offloading model that leverages MEC to yield sufficient capacities for performing the aforementioned computation-intensive tasks, benefiting from existing edge infrastructure. Our aim is to provide seamless MR applications for Digital Culture engagement to users visiting large-scale Cultural Heritage sites, without additional capital expenses to the content providers. Inspired by works such as [9] and [10], which call forth simple elements from Graph Theory, we then propose a preliminary distributed placement and service relocation scheme to autonomously adapt the model to address the network dynamicity and meet the MR demands of the visitors in a scalable fashion that optimizes their Quality of Experience (QoE).

The remainder of the paper is organized as follows: Section 2 presents a motivating example based on a real-world cultural heritage city; Section 3 introduces the model for the support of MR computational intensive services; Section 4 reports on the data flow and the operations transpiring for the realization of MR applications; Section 5 deals with the proposed MR relocation scheme; and, finally, Section 6 concludes the work, and draws lines for future research.

2. Motivating Example

A use case is considered next for the support of MR applications in large-scale cultural sites. According to this use case, users[1] visit places of cultural interest and make use of mobile devices in order to access immersive experiences via MR applications used to enhance cultural understanding and dissemination, or even assist them in digitization and documentation of the existing cultural assets. Note that places of cultural interest may vary from archaeological sites, or museums to religious sites, monuments, fortresses, galleries, etc., all located within the premises of a large-scale cultural heritage city, such as Corfu's Historical Center (CHC), in Greece, where tourists move freely from one point to another, by consulting their devices'

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[1] In this paper the terms users, visitors, and tourists are used interchangeably.

CHC map. Accordingly, the MR application captures images of the environment through the devices camera input, which are then used to perform image recognition and object detection, e.g., using Natural Feature Tracking (NFT), which is used for tracking objects without adding fiducial markers on them [11]. In addition, the sensors equipped on the mobile device assist in users' position and rotation tracking. When the process is over, virtual 2D or 3D elements that augment and annotate the environment appear on the display monitor, allowing users to interact with them accordingly.

However, such augmentations, especially the 3D ones, are required to be rendered and registered in real-time in order to offer seamless engagement [12]. Studies like [13] indicate that low *latency* is a force driver in order to achieve acceptable user experience in immersive MR environments. Actually, it has been shown that there exists an upper threshold of latency tolerance, above which users begin to notice significant delay that hurts QoE. According to their findings, this delay refers to a range of up to 100 ms of response time, beyond which the MR becomes laggy and inappropriate. Moreover, previous research, e.g., [14], points out that uploading generated input data from the users' devices to a remote cloud, i.e., the *upstream latency*, does not seriously affect the QoE since the data are small in size. On the other hand, in the case of the *downstream latency*, the size of the data packets, that encapsulate the newly rendered 3D frames, have a significantly larger size. In parallel, when considering indoor environments (e.g., museum exhibitions behind closed doors), where GPS tracking is not always applicable, then keeping track of visitors' movements, position and rotation becomes exceedingly complex, with alternative approaches such as Simultaneous Localization and Mapping (SLAM) [15], which are designed to construct a map of an unknown environment while simultaneously keeping track of an agent's location within it, being an ideal candidate. Nevertheless, SLAM is also computationally intensive, demanding an ultra-low delay-efficient design, which is not easily attainable under resource-constrained mobile devices, or remote cloud-only assisted infrastructure, with the latter (in terms of network distance) often incurring unstable connectivity and unacceptable latency. In this context, the MEC paradigm has been adopted in order to devise optimized solutions for clever service distribution, that will enhance the remote cloud infrastructure in terms of efficient service allocation and provision, by offloading necessary computational power to *edge servers* (ES) located at the outskirts of the network and in close proximity to the end users.

That said, for the current use case, we consider a MEC deployed on a Metropolitan Area Network (MAN), benefiting from existing infrastructure, e.g., *cellular towers* (CT), intended to cover large-scale cultural heritage sites, like CHC. By doing so, it can offer its visitors immersive MR applications, by hosting 3D rendering and SLAM services near the end users, in order for their mobile devices to fast gain access and enable augmentative content. For example in Figure 1, the locations of a popular telecommunications vendor's CT[2] within the CHC are depicted, which can be exploited to colocate the corresponding ES.

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[2] Map acquired by Cellmapper, accessible at: https://www.cellmapper.net/

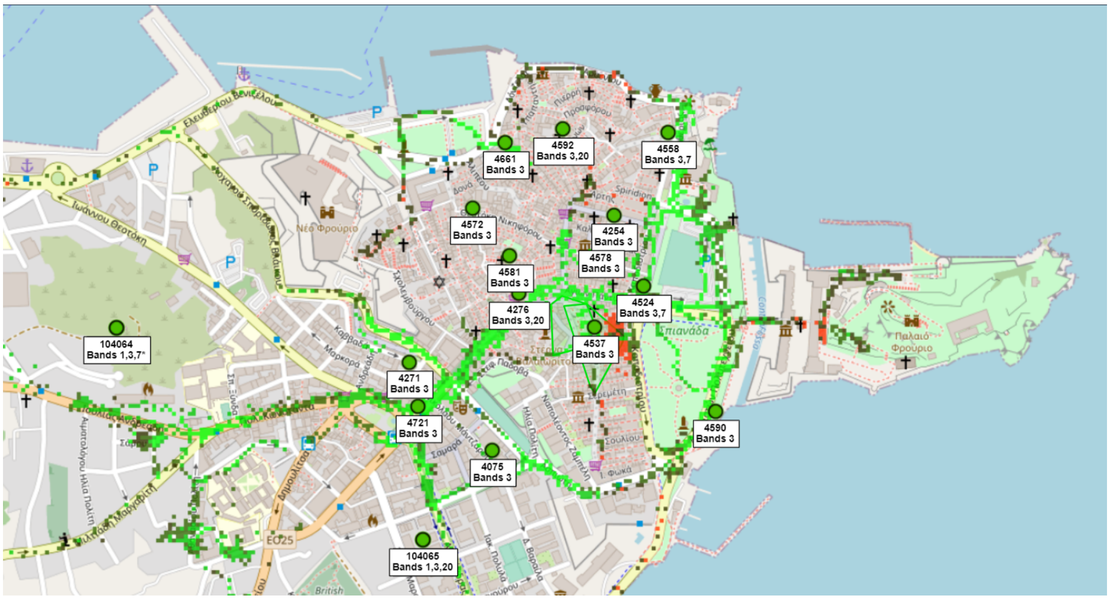


Figure 1: Cosmote LTE 4G cellular tower locations in Corfu's Historical Center.

3. Considered MEC for 3D/SLAM Support

A typical MEC media streaming service system is considered here for the support of MR applications in Digital Culture, where SLAM and 3D rendering occurs on ES that are dispensed near cultural landmarks and users engage with augmentable exhibits on diversified hardware devices. Although these devices can vary significantly (e.g., smartphones, tablets, head-mounted displays, etc.), the all share the need for high QoE, a factor that is crucial in immersive media streaming services [16]. To improve the coverage for the MR content provider and in parallel the QoE for the users, multiple CT are geographically distributed, that in turn connect to the deployed ES (i.e., the latter are co-located with the former), acting in this way as portals for accessing the previously mentioned services.

Figure 2 presents a small-scale example of such a Digital Culture MEC ecosystem. The visitors, as stated, connect to the CT in order to gain access to the ES. To do so, the visitors must lie within their coverage area. In Figure 2 ten visitors and four CT along with their associated ES are considered. The small clouds represent the coverage area of each CT. Ergo, visitor V3 can connect to either renderer ES1 or ES4, whereas visitors V6 and V7 may connect to either renderer ES3 or ES4 respectively since all of them are located within the coverage of multiple CT. Considering that each ES is typified by a maximum workload capacity, then if no ES can serve a particular visitor due to an overload, the visitor is redirected via the closest CT to the remote *cloud multimedia server* (CMS). Since MEC is inherently highly dynamic and expected to facilitate frequent changes, e.g., dynamic 3D content workloads, a fluctuating number of tourists, oscillating interaction inputs, etc., dynamic decision-making processes are required to orchestrate and provision appropriately the available services.

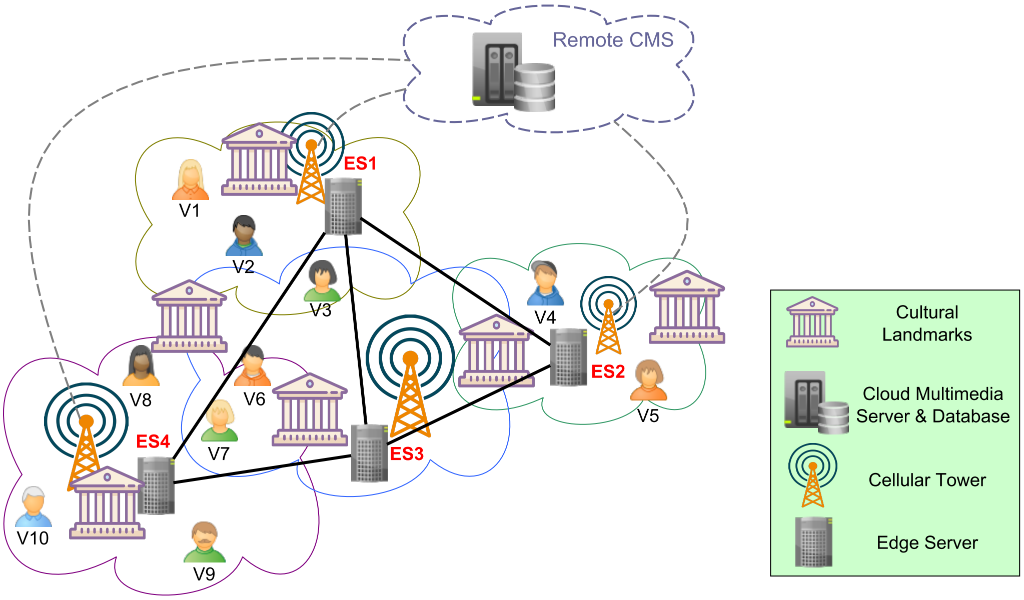


Figure 2: A small-scale example of the considered MEC system for the timely provision of Mixed Reality applications in Digital Culture.

Note, that the ES depending on the coverage of their associated CT, may connect with one another, forming a network overlay above the deployed MAN. By doing so, they can communicate and exchange data or even assist one another when overcapacity issues appear (see Section 5). In this way, they can efficiently balance the workload among them. Moreover, when visitor flows decrease in a particular cultural landmark below a certain lower threshold, the corresponding ES could shut down to preserve precious computing resources, by redirecting demands to the neighboring ES. The opposite can occur when a sudden spike in tourist flows, renders some ES incapable of coping with the increasing 3D/SLAM demands.

4. MR Application Data Flow

Given the preceding, it is now feasible to move on and provide a detailed overview of the service transactions that take place, as depicted in Figure 3, regarding the MR content delivery process.

Upon entering the coverage area of a CT, and after the connection is established with the ES, the latter begins tracking the visitor's movement and perspective, continuously updating the area's map, and providing feedback regarding the augmentable artifacts. The visitors, then, use their *mobile device* to scan potential exhibits. The camera input along with the user's commands are encapsulated into small data packets containing a few Bytes of information regarding the user's *interactions* with the artifacts, which are then sent into the cloud towards the CMS hosting relevant 2D interpretive cultural content.

Once there, the CMS are regular intervals, that correspond to its CPU *tick rate*, decodes the

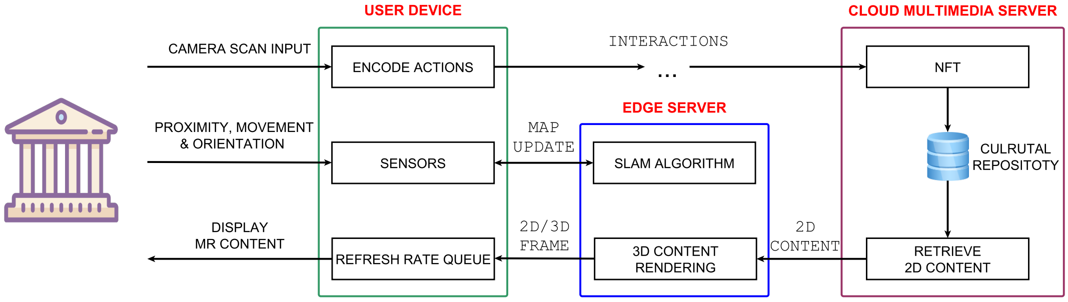


Figure 3: Data flow regarding the MR content delivery process in the considered MEC system.

data packets arriving from all users and performs necessary operations. For example, it uses the images captured to perform NFT recognition and translates the interactions into service calls for 2D or/and 3D content. In the first case, the relevant material, stored in cultural repositories is retrieved and subsequently sent back to the appropriate ES, associated with the particular user depending on their *proximity*, in the form of new 2D content data packets. The size of these varies depending on the amount of information enclosed. For example, it may consist of textual material or/and audiovisual annotation relating to the augmentable cultural point of interest. However, these data are already pre-stored inside the corresponding databases and so they can be fast accessed and retrieved. In the second case, however, i.e, when the user demands 3D feedback, which obviously must be rendered in real-time, then the corresponding service call is also included inside the new data packet. Upon reception from the ES, at regular intervals that refer to its GPU *frame rate*, the call is used to activate the 3D rendering process and a new video image scene is generated that captures the MR application's status update. It is then encapsulated, along with its accompanying informative content (acquired by the CMS), inside a new 3D frame, which is streamed back to the user's mobile device for display. In contrast with the previous packets, the 3D frame is comparably larger in size, usually in a factor of MBytes depending on image quality and resolution, containing all data regarding the newly rendered scene. When the frame reaches the user's device, the display then projects the complete MR content in a fixed *refresh rate* which depends on the monitor used and its technical specifications.

The above-outlined data flow is important because it frees CMS from the intensive operations of computing and rendering complex graphics on its own and then having to stream huge generated frames at long distances over the Internet to all users. Instead, with the intervention of the MEC renderers, the rendering takes place near the point of actual display, significantly reducing latency, while in parallel increasing user coverage. Moreover, by distributing the workload amongst many ES, each responsible for tracking the movement of only users connected to their associated CT, rather than requiring CMS to handle the totality of the users in a large-scale manner, it is feasible to perform SLAM in a much smaller scale, which substantially optimizes responsiveness. Thus, visitors can enjoy MR applications in a transparent fashion that seamlessly offers engagement with the cultural exhibits without lags or scene freezes.

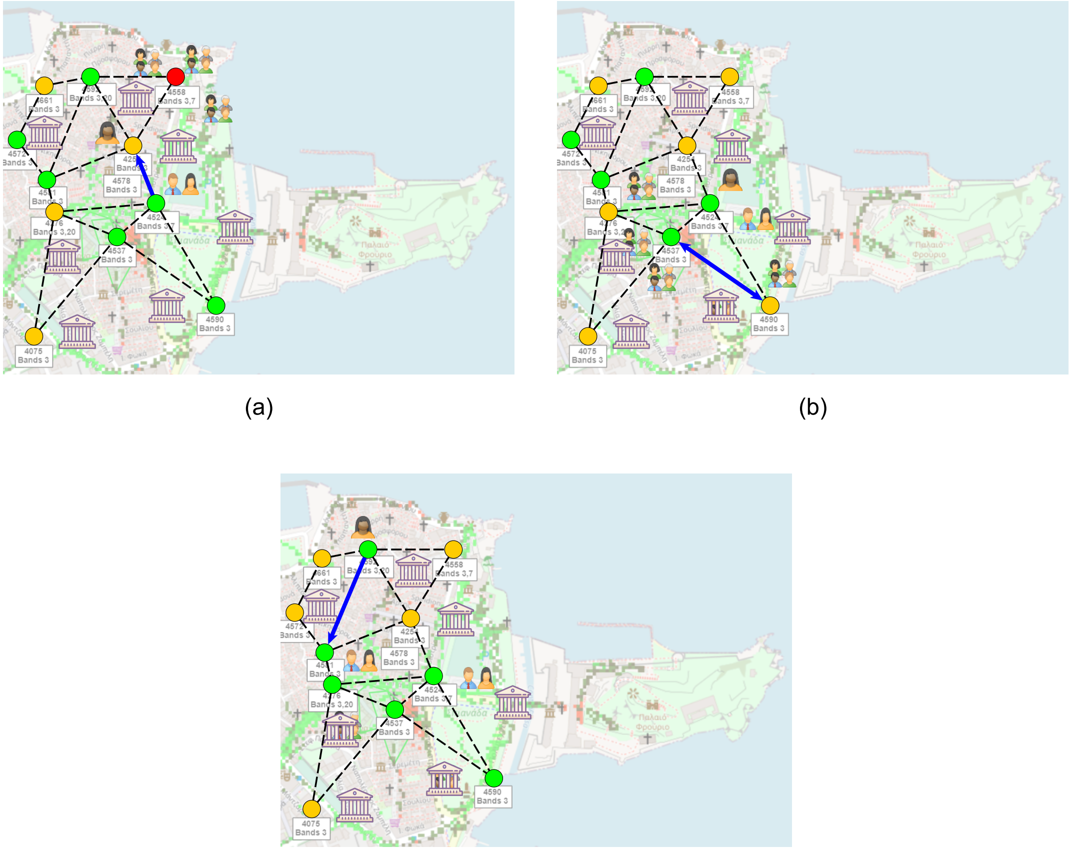
5. Distributed Edge Server Relocation

Recall at this point, that MEC systems are extremely dynamic due to oscillating network conditions and frequent fluctuations in user proportionality. For instance, during peak visiting hours or even during different tourist seasons, the user flows vary dramatically over time in Cultural Heritage cities [17, 18]. Given also the fact that they are expected to host large volumes of data (i.e., regarding each cultural monument and its collections, the informative material, the user-generated content, etc.), which are also necessary for smoothly running the services, it becomes evident that cases might manifest where some cultural landmark draws much attention and thus a large concentration of visitors, which in turn will lead to high demands for MR content from a particular ES. To avoid overwhelming the ES with such demands, which will undeniably hurt the timely service provision to its users, a prudent *service relocation* strategy should be implemented, which will be automatically activated when network overloads appear in order to shift the 3D/SLAM placement to suitable ES locations within the MEC, compensating in this way for the increased network traffic flows.

Although, the relocation may be initiated by a central computing entity, such as the CMS, past literature (e.g., [19, 20]) has shown that this will unavoidably require global topological knowledge of the MEC and its on-going workload conditions, which is generally a computationally demanding process since it requires continuous tracking of the visitors' geographical coordinates and re-computation of the optimal placement solutions. Moreover, global network permutation approaches, such as flooding-based algorithms, are deemed cost-unworthy in terms of message complexity, especially in large-scale instances. Instead, we argue here that the ES can benefit from the distributed properties of the MEC in order to autonomously monitor their CT's coverage area and actively partake in the decision-making process in tractable time [21]. In fact, when the need arises for a load-balancing to occur, the ES can independently relocate their 3D/SLAM services, and dynamically adapt their operation to address it.

Note that relocation may include any of the following rules: i) *service migration*, when the service needs to move towards an overloaded cultural site, and the initial site does not currently house many visitors; ii) *service replication* when a site accommodates many visitors, but a neighboring site also attracts much attention; and iii) *service merging* when the number of users in two or more sites depletes sufficiently enough to allow some ES to become inactive in order to alleviate the MR cultural content provider from redundant operational costs.

Figure 4 presents three examples regarding these relocation alternatives. In Figure 4(a), we can see that an ES, depicted with red color is overwhelmed by the number of requests of nearby visitors, thus a service migration is initiated from a neighboring active ES (depicted with green color), that currently serves a small number of users, towards a closer inactive ES (depicted with yellow color) that can help to alleviate the computational burden from the first, i.e., the overloaded one. In Figure 4(b), we witness that an inactive ES suddenly requires to serve a large number of visitors, hence a service replication occurs from a neighbor open ES, which also needs to remain active since many users are currently in its own vicinity, in order to bring the 3D/SLAM service to the ES that is close to the large visitor population. Finally, in Figure 4(c) the case where a service merge can happen is depicted since an active ES suddenly becomes under-utilized and needs to become inactive in order to reduce the unnecessary operation cost. In this case, its workload will be redirected to the remaining ES after the service merge



(a)

(b)

(c)

Figure 4: Relocation examples in Corfu Historical Center: Green color indicates active ES, yellow represents inactive ES, while red color means that an active ES is currently overloaded with MR cultural content requests. The blue arrows show the relocation process, wherein (a) single-direction arrows from green to yellow indicate migration; (b) double-direction arrows from green to yellow indicate replication; and (c) single-direction arrows from green to green indicate merge.

is completed. The above properties render the MEC resilient to the ever-changing network conditions, by scaling up and down to meet the current demands, without compromising the MR experience of its users.

6. Conclusions

In this paper, we propose elastic optimization approaches to bridge the large network gap in terms of delay, between visitors to a large-scale Cultural Heritage site, requesting MR applications, and the remote cloud responsible for delivering the Digital Culture 3D content. To this end, we leverage MEC on existing infrastructure to facilitate the complex processes of

SLAM and 3D rendering close to the visitors and in turn near the actual point of content display. Then, a distributed but scalable service relocation scheme is proposed, that can autonomously shift the placement of the edge servers, responsible for running these services, in order to efficiently meet the current demands and tourist flows, and thus offer constant QoE support guarantees for the realization of the MR augmentation of the cultural points of interest.

Although this work serves as a preliminary conceptual model, future research will investigate how the model behaves and conforms under real-world conditions with experimentation on actual Cultural Heritage sites, such as the CHC.

Acknowledgments

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Athanasios Tsipis received his B.Sc. and M.Sc. from the Dept. of Informatics of Ionian University, Greece, in 2015 and 2017 respectively, for which he was awarded scholarships for academic excellence. In 2021, he received his Ph.D. in Informatics with honors, from the same Department. His research interests lie at the intersection of digital cultural heritage and networked immersive systems, extended reality and 3D technologies, cloud/edge gaming, multimedia network optimization and performance issues, metaverse applications, gamification and interaction design, etc. Since 2015 he is a member and researcher of the "Networks, Multimedia and Security Systems Laboratory" (NMSLab), participating in various EC research and local development projects. Currently, he serves as an adjunct lecturer at the Dept. of Digital Media and Communication, as well as an academic scholar at the Dept. of Tourism, at Ionian University. He is a reviewer of numerous conferences and journals, and in 2021 he was the recipient of the best paper award from the 26th IEEE Symposium on Computers and Communications (IEEE ISCC 2021).

Vasileios Komianos is a faculty member at Dept. of Audio and Visual Arts, Ionian University, Greece, teaching courses related to Virtual/Augmented/Mixed Reality, video games and interactive multimedia. His research interests are mostly focused on Mixed Reality (MR) systems, on user interaction and user interfaces in MR systems and applications as well as on approaches for artistic expression and cultural communication. He has work experience on designing audiovisual content and installations in the cultural heritage sector, and his works are hosted or have been hosted in permanent and temporary exhibitions as well as in art festivals.

Konstantinos Oikonomou received his M.Eng. in Computer Engineering and Informatics from the University of Patras in 1998. In September 1999 he received his M.Sc. degree in Communication and Signal Processing from the Electrical and Electronic Engineering Department, Imperial College (London). He received his Ph.D. degree in 2004 from the Informatics and Telecommunications Department, University of Athens, Greece. His Ph.D. thesis focuses on medium access control policies in ad hoc networks. He has served as the Dean of the Faculty of Information Science and Informatics of the Ionian University, Corfu, Greece. Since 2006 he is a faculty member in Computer Networks, currently a Professor, at the Department of Informatics, at the same University. He has also served as the Head of the Department and Director of the Postgraduate Studies. Between December 1999 and January 2005 he was employed at Intracom S.A, as a research and development engineer. His research interests involve medium access control in ad hoc networks, performance issues in wireless networks, information dissemination, service discovery, facility location, energy consumption in wireless sensor networks, and network cost reduction in cloud computing environments. Professor K. Oikonomou has a long experience in wireless systems and has been coordinating a number of EC research projects in the computer networks area, and various local development projects (e.g., virtual worlds). He is currently a member of the editorial boards of Computer Networks Journal (Elsevier) and Journal on Future and Evolving Technologies (ITU). He has been a reviewer and TPC member of numerous conferences and journals, and he holds an award for the best paper from the Hawaii International Conference on System Service, as well as an award for the best paper from the 26th IEEE Symposium on Computers and Communications.