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Application-Driven Offloading of XR Mission Critical via Integrated TN/NTN

Olga Chukhno, Nadezhda Chukhno, Aleksandr Ometov, Sara Pizzi, Giuseppe Araniti, and Antonella Molinaro

***Abstract*—The emergence of eXtended Reality (XR) technologies is revolutionizing Mission Critical (MC) operations by enhancing situational awareness and decision-making. However, the high computational demands of XR MC applications, coupled with the limited capabilities of battery-powered wearable XR devices worn, e.g., by first responders, necessitate offloading strategies to more processing-powerful network nodes. Traditional terrestrial networks, while supporting XR MC services, may not be reliable in all scenarios, especially during emergencies or in remote areas. To address this, the integration of Non-Terrestrial Networks (NTNs) with Terrestrial Networks (TNs) offers various options to place and run in-network computing tasks, e.g., Low Earth Orbit (LEO) satellites and Unmanned Aerial Vehicles (UAVs). The potential of these offloading options for XR MC services has not yet been fully explored. In this work, we close this gap and analyze the performance of application-driven offloading of computational tasks of XR MC services at different locations in the integrated TN/NTN environment. Through system-level simulations, we assess the end-to-end latency cost under different traffic loads at the various system layers and analyze the energy consumption of XR device, identifying practical insights for system designers. For a small number of requests, offloading is more effective than local computing, improving performance by up to 93%, whereas, for a high number of requests, local computing is preferred but constrained by battery limitations.**

I. Introduction

The advancement of eXtended Reality (XR) technologies is transforming the visual perception of the world. Particularly relevant to Mission Critical (MC) operations, XR innovations enhance situational awareness [1] by providing users with immersive and real-time visualizations of complex data and live video feeds, thereby improving decision-making, problem-solving, and overall operational efficiency. For example, in Public Protection and Disaster Relief (PPDR) scenarios [2], firefighters can utilize real-time thermal imaging overlays within their field of view, enabling them to identify hotspots and locate victims with greater precision and safety.

In this vein, for XR MC, 3rd Generation Partnership Project (3GPP) defined the "Police Critical Mission with AR" use case [3], which envisions supporting teams with XR graphics such as maps, text, and location pointers of objects/people in the surroundings. The primary Quality of Service (QoS) requirements for XR MC include low end-to-end latency, high bandwidth, and accurate indoor/outdoor user location. While Global Navigation Satellite System (GNSS) can ensure high-accuracy positioning and network configuration facilitates bandwidth selection, meeting low-latency requirements is crucial and the central focus of this work.

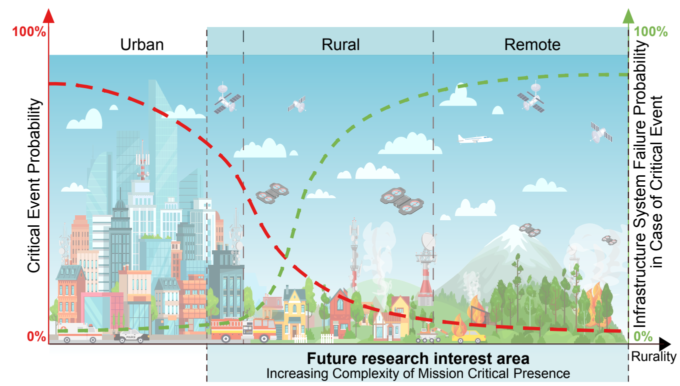

Fig. 1: Qualitative system readiness to operation failure.

XR MC applications, such as rendering complex 3D scenes with high-quality textures or processing camera feeds for object detection and tracking, are computationally demanding. XR devices, however, are often limited in terms of processing power, battery life, and thermal dissipation. To address these limitations, offloading computationally intensive tasks from battery-powered XR devices to more powerful network nodes is often necessary. Edge computing infrastructure and Mobile Edge Computing (MEC) can significantly enhance the performance of XR MC applications by bringing computing capabilities closer to the edge of the network, enabling minimized response times and optimized real-time data processing.

However, emergency situations may pose additional challenges, with the severely limited residual battery life and service reliability becoming significant barriers, particularly for first responders wearing XR devices. In such scenarios, communication and computing encounters difficulties due to either the high probability of critical events (urban areas) or infrastructure system failure (rural and remote areas), as depicted in Fig. 1. The latter scenario is of particular interest in this work. To address these issues, it is vital to investigate Non-Terrestrial Network (NTN) offloading options, including Unmanned Aerial Vehicles (UAVs) offering flexible deployments and Low Earth Orbit (LEO) satellites providing near-global coverage, or integrating Terrestrial Network (TN)

O. Chukhno, S. Pizzi, G. Araniti, and A. Molinaro are with University Mediterranea of Reggio Calabria and CNIT, Italy; A. Molinaro is also with University Paris-Saclay, France; N. Chukhno is with IMDEA Networks Institute, Spain; A. Ometov is with Tampere University, Finland.

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with NTN. Such multi-mode wireless connections can help ensure continuous connectivity in dynamic operational environments [1]. However, such options are not yet supported by standardization bodies and remain largely unexplored in the context of XR MC.

This article explores the possibility of offloading the computation of XR MC services at different locations of a three-dimensional (3D) environment. Our goal is to provide an application-driven approach and emphasize the role of integrated TN/NTN in mitigating potential failure risks during MC events, particularly in rural and remote areas. In this context, we explore present and future offloading schemes for XR MC applications in an integrated TN/NTN 3D environment including edge servers, UAVs, and LEOs. We then assess the benefits in terms of delay and XR device energy derived from the implementation of various offloading strategies in the TN/NTN network. We specifically focus on analyzing the delay metric since, in the context of XR MC services, high latency can severely degrade the user experience, leading to issues such as reduced immersion, impaired decision-making, and increased risk to life and property. Finally, we evaluate the effective utilization of diverse computational capabilities located at various network layers for XR MC.

II. Potential of XR in Critical Scenarios

The immense potential of XR is especially evident in critical scenarios, where every moment counts, and fast, safe, and efficient responses to emergencies are required. By leveraging XR technology, first responders will be able to efficiently navigate disaster zones, identify victims, and assess structural damage while being guided by digital overlays that provide real-time information on hazardous areas, trapped individuals, and optimal evacuation routes [1].

Ericsson has outlined a vision for XR MC [1] and discussed solutions to visualize complex datasets, sensor inputs, and live video feeds in real-time, utilize gesture-based controls for seamless manipulation of XR environments, and analyze real-time data using Artificial Intelligence (AI)/Machine Learning (ML) to predict potential incidents and provide actionable insights. In addition, advanced solutions are foreseen to categorize, filter, and prioritize incoming data while reducing information overload, generate and transmit alerts in real-time based on specific conditions, and share information seamlessly among connected users.

To realize this potential and address MC services in 5G, 3GPP has taken the initiative to introduce the concept of “XR Mission Critical” [3]. Currently, this includes a “Police Mission Critical with Augmented Reality (AR)” use case, where officers equipped with XR devices can access a range of capabilities, from simple overlays to immersive 3D environments, i.e., from 3 to 6 Degrees of Freedom (DoF). In this scenario, a team equipped with mission gears is connected to a control center. The control center supports team coordination by providing XR graphics and mixed audio from team members and the control center. The team members carry AR glasses, 360-degree helmet-mounted cameras, microphones, headphones, sensory devices, and fifth-generation (5G)-enabled accurate positioning systems.

Potential normative work involves various aspects to enhance the XR experience of MC services [3]. This includes uplink 3D audio using Multimedia Telephony Service for IMS (MTSI)/Framework for Live Uplink Streaming (FLUS), MTSI/FLUS/Mission Critical Video (MCVideo) uplink XR streams, and downlink XR video with overlaid graphics, benefiting from both local and cloud computing and rendering. In addition, downlink XR audio is improved through mixed-in 3D audio objects using similar local/cloud computing and rendering techniques. Moreover, MTSI/Mission Critical Push To Talk (MCPTT) Super WideBand (SWB)/FullBand (FB) voice communication plays a crucial role in ensuring efficient communication during MC operations among all devices, even in noisy environments.

Therefore, in XR MC, both audio (i.e., voice) and video streaming are essential. For audio, advanced technologies, such as noise-canceling microphones and spatial audio, are employed to ensure clear and immersive communication. Spatial audio creates a 3D soundscape, allowing users to perceive the direction and distance of sound sources. Furthermore, automatic speech-to-text transcription can aid in noisy conditions. This is often required for, e.g., tactical communications during public safety and emergency services when first responders need to communicate with each other in real-time. For visual information, the XR display overlays crucial information such as maps, teammate locations, and potential threats, directly onto the user’s field of view. Simultaneously, 360-degree cameras capture the entire scene, streaming high-definition video to a central command center [3]. Indeed, firefighters can use XR headsets to see through smoke and heat, identifying fire hotspots and potential hazards.

III. Offloading in the 3D Ecosystem

A. Opportunities of NTNs

The resource-constrained nature of users’ devices and the computation-intensive load of XR MC applications call for the design of offloading strategies to provide a prompt response in critical scenarios. In addition to the capabilities of traditional terrestrial networks, future sixth-generation (6G) infrastructures will rely heavily on the integration of air and space nodes within NTNs.

NTNs were first considered in 3GPP Rel. 16, wherein 5G outreach is broadened by incorporating solutions to allow New Radio (NR) operation in NTNs [4]. NR will be adapted to facilitate communications via LEO, Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellite constellations, as well as to support High Altitude Platform Station (HAPS) and Air-to-Ground (A2G) communications. The primary goal of Rel. 16 NTN development is to provide fixed wireless access and Mobile BroadBand (MBB) in locations where TN coverage is economically challenging or unavailable. In detail, in Rel. 16, 3GPP introduces basic features to enable NR operation over NTNs in frequency range 1 (FR1), below 7.125 GHz, and support Narrowband Internet of Things (NB-IoT) and Enhanced Machine Type Communication (eMTC)-based satellite access for massive Internet of Things (IoT) scenarios [5].

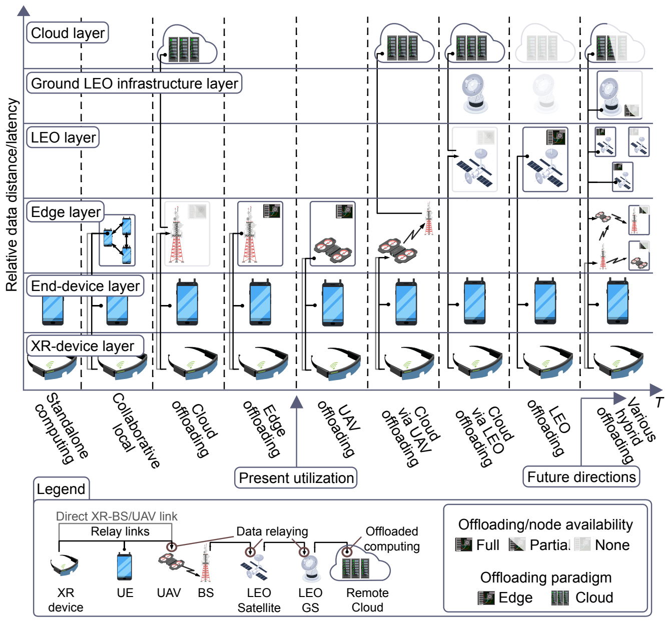


Fig. 2: Development of computational offloading strategies.

Advancements in hardware manufacturing enable equipping air/space nodes with advanced processing capability. As a result, NTNs represent not only a means for communication but also for computing. Energy and space constraints limit the payload onboard NTN nodes, which, however, can provide thousands of Giga Floating Point Operations Per Second (GFLOPS) of computing capability. Therefore, future 6G networks will take advantage of 3D computing opportunities.

According to the roadmap for 3GPP satellite vision support, the integration of TN and NTN is anticipated to take place under the umbrella of 5G and 5G-Advanced, which will pave the way for fully unified TN/NTN systems in 6G, expected to be realized beyond Rels. 20/21 [6].

The operation of integrated TN/NTN in the context of XR MC has not been thoroughly investigated, despite the clear need for enhanced solutions beyond current standardization to address their low latency, high reliability, and substantial traffic requirements. Accordingly, in the following section, we explore XR for critical scenarios via TN/NTN and evaluate various offloading schemes to address such intensive traffic processing.

B. TN/NTN Offloading Schemes

To effectively address the challenges posed by high-urgency services, such as limited battery life of devices, service reliability, and latency constraints, *standalone* and *collaborative local* computing (among XR devices and/or general-purpose end-devices, also establishing proximity communications), where the computation of a task is performed on the given device or its neighbor, may not always be sufficient. Thus, *cloud-native* architectures that enable remote in-network computational offloading are essential.

Currently, deployable computational offloading paradigms allow for remote computing at the nearest power-independent device, i.e., *network edge*, acting similarly but behaving differently in systems under diverse latency requirements, which is highlighted through the vertical axis in Fig. 2. Therefore, moving the computing closer to the network edge reduces latency [7]. The current stage of development facilitates this through standardization efforts by 3GPP and the availability of services provided by network infrastructure vendors.

Offloading schemes may incorporate *satellite-* and *UAV-aided* approaches, which, however, are not yet supported by 3GPP in the context of XR MC. Compared to traditional task offloading that relies on fixed Base Stations (BSs) and servers, UAV-assisted offloading addresses the limitations of service range in dynamic and challenging environments, such as forests and deserts, and reduces the costs associated with deploying large-scale edge servers [8]. Similarly, although LEO satellite constellations are mainly used to offer worldwide Internet access, the possibility of leveraging the computing capabilities of LEOs to implement an orbital computing continuum for equal access to computing is envisioned via simple scheduling techniques [9]. These offloading schemes represent the next generation of edge/cloud-based architectures.

Furthermore, current and future XR applications utilize a smartphone as a gateway to reach the network and cloud. While next-generation activities are still expected to rely on smartphones, they may allow for some level of direct XR-to-network connectivity. Still, the oncoming era of integrated TN/NTN via LEO and UAV communications may face limitations in direct network-to-headset communication due to power constraints and potential radio emission concerns.

These diverse offloading schemes demand comprehensive research across communication, hardware design, security, privacy, and their integration for emergency services. Given the variable nature of critical situations, computational offloading must adapt dynamically, considering factors such as infrastructure availability, request urgency, service type, latency demands, and computing node capabilities. Notably, the network should intelligently allocate resources between TN and NTN entities, such as terrestrial BS, UAV, and/or LEO, based on these evolving conditions.

IV. XR MC System-Level Analysis: Offloading vs. Local Computing in TN/NTN

In this section, we conduct a study on how offloading schemes, which exploit the diverse pool of resources available in the 3D TN/NTN environment, can manage different types of emergency requests in XR MC in the event of infrastructure system failures in rural and remote areas. We showcase a set of scenarios, including baseline local computing, presently standardized edge offloading, as well as more futuristic LEO and UAV scenarios, including hybrid deployments. The standardization activities in XR technology via TN/NTN integration are already around the corner, and thus, analyzing the behavior of 3D systems is of the utmost interest for future development.

A. Scenario, Offloading Strategies, and Settings

We assess the system performance for XR MC applications in terms of the end-to-end delay (that accounts for uplink and downlink transmission and processing on edge/device) and energy consumption. These metrics are crucial XR MC as excessive end-to-end latency can lead to misalignment of XR overlays. Consequently, even minor misalignments can severely compromise operational efficacy and safety due to the delay between user movement and the corresponding overlay update. Energy consumption impacts device longevity.

We consider two traffic types, audio and video XR [3], required for, e.g., tactical communications during emergency services and firefighting operations, respectively. To accurately reflect the interactions of the people in the area, we incorporate realistic pedestrian mobility and micro-mobility patterns. Specifically, we use a social force-based model to simulate pedestrian flow at a baseline speed of 3 km/h, capturing the dynamic nature of user movement in XR applications [10]. We model head and arm motions, which can lead to rapid signal strength fluctuations due to changes in the user's position relative to the terminal.

We investigate whether it is more convenient to perform computing tasks locally on the XR devices or to offload them to a virtualized control center function running on TN and/or NTN nodes, where the XR data, e.g., maps, text, locations of team members or objects/people in the area, is stored.

In a *local computing* scenario, User Equipment (UE) devices transmit requests to the BS via uplink channel. After processing these requests, the BS sends the required data back to the UE in the downlink direction. Specifically, retrieving audio XR involves *(i)* UE transmitting a 100-byte request to BS for the data needed to generate the mixed-in 3D audio objects locally and *(ii)* UE receiving a 10-KB information set [11]. Also, for video XR, the UEs transmits a 100-byte request, specifying the information needed to select overlaid graphics [11]. In response, UEs receive a 24-KB (i.e., 1280x720 image with 8-bit depth, RGBA color model, and 150:1 compression rate) information package containing the overlaid graphics.

Differently, in an *offloading* scenario, UE sends base media to a computing node (the edge, UAV, or LEO), which processes it with XR elements and returns the enhanced media to the UE. For audio XR, the UE sends the audio of 2.4 MB (5 min audio with 64 kbps bitrate, 2 channels, 8-bit depth, sample rate of 44.1 kHz, and MP3 compression) and receives it with mixed-in 3D audio objects of the same size as the original audio. Instead, for video XR, the UE sends the 360-degree video of 126 MB (30 seconds video with the resolution of 3840x1920 pixels, H.264 encoding, 150:1 compression rate, 30 fps) and receives the overlaid video of the same size as the original video.

We focus on rural areas susceptible to infrastructure system failures, which can lead to the temporary unavailability of one or two entities. Consequently, in addition to the example cases in Fig. 3, we investigate the following schemes:

- *fully local*: with audio and video XR processing executed only at the UE (dashed curves labeled as *Local computing*);
- *all-in-one-layer offloading*: with only one infrastructure coverage level (TN, UAV or LEO) available for offloading both audio and video XR processing; curves labeled as `TN (audio, video)`, `UAV (audio, video)`, and `LEO (audio, video)`;
- *hybrid offloading*: with two different layers used to offload audio and video XR processing, respectively. Curves consider all possible combinations and are labeled as `TN(audio)-UAV(video)`; `TN(audio)-LEO(video)`; `UAV(audio)-LEO(video)`; `TN(video)-UAV(audio)`; `TN(video)-LEO(audio)`; `UAV(video)-LEO(audio)`.

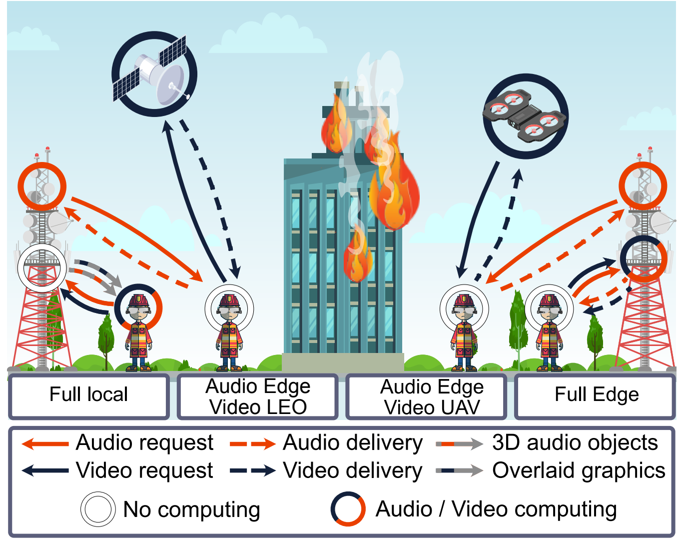
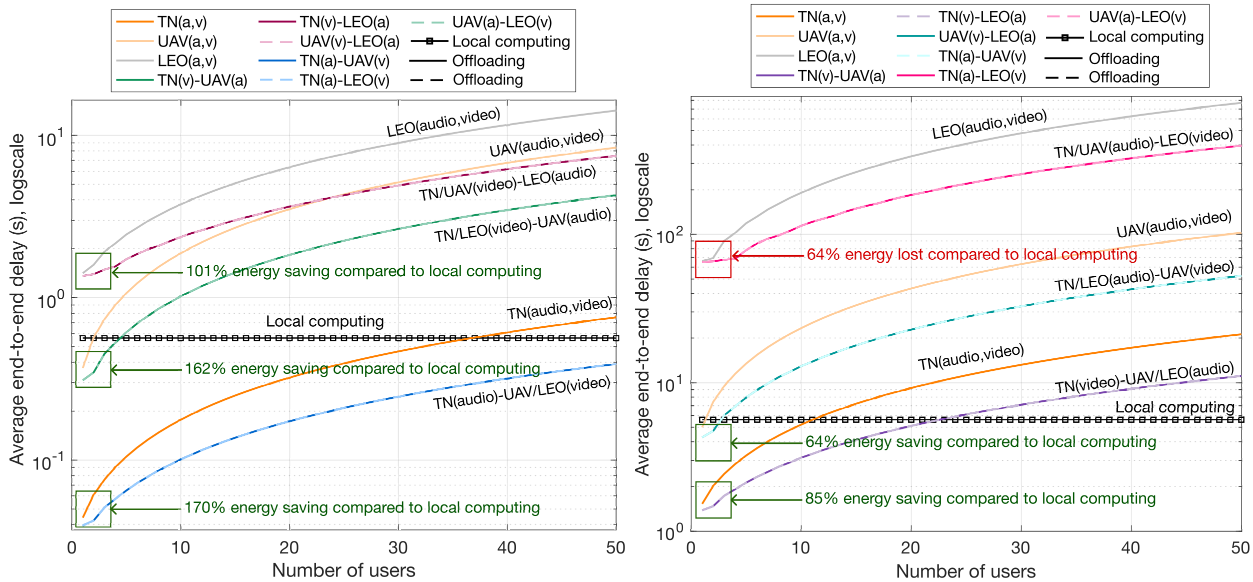


Fig. 3: Selected future XR delivery approaches.

We evaluated communication scenarios for terrestrial and UAV systems utilizing the 3GPP channel model in an Urban Macro (UMa) environment. Users are connected to the mmWave terrestrial BS and the UAV BS, with co-located edge computing servers. We consider LEOs orbiting at an altitude of 600 km and assume the basic path loss with shadow fading and clutter loss for dense urban scenarios and Line-of-Sight (LoS), along with scintillation and atmospheric losses of 0.3 dB and 0.5 dB and tropospheric attenuation of 1.2 dB. Poisson request arrivals are assumed for each XR device.

The analysis takes into account different processing capacities of the device (Thundercomm XR2 VR HMD, Qualcomm Snapdragon XR2, one Kryo 585 Prime at 2.84 GHz), the terrestrial edge (Lenovo ThinkEdge SE450 Edge Server, Intel Xeon Gold 6354 18/36 cores/threads at 3.0 GHz), UAV (Qualcomm QRB5165 processor, one Kryo Gold prime core at 2.842 GHz), and LEO (Unibap iX5–100, a SpaceCloud, Unibap Qseven e20xx/e21xx compute modules, AMD Embedded G-Series LX Family SOCs, GX-218GL model with 2 cores at 1.8 GHz). Additionally, the computational intensity required to process the content to be included in the XR video/audio corresponds to 100 CPU cycles per bit [12], and the content size is set to 1 MB and 10 MB, for audio and video XR traffic [13]. Note that the content size includes both the instructions (i.e., mesh, material, and transform data for XR video and spatial audio metadata and audio effect parameters for audio XR) and the overlaid graphics/spatial audio data itself. All tasks are parallelizable. The main parameters are



(a) Audio XR (b) Video XR

Fig. 4: End-to-end delay and percentage difference between offloading and local computing in energy consumption Vs. number of users: solid and dashed (to resolve overlapping curves) lines represent different offloading schemes, solid line with square markers – local computing, squares with text arrows – energy consumption difference for a single XR device.

listed in Table I.

TABLE I: Simulation parameters [11]–[13].

Parameter	Value
Terrestrial/UAV/LEO Satellite	
Operational frequency	30/30/30 GHz
Bandwidth	100/100/400 MHz
Altitude	25/200/600000 m
Downlink transmit power	35/23/40.6 dBm
Noise power power density	-174 dBm/Hz
Noise figure	9 dB
Antenna gain	30/30/38.5 dBi
Noise temperature	354.81 K
Processing capacities	54/2.842/3.6 GHz
Computational intensity	100 CPU cycle per bit
XR device	
Transmit antenna gain	43.2 dBi
Receive antenna gain	39.7 dBi
Noise figure	1.2 dB
Uplink transmit power	33 dBm
Height	1.5 /m
Processing capacities	2.84 GHz
Computational intensity	100 CPU cycle per bit
Baseband electric circuit power	5.34 W
General parameters	
Arrival rate	$2\,s^{-1}$
Number of requests per XR device	5

B. *Local Computing Vs. Offloading for XR MC in TN/NTN*

In Fig. 4, we investigate the trade-off between local computing and offloading in terms of the end-to-end latency, separately for audio and video XR flows, as user numbers increase. While offloading can introduce an increase in latency compared to local computing due to an increased propagation delay, it leverages the greater computational capacity of terrestrial edge, UAV, and LEO nodes compared to UEs to offset this impact in some cases.

The results show that the **local computing** scheme exhibits minimal sensitivity to the number of users since it responds only to individual requests. In contrast, the volume of concurrent requests from various devices significantly influences the **offloading** schemes. Most of them initially achieve lower delays compared to local computing up to a turning point; this point is different among the considered offloading schemes. For example, the turning point from terrestrial layer (`TN(audio,video)`) to local computing for audio and video XR is at 37 and 10 users, respectively. Moreover, offloading all requests to a single terrestrial layer (`TN(audio,video)`) provides both audio and video XR with a longer delay compared to `TN(audio)-UAV(video)` and `TN(audio)-LEO(video)`, because, in such hybrid schemes, the queue of requests is distributed between layers.

Another interesting observation is that offloading solutions that involve terrestrial infrastructure provide reduced communication distances (compared to UAV and LEO) and propagation losses (compared to LEO). In particular, the lowest latency is exhibited by TN-UAV and TN-LEO offloading schemes, while UAV- and especially LEO-aided solutions show in general higher latencies. Local computing is, in most cases, preferred to LEO/UAV and LEO/UAV-aided schemes because of the increased uplink and downlink transmission delays, along with queuing delays at the edge server.

Despite the latency advantages of local computing, particularly with high request volumes or when utilizing LEOs, it incurs a significant energy penalty on the device. Fig. 4 illustrates the difference in energy consumption between local computing and offloading approaches. The integration of local computing must be carefully considered due to its high energy demands. Notably, only one offloading scheme exhibits higher energy consumption than local computing – video delivery via LEO – due to higher propagation losses, longer distances, and the heavy nature of video traffic.

In general, the decision on how to distribute different traffic types among various network layers can be made based on the priority of the applications and their requirements, while the selection of NTN technology depends on the latency requirements and the airship operation time. For example, UAVs are located closer to end users compared to LEO (leading to lower transmission latency) and can operate from around 20-30 minutes to a couple of hours on a single charge, while a typical LEO satellite might have a lifespan of years with a coverage time of a certain area in the order of minutes. Infrastructure availability also influences this decision, which includes considerations of potential damages or blockages of BS, UAV, and/or LEO, UAV departures, LEO coverage gaps, alongside factors such as security, regulatory constraints, and environmental conditions.

As a final remark, we wish to highlight that XR MC demands not only rapid response times but also reliable and consistent performance. The decision to offload or execute tasks locally is not merely a matter of performance; it directly influences the reliability and availability of critical services. To ensure performance comparable to TN when employing UAV and LEO architectures, also in case of high request volume, a higher number of airborne/spaceborne nodes need to be employed. Moreover, power efficiency is paramount in MC scenarios, as devices often operate in resource-constrained environments, and prolonged battery life is required for uninterrupted functionality. As such, the energy implications of computation, whether local or offloaded, play a vital role in sustaining the operation of XR MC and require particular attention from the research community.

V. Open Issues

The delivery of XR MC services in integrated TN/NTN calls for an additional set of aspects to be investigated.

Standardization Pace: Integrating LEO and 5G-Advanced communication requires proper protocol standardization and coordination between different stakeholders. This includes defining handover procedures, security measures, spectrum allocation, traffic management, and QoS parameters to ensure smooth communication for XR applications. This must also account for dynamic infrastructure availability, recognizing that network elements may experience temporary unavailability, integrating adaptive frameworks to enable real-time network adjustments and ensure continuous, reliable XR services.

Network Slicing, QoS, and Prioritization: XR applications have diverse requirements in terms of data rates, latency, and reliability [14]. Network slicing, a key feature of 5G-Advanced, allows dedicated virtual networks to be created for different services while it is not yet integrated in NTN. Moreover, as network slicing is dependent on the rollout of 5G standalone, and so far, only a few service providers have implemented the standalone core for 5G networks, network slicing deployment is still in its early stages.

Interference and Signal Quality: The integration of LEO and 5G-Advanced systems should consider potential interference between LEOs and TNs and the impact of atmospheric conditions on signal quality. Interference from other satellites, poor atmospheric conditions causing degraded signal quality, and cross-network synchronization aspects can affect the stability and performance of XR applications, leading to suboptimal Quality of Experience (QoE).

Specialized Power-Saving and Heat Optimizations for XR devices are essential to address battery and heat issues in XR glasses, especially for integrated TN/NTN operation requiring potentially longer communication links. 3GPP is exploring adaptive solutions to determine the best configuration for power-saving techniques such as Wake Up Signals or Discontinuous Reception (DRX) and adapt those in other systems [11]. Dynamic adjustments and monitoring frequency based on XR traffic, requirements, network load, and radio channel status may improve the QoE of XR.

Environmental Resilience & Security: The integration of LEO and 5G-Advanced systems for XR presents challenges in various domains, including remote areas and mountains. Unique environmental factors, such as atmospheric conditions, space weather events (solar flares and geomagnetic storms), extreme temperatures, and radiation, can significantly impact the cross-integration of NTN/TN systems. In PPDR, environmental resilience becomes crucial for XR systems to withstand and recover from emergencies and support critical communication needs. The TN/NTN integration enhances global mission-critical connectivity but introduces new security risks. 3GPP TS 33.501, TS 23.501, TS 38.811, and TS 38.821 address authentication, mobility, and encryption in these hybrid environments. ETSI TR 103 611, the MEC framework, and ITU-R M.2083 further support secure, harmonized architectures across heterogeneous domains. Yet, many aspects are still to be studied in more detail. Addressing these challenges requires robust system design to ensure reliable and secure communication under diverse and adverse conditions.

Interoperability: PPDR scenarios often involve multiple organizations and agencies working together in the same area but not necessarily utilizing the same infrastructure due to, e.g., legal reasons or level of NTN integration. Thus, the integration of LEO and 5G-Advanced systems may involve different regulatory frameworks and requirements in different countries. Standardizing compliance with regulatory guidelines and ensuring consistent adherence to international standards is necessary for a globally compatible XR communication system to ensure seamless data exchange between different XR systems, first responders, and communication networks.

Customized Immersive Content: In MC applications, deploying robust tools to construct and customize immersive content within virtual environments is paramount. This entails, e.g., empowering first responders with user-friendly 3D modeling instruments and related training, facilitating the creation and modification of essential virtual elements, and integrating spatial computing features that enable first responders to manipulate digital content within their remote & present physical surroundings and fostering a heightened level of interaction and immersion.

Enhanced Accessibility Features: Ensuring service availability to first responders with diverse abilities is imperative. Those cover, e.g., *(i)* providing voiceover and text-to-speech features to assist first responders with visual impairments, *(ii)* facilitating efficient navigation; *(iii)* integrating haptic feedback to enhance the overall experiential facet and convey critical information with hearing impairments through tactile sensations; and *(iv)* enabling first responders to customize settings to align with individual needs and operational requirements, thereby fostering a more accessible and personalized XR experience.

VI. Conclusions

The potential of XR to transform MC operations through immersive and real-time insights is unquestionable. However, the high computational demands of these applications often exceed the capabilities of wearable XR devices. To mitigate this limitation, offloading computationally intensive tasks to more powerful network nodes is crucial. While terrestrial networks can support XR services, their reliability may be compromised during emergencies or in remote areas.

In this work, we leveraged the integration of NTN and TN while delving into offloading schemes to ensure high-resilience communication in MC scenarios. We provided a case study that analyzed the performance of application-driven offloading for computationally intensive XR MC services across various network nodes in the 3D ecosystem. We evaluated end-to-end latency under diverse traffic loads at different network layers. The results indicated that offloading is more efficient for handling a small number of requests compared to local computing. However, for a high number of requests, local computing is the preferred approach.

The XR technology is continuously evolving nowadays with XR offloading and power saving study being included within the scope of 3GPP Release 18. The XR technology roadmap can be divided into three phases [15]. The current phase emphasizes the integration of digital content with physical environments using Virtual Reality (VR) and basic AR that are beginning to shape. In 1-2 years, wherein AR will advance and become more prevalent, facilitating seamless interaction between digital elements and real-world spaces is anticipated. Within 3-5 years, XR technologies are expected to become fully immersive and ubiquitous. In the context of XR MC, the evolution of XR will lead to a fully immersive MC experience over the years, pushing the need for integrated TN/NTN offloading levels even more.

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Olga Chukhno (olga.chukhno@unirc.it) is an Assistant Professor in Telecommunications at University Mediterranea of Reggio Calabria and CNIT, Italy. Her research interests include wireless communications and edge computing.

Nadezhda Chukhno (nadezda.chukhno@imdea.org) is a Post-Doc Researcher at IMDEA Networks Institute, Spain. Her research interests include wireless communications and ML.

Aleksandr Ometov (aleksandr.ometov@tuni.fi) is a Senior Research Fellow at Tampere University, Finland. His research interests include computing paradigms and wearable applications.

Sara Pizzi (sara.pizzi@unirc.it) is an Assistant Professor at University Mediterranea of Reggio Calabria and CNIT, Italy. Her research interests focus on resource management for multicast service delivery, 5G/6G networks, and NTN.

Giuseppe Araniti (araniti@unirc.it) is an Associate Professor at University Mediterranea of Reggio Calabria and CNIT, Italy. His research interests include enhanced wireless and satellite systems.

Antonella Molinaro (antonella.molinaro@unirc.it) is a Full Professor at University Mediterranea of Reggio Calabria and CNIT, Italy and with University Paris-Saclay, France. Her research mainly focuses on wireless and mobile networking, vehicular networks, and future Internet.