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TOPICAL REVIEW

On the Way to Holographic-Type Communications: Perspectives and Enabling Technologies

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ABSTRACT Holographic-type communication (HTC) is on the verge of revolutionizing current communication paradigms. It will seamlessly connect people from distant locations through a fully immersive experience that will engage all five senses: sight, hearing, touch, smell, and taste. However, the practical realization and widespread adoption of HTC impose significant demands on current networks and end-user devices. While recent studies have primarily focused on discussing the HTC challenges and potential research directions, this paper takes a further step by evaluating the capabilities of wireless networks to meet HTC requirements. Specifically, it highlights the limitations of the fifth-generation (5G) networks by identifying HTC-related Key Performance Indicators (KPIs) and explores the potential of the sixth-generation (6G) networks. Moreover, it not only proposes potential research approaches for HTC enhancement but also analyzes their impact on the challenges in HTC implementation. Finally, the paper questions the ubiquitous potential of 6G, suggesting that a coordinated approach leveraging artificial intelligence (AI) for jointly optimizing user sites and communication networks is the most promising strategy, rather than solely relying on the capabilities of specific network generations.

INDEX TERMS 5G, 6G, AI, communication network, HTC, KPIs, user site.

I. INTRODUCTION

HTC is a groundbreaking technology that enables real-time transmission of holographic data across the network. It permits new levels of engagement between remote users, integrating all five human senses and facilitating interactions that closely mimic realistic face-to-face scenarios. Many diverse fields of everyday life, such as remote communication and collaboration, healthcare, education, and entertainment, will benefit from its potential. Furthermore, holography and holographic telepresence are pivotal enablers for the Metaverse [1], [2], by contributing to the creation of new digital realms, wherein human representations and systems closely imitate their physical counterparts. Consequently, a profound correspondence between the digital and physical worlds can be created, as the role of HTC is to extend this correspondence beyond mere visual representations. Therefore, holograms, serving as three-dimensional (3D) digital copies of real individuals and objects, must faithfully convey not only their physical appearance but also their motions and interactions granting users six degrees of freedom (6DoF) [3], [4]. In terms, HTC must guarantee seamless execution of the entire process, encompassing interactive holographic data capture, transmission, and reproduction.

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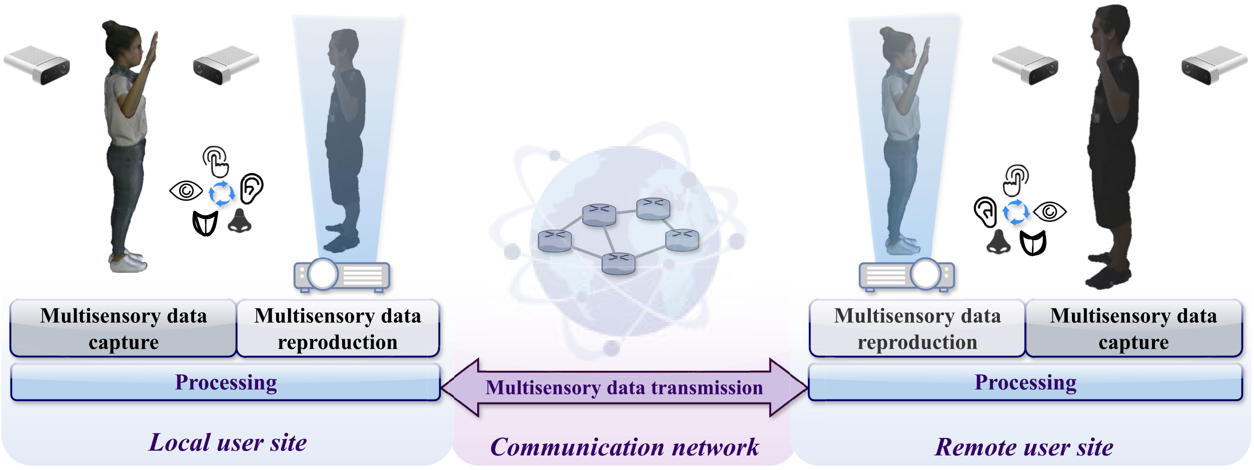

FIGURE 1. Conceptual block diagram of HTC system, comprising local and remote user sites connected via the communication network.

Fig. 1 presents a conceptual diagram of HTC system, where users in distinct locations (visualized as local and remote user sites) communicate with each other by perceiving 3D visual representations of their remote interlocutor. The Multisensory data capture and the Multisensory data reproduction blocks are responsible for engaging multiple human senses during communication. The Processing block processes the captured data, which are transmitted through the communication network. However, to ensure an authentic and interactive user experience in a face-to-face manner, detailed capture, fast data processing, and extreme data transmission are required. This places significant demands on both communication networks and user sites.

Emerging 5G networks promise to support data rates up to 20 gigabits per second (Gb/s) and 1 millisecond (ms) round-trip latency [5]. However, the transmission of holographic content calls for exceeding these limits. A high-resolution hologram of a single physical object captured from multiple views may require data rates of up to a few terabits per second (Tb/s). The real-time transmission of such a vast amount of data is unattainable with 5G, prompting the consideration of 6G networks as a potential solution. Factors contributing to this prospect include the integration of higher frequency bands in 6G, such as THz-bands and the visible light spectrum, along with a reduced network transmission delay and a network architecture enriched with embedded intelligence. Nevertheless, enhancing communication technology by transitioning to next-generation networks is not the sole aspect on which HTC researchers and developers should focus. Achieving a fully immersive and interactive communication experience necessitates a coordinated approach that considers both communication networks and user-site optimization.

In short, the contributions of this paper are summarized as follows:

- identifying the major technological challenges of HTC systems, introducing HTC-related KPIs, and emphasizing the 5G network limitations in the context of the indicated challenges and KPI target values;
- exploring the 6G vision for the future HTC realization through an analysis of some of the most cited 6G publications from the last five years;
- proposing potential approaches for HTC enhancement from the perspective of both the communication network and the user site;
- evaluating the impact of the proposed approaches on the identified HTC major technological challenges;
- outlining the roles of 6G and AI in enabling a truly immersive holographic communication experience.

The structure of the paper is shown in Fig. 2. Section II introduces notable studies related to HTC and highlights the contributions of this paper. The specifics of HTC are presented in Section III, exploring critical applications, the typical architecture of HTC systems, and major technological challenges. Section IV introduces HTC-related KPIs and emphasizes the motivation behind this work by explaining why 5G networks are pushed to their limits when facing heavy HTC requirements. In terms, the 6G vision for the future HTC realization is explored in Section V. Further, the impact of the potential approaches for HTC enhancement, proposed in Section VI, on the identified technological challenges is evaluated in Section VII. Section VIII outlines the roles of 6G and AI in enabling an immersive communication experience. Finally, Section IX concludes the paper.

II. RELATED WORKS

Considering the significant potential of holographic technology in communication, the following studies propose current research directions to advance the realization of HTC.

The need for moving to 6G networks by performing a gap analysis of 5G and predicting the synthesis of near-future applications such as HTC was motivated in [6]. Specifically, critical 6G enablers, such as a new network architecture, a pervasive introduction of AI at the network edge,

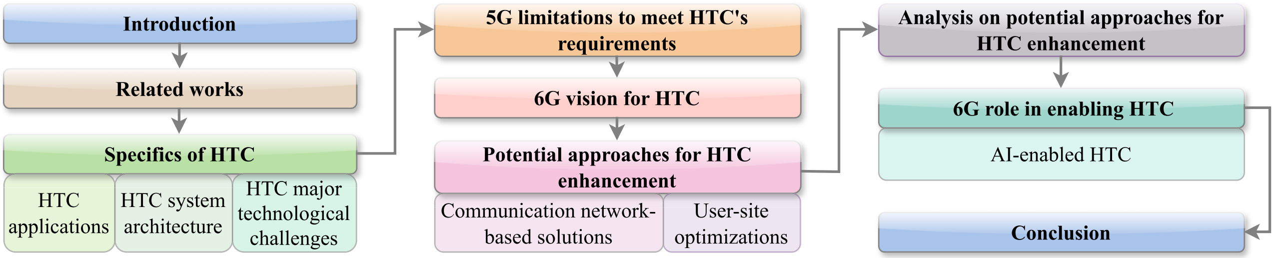

FIGURE 2. Paper structure.

3D coverage, a new physical layer incorporating sub-THz and visible light communications (VLC), and distributed security mechanisms, which will facilitate holographic communication, are identified. A description of the HTC technological challenges is provided in [7], where a cross-layer approach toward achieving a fully interactive holographic experience is presented. This includes optimization at the user side, transport and application layer optimization, and network layer optimization. Furthermore, the status and challenges of volumetric media applications regarding 6DoF content delivery are outlined in [8]. The authors proposed an architecture that enables an end-to-end system for immersive 6DoF media streaming and consists of four components: source side, network domain, client side, and a component for quality and perception evaluation. In [9], a highlight of the limitations of existing wired and wireless networks that impede the realization of HTC was provided. 6G and beyond promising networking technologies are discussed as an emphasis is placed again on HTC sources, HTC networking, and HTC destinations. The authors of [10] introduce future immersive communications in 6G networks, specifically extended reality (XR) based communications, haptic communications, and holography and holographic communications, their challenges, and possible solutions.

However, whereas the aforementioned publications only highlight the problems associated with HTC, this paper identifies HTC technological challenges based on our prior analysis of practical implementations and simulations of HTC systems and on our own experience in developing a Holographic Telepresence System (HTPS) [11], [12]. Furthermore, this paper outlines various HTC-related KPIs and categorizes them into four classes. In addition to presenting their target values for both 5G and 6G, where feasible, the KPIs specifically demanded by the HTC are also indicated. The objective is to underscore the limitations of 5G in fulfilling the HTC requirements. In alignment with the aforementioned publications, we propose potential approaches for HTC enhancement. These approaches are categorized based on the principal HTC entities outlined in Fig. 1, more specifically, the user sites and the communication network. Therefore, we delineate two distinct groups of approaches: communication network-based solutions and user-site optimizations. However, unlike the reviewed papers above, we evaluate the impact of each proposed approach on the identified technological challenges and outline the role of 6G and AI in universally enabling HTC.

Table 1 emphasizes the research perspectives of related papers and outlines the contributions of this work.

III. SPECIFICS OF HTC

This section presents the specifics of HTC, indicating prominent HTC applications, the basics of HTC system architectures, and the major systems' technological challenges.

A. HTC APPLICATIONS

Anticipated to become increasingly prevalent across various sectors of everyday life, HTC is set to revolutionize not only communications but also education, healthcare, entertainment, and more. Furthermore, it is expected to play a pivotal role in constructing the Metaverse. Figure 3 showcases the most prominent HTC applications, encapsulated within the domain of the Metaverse and founded upon HTC technology.

1) COMMUNICATIONS

Holographic teleconferencing and holographic telepresence [13], [14], [15], [16], [17], [18] are impressive HTC applications. There is a small conceptual difference between these terms. Whereas holographic teleconferencing aims to virtually meet participants in a 3D manner, holographic telepresence specifically refers to technology that allows people to be immersed in a different location without being physically there. However, both technologies refer to HTC and depend on enabling real-time and real-life communication and interaction with other people or objects. People should be presented by their virtual 3D avatars, which are exact copies of their physical bodies and should accurately convey their movements, gestures, and emotions. Current 2D video conferencing systems, such as Webex, Zoom, and MSTeams cannot support typical communication cues from actual face-to-face communication, such as gaze direction, gestures, tactile feedback, spatial faithfulness, depth perception of the physical environment, and physiological signals. However, HTC promises to support the above while assuring users of immersive and spatially aware communication and interaction. This will lead to the possibility of remote task collaboration in many application fields, such as education, healthcare, and entertainment.

TABLE 1. Summary of related HTC surveys.

Reference	Puplication time	Topic	Research contributions
[6]	September, 2019	5G gap analysis and near-future applications in 6G	Specification of critical 6G enablers that will help to fulfill new services' challenging requirements, such as new network architecture, AI at the network edge, 3D coverage, new physical layer, and distributed security mechanisms; Introduction of the concept of semantic communications.
[7]	January, 2020	Challenges and solutions of truly-immersive HTC	Description of the main HTC technological challenges and proposition of a cross-layer approach (optimization at the user side, transport and application layer optimization, and network layer optimization) for enabling fully interactive HTC.
[8]	October, 2020	Status and challenges of volumetric media applications regarding 6DoF content delivery	Proposition of an architecture for enabling an end-to-end system for immersive 6DoF media streaming consisting of four components: source side, network domain, client side, and a component for quality and perception evaluation.
[9]	September, 2022	HTC architectures, limitations, and possible 6G and beyond solutions.	Discussion of promising research direction by emphasizing HTC sources, HTC destinations, and HTC networking that includes physical and data link layer, network layer, transport layer, and AI at the network edge.
[10]	January, 2023	Concepts of future immersive communications in 6G networks: XR-based, haptic, and holography-based	Review on challenges and possible research directions for enabling HTC including in the aspects of data processing, communication, and networking, regarding the physical layer, the transport layers, and computing architectures.
[11]	December, 2022	HTC system framework, experienced challenges, and HTC system comparison	Review of HTC system implementation challenges, systematized in main technological challenges, representation challenges, and other challenges; Outline of the limitations of existing HTC systems, and a proposition of a conceptual framework for future HTC system development.
[12]	October, 2023	Modular and interoperable approach for HTPS development	Proposition of a novel, modular architecture for HTPS, consisting of a Data Acquisition Layer, Processing Layer, Transmission Layer, and Immersion layer; Substantiation of the proposed approach through practical HTPS implementation and extensive performance evaluation.
THIS PAPER		HTC specifics, HTC-related KPIs and 5G limitations in meeting HTC requirements, 6G vision for HTC, potential approaches for HTC enhancement and their impact on indicated HTC technological challenges	Identification of HTC challenges based on prior analysis of HTC systems and HTPS implementation; Indication of HTC-related KPIs categorized in four groups; Highlight of 5G limitations to meet HTC requirements; Exploration of the 6G vision for enabling HTC through an analysis of some of the most cited 6G publications; Proposition of potential approaches for HTC enhancement systematized in communication network-based solutions and user-site optimizations; Evaluation of the proposed approaches' impact on each of the identified challenges emphasizing the role of 6G and AI for fully enabling HTC.

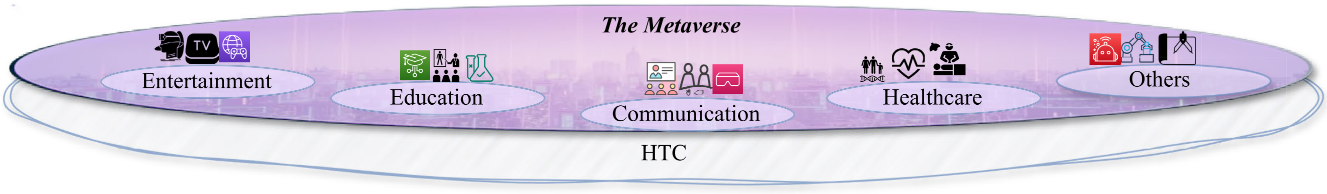

FIGURE 3. Emerging domains of HTC applications.

2) HTC IN EDUCATION

HTC will play a significant role in education by providing immersive and interactive learning experience [19], [20], [21], [22], [23], [24], [25]. Students can explore distant locations while interacting with virtual 3D objects, and receive real-time guidance without leaving the classroom. They will manage to attend meetings with invited speakers from all over the world in an immersive and interactive manner. Students will accomplish collaborative learning by working together on projects or problem-solving activities, even if they are physically located in different places. Examining complex concepts, structures, and organisms using appropriate 3D models will enable interactive and detailed understanding. Using HTC, the students will get hands-on training experience in various fields, such as medicine, aviation, engineering, etc. In this way, they will practice different procedures and manipulations and receive real-time feedback in a controlled and safe environment.

3) HTC IN HEALTHCARE

HTC has significant potential in the healthcare field [24], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38]. First, it is expected that HTC will boost telemedicine, remote consultations, and diagnosis by allowing healthcare professionals to interact with distantly located patients in a more realistic and immersive manner. Doctors will be able to examine patients remotely, provide visual guidance, and demonstrate different medical procedures. Second, the use of HTC will also enhance surgical planning. For example, surgeons will visualize and plan complex surgeries using holographic representations and will gain a better understanding of the procedure. Surgical training can be facilitated by providing young surgeons with realistic simulations. Third, remote collaboration and expert consultation between distantly located medical professionals in a real-life manner become possible via HTC. Doctors will receive real-time guidance and support during complex medical procedures by sharing holographic representations. Furthermore, augmenting some specific virtual objects in the surgeons' Field of View (FoV) will provide them with immediate access to patient data. Finally, HTC will also help patients' education and rehabilitation by providing them with a better understanding of their physical state, treatment plan, and post-operative care.

4) HTC IN ENTERTAINMENT

In the field of entertainment, HTC will bring many new and immersive experiences [39], [40], [41], [42], [43], [44], [45], [46]. Live concerts and performances will be brought to the audience even if the artists are physically absent or if the audience is not located in the performance place. HTC will influence the gaming experience by allowing users to immerse themselves in different worlds and view themselves and others like virtual avatars in a more social gaming environment. Holographic television, including movies, advertisements, news, and TV shows will make the audience feel like it is part of them, with all the characters and scenes appearing in 3D space. Museums, virtual parks, and attractions will be attended by distantly located users providing them with a unique entertainment experience and performing the idea of virtual tourism. Interactive storytelling will immerse people in a narrative, allowing them to engage with the characters.

5) THE METAVERSE

In addition to being standalone HTC applications, all the mentioned use cases above are increasingly becoming integral parts of the Metaverse [47]. The Metaverse refers to a virtual universe encompassing interconnected digital realms where individuals are represented by their 3D virtual avatars. Since enabling social interactions between users is an important aspect of the Metaverse, allowing people from different locations to connect, communicate, interact, and engage in various real-life activities is crucial. Therefore, HTC emerges as a foundational technology facilitating immersive and engaging experiences among users, making it one of the key enablers for constructing the Metaverse [48], [49].

B. HTC SYSTEM ARCHITECTURE

As elaborated in the preceding subsection, HTC has the potential to revolutionize numerous sectors of our everyday lives, reshaping current voice- and video-based communication paradigms. This transformation was due to the introduction of a third-dimensional perspective, fostering lifelike interactions enriched with a multisensory human experience. A block diagram of a general HTC system based on [11] is shown in Figure 4. Each block is responsible for the following functions: multisensory data capture, data processing, data transmission, and multisensory data reproduction.

Multisensory data capture requires the use of different sensors (visual, audio, tactile, olfactory, and gustatory) to capture multi-sense physical data. These data are then subjected to various processing steps during the data processing stage. For example, if visual data are captured from different views, they must be aligned and reconstructed as a common 3D model. It must also be synchronized and encoded with the rest of the sensory data and streamed to a remote destination. When the holographic data arrive at the destination, they must be decoded and processed further. For example, the visual component must be calibrated and rendered synchronously within the local coordinate system. Finally, the rendered model and the rest of the sensory data must be reproduced for the user by the multisensory data reproduction block. The data transmission block is representative of the communication network.

C. HTC MAJOR TECHNOLOGICAL CHALLENGES

Implementing a system similar to the one proposed in Fig. 4, which is capable of real-time holographic data transfer, faces significant technological challenges. As a result of the HTC system analysis in [11], several key considerations can be revealed. Firstly, ensuring a lifelike representation and interaction with human avatars, virtual objects, or complete environments demands the assurance of 6DoF through detailed capturing from various perspectives and substantial subsequent processing [3], [4]. Fig. 5 illustrates the concept of 6DoF, representing the six mechanical degrees of freedom governing the movement of a rigid body in a 3D space. These encompass translational movements along the three orthogonal axes: up/down (heave), left/right (sway), and forward/backward (surge), as well as the rotational movements around them, commonly denoted as yaw, pitch, and roll. This feature allows users to interact and freely explore holograms that adjust seamlessly when observed from different viewpoints, similar to interacting with tangible physical objects. However, the human eye is susceptible to visual disparities; therefore holograms must be transmitted and rendered at remote locations with very high data rates and ultra-low latency which will inevitably strain network bandwidth and user computational resources. Secondly, a unified network paradigm for the transmission of holographic

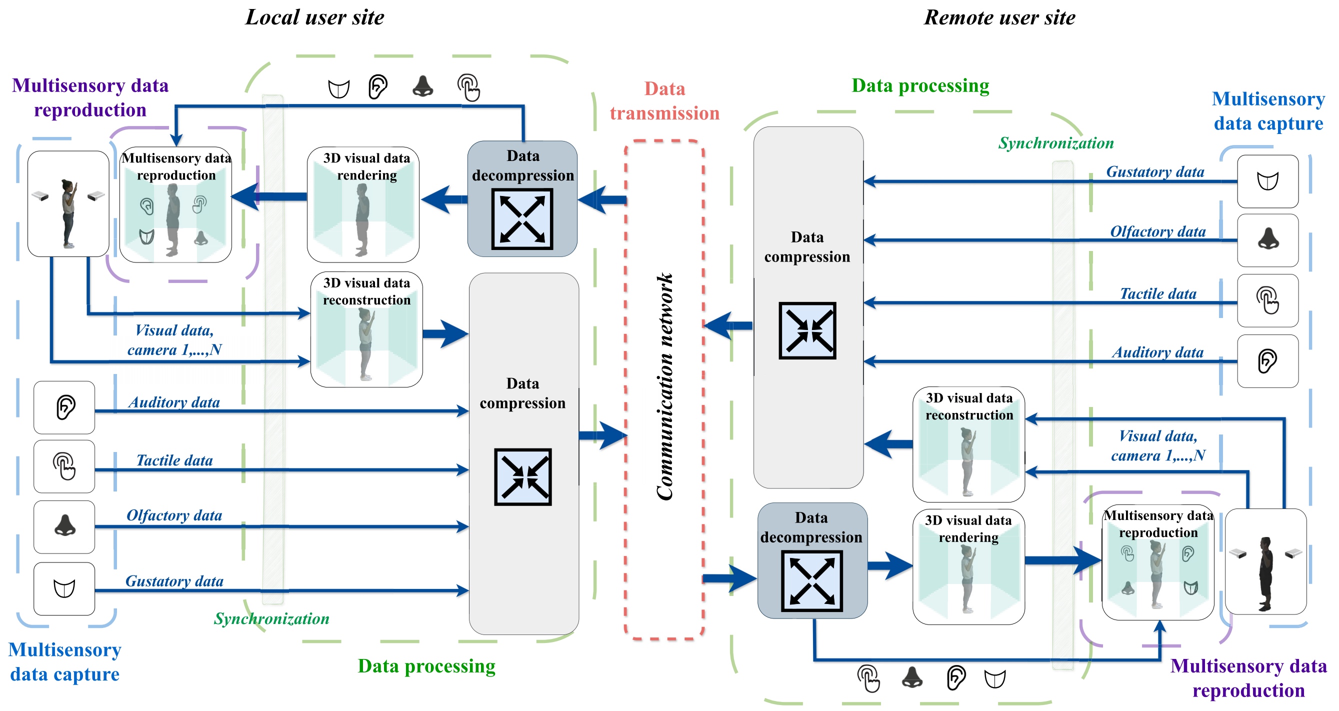

FIGURE 4. Block diagram of general HTC system featuring Multisensory data capture, Multisensory data reproduction, and Data processing blocks at each user site, and Data transmission block embodying the communication network.

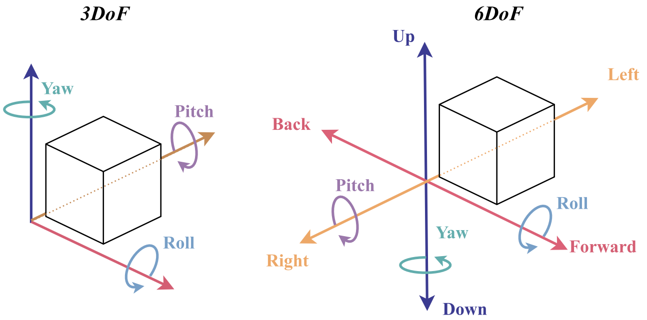

FIGURE 5. Concept of 3DoF (left) and 6DoF (right).

content is notably absent. Thirdly, the observed latency exceeds the HTC thresholds, thereby adversely affecting the perceived Quality of Experience (QoE). Finally, the systems exhibit limited scalability, as they support mainly video and audio data flows originating from individual HTC sites. This conceals the challenges posed by stringent synchronization requirements, which inevitably appear when HTC attempts to link multiple users from diverse locations.

The performance results of HTPS, as reported in [12], validate the above observations. Firstly, the substantial amount of data captured, facilitated by the data acquisition network, imposes a limitation on the maximum stable frame rate of only eight frames per second. To address this limitation and enhance the frame rate, adjustments, such as reducing the frame size or extending the bandwidth capacity, are necessary. Secondly, the use of a Transmission Control Protocol (TCP) as a transport layer protocol introduces drawbacks. Whereas TCP ensures reliable data delivery and congestion control, it brings additional overhead and latency early in the data delivery process. This leads to stuttering and desynchronization between the sensor units. Notably, the analysis lacks a comparison of TCP behavior with other transport layer solutions based on the User Datagram Protocol (UDP). However, a more efficient transport layer protocol is required. Thirdly, the incurred latency, resulting from the cumulative time delays during data transmission and processing (excluding compression), exceeded 300 ms, negatively impacting the perceived QoE. Furthermore, introducing compression increases latency, so sufficient computational resources are demanded. Finally, the practical implementation of HTPS needs to be expanded to connect distant users, potentially facing scalability limitations and hidden synchronization problems.

Based on the aforementioned discussion, we can emphasize four significant technological requirements that pose challenges to HTC:

- The first HTC requirement is a large bandwidth to ensure very high data rate transmission of the vast volume of holographic content. The required bandwidth depends on hologram type, size, resolution, and transmission frame rate. As an illustration, let us consider a point cloud hologram represented by 3D points, with each point characterized by its x, y, z coordinates and r, g, b color attributes. If a single Microsoft Kinect v2 sensor captures the point cloud, it generates 217,088 points, with each point encoded with 15 bytes. Assuming three sensors working at 30 fps, approximately 2.2 Gb/s would be required to transmit the data over the network. Conversely, image-based holograms, particularly Light Field Views (LFVs), represent physical objects through multiple 2D images captured from different angles and tiles. This approach would demand a significantly higher bandwidth capacity for subsequent data transmission, reaching the order of Tb/s.

- The second main requirement is the reduction of the end-to-end latency. According to [50] the required end-to-end latency varies for different HTC applications. Applications that tolerate buffering may have latency tolerances in the range of 50-100 ms, highly interactive services may target 20-50 ms, and ultra-low latency services may aim for approximately 1 ms. Note that each stage of the holographic communication pipeline adds a delay to the end-to-end latency. The 3D object reconstruction, compression, decompression, synchronization, etc., consume the time for data transmission, whose speed cannot exceed the speed of light.
- The third technology requirement is the need to support strict synchronization between multiple flows. Once, synchronization must be maintained between the different data sources at the local site [51], and then, between the packages arriving at the destination [52], [53]. Desynchronization decreases the perceived QoE. The advantages of different buffering schemes and various synchronization techniques may benefit this requirement, but holographic data is very storage-intensive, so large buffer sizes are practically inapplicable. In addition, achieving stricter synchronization will inevitably increase latency.
- Finally, HTC processing is often performed by implementing heavy computation algorithms that increase the processing delay, thereby affecting the overall latency. This often requires the user to be equipped with high-performance computational hardware, which will hurdle the widespread adoption of HTC.

All these requirements are closely related. For instance, improving the compression ratio will significantly decrease the required bandwidth. However, this will also increase the processing time, thereby negatively affecting the overall latency. In contrast, the critical latency requirement may benefit from lightweight computation; however the amount of transmitted data may exceed the link capacity. Therefore, all of these challenges must be addressed together, and an optimal trade-off between their solutions must be achieved.

IV. 5G LIMITATIONS TO MEET HTC KPIs

This section justifies the need to move to 6G networks by emphasizing the 5G limitations to meet the major technological challenges of HTC. To illustrate this, we present several network KPIs [5], [54], [55], [56], [57] related to HTC systems and categorize them into four groups. The first category encompasses KPIs directly associated with the HTC system performance, such as peak and user-experienced data rates and latency. The second category consists of KPIs indirectly linked to the HTC system performance, including maximum bandwidth, area traffic capacity, coverage, jitter, and reliability. Optimizing their values is crucial for the KPIs from the first group, and consequently, for the overall system performance. The third group includes KPIs related to HTC system capabilities, such as system intelligence, sensing (imaging) resolution, mobility, and system security. Although not exclusive to HTC system performance, maximizing these factors can significantly enhance it or incorporate additional features to improve QoE. The final group covers the KPIs associated with system efficiency, including spectral, energy, and cost efficiency. This categorization aims to highlight which KPIs must be optimized during HTC system implementation and which, although optional, are highly desirable for the improving system performance and QoE. Table 2 provides an overview of these categories, presenting the respective KPIs, definitions, measurement units, and target values for both 5G and 6G networks.

Since the perceived QoE is a crucial performance indicator for holographic telepresence applications [58], [59], meeting HTC demands is essential. However, this is not a trivial task and 5G networks encounter challenges in this context. To emphasize the limitations of 5G, Table 3 offers insights into the identified HTC technological challenges and the respective 5G and 6G KPI target values. As indicated in the table, the optimal 5G KPIs appear insufficient to adequately address HTC demands. Firstly, despite the varied bandwidth requirements introduced by the level of detail in hologram representations, the specified 5G peak data rates of up to 20 Gb/s fall short of transmitting high-resolution holograms that require anywhere from a couple of Gb/s to a few Tb/s. Secondly, latency demands, depending on the assumed interactivity, range from a couple of tens of ms up to only 1 ms. For highly interactive scenarios targeting end-to-end latency below 50-20 ms, the 5G network transmission latency of above 1 ms poses a limitation, especially when considering significant processing times at the source and destination user sites. Thirdly, maintaining strict synchronization is vital to support scalable HTC systems that connect multiple users from different locations. Reasonably, transmission latency and its variance, known as jitter, are crucial parameters for synchronizing data flows from multiple sources. However, jitter values of 1ms are too high and can corrupt the rendering process at the user site, particularly when multiple data flows arrive. The application of more precise synchronization algorithms capable of mitigating jitter will further increase experienced latency.

Consistent with the above discussion, it is clear that 5G networks will face significant challenges in meeting the HTC requirements. In contrast, the 6G KPIs indicated in Tables 2 and 3 significantly surpassed those of 5G, making 6G networks a promising solution. Specifically, 6G data rates, bandwidth resources, and area traffic capacity are noteworthy when compared to those of 5G, suggesting the potential for transmitting much larger volumes of content through

TABLE 2. HTC-related KPIs and their target values in 5G and 6G networks, classified into distinct groups regarding HTC system performance, capabilities, and efficiency.

KPI class	KPI	KPI definition	Unit	5G	6G
KPIs directly related to HTC system performance	Peak data rate	Maximum data rate achievable under optimal conditions, wherein all available radio resources are entirely allocated to a single mobile station.	Tb/s	0.02 Tb/s	1 Tb/s
	User experienced data rate	5th percentile point (5%) on the cumulative distribution function of user throughput, ensuring users have a 95% probability of achieving at least this throughput level, irrespective of the time or location.	Gb/s	0.1 Gb/s	10 Gb/s
	Latency	One-way time it takes for the network to successfully deliver an application layer packet or message from source to destination.	ms	1 ms	0.1 ms
KPIs indirectly related to HTC system performance	Maximum bandwidth	Maximum cumulative system bandwidth that can be accommodated by single or multiple radio frequency carriers.	GHz	$1GHz$	$100GHz$
	Area traffic capacity	Evaluation of the complete mobile data load that a network can handle within a specific unit area, considering factors such as available bandwidth, spectrum efficiency, and network densification.	$Gb/s/m^2$	0.01 $Gb/s/m^2$	10 $Gb/s/m^2$
	Coverage	The coverage percentage of network service.	–	10%	99%
	Jitter	Variability in latency times.	ms	$1ms$	$0.001ms$
	Reliability	Network's ability to successfully transmit a specified amount of data within a predefined time duration with a high probability of success.	-	99.999%	$\geq$ 99.99999%
KPIs related to HTC system capabilities	Mobility	Maximum speed at which a mobile station can move while still maintaining an acceptable QoE with network support.	km/h	500 km/h	1000 km/h
	Sensing (Imaging) resolution	Resolution of sensing and imaging.	m	$1m$	$0.001m$
	System intelligence	Intelligence level of the communication system.	–	Low	$High$
	System security	Rate of trustworthy information transmission under the threat of eavesdroppers.	–	Low	$High$
KPIs related to HTC system efficiency	Spectral efficiency	Average data rate under optimal conditions, adjusted by the channel bandwidth.	$b/s/Hz$	30 $b/s/Hz$	$\geq$ 90 $b/s/Hz$
	Energy Efficiency	Amount of network energy consumption related to the traffic capacity provided.	b/J	10^7 b/J	10^9 b/J
	Cost Efficiency	Amount of data traffic cost related to the user's data consumption benefit.	$Gb/\$$	$10Gb/\$$	$500Gb/\$$

TABLE 3. Comparison of major HTC technological challenges with corresponding requirements and target KPI values in 5G and 6G networks.

Technological challenge	HTC requirement	5G	6G
Data rate	$0.5-2$ Gb/s Point cloud hologram, $0.1-2$ Tb/s Light field hologram, [7]	0.02 Tb/s Peak data rate, 0.1 Gb/s User experienced data rate	1 Tb/s Peak data rate, 10 Gb/s User experienced data rate
Latency	End-to-end latency (including processing): $50-100$ ms with buffering tolerance, $20-50$ ms highly interactive applications, 1 ms ultra-low latency applications, [50]	Network transmission latency: 1 ms	Network transmission latency: 0.1 ms
Synchronization	Synchronizing multiple flows arriving from different locations at the destination [52], [53]	Transmission latency up to 1 ms, Jitter values - $1ms$	Transmission latency up to 0.1 ms, Jitter values up to 0.001 ms
Computation	Requirement of running heavy computation algorithms for 3D model reconstruction, compression, etc.	Introducing network cloud computing	6G accommodating both computation and communication

the network. In addition, the reduction in latency and jitter, along with improved reliability, facilitates real-time data transmission and better synchronization. Some other new KPI values, such as intelligence, sensing, and security, are to be incorporated into 6G [57] because of their importance for emerging immersive communications.

Fig. 6 provides a comparative visualization of the HTC-related KPIs, organized into four groups, as outlined in Table 2. The inner flag blocks present the KPIs, followed by their 5G target values in the solid-lined flag blocks. These values are compared with the 6G target values from the dash-lined flag blocks. The outer circular blocks present enhancements in the KPI values in the context of 6G. Fig. 7 depicts the progression of network generations based on the provided data rates and services, highlighting HTC as one of the main service types that will be offered by future 6G networks.

V. 6G VISION FOR HTC

The current section analyzes relevant 6G publications from the last five years to explore the 6G vision for future HTC realization. Although they cover various aspects, each of them particularly specifies HTC. Indeed, different terms are used for it, such as holographic-type

FIGURE 6. Comparison of KPIs target values in 5G and 6G networks.

communications, holographic communications, holographic teleportation, holographic telepresence, holographic technology and communications, multisensory XR applications, multisensory holographic teleportation, and multisensory XR experience. Nevertheless, all of them refer to the same concept, i.e. the technology of holographic data transmission through the communication network.

The concept of future 6G networks is presented in [60], where primary use case scenarios and their corresponding network requirements are outlined. A large-dimensional and autonomous network architecture for achieving pervasive and ultimate wireless connectivity is proposed. The discussion extends to various key enabling technologies for 6G and the role of AI and ML in constructing autonomous networks and air-interface design. In the context of HTC, the envisioned driving forces behind 6G are the mobile Internet and the Internet of Everything, supporting holographic and high-precision communications to deliver a comprehensive sensory experience. Innovative 6G applications are identified, highlighting holographic verticals and full-sensory digital reality as representatives of a new 6G service type, referred to as Further-enhanced Mobile Broadband (FeMBB).

Multisensory XR applications are identified as the primary driver of 6G [61]. Although not explicitly referred to as HTC, they underscore a specific aspect of holographic technology, enabling truly immersive Augmented Reality

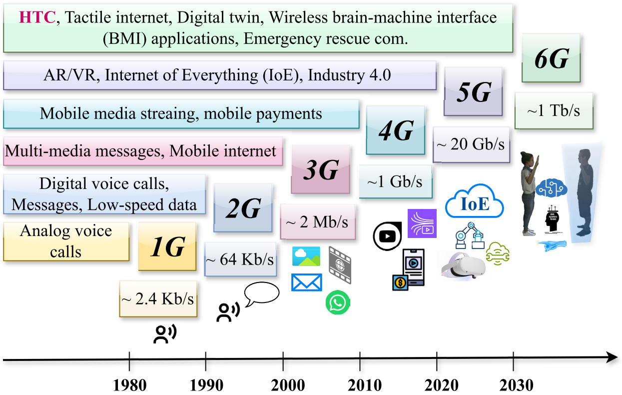

FIGURE 7. **Evolution of mobile network generations in terms of data rates and provided services.**

(AR), Virtual Reality (VR), and Mixed Reality (MR) experiences by incorporating various human perceptions and including multiple senses, cognition, and physiology. New 6G service classes are introduced, such as Mobile Broadband Reliable Low Latency Communications (MBR-LLC), Massive Ultra-Reliable Low Latency Communications (MURLLC), Human-Centric Services (HCS), and Multi-Purpose 3CLS and Energy Services, where 3CLS represents the Convergence of Communications, Computing, Control, Localization, and Sensing. Given that upcoming services such as multisensory XR will demand both high data rates and ultra-low latency, the clear distinction between enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low Latency Communications (URLLC) proposed in 5G may no longer suffice. Consequently, 6G is anticipated to support services existing within the realm of rate-reliability-latency encapsulated by MBRLLC.

The perspective that human-centric mobile communications will continue to be the foremost application of 6G networks is presented in [62] where a systematic framework outlining potential 6G application scenarios substantiates this viewpoint. Among these scenarios, holographic communication is highlighted as a significant use case, marking the shift from conventional video conferencing to more immersive interactions, with 6G identified as the primary catalyst for this transformation. Additionally, 6G essential features, necessary communication technologies, and potential challenges that might hinder its practical deployment are explored.

Various new use cases, whose requirements extend beyond the capacity of 5G networks, emphasize the necessity for advancements beyond 5G [63]. Among these, holographic telepresence, also referred to as "teleportation," is recognized as a challenging scenario with significant communication demands. In this context, three fundamental aspects crucial for the transition to 6G are outlined, including the introduction of new communication technologies, network architectures, and deployment models.

Insights into emerging network trends that will influence the future landscape of 6G are shared in [64], envisioning the interconnection of physical, biological, and digital worlds. These trends include novel man-machine interfaces, widespread distribution of ubiquitous universal computing across user devices and the cloud, multisensory data fusion, enhanced mixed-reality experiences, and precision sensing and actuation for controlling the physical world. The concept of holographic telepresence is anticipated to play a prominent role in both social interactions and professional settings. To pave the way for the integration of new services, such as HTC in 6G, six requirements and key performance measures are proposed. Another six fundamental dimensions for designing 6G, encompassing data, computing, energy, spectrum, spectrum efficiency, and space, are identified. Additionally, six technologies expected to shape future 6G networks are introduced: AI and ML, exploration of new spectrum bands, advancements in localization and sensing, extreme networking capabilities, novel network architectures, and the development of new security, privacy, and trust paradigms.

Another perspective for the future of 6G and beyond wireless communication systems is presented in [65]. The authors commence by introducing a range of critical use cases enabled by 6G, highlighting multisensory holographic teleportation as one of them. They assert that this particular use case will demand both very high data rates and ultra-low latency simultaneously, rendering 5G eMBB and URLLC inadequate for meeting such requirements. Furthermore, they present potential groundbreaking technologies that would facilitate the practical realization of new use cases, such as HTC, categorizing these technologies into two groups: 6G and beyond 6G.

Anticipating 6G to address the fundamental problems of its predecessor, such as higher system capacity, increased data rates, lower latency, improved security, and enhanced QoS, a vision of 6G networks and architectures is presented in [66]. First, a few 6G-specific service types, including ubiquitous Mobile Broadband (uMBB), ultra-High-Speed with Low-Latency Communications (uHSLLC), massive Machine-Type Communication (mMTC), and ultra-High Data Density (uHDD), are introduced. Specifically, the multisensory XR experience and holographic telepresence fall under the category of uHSLLC. Then, numerous emerging technologies that are expected to bring 6G to reality, including AI, big data analysis, terahertz and free-space optic communications, unmanned aerial vehicles, cell-free communications, integrated sensing and communications, etc., are presented. Finally, potential challenges and research directions are outlined.

A state-of-the-art analysis of the progress made in the development of 6G networks is proposed in [67]. It presents a taxonomy of 6G wireless systems, outlining main use cases, key enablers, and ML schemes, as well as communication, networking, and computing technologies. In addition, open research problems and potential solutions are explored. Holographic communication-based services are highlighted as one of the main use cases, offering remote connections with high accuracy and data rates.

A perspective on the future 6G ecosystem is provided in [68]. An emphasis is placed on 6G KPIs applicable to specific use case scenarios. In contrast to 5G, the vision for future services in 6G encompasses a variety of new service classes, including further enhanced Ultra-Mobile Broadband (feUMBB), ultra-High Sensing Low Latency Communications (uHSLLC), ultra-High Density Data (uHDD), ultra-High Energy Efficiency (uHEE), ultra-High Reliability and Sensing (uHRS), ultra-High Reliability and User experience (uHRUx), ultra-Low Latency Reliability and Secure (uLLRS), ultra-High Security (uHS), ultra-High Sensing, and others. Holographic communications are envisioned as one of the use cases of 6G networks with great potential to replace physical and other types of virtual meetings. According to [68], holographic communication will benefit from the combination of uHSLLC, uHDD, and uHRS service classes.

To address the question of whether human society truly needs 6G, the authors of [69] conduct a state-of-the-art analysis of 6G-related papers. They refer to key drivers for 6G, including the exponential growth of mobile traffic and subscriptions until 2030 and disruptive use cases, with HTC highlighted as an example. Given the diverse and demanding network requirements of such disruptive applications, the authors identify three new use cases absent in 5G networks: ubiquitous Mobile Broadband (uMBB), Ultra-reliable Low-latency Broadband Communication (ULBC), and massive Ultra-reliable Low-latency Communication (mULC), with HTC specified as ULBC. The technical requirements of 6G are discussed in terms of KPIs and enabling technologies are categorized into groups, such as New Spectrum, New Networking, New Air Interface, New Architecture, and New Paradigm. Finally, insights into “What 6G may look like?” are provided.

The future of 6G networks, system requirements, and key features are outlined in [70]. Driving applications and new services for 6G with a specific emphasis on multisensory XR applications are also proposed. Owing to the perceived inability of 5G to meet the network requirements for such services, it is anticipated that 6G will evolve from the original 5G services (eMBB, URLLC, and mMTC) and introduce new service types such as mobile broadband reliable low latency communications, network slicing, massive URLLC, HCS, and multi-purpose 3CLS and energy efficiency. Additionally, ongoing research and open problems regarding the 6G development and applications are presented.

A discussion of 6G systems, highlighting lifestyle and societal changes that are steering the direction toward next-generation networks is provided in [71]. The paper initially outlines 6G use cases and technological requirements, emphasizing holographic communication as a fundamental part of future networks, where holograms are envisioned as the primary medium of communication. To address the heavy demands imposed by holographic communication and other emerging applications, a top-down approach for necessary technological enhancements in core and transport networks is proposed. Additionally, new physical layer techniques, wave propagation characteristics in 6G networks, and challenges associated with developing specific hardware for the 6G physical layer are explored.

An extensive survey on 6G frontiers covering 6G driving trends, emerging applications, 6G requirements and visions, enabling technologies, recent projects, research work, standardization approaches, and future research directions is conducted in [72]. Holographic telepresence is identified as an emerging application that highlights the limitations of existing 5G networks. In contrast, 6G is anticipated to be a key enabler for such services, offering seamless and high-quality connections between remote users and ensuring high data rates and extremely low latency.

According to [73], 6G will couple and enable interactions between the physical world of objects and organisms, the human world of senses, bodies, and intelligence, and the digital world of information, communication, and computing, creating a common cyber-physical continuum. The authors outline the main 6G research directions, defined as connected intelligence, network of networks, sustainability, global service coverage, extreme experience, and trustworthiness. Further, 6G use cases are highlighted, defining immersive telepresence as an extreme and immersive experience that will blur the boundary between the physical and digital worlds and will serve as a communication tool for the future “fully merged cyber-physical worlds.”

The 6G vision, application scenarios, and technological trends from an industrial perspective are outlined in [74]. Three types of 6G application scenarios are introduced: immersive, intelligent, and ubiquitous applications. In addition, key enabling technologies for the realization of these applications are proposed. Holographic communication, aimed at providing an extremely immersive experience, falls into the category of immersive applications. The development of 6G networks must consider high data rates, low latency, transmission security, and reliability to satisfy its requirements.

The discussion presented in [75] focuses on the evolution toward 6G networks, with an emphasis on architectural evolution, post-2030 application landscape, region-wise statistics of 6G patents, 6G key enabling technologies, major challenges, and research directions. Within this context, holographic telepresence is identified as one of the key emerging applications whose requirements cannot be adequately addressed by the capabilities of 5G networks. These challenges are considered to be the core of 6G research.

The evolution of wireless communication networks from 1G to 6G is also traced in [76]. Specifically, three 6G milestones in terms of technologies, KPIs, and use case scenarios are delineated. Holographic communication is explicitly identified as one of the main 6G applications.

QoE management challenge in networks beyond 5G is addressed in [77], where the QoE provisioning ecosystem for emerging multimedia streaming services is introduced.

The work expands to provide a road map for future 6G networks, discussing requirements, use case scenarios, new service classes, and potential technologies. Emphasis is placed on 6G management, orchestration, and monitoring of multimedia 3D service, envisioning holographic and future media communications as one of the three main use case scenarios, similar to eMBB, URLLC, and mMTC in 5G.

The authors of [78] motivate the necessity of advancements beyond 5G in cellular networks, emphasizing the potential applications, vision, and requirements of 6G, along with enabling technologies and KPIs. Additionally, cutting-edge computing paradigms that are anticipated to drive the transition to the 6G era are explored. Insights into the latest 6G research, design activities, and existing challenges are also provided. With regard to holographic telepresence and immersive communications with their substantial demands on wireless networks, it is anticipated that 6G will be essential to meet their criteria. Consequently, holographic technology and communications are identified as among the most notable prospective applications of 6G.

An extensive survey on 6G, beginning with highlighting the limitations and challenges of 5G networks, is conducted in [57]. It presents a global vision of 6G, covering various aspects of future network technology. The survey outlines 6G technical requirements and application scenarios. In addition, it presents a vision of 6G network architecture, supplemented with 6G enabling technologies and existing testbeds. Finally, the survey addresses open research directions and challenges. The survey allocates space for holographic communication within the context of the application scenarios. 6G is expected to offer users a full sensory experience through various applications, with holographic communications leading the way.

In [79], the authors explore twelve scientific challenges aimed at reconstructing the theoretical foundation of communications. They revise various areas, including electromagnetic information theory, non-linear signal processing, multi-agent learning systems, super-resolution theory, thermodynamics of computation and communication, signals for time-varying systems theory, semantic communication theory, signals for integrated sensing and communication, large-scale communication theory, non-equilibrium information theory, combining queuing and information theory, and non-coherent communication theory. Within this context, the paper delineates the connection between diverse 6G applications, including holographic communication, and the scientific challenges posed by 6G.

A review of 6G mobile communication technology, covering its vision, importance, use case scenarios, and opportunities is presented in [80]. This review emphasizes key enabling technologies, challenges, and research directions. Three new service types are highlighted in terms of usage scenarios: Ultra-reliable Low latency Broadband Communications (ULBC), massive Ultra-reliable Low latency Communication (mULC), and ultra-Mobile Broadband (uMBB). Notably, HTC is expected to benefit from ULBC, which simultaneously offers ultra-low latency and high throughput.

Table 4 summarizes the insights from the reviewed 6G papers, focusing on HTC as a prominent application in the upcoming 6G era. Key observations include the anticipation of holographic technology and communication playing a central role in both social and professional contexts, spanning various application domains. Almost all of these papers explicitly highlight HTC as a major application, which will be uniquely enabled by the advancements in 6G technology. Moreover, HTC is envisioned as a tool capable of merging cyber-physical worlds. With 5G being perceived as inadequate for realizing this vision, HTC stands out as a pivotal driving force for the future development of 6G. In particular, 5G supports three primary service types: high-data-rate-demanding applications (eMBB), ultra-low latency-demanding applications (URLLC), and applications for massive device connectivity (mMTC). However, HTC falls somewhere between eMBB and URLLC, necessitating both very high data rates and ultra-low latency and reliability. In contrast, as evident from the reviewed papers, 6G proposes new service types to meet the diverse requirements of emerging technologies. Several of the reviewed papers propose new service types that facilitate HTC, albeit labeled under different names like MBRLLC [61], uHSLLC [66], ULBC [69], [80], all referring to the same concept.

VI. POTENTIAL APPROACHES FOR HTC ENHANCEMENT

Potential approaches for addressing the major HTC technological challenges identified in Section III-C are presented below. They are classified into communication network-based solutions and user-site optimizations according to Fig. 1. This classification is illustrated in Fig. 8.

A. COMMUNICATION NETWORK-BASED SOLUTIONS

In the context of the communication network, the current subsection introduces some 6G network-based solutions to enhance the practical implementation of HTC. They are categorized into physical layer enhancements, network architectures, and transport layer improvements. Each of them is thoroughly explored in the following text.

1) PHYSICAL LAYER ENHANCEMENTS

Current networks are challenged to meet the escalating data rate demands of emerging technologies, such as HTC. The transmission of high-resolution holograms captured from multiple angles and tiles may necessitate data rates reaching a few terabits per second, surpassing the limits set by 5G, as specified in Tables 2 and 3. To address this challenge, 6G networks are anticipated to leverage higher frequency bands beyond 300 GHz, enabling access to wider bandwidths and consequently achieving enhanced data rates. An added benefit of using high-frequency radio waves is the ability to form narrow beam widths through highly directional antennas, resulting in reduced interference and improved Signal-to-Noise ratio (SNR) at the receiver.

TABLE 4. Summary of 6G-related papers announcing HTC as a forthcoming 6G application.

Reference	Publication time	Paper topic	Vision for HTC
[60]	July, 2019	A vision of 6G wireless networks, requirements, architecture, and key technologies	Identification of holographic verticals and full-sensory digital reality as representatives of a new 6G service type, referred to as Further-enhanced Mobile Broadband (FeMBB))
[61]	October, 2019	A vision of 6G wireless systems in the context of 6G driving applications, 6G driving trends, and 6G enabling technologies	Introduction of multisensory XR reality application as a 6G driving application and associating it to a new 6G service class called Mobile Broadband Reliable Low Latency Communications (MBRLLC)
[62]	January, 2020	A vision of 6G to support human-centric mobile communications - application scenarios, requirements, enabling technologies, and challenges	Identification of 6G as the primary catalyst for transiting from conventional video conferencing to more immersive interactions in terms of holographic communications
[63]	March, 2020	Use cases and driving technologies towards 6G wireless networks	Identification of holographic telepresence as one of the future main use cases whose requirements will go beyond 5G system performance (in terms of throughput, latency, and multisensory experience)
[64]	March, 2020	A vision of the future look of 6G, its requirements, key performance measures, dimensions for system design, and enabling technologies	Introduction of holographic telepresence by its ability to provide an immersive experience and multisensory data fusion as one of the emerging themes for shaping 6G system requirements and technologies
[65]	July, 2020	A vision of future 6G and beyond wireless communication systems in terms of use cases, and 6G and beyond enabling technologies	Highlight of multisensory holographic teleportation as one of the main use cases that will be enabled by future 6G technologies
[66]	July, 2020	A vision of future 6G wireless communication and its network architecture, enabling technologies and open research directions	Specification of new 6G service types, identifying multisensory XR and holographic telepresence as ultra-High-Speed with Low-Latency Communications (uHSLLC)
[67]	August, 2020	State-of-the-art 6G wireless systems in terms of vision, architectural elements, and open research challenges	Specification of holographic communication-based services as one of the main 6G use cases that is considered to connect distant users in an immersive way.
[68]	January, 2021	6G ecosystem - current status, use cases, enabling technologies, network architecture, and future trends	Vision for holographic communications as a combination of ultra-High Sensing Low Latency Communications (uHSLLC), ultra-High Density Data (uHDD) services, ultra-High Reliability and Sensing (uHRS) 6G service classes
[69]	February, 2021	A comprehensive survey on the road towards 6G, answering the question if we really need 6G	Identification of HTC as a main disruptive use case scenario in 6G and its classification to one of the new types of 6G services termed as massive Ultra-reliable Low-latency Communication (mULC)
[70]	February, 2021	6G survey on technologies, applications, challenges, and research problems	Specification of multisensory XR as an emerging application in 6G which will impose both technological and physiological requirements and perceptual criteria that must be met during the 6G design stage
[71]	March, 2021	A vision of 6G wireless systems, main use case scenarios, their requirements, 6G enabling technologies, challenges, and opportunities	Introduction of holograms as an evolved communication media pacing the holographic communications as one of the main use case scenarios in 6G networks impacting their future outlook and design
[72]	April, 2021	A survey on 6G frontiers in terms of driving trends, applications, requirements, technologies, and future research directions	Anticipation of 6G as a key enabler for holographic telepresence by enabling seamless and high-quality connections between remote users
[73]	November, 2021	A vision of 6G values, use cases, and technologies	Definition of holographic telepresence as a communication tool for enabling the future "fully merged cyber-physical worlds"
[74]	March, 2022	A review of 6G vision, application scenarios, and technological trends from an industry perspective	Specification of holographic communications as one of the main 6G service types, referred to as immersive applications
[75]	May, 2022	A discussion on the network evolution to 6G in terms of network architectures, potential applications, and research directions	Identification of holographic telepresence as one of the key emerging applications unsatisfied by the 5G capabilities and a driver of the 6G research and development
[76]	August, 2022	Details on wireless communication networks evolution: from 1G to 6G, and specification of future 6G perspectives.	Identification of holographic communication as one of the main use case scenarios of future 6G networks

TABLE 4. *(Continued.)* Summary of 6G-related papers announcing HTC as a forthcoming 6G application.

Reference	Publication time	Paper topic	Vision for HTC
[77]	September, 2022	Discussion on QoE management in 5G and beyond networks and road map toward 6G and beyond	Vision for holograms and future media communications as one of the three main use case scenarios in 6G, similar to eMBB, URLLC, and mMTC in 5G
[78]	December, 2022	A research on 6G trends, vision, requirements, technologies, research, and standardization efforts	Identification of holographic technology and communications as one of the prospective 6G applications whose substantial demands are expected to be met by 6G
[57]	February, 2023	An extensive survey on 6G vision, requirements, enabling technologies, and testbeds	Expectation of 6G to offer users a fully sensory experience through a variety of applications, with holographic communications leading the way
[79]	February, 2023	Investigation of 6G scientific challenges	Definition of the mapping between 6G applications, in particular holographic communication, and the specified scientific challenges
[80]	February, 2023	A review of 6G mobile communication technology in terms of 6G vision, opportunities, enabling technologies, challenges, and open research directions	Vision for HTC as a representative of one of the new service types in 6G networks - Ultra-reliable Low latency Broadband Communications (ULBC) to benefit both ultra-low latency and high throughput

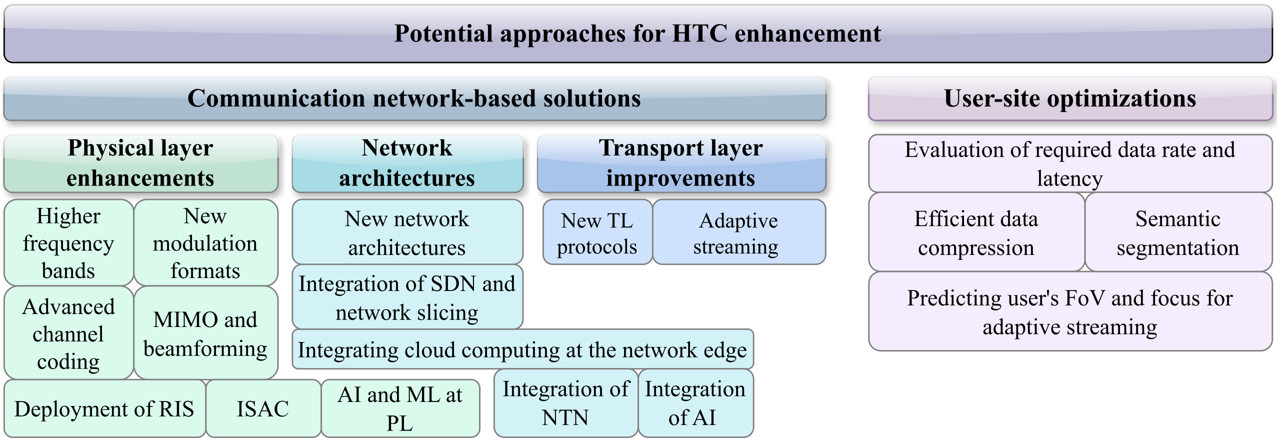

FIGURE 8. Potential approaches for HTC enhancement classified into communication network-based solutions and user-site optimizations.

However, this advantage is countered by severe path loss due to environmental absorption and blockages, which limit propagation distances to a few meters. Consequently, high-frequency links may experience wild and frequent fluctuations in link capacity, leading to a decrease in the overall network performance [81]. Visible Light Communication (VLC) has the potential to provide optical-like performance, offering ultra-high bandwidths with zero electromagnetic interference. However, its main drawback is its extreme sensitivity to blockages, necessitating a Line of Sight (LoS) channel. Moreover, achieving optimal optical transmission will require significant advancements in optical systems, including the use of new light sources such as micro LEDs, enabling optical beamforming, spatial multiplexing, and other innovations. Therefore, in addition to utilizing higher frequency bands, the increase in data rates should be accompanied by other physical layer improvements [71] given below.

First, new modulation formats will be required. The widely adopted Orthogonal Frequency Division Multiplexing (OFDM) in 4G and 5G is known for its few drawbacks: sensitivity to frequency dispersion, a decrease in the spectral efficiency due to the cyclic prefix, and a high peak-to-average power ratio (PAPR). These challenges become more critical in higher frequency bands.

Second, advances in channel coding at the physical layer are required to ensure reliable and low-latency transmission. Codes with short block lengths are more susceptible to errors, and error-free transmission cannot be guaranteed. However, blocks with longer lengths imply increased latency. Therefore, a trade-off between the code block length and the robustness of the code to errors must be achieved.

Regarding the use of multiple antenna arrays and massive multiple input multiple output (MIMO) systems, it is foreseen that they will still be utilized to improve spectral efficiency. However, beamforming at higher frequency bands increases the circuit complexity, power consumption, and cost of operation. Signal processing algorithms and beamforming architectures that balance the ease of real-time implementation, low complexity, and high efficiency are subject to further investigation.

Further, the deployment of Reconfigurable Intelligent Surfaces (RISs) or Large Intelligent Surfaces (LISs) across buildings, highways, and various structures emerges as a prominent subject of interest for the forthcoming 6G networks. They are metasurfaces that can tune the phase of their elements to reflect the incoming electromagnetic signals in the desired directions. RIS-aided communications are considered to improve spectral and energy efficiency, data rates, and high-frequency wave utilization. However, energy consumption optimization, inference minimization, and the possibility of real-time steering require further development.

High-demand immersive services, along with other emerging applications like autonomous vehicles and digital twins, stand to benefit from integrated sensing and communication (ISAC) capabilities in 6G networks. These applications necessitate wireless systems to provide not just communication services, but also sensing, localization, and control functionalities while delivering ultra-high data rates, near-zero latency, and instant reliability. ISAC functionality in 6G aims to efficiently merge communication and sensing on a single hardware platform, optimizing frequency resources for improved spectral, energy, and cost efficiency. Recent research efforts have proposed various ISAC frameworks [82], [83], [84], [85], with some exploring its potential for enabling wireless XR at THz bands [86], [87]. Certain systems harness holographic beamforming, employing holographic MIMO-based stations or reconfigurable holographic surfaces (RHS) to sense, control, and optimize the wireless environment, thus realizing the vision of low-power, high-throughput, massively-connected, and low-latency communications [88]. However, holographic MIMO and RHS should be distinguished from typical MIMO and RIS, as they have the unique ability to dynamically compose desired beams following holographic principles [89]. On the other side, while often referred to as holographic communication, they should not be confused with the term "HTC" used in this paper, considering that HTC denotes the entire process of transmitting holographic content through the communication network providing users with an immersive communication experience.

The application of AI and ML at the physical layer in 6G is expected to generally impact the wireless communication systems [90]. The primary research directions of the ML-driven physical layer include channel coding, synchronization, positioning, and channel estimation. ML-based channel state prediction will also be very beneficial, especially in noisy and degraded channels with significant time variations in the link capacity [81]. Some ML methods at the Media Access Control (MAC) layer are also important [90]. More specifically, ML can be exploited in different use case scenarios in the MAC layer, such as federated learning for orientation and mobility prediction in wireless VR networks, predictive resource allocation in Machine-Type Communications (MTC), predictive power management, and asymmetric traffic accommodation. Research on the potential benefits and challenges of deep learning (DL) based wireless communication systems with a focus on the physical layer is provided in [91]. A highlight of the DL methodologies used in conventional techniques, such as MIMO detection, channel estimation, channel coding/decoding, resource allocation, RIS, and MIMO-based index modulation is presented, as well as DL-based end-to-end (E2E) communication approach.

2) NETWORK ARCHITECTURES

Although 5G is underway and shows significant improvements compared to its predecessors, the transmission of holographic content with assured QoE is still far from implementation. HTC demands future networks to support very high data rates, as well as deterministic and ultra-low latency. Furthermore, beyond holographic data transportation, future networks should be capable of offloading a significant portion of holographic data processing from the user site, particularly in the absence of sufficient computational resources. This underscores a crucial characteristic of future networks, namely, their ability to accommodate both data transportation and computation.

To support HTC, the future network architectures should include a new data plane that will be able to dynamically adapt to different operating nodes, a new control plane that will be able to strictly synchronize holographic streams routed within deterministic and low latency links (i.e., jitter values decreased to minima), and a new management plane which will be able to configure and optimize network capabilities, leveraging the support of AI [6]. Currently, the 5G integration of Software Defined Networks (SDNs) that support the separation of the control plane, data plane, and management plane [92] provides the ability for dynamic and flexible network adaptation and on-demand resource allocation according to various network conditions and user requirements. The virtualized control plane applies QoS-oriented management of network resources, filling the gap between the common network architectures and services-oriented network support. Further, 5G network slicing based on SDNs and Network Function Virtualization (NFV) [93] allows the deployment of numerous logical networks sharing common physical infrastructure. Each logical network is optimized to provide guaranteed QoS for different service types, such as delay-sensitive services, wide broadband demanded services, and massive connectivity. Although it is anticipated that these technologies will continue to play an essential role in the future 6G networks, they need to be further improved to support diverse capabilities such as communication, computation, caching, and control.

Looking forward to the future beyond 5G and 6G networks [94], multi-access edge computing (MEC) will contribute to the integration of data computation throughout the network. It extends cloud computing capabilities to the network edge, bringing them close to users. This allows the offloading of user-site processing and reduction in end-to-end latency. Consequently, MEC is highly advantageous for real-time data processing and transmission services, such as driverless vehicles, robotics, and immersive communications, particularly HTC. As evidence, one can refer to the outcomes documented in [52], [53], and [95].

Another area of research is the integration of terrestrial and non-terrestrial networks in 6G. They can ensure higher communication reliability, multi-path routing for load balancing, and support for deterministic and low-latency data transmission. The authors of [96] introduce an envisioned deterministic networking-enabled non-terrestrial network (NTN) architecture in the context of holographic-type services.

Implementing intelligence in the networks will be the most significant improvement of 6G compared with 5G networks [97]. Running AI algorithms distributed across the network will enable it to dynamically learn and improve its performance based on deep analysis and predictions. Allowing AI at the network edge will be beneficial for restoring/rendering the holographic content with better quality, even under worse network conditions.

3) TRANSPORT LAYER IMPROVEMENTS

In the field of 6G research and development, considerable focus is directed toward network architectures and physical layer enhancements. However, despite the imperative role of the transport layer in efficiently transmitting data through the network, it receives comparatively less attention. This is noteworthy given the stringent HTC requirements of ultra-low latency and high reliability, which are dependent on the transport layer efficiency and can be positively affected by its optimization.

At the transport level, the ultra-low latency and the very high reliability are usually contradictory, but both are important for optimizing the perceived QoE in HTC. Excessive latency due to the establishment of reliable connections can undermine real-life experience, especially in scenarios where real-time multisensory interactions are crucial. Conversely, unreliable connections leading to packet loss may necessitate frequent retransmissions, increasing the latency, and again resulting in decreased QoE. Additionally, the introduction of new radio links with higher frequencies at the physical layer, while promising greater data rates, also heightens the susceptibility to losses and distortions. This further complicates the task of transporting holographic content with high reliability, determinism, and low latency. Therefore, it is crucial to develop suitable transport layer protocols for holographic data transmission. These protocols should incorporate adaptive streaming mechanisms to prioritize specific segments of holographic content, ensuring better quality for the parts of the hologram observable to the user.

Current video streaming applications rely on dynamic adaptive streaming over hypertext transfer protocol (HTTP) (DASH). It allows data to be segmented into different sequences of small segments served over HTTP and assigned different bit rates according to the available bandwidth. Thus, prioritizing some data over others becomes possible. This is beneficial when trying to transmit some part of the content, which is more valuable to the user, with higher quality. However, DASH relies on Transmission Control Protocol (TCP) in the transport layer, which is not optimized for real-time transmission. Since TCP is a connection-oriented protocol aimed at preserving the reliability of the connections, it experiences slow connection establishment and often retransmissions due to package loss. Another disadvantage is the head-of-line (HOL) blockage, which occurs due to the blocked transmission of the following packages as a result of a previously lost package. Such behavior is undesirable in HTC scenarios.

One approach to partially meet the challenges of DASH is to use HTTP3, which relies on the Quick UDP Internet Connections (QUIC) protocol at the transport layer. QUIC attempts to combine the features of both the UDP and TCP. It uses UDP datagrams and establishes multiplexed connections between user sites while integrating transport layer security (TLS), TCP flow control, and reliable delivery. It operates in the user space, allowing users to configure the protocol using their own congestion and flow control algorithms. QUIC reduces the connection establishment time and partially resolves the HOL blockage. It can support different streams in the transport layer and can map them to the respective streams in the application layer, where they are multiplexed. Two user sites can sustain a few streams simultaneously, which are maintained individually in the transport layer. If a blockage occurs in one of the streams, the other streams remain unaffected. However, the HOL blockage may still occur in a single stream. Thus, there may be a problem if the data between different streams are interdependent [98], [99].

Another approach is the proposal of a partially reliable QUIC-based data delivery mechanism [98] that can support both reliable and unreliable 360-degree video and point cloud data delivery. This approach is extended in [99] by integrating DASH to increase the quality of the delivered immersive content on lossy networks. However, these solutions are more suitable for immersive video delivery on demand or for live immersive videos. For real-time holographic communication, further evaluation is needed. In [4], the differences between video on demand, live video, and real-time video are explored and the entire end-to-end immersive video delivery chain for three different types of immersive media (3DoF omnidirectional video, 6DoF volumetric video, and 6DoF imagery video) is provided.

A different approach for optimizing data transmission is the development of an entirely new transport layer protocol that operates directly over the Internet Protocol (IP) layer. Such a protocol is PRISM proposed in [100] - a new transport layer protocol running over IP and designed in the context of low latency and high reliability. It can support multiple flows, providing them with per-flow granular and dynamic QoS to couple multiple flows from the same application together, enabling inter-flow synchronization. However, future research may focus on increasing the number of different data flows and utilizing other transport layer protocols to shorten the connection establishment latency.

UDP-based solutions that prioritize latency over reliability have better latency performance but do not perform well in lossy networks. Potential is seen in some approaches using WebRTC for transporting holographic content [4], but further exploration is still needed. One of their problems is that WebRTC was initially designed as peer-to-peer and needs to scale better in the context of HTC. However, according to [11], WebRTC and Photon Unity Networks (PUN) are used the most in realizing HTC systems.

From the discussion above, two main conclusions for transport layer optimization can be drawn. First, the transportation of holographic content should rest on both reliable and low latency-oriented protocols. Second, managing multiple data flows will result in faster data transmission, blockage avoidance, and data prioritization. The latter will allow the application of adaptive content streaming at the user site.

B. USER-SITE OPTIMIZATIONS

The realization of HTC will be facilitated by optimizing the data processing and transmission yet at the user site. First, the tremendous amount of holographic content should be effectively compressed considering the available bandwidth resources and the processing power of the user site's processing node. Finding a trade-off between applying efficient compression and experienced latency is vital. However, available 3D content compression software such as Point Cloud Library (PCL), Google Draco, MPEG-TMC2, and MPEG-TMC13 [101], [102], [103], [104] can achieve a very high compression ratio, but at the cost of an inadmissible processing delay of a couple or even tens of seconds. Some ML methods also gain popularity in developing innovative compression techniques [105], [106], [107], [108]. These approaches primarily use DL-based autoencoders trained preliminarily with 3D data. The latent data are transmitted across the network significantly reducing the required bandwidth. Although remarkable results for the compression ratio and compression time have been achieved, these methods still need to be optimized to support real-time immersive communication. In turn, the remote user site should decompress and render the received data. However, since data may reach the destination with worsening quality owing to its transmission over highly variable and noisy channels, the user site may benefit from some ML-based error detection and correction algorithms for restoring corrupted 3D content [109], [110].

Another approach for facilitating HTC and decreasing the colossal bandwidth demands is the application of adaptive data streaming according to the user FoV, distance to the observed objects, and available bandwidth [111], [112], [113], [114], [115], [116], [117]. The idea is to transmit with much lower quality (or not transmit at all) particular data that are not observed or are very distant to the remote user. Hence, for the effective utilization of adaptive streaming, the remote user site needs to execute precise head and eye movement tracking (sensing) and prediction. Additionally, it should provide this information to the communicating user site to optimize data transmission while still considering QoE. Consequently, the design of a QoE-aware HTC system that considers both local and remote user sites should be considered [9].

The next valuable approach for realizing HTC relies on the semantic knowledge transfer of holographic data. In fact, semantic communication is considered one of the frontiers of 6G, which is believed to help evade Shannon's rule [118]. In contrast to traditional data transmission, which prioritizes error-free symbol delivery, semantic communication relies on shared knowledge between users and places emphasis on understanding, transmitting, and interpreting the meaning of the data. Therefore, by transmitting only meaningful data parts instead of the raw data itself, significant reductions in communication and storage capacity requirements can be achieved. Since HTC is expected to examine network limits, semantic communication would be incredibly beneficial and worth implementing. Considering the HTC scenario, where both local and remote user sites share common semantic knowledge about holographic content, the latter can be restored even if part of the information is missing [6]. Our recent work [119] proposes a model of context-aware holographic architecture for real-time communication based on semantic knowledge extraction. The presented model requires the analysis and development of methods and algorithms for 3D human body model acquisition, semantic knowledge extraction for DL-based human behavior prediction, analysis of biometric modalities, and context-aware optimization of network resource allocation to create a multi-party, from-capturing-to-rendering HTC framework. Another work of ours [120] introduces a system based on semantic representation to communicate 3D video data. Specifically, the system comprises an encoder-decoder architecture designed for encoding 3D video content, where semantic information is employed to highlight the significance of human body parts throughout the encoding-decoding process. Although the practical implementation of HTC systems is still in its early stages owing to stringent system requirements and various network conditions, the findings in [119] and [120] offer promising insights. These results indicate the potential to reduce latency and achieve superior data compression compared to traditional methods. Such advancements reveal the great potential of semantic communication for mitigating the dependency of HTC on communication network resources.

VII. ANALYSIS ON POTENTIAL APPROACHES FOR HTC ENHANCEMENTS

Based on the influence of 6G enabling technologies on diverse network KPIs, as outlined in [69], we analyze whether the potential approaches for HTC enhancement from Section VI can impact the major HTC technological challenges. Table 5 presents the categorized potential approaches, emphasizing whether they directly impact the listed challenges. The following insights can be outlined from this table.

The group of physical layer improvements has the greatest potential to meet the bandwidth requirements. It can be seen from the table that each of the listed physical layer approaches can influence the HTC-demanded data rate. However, the other challenges, i.e. latency, synchronization, and computation, are less related to them. Some consequential problems resulting from certain physical layer improvements may even arise. For example, the utilization of higher frequency bands, including the visible light spectrum, MIMO, advanced beamforming, and RIS may lead to additional processing complexity at the user site, thereby increasing the computational burden. Therefore, a trade-off between evident advantages and the induced difficulties must be achieved. Integrating AI and ML into the physical layer could help sustain this balance.

The group of network architecture approaches will have an overall impact because it tends to solve each technological challenge. Compared to the other approach types, this one will have the most significant impact, specifically on the experienced latency, synchronization problems, and computational burden on the user site. The distribution of AI-based algorithms for network management and control throughout the network, a fundamental concept in 6G, will enhance network performance by allowing networks to adapt according to user behavior and network conditions. Furthermore, networks will be able to build themselves according to specific service types and their requirements. Therefore, the realization of AI-embedded, adaptive, and self-sustaining network architectures is believed to be one of the fundamental enabling technologies that will make immersive communications possible and available to end users.

The most significant effect of the transport layer approaches will be the fulfillment of the critical latency requirements. Combining network architecture improvements with the development of an appropriate transport layer protocol for serving multiple users with low latency, while still considering reliability, will be vital for the realization and wide adoption of HTC.

Optimizations at the user site are also essential. Enhancing the data processing and transmission at the user by applying AI-based methods for data compression, adaptive streaming, and semantic knowledge extraction will reduce the heavy demands on the rest of the communication pipeline. It can be observed from Table 5 that the end-user optimizations, as the physical layer improvements, will significantly impact the required bandwidth by applying a variety of application-specific algorithms. Latency and computation challenges may also benefit from some optimizations at this point. However, the technological requirements for specific HTC scenarios and the network's state must be evaluated to complete the appropriate end-user optimization task. Traditionally, AI and ML will significantly affect the various processing steps at this point.

Referring to Table 5, Fig. 9 depicts the comprehensive impact of the four groups of approaches on the HTC technological challenges. Each ellipse signifies a distinct group of approaches and highlights the challenges it tends to solve. While this representation is more qualitative, and providing specific quantitative measures for the level of impact is currently not feasible, it offers clarity regarding the potential of the proposed approaches to meet specific HTC requirements.

However, it is essential to acknowledge that implementing certain approaches is not always a straightforward task. For instance, while some approaches aim to address specific HTC challenges, they may negatively affect others. As mentioned, leveraging higher frequency bands or utilizing MIMO and RIS technologies may increase processing complexity at the user site, leading to a heavier computational burden. Conversely, when available bandwidth is limited, advanced compression techniques at the user site could benefit HTC applications, but at the cost of requiring more powerful computational resources and potentially increasing latency. Introducing MEC at the network edge could alleviate user loads, but it will necessitate sufficient links between users and network nodes. Therefore, a careful trade-off analysis is imperative when implementing different approaches. Furthermore, this analysis must align with specific HTC scenarios, as diverse scenarios may have distinct requirements regarding bandwidth, latency, synchronization, and computation. To infer, maintaining optimal coordination among various approaches under dynamic network conditions and across different user scenarios is crucial to ensure the highest QoE.

VIII. 6G ROLE IN ENABLING HTC

Referring to the 6G vision for HTC realization explored in Section V, the proposed 6G communication network-based solutions in Section VI-A, and the analysis in Section VII, it is evident that 6G will play a significant role in enabling HTC-based applications. The ubiquity of bandwidth resources, the reduction in latency times, and the potential for offloading user computation are promising factors that support this idea. However, a substantial improvement in communication

TABLE 5. Impact of the potential approaches for HTC enhancement on the major HTC technological challenges.

Potential solutions		Impacted Challenges			
Type of solution	**Solution**	**Data rate**	**Latency**	**Synchronization**	**Computation**
Physical layer improvements	Utilization of higher frequency bands above 300 GHz, Utilization of the visible light spectrum	✓	✓	✗	✗
	Utilization of new modulation formats	✓	✗	✗	✗
	Advances in the physical layer coding	✓	✓	✗	✗
	Deployment of MIMO and beamforming techniques together with signal processing algorithms	✓	✗	✗	✗
	Deployment of RIS over surfaces of buildings, highways, and other objects	✓	✗	✗	✗
	Integrating sensing and localization	✓	✓	✗	✗
	Exploitation of the AI and ML potential at the physical layer	✓	✓	✓	✓
Network architectures	Deployment of new flexible, adapting, and easily scalable network architectures in 6G	✓	✓	✓	✓
	Integration of SDN and network slicing within the network architectures	✓	✓	✓	✓
	Integration of cloud computing in the network edge	✗	✓	✓	✓
	Exploitation of the potential of non-terrestrial connectivity	✓	✓	✓	✗
	Integrating intelligence in the 6G networks by running AI algorithms distributed across the network	✓	✓	✓	✓
Transport layer improvements	Development of a new transport layer protocol optimized for both low latency and high reliability data transmission	✗	✓	✓	✗
	Enablement of adaptive streaming of the holographic content by supporting streams with different priority	✓	✓	✗	✗
Optimizations at the user site	Evaluation of the required bandwidth capacity and experienced latency for different HTC scenarios	✓	✓	✓	✓
	Optimization of the data compression efficiency and time by utilizing devoted compression techniques	✓	✓	✗	✓
	Appliance of adaptive streaming according to user FoV and focus	✓	✗	✗	✗
	Exploiting semantics for enabling semantic communication	✓	✗	✗	✗

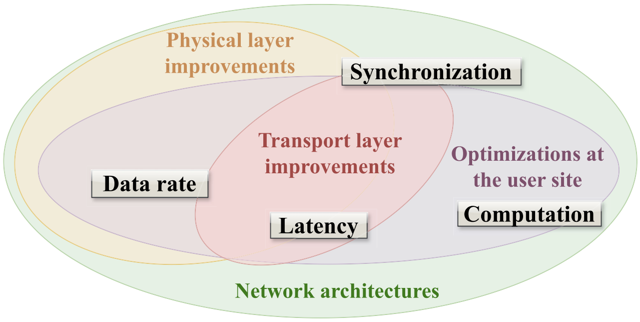

FIGURE 9. Mapping between the major HTC technological challenges and the categories of potential approaches for HTC enhancement.

technology performance does not always account for the potential increase in emerging application requirements. Assuming the great potential of 6G, what if the future applications place even larger network demands? Could this be a challenge for the future 6G networks? The answer, although uncertain, is likely "yes." Given the historical trend in which each emerging technology drives the development of next-generation networks, a similar scenario may unfold with 6G. Therefore, although 6G is believed a fundamental enabler for HTC, it's essential to look ahead and consider the future evolution of immersive communications.

A. AI-ENABLED HTC

In the context of potentially increasing network requirements surpassing 6G capabilities, we emphasize the significance of adopting a strategy that optimizes both the communication network and the user site. This optimization involves the integration of AI which will play a central role by concurrently improving their performance. We highlight several aspects to support this perspective.

Incorporating AI into the user site will play a key role in achieving an adaptive QoE. Specifically, AI-empowered algorithms can analyze user behavior, environmental factors, and available network resources. This analysis allows dynamic adjustments in real-time content processing and transmission, ensuring the maintenance of optimal QoE tailored to user interactions and predicted network conditions.

Moreover, AI contributes to low-latency content processing by leveraging previously trained DL models. Innovative compression strategies, including DL-based autoencoders and adaptive streaming, deviate from the traditional approaches with the aid of AI. As mentioned earlier, adaptive streaming is effective in reducing bandwidth requirements by transmitting only essential data to remote users. The effectiveness of this approach, however, relies on AI methods for accurate body and eye movement tracking and prediction.

AI also plays a pivotal role in enhancing content semantic understanding and facilitating context-aware communication. Its involvement is mainly reflected in the transition from accurate data transmission to precisely representing data semantics at the transmitter and effectively interpreting these semantics at the receiver. In the context of HTC, envision a scenario where multiple users from various locations engage in a virtual meeting. Given that traditional virtual meeting platforms fail to deliver the immersive experience promised by HTC and considering the substantial network resources required by HTC, an alternative approach involving semantic communication can address these issues. This approach entails all users having access to shared 3D human body models of the meeting participants before the meeting commences. Throughout the meeting, AI algorithms operate at each user site to track, extract, and predict the semantics of participants' behavior, such as posture, movements, and facial expressions. This extracted information is then exchanged among users, who interpret it by deforming the available 3D models with the assistance of AI.

The deployment of AI in communication networks is anticipated to be the game changer in future networks. The primary area where AI is expected to play a pivotal role is in big data analysis [97]. This analysis encompasses descriptive tasks for historical insights to ensure situational awareness among network operators and service providers, diagnostic functions for autonomous fault detection, predictive capabilities for forecasting future network status, events, user behavior, content popularity, etc., and prescriptive functionalities for suggesting decision options. Through such comprehensive data analysis, future networks can acquire the ability to learn and self-optimize. This facilitates adaptive network planning and real-time control from the core to the network edge. Consequently, future networks will transform into flexible and agile entities, capable of supporting a diverse range of QoE-oriented applications. Thus, despite the substantial resources of 6G, its efficiency is truly realized when complemented with intelligence.

Finally, we envision a scenario in which communication network resources and intelligence will be seamlessly combined with user site resources and intelligence, all orchestrated by a coordinating AI management entity. This entity will be trained to efficiently govern the network and the user site together. Such integration presents tremendous potential

TABLE 6. **Table of acronyms and their definitions.**

Acronym	Definition
3CLS	Convergence of Communications, Computing, Control, Localization, and Sensing
3D	Three-dimensional
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
ARQ	Automatic Repeat Request
DASH	Dynamic Adaptive Streaming over HTTP
DL	Deep Learning
DoF	Degree of Freedom
E2E	End-to-end
eMBB	enhanced Mobile Broad Band
FeMBB	Further-enhanced Mobile Broadband
feUMBB	further enhance Ultra-Mobile Broadband
FoV	Field of View
HOL	Head-of-Line
HTC	Holographic-Type Communication
HTTP	Hypertext Transfer Protocol
HCS	Human-Centric Services
ISAC	Integrated Sensing and Communication
KPI	Key Performance Indicator
LIS	Large Intelligent Surfaces
LoS	Line of Sight
mMTC	massive Machine Type Communication
mULC	massive Ultra-reliable low-Latency Communication
MURLLC	Massive URLLC
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MBRLLC	Mobile Broadband Reliable Low Latency Communications
MPEG	Moving Picture Experts Group
MPS	Multi-Purpose 3CLS and Energy Services
MTC	Machine-Type Communications
NFV	Network Function Virtualization
NTN	Non-terrestrial Network
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-average Power Ratio
PCL	Point Cloud Library
PUN	Photon Unity Network
QoE	Quality of Experience
QoPE	Quality-of-Physical-Experience
QoS	Quality of Service
QUIC	Quick UDP Internet Connections
RHS	Reconfigurable Holographic Surfaces
RIS	Reconfigurable Intelligent Surfaces
SDN	Software Defined Networks
SNR	Signal-to-noise Ratio
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
uHDD	Ultra-High Data Density services
uHDD	Ultra-High Density Data
uHEE	ultra-High Energy Efficiency
uHRS	ultra-High Reliability and Sensing
uHRUx	ultra-High Reliability and User experience
uHS	ultra-High Security
uHSLLC	ultra-High Sensing Low Latency Communications
uHSLLC	ultra-high-Speed with Low-Latency Communications
uHSLo	ultra-High Sensing and Localization
uMBB	ubiquitous Mbile Boardband
uMBB	ultra-Mobile Broadband
uMUB	ubiquitous Mobile Ultra-Broadband
ULBC	Ultra-reliable Low-latency Broadband Communication
uLLRS	ultra-Low Latency Reliability and Secure
URLLC	Ultra-Reliable Low-Latency communication
VLC	Visible Light Communications
VR	Virtual Reality
XR	Extended Reality

for ensuring optimal and consistent QoE for end users, going beyond reliance on available bandwidth or computational resources. Therefore, prioritizing an intelligent approach, rather than merely increasing limited capacities, is the most effective strategy among those presented in Section VI.

IX. CONCLUSION

This paper explores the capabilities of wireless networks to meet the demands of HTC. Specifically, it highlights the inability of 5G in addressing HTC challenges and investigates the potential of upcoming 6G networks. To emphasize its superiority over 5G, the paper examines various approaches expected to be integrated into 6G implementations. While physical layer enhancements primarily address the challenge of extreme data rates, other obstacles like latency, synchronization, and computation are tackled through improvements in network architecture and the transport layer. In addition, user site optimizations are also crucial for HTC enhancement, particularly in scenarios where communication network resources are insufficient. This raises the question: Can immersive communication requirements exceed the capacity of future 6G networks? An example highlighting this concern is the potential strain on 6G capacity posed by high-quality light field holograms, as illustrated in Table 3. Therefore, it's not solely the communication network that requires improvement, nor is it solely the user site optimization.

To conclude, despite the valuable insights gained, we emphasize that although 6G represents a notable advancement for HTC, it may not ensure the fulfillment of even more demanding HTC requirements. Thus, rather than relying solely on ubiquitous network capacity, the integration of an intelligent approach that coordinates both the user site and communication network becomes crucial for achieving QoE-oriented immersive applications. Consequently, it is important not to be overly optimistic about the capabilities of certain network generations and instead to remain vigilant and forward-thinking.

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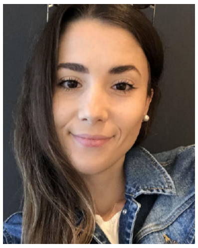

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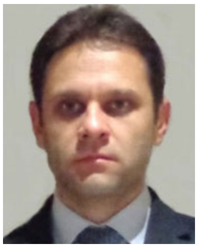

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