Ultra-Reliable Low-Latency Communication (URLLC) for Human Digital Twins: Challenges and Opportunities in 5G and Beyond

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***Abstract*—Human Digital Twins (HDTs) are emerging as key components in personalized healthcare and require significantly more sophisticated communication capabilities than conventional digital twins (DTs). The essential need for fast and reliable synchronization highlights the significance of Ultra-Reliable Low-Latency Communication (URLLC) in the 5G wireless standard, which is designed for machine and time-sensitive applications. This concise survey systematically outlines the key communication demands of HDT applications in clinical settings, examines the architectural and technological solutions offered by advanced 5G and 6G to address stringent URLLC needs, and identifies the main challenges, opportunities, and future research directions of this vital convergence. Future 6G URLLC advancements, leveraging terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), and integrated Sensing and communication (ISAC), aim to build strong, self-governing digital twin networks (DTNs). These are crucial for creating secure, verified and ethically managed HDTs that influence the future of personalized healthcare.**

***Index Terms*—Human Digital Twins, URLLC, Low-Latency, Survey, 5G, 6G, Terahertz, personalized healthcare, Edge server**

I. INTRODUCTION

The concept of the DT, a precise virtual replica of a physical system or entity, has transformed industrial and technological landscapes by allowing real-time monitoring, predictive analytics, and risk-free simulation environments [1]. Originally rooted in manufacturing and product lifecycle management, this paradigm now extends to the human body, leading to the advanced idea of the HDT [2]. Moreover, the healthcare sector has traditionally lagged in integrating a broad range of digital technologies, primarily due to the complex, patient-specific nature of 'human-human' interactions required for service delivery [3]. HDTs are digital models of individuals, designed to replicate intricate biological, physiological, and behavioral traits throughout a person's life [2]. In healthcare, HDTs aim to transform care by enabling personalized and predictive medicine, facilitating tailored drug development, disease forecasting, surgical planning, and rehabilitation [4].

The functionality and usefulness of an HDT hinge on maintaining accurate synchronization with its human entity counterpart. Unlike mechanical DTs, which replicate non-living objects, HDTs must handle the complexity and variability of human data, such as physiology, behavior, environment, and cognition. This requires continuous, two-way data exchange to ensure that the virtual model accurately represents the current state of the patient [2] [1]. Poor communication quality or delays, such as high latency or packet loss, can cause model inaccuracies, affecting the predictive accuracy of the twin and potentially resulting in incorrect diagnoses or delayed, critical interventions, notably in crucial areas like remote surgery or intensive care monitoring [5]. Therefore, unlocking the full capabilities of HDTs requires communication networks with quality-of-service (QoS) guarantees that surpass traditional systems.

The essential need for instant and reliable synchronization highlights the critical importance of URLLC. This service, introduced in 5G and advanced to 6G and beyond, delivers extremely high reliability and very low latency [6]. URLLC is essential for HDTs in time-sensitive tasks, ensuring instant and reliable data packet delivery for real-time analysis and feedback. This is crucial for applications such as robotic-assisted surgery, where even millisecond delays can affect safety and success, or for real-time systems that increase human abilities [2].

The expansion of HDTs aligns with the swift development of 5G and the idea of 6G, introducing key technological innovations vital for managing the complexity of human twinning. 5G networks and beyond feature advanced designs such as network slicing (NS), creating customized virtual networks tailored for URLLC traffic crucial to HDT functionality. Upcoming 6G systems enhance this with mobile edge computing (MEC), which reduces latency by handling complex tasks near the user's location, facilitating real-time cognitive and physiological modeling [4]. Artificial intelligence (AI) and machine learning (ML) power HDTs by analyzing data, forecasting results, and guiding their evolution. Future innovations such as THz communication offer vast bandwidth for high-quality medical imaging . However, given the high susceptibility of THz to blockage by human movement, RIS must be deployed to create non-line-of-sight (NLoS) virtual links to ensure strong connectivity for mobile users [5].

While the alignment between URLLC features and the essential requirements of HDTs is evident, a thorough comprehension of their combined challenges and opportunities is still developing. Existing researches often examine HDTs and advanced communication networks independently or emphasizes general DT applications in industrial contexts. There is a significant lack of research dedicated to integrating URLLC parameters, such as latency constraints, reliability standards, and security measures, tailored specifically for the sophisticated, multi-domain frameworks of 5G and 6G+ networks to accommodate specialized and evolving HDT needs in healthcare [5]. To bridge this research gap, it is essential to conduct a detailed investigation into the distinctive trade-offs of HDT implementation. This includes balancing model accuracy with computational delays, protecting sensitive personal data, and managing synchronization challenges for mobile patients in diverse network environments [7].

This survey analyzes the convergence of the URLLC and HDT systems in 5G and beyond. It aims to: (1) outline critical HDT communication needs in clinical settings; (2) explore 5G/6G architectural solutions meeting strict URLLC requirements; and (3) evaluate the challenges and future research directions of this convergence. The remainder of this paper is structured as follows: Section II reviews the background of the URLLC and HDT communication requirements. Section III explores specific URLLC enablers that are relevant to HDTs. Section IV identifies unique implementation challenges, while Section V discusses future opportunities and research directions. Finally, Section VI concludes with the key takeaways.

II. BACKGROUND

A. Overview of URLLC

URLLC is a key service category in the 5G wireless standard aimed at supporting applications that are both machine and time-critical. This represents a major shift in wireless system design [8]. URLLC's main goals focus on strict performance requirements such as low latency, high reliability, and consistent availability. In terms of latency, the time delay from start to end, should be extremely low, with 5G aiming for 1 ms or less. In 6G systems, air-interface target is even more ambitious at 0.1 ms, which is critical to accommodate the additional edge processing and transmission delays inherent in the total < 1 ms end-to-end budget required for haptic HDT feedback. Reliability demands nearly perfect packet delivery, often between $1-10^{-5}$ and $1-10^{-9}$. Typically, 5G requires a 99.999% success rate for short messages. Availability ensures that the network remains functional and resilient, which is crucial for mission-critical tasks [9].

To meet the stringent performance requirements of 5G and beyond 5G (B5G) architectures, the integration of specialized technologies is essential. Short blocklength codes are vital, as URLLC often uses very small packet sizes, making traditional information theory, which assumes infinite blocklengths, less applicable [10]. These smaller packets shorten the transmission time but require specialized encoding for high reliability [8]. Grant-free access (GFA) reduces latency by minimizing control plane signaling overhead from the scheduling request and grant process, enabling user equipment (UE) to transmit without waiting for base station resource allocation. Multi-connectivity boosts reliability and capacity by allowing simultaneous connections to multiple base stations, whereas NS ensures resource isolation and customization, supporting URLLC along with other services like enhanced mobile broadband (eMBB) and massive machine type communication (mMTC) within the same framework [8] [9].

Emerging 6G systems are integrating advanced features to meet increasingly stringent demands. AI-driven resource allocation uses advanced ML, including deep and reinforcement learning, to optimize scheduling in dynamic settings [8] [11]. Semantic communication focuses on transmitting only essential "semantic" information, reducing bandwidth and processing load while improving data security [10]. Moreover, THz links (0.1–10 THz) provide ultra-broadband connectivity, supporting data rates of up to 1 Tbps to meet URLLC throughput needs [11].

B. HDT Communication Requirements

HDTs are high-fidelity virtual models that dynamically mirror the physiological, psychological, and lifestyle changes of individuals [1]. The primary aim of HDTs is to enhance personalized healthcare services [12]. HDTs greatly strain communication systems because of the complexity and volume of required data. HDTs demand advanced multimodal data collection, aggregating diverse physiological, behavioral, and environmental datasets from heterogeneous sources (wearables, implants) that vary significantly in spatiotemporal resolution. It's crucial for synchronized updates to keep the virtual twin (VT) as a real-time reflection of the physical twin (PT) [10]. This requires very low end-to-end latency, matching the core function of URLLC. In highly interactive HDT applications such as remote surgical training or robotic control, latency is particularly strict, requiring round-trip times (RTT) of less than 1 ms for haptic feedback and quick decisions [8] [12].

Implementing and maintaining HDT communication presents several technical hurdles. The variety of data sources, from structured EHRs to unstructured sensor outputs, complicates data integration and interoperability across medical and technical platforms [12]. The high transmission rates and continuous connectivity required for synchronization can rapidly deplete battery life, necessitating the adoption of energy-efficient network strategies [13]. Privacy and security are crucial, as patient data are sensitive and prone to breaches. Robust mechanisms, possibly using decentralized ledger technologies, are essential for maintaining data confidentiality and integrity during transit and storage [1]. Additionally, ensuring reliability in the face of mobility is challenging, requiring advanced protocols and architectural solutions, such as dynamic placement within edge computing to maintain seamless connectivity [12]. The demanding requirements of HDT, particularly the need for real-time, reliable data synchronization, align with the capabilities of URLLC, indicating that URLLC is essential for effective HDTs in the 5G and future 6G eras. This concept is visualized in Fig. 1, which depicts a closed-loop framework designed to meet the strict < 1ms RTT constraint. The architecture bypasses core network latencies by offloading physiological data from internet of healthcare things (IoHT) sensors (white nodes) to a local intelligent edge server via the GFA and non-orthogonal multiple access (NOMA) to manage massive access. Subsequently, the edge server delivers immediate feedback through RIS-aided beamforming and THz links to ensure robust connectivity despite signal blockages, while physical layer security (PLS) protects the transmission hop against eavesdropping without adding cryptographic latency.

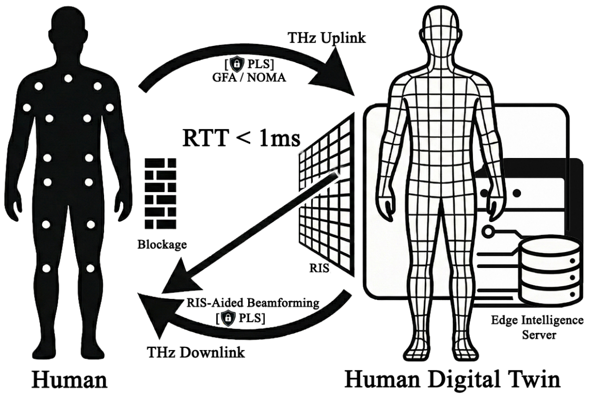

Fig. 1. Closed-Loop URLLC Synchronization Framework for HDTs

III. URLLC ENABLERS FOR HDTs

A. Physical & Link Layer Techniques

Physical and link layer techniques are fundamental to meeting URLLC's stringent latency and reliability metrics, particularly by addressing the challenges posed by short-packet transmission [14]. A core mechanism employed is finite blocklength (FBL) communication, which is necessary because the *classical Shannon capacity formula*, which assumes infinite blocklength transmission, is inadequate for URLLC's time-sensitive traffic. FBL faces performance constraints from a significant decoding error probability, necessitating precise optimization of transmission parameters such as rate and power. This is essential for delivering small data payloads including critical patient vital signs or haptic feedback for remote surgical procedures, within a latency of hundreds of microseconds [15]. To further mitigate decoding errors, network coding methods, where data packets are combined to maximize throughput, have progressed into sophisticated schemes such as cooperative network coding (CoNC) and hybrid network architectures. These approaches are crucial for lowering packet and bit error rates in lossy channels, thereby providing the reliability demanded by critical HDT data streams [16]. Complementing these link-layer optimizations, massive multiple-input multiple-output (MIMO) and the subsequent evolution, cell-free massive MIMO (CF-MIMO), are key to enhancing physical reliability. The strict latency limits hinder time and frequency diversity, thus spatial diversity via multiple antennas is essential. CF-MIMO disperses access points (APs) geographically to minimize path loss and inter-cell interference, ensuring coverage and reliable connectivity, which is crucial for HDT components such as body sensors at the network edge [17] [18] [19].

Furthermore, beamforming techniques are implemented to focus transmission energy on the target UE to enhance efficiency and reduce interference. Advanced designs, such as regularized zero-forcing (RZF), optimize power allocation and beamforming vectors to boost the minimum data rate or energy efficiency within reliability limits [20] [21]. These robust methods are crucial for sustaining continuous, high-quality links that are vital for real-time HDT synchronization and critical control loops [22].

Finally, GFA and NOMA address the need for low connection latency and efficient resource utilization, which are especially vital for supporting massive sensor connectivity associated with HDTs. GFA reduces the traditional signaling overhead associated with scheduling, allowing devices to transmit immediately, thereby minimizing access delay [23]. To mitigate the resulting collision risks with GFA, NOMA enables multiple users to share resources concurrently, improving efficiency, particularly for short-packet uplink transmissions. Enhancements to medium access strategies, such as compressing messaging in processes like random access, further minimize the overall signaling time for delay-sensitive applications [24].

B. Scheduling & Resource Management

URLLC's intricate balance of latency, reliability, and energy efficiency demands smart resource management for dynamic radio resource allocation [15] [25]. Joint resource optimization is crucial and typically involves the simultaneous optimization of interconnected, non-convex parameters like transmit power, bandwidth, and beamforming vectors to fulfill reliability and latency requirements [20] [26]. For HDTs, this adjusts the physical layer settings in real-time to adhere to strict QoS, potentially enhancing metrics such as energy efficiency or weighted sum rate under FBL constraints [21].

Adaptive management and coexistence mechanisms are necessary for supporting heterogeneous network traffic, such as URLLC for real-time HDT data and enhanced mobile broadband (eMBB) for high-bandwidth HDT interfaces (e.g., AR/VR visualization). Solutions often involve dynamic scheduling, NS, and prioritization schemes (e.g., giving URLLC requests priority access to virtualized resources over eMBB requests) [25] [19]. ML and deep reinforcement learning (DRL) are increasingly employed to learn optimal resource allocation policies and manage massive access requests. These approaches enhance responsiveness and adapt to dynamic network environments significantly faster than traditional optimization methods [27] [28].

C. Edge / Network-Level Methods

To reduce end-to-end latency, network architectures need revision, highlighting the importance of edge and distributed computing for HDTs. MEC and multi-tier computing are crucial as they decrease the service latency by bringing processing and storage capabilities closer to the UE. This architecture is critical for HDTs because it reduces communication delays by eliminating the backhaul and core network latencies typical of centralized cloud processing [25] [20]. MEC facilitates task offloading, allowing resource-limited devices, such as body sensors, to transfer computational tasks to nearby edge servers (ESs) for quicker processing.

DT - enabled network orchestration leverages MEC infrastructure by creating real-time virtual replicas of physical entities, including UEs, access points (APs), and ESs [19] [29]. The DT allows for offline training of deep learning algorithms and real-time monitoring of the network environment [28]. This enables the DT to propose and implement optimal policies such as user association, task offloading, processing rate allocation, and resource dimensioning, with a reduced computation time and enhanced awareness of the underlying system dynamics, which is crucial for guaranteeing HDT performance goals [20] [19]. NS complements MEC and DT architectures by logically partitioning physical network resources to provide isolation and customized virtual networks tailored for distinct services. NS is fundamental for ensuring that HDT traffic receives dedicated, guaranteed URLLC resources, facilitating efficient coexistence with other service categories (eMBB, mMTC) on the shared physical infrastructure. On the physical layer, RIS and unmanned aerial vehicles (UAVs) represent advanced components used to actively shape the wireless environment and provide aerial edge computing capacity, respectively. Specifically, RIS utilizes adjustable passive reflective elements to enhance channel quality, thereby increasing transmission rates and reducing latency for task offloading [25] [29]. UAVs serve as flexible, deployable MEC nodes, offering coverage and computation resources closer to users, which is particularly beneficial for time-sensitive HDT services, such as monitoring ambulatory patients in remote or dynamic environments [29] [19].

D. Security, Privacy & Trust

For HDT applications dealing with highly sensitive human data, security and privacy must be guaranteed without violating the stringent latency demands [24] [19] [30]. Traditional network security, which relies on complex, key-based cryptography at upper layers, often introduces substantial overhead and delay, making it incompatible with URLLC requirements [27]. Consequently, lightweight security solutions are necessary. PLS offers a crucial complement to upper-layer cryptography by leveraging the intrinsic physical properties of the wireless channel to secure the transmission hop with minimal latency overhead, while leaving data-at-rest encryption to higher layers. PLS techniques minimize the need for computationally burdensome cryptographic processes, thereby drastically reducing latency overhead. Confidentiality often involves joint optimization of physical layer parameters, such as transmission power and blocklength, to maximize the secure data rate against eavesdroppers [31] [24] [30].

Authentication can be achieved efficiently via physical layer authentication (PLA), which uses unique channel-based attributes or intrinsic hardware imperfections (radio-frequency fingerprinting) to verify device identity with minimal overhead. This is crucial to stop spoofing attacks in vital HDT control systems, preventing life-threatening manipulation of implantable medical devices [31]. Complementing this, establishing robust trust mechanisms is essential, particularly in distributed edge environments. Architectures leveraging technologies such as blockchain are being explored to manage trust relationships and guarantee data integrity across network elements. Together, these methods safeguard sensitive human data while striving to maintain the strict latency constraints of the HDT ecosystem [24] [26] [30].

IV. HDT IMPLEMENTATION CHALLENGES

HDTs are increasingly vital in personalized healthcare, requiring more sophisticated communication than standard DTs do in engineered systems [10] [32]. Owing to their association with complex and sensitive entities, HDTs impose unique constraints on deploying URLLC. One major challenge is meeting the tight worst-case latency and reliability requirements in health-critical HDT loops. Real-time tasks such as monitoring, diagnosis, and intervention demand exceptionally high service quality, often requiring latency under 1 ms. This challenge may necessitate URLLC technology enhancements through the tactile internet. Failure to achieve these standards can result in severe health outcomes or inaccurate predictions [12] [33]. HDTs depend on data from various wearable and implantable IoHT devices, which face limitations in processing, memory, and energy. Thus, computational tasks are offloaded to edge devices to reduce latency and data bottlenecks. This setup must also handle diverse data types and priorities from multiple sensors. Data urgency varies; high-priority alerts require fast action, unlike low-priority data such as ambient light. Efficient data fusion and priority-based scheduling are essential for avoiding congestion and ensure critical information is processed promptly [32] [10].

A critical technical difficulty is ensuring the consistency and synchronization of multimodal data from various sources, such as different sampling rates and protocols. For the VT to accurately mirror the patient's condition, real-time physical-cyber synchronization is essential. This task is complicated by patient mobility and changing channel conditions, necessitating that the VT or its data processing capabilities dynamically relocate to nearby edge servers to maintain high-fidelity connectivity as the PT moves. The complex, high-dimensional nature of HDT applications poses significant scaling and security challenges. To support large HDT populations, vastly distributed processing capabilities and new resource management techniques, such as federated HDT architectures spanning multiple cloud and edge servers, are essential for managing extensive data and computational demands [32] [33]. Simultaneously, addressing trust, privacy, and ethical issues within strict latency limits is crucial due to the sensitivity of healthcare data. Although encryption and blockchain enhance security, they often increase computational load, affecting low-latency needs. Thus, innovative solutions such as optimizing differential privacy or homomorphic encryption are needed to reduce the latency impact [12]. Additionally, effective large-scale deployment depends on overcoming the lack of standardization and interoperability between medical and telecom systems, which currently impedes broader data integration and solution generalization. These challenges demand ongoing advancements in URLLC technology, specifically for the dynamic and critical HDT environment [10] [12].

V. OPPORTUNITIES & FUTURE DIRECTIONS

Integrating URLLC capabilities in 6G networks offers significant potential for real-time, reliable HDTs. Future research must focus on the joint evolution of architecture and algorithms to integrate the physical and digital worlds, advancing to more autonomous and reliable systems.

A significant change involves the joint design of communication and twin models, necessitating an integrated approach that combines software and hardware for efficient DT deployment [34]. AI-driven methods like DRL offer opportunities for predictive resource management, enabling networks to self-optimize and self-heal based on real-time data states. This predictive capacity is crucial for proactive failure mitigation, avoiding system malfunctions and potential cyber attacks [35] [36]. Frameworks integrating predictive ML and blockchain at the edge [37] demonstrate resource efficiency models that can be adapted to secure HDT data integrity. Achieving this relies heavily on edge intelligence (EI) and lightweight on-device AI [38]. Edge computing reduces latency and facilitates real-time data processing by handling data close to the source. Research should focus on creating lightweight ML models and edge AI frameworks to lower computational overhead, enabling real-time, autonomous decision-making, which is essential for mission-critical HDT applications [35] [34]. This distributed model also inherently enhances hybrid, resilient, and privacy-preserving HDT systems, where a combination of a centralized cloud and distributed edge twins ensures durability and efficient resource allocation [39].

The adoption of advanced 6G technologies is essential for real-time HDTs, with future URLLC harnessing the THz spectrum for data rates up to 1 Tbps and minimal latency [11] [40]. The RIS enhances coverage and reliability by adjusting signal paths, and optimizing wireless channels [41] [34]. ISAC will allow precise environmental and user data capture, aiding resource management in the DTN [42]. Semantic communications (SC) will improve efficiency by emphasizing meaning over data transfer [19]. For accurate virtual models, research must focus on adaptive fidelity and context-aware updates, developing predictive synchronization and unified time protocols to reduce latency and jitter, ensuring HDT accuracy amid real-world dynamics [36].

Finally, future deployment must focus on strict governance and societal factors [43]. Broad adoption, standardization and interoperability for HDTs that work seamlessly across platforms, demand unified AI models, interfaces, and robust data governance. Emphasis on safety, validation, and certification is crucial [34] [42] [35]. The DT acts as a critical validation environment for complex tasks such as surgical planning and virtual drug testing, ensuring validation before human use. Additionally, ethical concerns necessitate explainable AI (XAI) to ensure transparency and trust in automated, healthcare-critical decisions [36]. Federated learning (FL), also offers critical paths toward ensuring privacy-preserving HDT systems by managing data securely and maintaining confidentiality [38]. However, ensuring the reliability of PLS for immobile, bedridden patients remains a key open challenge. Future work should explore RIS-assisted PLS to create artificial channel randomness, enabling high secrecy rates even under static channel conditions.

VI. CONCLUSION

This concise survey establishes that the realization of HDTs requires a fundamental shift from standard data transmission to URLLC, and identifies three critical takeaways. First, while 5G enablers such as MEC and NS are foundational, the strict sub-millisecond latency required for haptic feedback and remote surgery necessitates the integration of 6G technologies, specifically THz spectrum and RIS. Crucially, these frameworks must be enhanced to guarantee key generation rates in static environments, ensuring reliability for non-ambulatory patients. Finally, the evolution of personalized healthcare will require a transition from static, preconfigured architectures to autonomous, AI-enabled DTNs that can dynamically "self-heal" in real time while jointly optimizing both communication and computational resources.

REFERENCES

[1] G. Araniti, C. Garibotto, A. Jose, F. Marcello, V. Pilloni, A. Sciarrone, C. Suraci, P. Zema, and M. Zerbino, "Medical digital twin and IoT devices: Monitoring patients through human-centered technologies," *IEEE Internet of Things Magazine*, vol. 8, pp. 107 – 114, 2025.

[2] W. Shengli, "Is human digital twin possible?," *Computer Methods and Programs in Biomedicine Update*, vol. 1, p. 100014, 2021.

[3] A. Jose, A. F. Mac Cawley, L. E. Gaete, G. L. Tortorella, R. Vassolo, M. Kumar, N. Rich, and M. Kumar, "Determinants of ICT adoption and performance in healthcare: The role of individual attributes and organizational contextual factors," *IEEE Access*, 2025.

[4] S. L. Chaparro-Cárdenas, J.-A. Ramirez-Bautista, J. Terven, D.-M. Córdova-Esparza, J.-A. Romero-Gonzalez, A. Ramírez-Pedraza, and E. A. Chavez-Urbiola, "A technological review of digital twins and artificial intelligence for personalized and predictive healthcare," in *Healthcare*, vol. 13, p. 1763, MDPI, 2025.

[5] C. Suraci, O. Chukhno, G.-M. Muntean, A. Molinaro, and G. Araniti, "Migrate or not: Medical digital twins in the era of 6G edge-based networks," *IEEE Access*, 2025.

[6] S. Kharche and J. Kharche, "6G intelligent healthcare framework: A review on role of technologies, challenges and future directions," *Journal of Mobile Multimedia*, vol. 19, no. 3, pp. 603–644, 2023.

[7] Y. Kim, S. Oh, and G. Kim, "Convergence of integrated sensing and communication (ISAC) and digital-twin technologies in healthcare systems: A comprehensive review," *Signals*, vol. 6, no. 4, p. 51, 2025.

[8] M. E. Haque, F. Tariq, M. R. Khandaker, K.-K. Wong, and Y. Zhang, "A survey of scheduling in 5G URLLC and outlook for emerging 6G systems," *IEEE access*, vol. 11, pp. 34372–34396, 2023.

[9] S. S. Sefati and S. Halunga, "Ultra-reliability and low-latency communications on the internet of things based on 5G network: literature review, classification, and future research view," *Transactions on Emerging Telecommunications Technologies*, vol. 34, no. 6, p. e4770, 2023.

[10] J. Chen, C. Yi, S. D. Okegbile, J. Cai, and X. Shen, "Networking architecture and key supporting technologies for human digital twin in personalized healthcare: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 1, pp. 706–746, 2023.

[11] A. Salh, L. Audah, N. S. M. Shah, A. Alhammadi, Q. Abdullah, Y. H. Kim, S. A. Al-Gailani, S. A. Hamzah, B. A. F. Esmail, and A. A. Almohammedi, "A survey on deep learning for ultra-reliable and low-latency communications challenges on 6G wireless systems," *IEEE Access*, vol. 9, pp. 55098–55131, 2021.

[12] S. D. Okegbile, J. Cai, D. Niyato, and C. Yi, "Human digital twin for personalized healthcare: Vision, architecture and future directions," *IEEE network*, vol. 37, no. 2, pp. 262–269, 2022.

[13] A. Masaracchia, Y. Li, K. K. Nguyen, C. Yin, S. R. Khosravirad, D. B. Da Costa, and T. Q. Duong, "UAV-enabled ultra-reliable low-latency communications for 6G: A comprehensive survey," *IEEE access*, vol. 9, pp. 137338–137352, 2021.

[14] S. He, Z. An, J. Zhu, J. Zhang, Y. Huang, and Y. Zhang, "Beamforming design for multiuser uRLLC with finite blocklength transmission," *IEEE Transactions on Wireless Communications*, vol. 20, no. 12, pp. 8096–8109, 2021.

[15] Y. Huang, Y. Jiang, F.-C. Zheng, P. Zhu, D. Wang, and X. You, "Energy-efficient optimization in user-centric cell-free massive MIMO systems for URLLC with finite blocklength communications," *IEEE Transactions on Vehicular Technology*, vol. 73, no. 9, pp. 12801–12814, 2024.

[16] H. Attar, H. Issa, J. Ababneh, M. Abbasi, A. A. Solyman, M. Khosravi, and R. Said Agieb, "5G system overview for ongoing smart applications: structure, requirements, and specifications," *Computational intelligence and Neuroscience*, vol. 2022, no. 1, p. 2476841, 2022.

[17] A. Lancho, G. Durisi, and L. Sanguinetti, "Cell-free massive MIMO for URLLC: A finite-blocklength analysis," *IEEE Transactions on Wireless Communications*, vol. 22, no. 12, pp. 8723–8735, 2023.

[18] J. Östman, A. Lancho, G. Durisi, and L. Sanguinetti, "URLLC with massive MIMO: Analysis and design at finite blocklength," *IEEE Transactions on Wireless Communications*, vol. 20, no. 10, pp. 6387–6401, 2021.

[19] A. Masaracchia, D. Van Huynh, T. Q. Duong, O. A. Dobre, A. Nallanathan, and B. Canberk, "The role of digital twin in 6G-based URLLCs: Current contributions, research challenges, and next directions," *IEEE Open Journal of the Communications Society*, 2025.

[20] T. Q. Duong, D. Van Huynh, S. R. Khosravirad, V. Sharma, O. A. Dobre, and H. Shin, "From digital twin to metaverse: The role of 6G ultra-reliable and low-latency communications with multi-tier computing," *IEEE Wireless Communications*, vol. 30, no. 3, pp. 140–146, 2023.

[21] A. A. Nasir, H. D. Tuan, H. H. Nguyen, M. Debbah, and H. V. Poor, "Resource allocation and beamforming design in the short blocklength regime for URLLC," *IEEE Transactions on Wireless Communications*, vol. 20, no. 2, pp. 1321–1335, 2020.

[22] T. Li, H. Zhang, J. Qiao, and J. Tian, "Robust beamforming design with finite blocklength for URLLC," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 2, pp. 2604–2608, 2022.

[23] Y. Liu, Y. Deng, M. Elkashlan, A. Nallanathan, and G. K. Karagiannidis, "Analyzing grant-free access for URLLC service," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 3, pp. 741–755, 2020.

[24] M. Martalò, G. Pettorru, and L. Atzori, "A cross-layer survey on secure and low-latency communications in next-generation IoT," *IEEE Transactions on Network and Service Management*, vol. 21, no. 4, pp. 4669–4685, 2024.

[25] C. Souza, M. Falcão, A. Balieiro, E. Alves, and T. Taleb, "Dynamic resource allocation for URLLC and embb in MEC-NFV 5G networks," *Computer Networks*, vol. 260, p. 111127, 2025.

[26] Z. Zhou, Z. Jia, H. Liao, W. Lu, S. Mumtaz, M. Guizani, and M. Tariq, "Secure and latency-aware digital twin assisted resource scheduling for 5G edge computing-empowered distribution grids," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 7, pp. 4933–4943, 2021.

[27] J. Zhang, X. Xu, S. Han, K. Zhang, P. Zhang, and S. Ren, "Intelligent ultra-reliable and low latency communications: Security and flexibility," *IEEE Transactions on Wireless Communications*, vol. 22, no. 11, pp. 8392–8406, 2023.

[28] R. Dong, C. She, W. Hardjawana, Y. Li, and B. Vucetic, "Deep learning for hybrid 5G services in mobile edge computing systems: Learn from a digital twin," *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4692–4707, 2019.

[29] T. Q. Duong, D. Van Huynh, Y. Li, E. Garcia-Palacios, and K. Sun, "Digital twin-enabled 6G aerial edge computing with ultra-reliable and low-latency communications," in *2022 1st International Conference on 6G Networking (6GNet)*, pp. 1–5, IEEE, 2022.

[30] A. K. Yerrapragada, T. Eisman, and B. Kelley, "Physical layer security for beyond 5G: Ultra secure low latency communications," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2232–2242, 2021.

[31] E. Illi, M. Qaraqe, S. Althunibat, A. Alhasanat, M. Alsafasfeh, M. De Ree, G. Mantas, J. Rodriguez, W. Aman, and S. Al-Kuwari, "Physical layer security for authentication, confidentiality, and malicious node detection: A paradigm shift in securing IoT networks," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 1, pp. 347–388, 2023.

[32] E. Bozkaya-Aras, T. Onel, L. Eriskin, and M. Karatas, "Intelligent human activity recognition for healthcare digital twin," *Internet of Things*, vol. 30, p. 101497, 2025.

[33] M. D. Xames and T. G. Topcu, "A systematic literature review of digital twin research for healthcare systems: Research trends, gaps, and realization challenges," *IEEE Access*, vol. 12, pp. 4099–4126, 2024.

[34] M. Sheraz, T. C. Chuah, Y. L. Lee, M. M. Alam, A. Al-Habashna, and Z. Han, "A comprehensive survey on revolutionizing connectivity through artificial intelligence-enabled digital twin network in 6G," *IEEE Access*, vol. 12, pp. 49184–49215, 2024.

[35] A. Pourkabirian, M. S. Kordafshari, A. Jindal, and M. H. Anisi, "A vision of 6G URLLC: Physical-layer technologies and enablers," *IEEE Communications Standards Magazine*, vol. 8, no. 2, pp. 20–27, 2024.

[36] D.-H. Tran, N. Waheed, Y. M. Saputra, X. Lin, C. T. Nguyen, T. S. Abdu, V. N. Vo, V.-Q. Pham, M. Alsenwi, A. B. M. Adam, *et al.*, "Network digital twin for 6G and beyond: An end-to-end view across multi-domain network ecosystems," *IEEE Open Journal of the Communications Society*, 2025.

[37] C. Feng, A. K. Jumaah Al-Nussairi, M. H. Chyad, N. S. Sawaran Singh, J. Yu, and A. Farhadi, "AI powered blockchain framework for predictive temperature control in smart homes using wireless sensor networks and time shifted analysis," *Scientific Reports*, vol. 15, no. 1, p. 18168, 2025.

[38] W. M. Othman, A. A. Ateya, M. E. Nasr, A. Muthanna, M. ElAffendi, A. Koucheryavy, and A. A. Hamdi, "Key enabling technologies for 6g: The role of uavs, terahertz communication, and intelligent reconfigurable surfaces in shaping the future of wireless networks," *Journal of Sensor and Actuator Networks*, vol. 14, no. 2, p. 30, 2025.

[39] L. U. Khan, W. Saad, D. Niyato, Z. Han, and C. S. Hong, "Digital-twin-enabled 6G: Vision, architectural trends, and future directions," *IEEE Communications Magazine*, vol. 60, no. 1, pp. 74–80, 2022.

[40] B. Hassan, S. Baig, and M. Asif, "Key technologies for ultra-reliable and low-latency communication in 6g," *IEEE Communications Standards Magazine*, vol. 5, no. 2, pp. 106–113, 2021.

[41] A. A. Shamsabadi, A. Yadav, Y. Gadallah, and H. Yanikomeroglu, "Exploring the 6G potentials: Immersive, hyperreliable, and low-latency communication," *IEEE Vehicular Technology Magazine*, 2025.

[42] N. P. Kuruvatti, M. A. Habibi, S. Partani, B. Han, A. Fellan, and H. D. Schotten, "Empowering 6G communication systems with digital twin technology: A comprehensive survey," *IEEE access*, vol. 10, pp. 112158–112186, 2022.

[43] A. Kharbouch, F. H. Aghdam, N. Gholipoor, and M. Rasti, "Digital-twin-6G empowered future smart grid applications," *IEEE Wireless Communications*, vol. 32, no. 3, pp. 90–97, 2025.