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G. Araniti *et al.*, "Medical Digital Twin and IoT Devices: Monitoring Patients Through Human-Centered Technologies," in *IEEE Internet of Things Magazine*, vol. 8, no. 6, pp. 107-114, Nov. 2025.

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The publisher's version is available at:

<http://dx.doi.org/10.1109/MIOT.2025.3591039>

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Medical Digital Twin and IoT Devices: Monitoring Patients Through Human-Centered Technologies

Giuseppe Araniti ¹, Chiara Garibotto ², Abey Jose ³, Francesca Marcello ⁴, Virginia Pilloni ⁵, Andrea Sciarrone ⁶,
Chiara Suraci ⁷, Pietro Zema ⁸, and Matteo Zerbino ⁹

Abstract:

The healthcare landscape is undergoing a transformative shift driven by the rapid advancements of sixth-generation (6G) cellular networks and Internet of Things (IoT) technologies. This convergence has led to the emergence of medical digital twins (MDTs) – innovative virtual replicas of physical entities or processes. MDTs enable safe monitoring and testing of therapeutic decisions, resulting in substantial cost savings and enhanced decision-making capabilities for physicians. Furthermore, they provide real-time assistance and facilitate comprehensive data analysis, revolutionizing patient care. However, their full potential is constrained by the intricate nature of human life cycles. Key factors include the choice of data types and the communication protocols used to connect physical and digital twins. For individuals with disabilities, integrating wearable devices with edge computing and WiFi-based Channel State Information (CSI) can effectively monitor health metrics and recognize activities. Although the integration of 6G and IoT technologies holds the promise of enabling seamless communication between physical and digital twins, this paper, which is developed in the framework of the HIPPOCRATES project, focuses on a currently implementable architecture for MDTs based on the Message Queuing Telemetry Transport (MQTT) protocol. The proposed system integrates CSI to augment health monitoring and intervention, particularly for individuals with disabilities.

I.

Introduction

Technology improves quality of life by supporting recovery, independence, and safety of individuals, especially in healthcare. It enhances monitoring through sensors and wearables, enabling early issue detection and timely care. Additionally, real-time feedback systems promote autonomy, boosting confidence and well-being. The advancements in next-generation communication architectures such as fifth generation (5G), sixth generation (6G), and the Internet of Things (IoT) are enabling complex use cases such as eHealth, assisted living, and personalized care. All of these require context-awareness and user profiling techniques, which can be included in digital replicas of the people they are associated with. In recent years, Medical Digital Twins (MDTs) have emerged as innovative approaches in healthcare, as they virtually replicate physical entities to monitor conditions and test treatment decisions in a safe and low-risk environment. They can provide real-time assistance by allowing remote patient monitoring while supporting decision making, both for professional and non professional caretakers, which in turn helps reducing healthcare costs. Fig. 1 shows some possible applications of MDTs with an emphasis on targeting people with disabilities.

Implementing MDTs is not devoid of challenges [1], particularly in managing the complexity of human behaviour and health. The two main priorities are accurately selecting parameters for the digital replica and ensuring efficient data transfer between the individual and the MDT. Wearable devices combined with edge computing can monitor vital metrics such as electrocardiogram (ECG), peripheral oxygen saturation (SpO₂), and blood pressure. Additionally, for individuals with disabilities, Channel State Information (CSI) can be used non-intrusively to gather spatial data for fall detection and activity recognition (e.g., standing, walking), enriching MDT monitoring and enabling responsive interventions, such as in home rehabilitation. In general, data transmission to MDTs can benefit from cutting-edge technologies such as 6G, which are expected to significantly improve latency, data rate, and overall Quality of Service (QoS) and Quality of Experience (QoE) [2]. Furthermore, 6G-enabled technologies, such as artificial intelligence (AI), machine learning, 3D networks, and extended reality (XR), can further facilitate seamless communication between physical and digital twins. While emerging technologies are expected to offer enhanced capabilities for the realization of digital twins, this work focuses on currently deployable solutions. Specifically, we propose the use of MQTT (Message Queuing Telemetry Transport) due to its distinctive features and lightweight design. MQTT is a widely used protocol in IoT applications, where reliable transmissions, low bandwidth, and high scalability are mostly needed [3]. It is a lightweight messaging protocol based on TCP/IP and a publish/subscribe architecture, whereby sensors publish data on a topic, the digital twin could receive them by subscribing to that topic, and the broker is the central element that routes messages from the publisher to the subscribers. This brings several useful benefits to the efficient implementation of MDTs, including increased scalability, support for different levels of QoS, and message retention that ensures more

reliable communication.

A. Main Contributions

The primary goal of this work, realized under the HIPPOCRATES project, is to propose an innovative system for the implementation of MDTs, integrating CSI and wearable devices information (*e.g.*, smart watches), leveraging the MQTT protocol for data transmission. In addition to monitoring vital signs, such as heart rate and blood oxygen levels, via wearable devices, CSI can also potentially be used to determine a person's approximate location within a home environment, for instance, by identifying whether they are in the living room or kitchen, as well as the activity which is being performed. This capability enables the detection of critical events, such as falls, allowing timely alerts to designated caregivers or emergency responders. The data gathered through this system furnishes a comprehensive assessment of a person's health condition, proving particularly advantageous for elderly individuals, those with chronic illnesses, people with disabilities, or individuals convalescing at home. This information can be analyzed in real time and shared with specialized personnel who can identify potential issues and respond as promptly as possible. As shown in Fig. 2, data is transmitted in real time using an MQTT system to a digital twin, which serves as a centralized repository where it is stored and made available for consultation. In addition to supporting caregivers, the system can also directly benefit the individual. For example, a visually impaired person can receive auditory feedback based on CSI positioning data to assist with navigation, improving their spatial orientation and independence, reducing the risk of accidents and enhancing quality of life.

As will be demonstrated in the subsequent analysis of related works, the integration of CSI, wearables, MQTT, and MDTs to support people with disabilities proposed in this paper represents a novel approach compared to the existing literature. The significance of CSI and the role of IoT and edge computing will be discussed, emphasizing how their convergence forms a state-of-the-art digital twin framework that enhances assistive technologies. Our analysis highlights the integration of these components, illustrating their collective capabilities and implications for future advancements in the field. Through this exploration, we aim to showcase how a well-structured digital twin can significantly improve the functionality and effectiveness of assistive technologies.

II.

Related Work

The latest research on MDTs highlights their potential to personalize treatments by predicting disease progression and treatment outcomes. A key example is presented in [4], where the authors propose the use of immune digital twins to diagnose and treat diseases such as cancer and autoimmune disorders, highlighting challenges and advancements in developing digital twins, emphasizing their role in predictive analytics and personalized interventions. This approach aligns with the real-time MQTT data transfer architecture presented in this work. Similarly, [5] discusses human digital twins in healthcare, particularly for personalized medicine, with potential applications for people with disabilities, such as knee health monitoring cases of in osteoarthritis, congenital issues, and trauma, common causes of disability. The combination of digital twins and the metaverse could revolutionize healthcare, as explored in [6]. The study illustrates how this integration enhances care accessibility, surgical training, and proactive health monitoring. One proposed example is a that of virtual health consultation model where digital twins facilitate communication between patients and physicians. Another one involves surgical simulations, allowing medical professionals to practice complex procedures in a virtual, safe environment. Patients can also use digital twins to monitor health parameters in real time, promoting active health management. Additionally, [7] highlights the benefits for students with learning difficulties, enhancing inclusive education through realistic and immersive experiences. Sticking to the topic of education, digital twins and IoT are shown to improve medical learning accessibility for students with physical disabilities [8]. Likewise, [9] introduces the interface digital twin (IDT) to enhance accessibility to physical devices for people with visual disabilities. Finally, in [10], the authors explore how human digital twin (HDT) technology can be used together with AI-generated mobile content (AIGC) to develop new personalized healthcare services. Using generative AI at the edge of the network, on-demand health services can be provided in real time, tailored to the specific needs of individual patients. This tailoring is achieved by integrating patient-specific data, such as vital signs, medical history, and real-time sensor input, into the generative model at the edge. This allows the system to produce adaptive outputs, such as personalized recommendations or predictive insights, that reflect the unique health profile and current condition of each individual. In the case of data scarcity, which is particularly relevant in the case of rare diseases or specific health conditions, the authors propose the use of AIGC as a means of continuous monitoring and prediction of health with HDT. This is accomplished by generating data that is similar to real medical information, which can be highly beneficial in the context of proactive healthcare. Furthermore, the paper addresses the potential of HDTs as a highly realistic testing platform for applications such as surgical planning and virtual drug testing. This allows healthcare professionals to make the necessary adjustments before implementing them in the actual clinical setting. The authors present a comprehensive system architecture that includes the use of cloud, edge, and mobile devices, as well as an analysis of the challenges associated with data management, cybersecurity, and latency.

Despite recent advancements, current approaches often target specific applications or depend on centralized architectures, limiting scalability, responsiveness, and adaptability in diverse healthcare contexts. In contrast, the framework proposed in our paper integrates human digital twins with a real-time, MQTT-based edge-cloud architecture, enabling low-latency, decentralized data exchange. This design supports dynamic personalization based on individual health profiles and is ideal for scenarios requiring immediate feedback and high availability, such as remote monitoring

or assistive technologies. Additionally, our framework prioritizes interoperability and modularity, allowing seamless integration with various medical IoT devices and virtual environments, areas only lightly covered in existing research. These strengths make our approach a flexible, robust foundation for next-generation digital health ecosystems.

III.

The HIPPOCRATES Project

A. Channel State Information (CSI)

Channel State Information (CSI) describes the state of a wireless channel, providing details on how a signal propagates from the transmitter to the receiver and illustrating the effects of phenomena like scattering, fading, and power decay. Introduced in the IEEE 802.11n standard in 2009, CSI allows WiFi systems to adapt to changing channel conditions, improving communication stability and reliability. Differently from traditionally well-known indicators like RSSI, CSI provides information about the frequency response of a channel related to each TX-RX antenna pair and to each subcarrier in the form of the CSI matrix, a three-dimensional matrix of size $N_{tx} \times N_{rx} \times S$, where N_{tx} is the number of transmitting antennas, N_{rx} is the number of receiving antennas, and S is the number of considered subcarriers. CSI has sparked a wide range of research topics. While many studies focus on well-established applications such as localization, movement detection and tracking, some more specialized and unconventional uses are also present, including fire detection and concealed object recognition. Compared to traditional techniques, such as those relying on the RSSI, CSI retains their simplicity and accessibility, while also benefiting from a superior precision [11].

In the specific case of this work, two PCs capable of extracting CSI information were used during the experimental phase, placed at opposite ends of an otherwise empty room. Four people performed various movements within the Line Of Sight (LOS) between the two devices, specifically: *standing*, *sitting*, *walking* and *running*. Measurements were also taken in the empty room to further demonstrate the discriminative capabilities of CSI. Alongside movement-related data, positioning measurements within the room were also collected: four positions, chosen by dividing the room into four sectors, were used to test the ability of CSI to distinguish, at a macroscopic level, where a person is located in the environment. CSI data was fed into an LSTM network for classification. Two networks process the data after a filtering operation and are trained separately: the first one to distinguish among the 4 activities plus the empty room case, the second one to differentiate among the 4 positions. Once the training phase was completed, tests were conducted using measurements related to the aforementioned classes, providing the network with data blocks containing several seconds of measurements. Intuitively, increasing the measurement time improves classification accuracy, particularly for activity estimation. The obtained results demonstrate the feasibility of using CSI for this type of operation, achieving 94% average accuracy in activity classification and 96% average accuracy in localization. All data thusly obtained can then be sent to the digital twin using MQTT to enhance its descriptive capabilities regarding an individual's health status and enable monitoring in cases where it is required.

B. Wearable Healthcare

Wearable IoT devices are pivotal in rapidly collecting and pre-processing data, monitoring user habits, and gathering insights into physical activities. The ISO/IEEE 11073 Personal Health Device (X73-PHD) standards [12], intricately linked to the Internet of Things (IoT), have garnered significant attention in the IoT healthcare domain. These devices play a vital role in addressing the pressing issues of widespread physical inactivity and the alarming rise in chronic diseases such as diabetes and high blood pressure. PHDs enable individuals to monitor their health, manage medications and transmit the information collected to healthcare professionals [13]. Health metrics are generated by PHDs and subsequently transferred to a nearby mobile application for further analysis.

Given the nature of the system to be developed, the choice of devices to be used and the method of data acquisition should consider these three fundamental requirements:

- Privacy-aware design: Ensuring that user data is collected, processed, and shared in a manner that respects privacy and complies with relevant regulations (*e.g.*, General Data Protection Regulation).
- Real-time data availability: Enabling immediate access to updates as user activities or vital parameters change.
- Ease of management and scalability: Simplifying the integration and use of data from different wearable devices, reducing complexity in handling multiple brands and models.

Therefore, the proposed solution for data collection from wearable devices leverages data from devices of different brands and models and on established platforms such as Health Connect for Android devices and Apple Health for iOS devices. These platforms aggregate data from a multitude of wearable devices and sensors, providing consistent, real-time access to key metrics. By utilizing such centralized ecosystems, data collection becomes:

- Privacy-aware: Platforms like Health Connect and Apple Health incorporate robust privacy features, including user consent mechanisms and secure data handling, ensuring compliance with privacy requirements.
- Real-time enabled: These platforms allow access to activity metrics, vital parameters (*e.g.*, heart rate, SpO2), and sleep reports as they are updated, enabling prompt synchronization with external systems.
- Efficient and scalable: Both platforms support seamless data integration from diverse sources, eliminating the need to design specific interfaces for different wearable brands and models.

In this way, this solution ensures compliance with the previously outlined requirements.

C. Edge Computing

Digital twins require diverse real-time data streams to construct a comprehensive and dynamic model. Edge computing, a revolutionary technology in the IoT ecosystem, facilitates the seamless integration of data generation and real-time processing. It ensures low-latency communication and real-time data handling, making it ideal for time-sensitive applications like health monitoring, enabling data safety and privacy and facilitating near instantaneous analysis and decision making [14]. The preprocessed data is sent to the main digital twin system for analysis and storage, while ensuring individual safety and well-being.

Hence, once data has been collected through wearable devices, a mobile app, Health Twin (HT), installed on a user's smartphone, retrieves health data from the primary health app of the user. HT then processes the data locally to provide the most immediate real-time alerts, health trend analysis, and anomaly detection. Securely, HT transmits the refined data to an external system via an integrated MQTT interface. In real time, the data is published to the main digital twin system using an MQTT broker. In order to give more control to the user, the app provides the option to choose a reliable MQTT broker that offers data encryption while transmitting. The new app could extend its possibilities by adding additional features such as sending manual input data such as mood, symptoms, etc., and receiving recommendations from the digital twin.

The system collects health and activity data from a smartwatch, including metrics like heart rate, blood oxygen, step count, sleep details, etc., to monitor the user's physiological state. On the other hand, CSI, which collects non-X73 compliant data from WiFi devices, is used to monitor spatial dynamics, movement, and potential obstacles. This information is particularly valuable for individuals with mobility impairments or sensory limitations. Additionally, the data needs to be preprocessed and transmitted in real time. Integrating data streams of internal (health) and external (environmental) conditions allows the MDT to make informed recommendations in real-time. Data transmission occurs with minimal latency, thus ensuring that the MDT is an accurate replica of the patient.

IV.

Physical and Digital Twins

The network architecture proposed in this work to enable the transfer of real-time data from the physical twin to its digital counterpart leverages the MQTT protocol, with the aim of streamlining the processes for implementing and updating the MDT. This section will provide an overview of the general characteristics of the digital twin realizable through the proposed framework and a description of the architecture on which the MQTT protocol runs.

A. Features of the Digital Twin

The following features define the digital twin that could be realized by exploiting the proposed framework.

- **Data acquisition layer:** The digital twin is continuously fed with data about the real twin. The Mi Fit band 8 (smart band) is used as a wearable device to capture the vital parameters of the physical twin, including heart rate, blood oxygen, vitality, and sleep details that are aggregated as total duration, deep, light, and REM (Rapid Eye Movement). This data is catered to the respective health framework; for instance, for iOS, the health app is driven by the HealthKit framework, and the health twin app fetches data in real time and is intended to be used in the MDT dashboard. At the same time, CSI data is acquired and processed to infer activity and positioning data.
- **MQTT protocol:** Seamless communication with the physical twin is the backbone of every digital twin. The lightweight and reliable MQTT protocol can ensure the rapid transfer of data from physical space to digital space.
- **Real-time data integration:** Data collected through the various sensors is integrated to provide a comprehensive, overall view of the person. Delays in this process are optimized through the use of edge computing. This can be of considerable benefit for latency-sensitive applications such as fall detection, mobility assistance, and indoor assistive navigation.
- **Visualization:** Data collected and integrated into the digital twin could be transformed into an interactive 3D representation of the physical twin. Software such as Unity or Unreal Engine 5 could be used for this purpose. These tools offer high-fidelity simulations that allow dynamic visualization of data and behaviors, which can be particularly useful in health care, education, and accessibility applications for people with disabilities.
- **What-if analysis:** Conducting what-if analyses on the digital twin allows users to simulate different scenarios and predict potential outcomes without real risks.

B. The MQTT Architecture

The architecture supporting MQTT includes three key components: client, broker, and subscriber.

The MQTT *broker* is hosted on a remote server that acts as an intermediary between the MQTT client and the MQTT subscriber. It is responsible for receiving the data published by the MQTT client and managing the distribution of such data to the subscribing entities. Taking into account the critical sensitivity of personal data, the MQTT broker oversees the implementation of different levels of QoS, with the purpose of ensuring reliable and correct delivery.

The MQTT *subscriber* is located on a different computer, where the digital twin can be represented by the use of specialized software. The MQTT subscriber receives real-time data about the physical twin through the broker. Upon reception of data, the parameters of the digital twin can be updated, thus ensuring that the digital model accurately reflects the current physiological state of the real twin.

This MQTT-based architectural solution provides a robust and scalable framework for real-time data transfer and dynamic updating of digital twins, which could be very useful in healthcare applications supporting people with disabilities. MQTT is exploited because it is a lightweight and reliable communication protocol that can ensure the efficient transmission of critical personal data from the physical twin to its digital counterpart. This would enable continuous monitoring and advanced simulations, which could potentially improve the quality of life of the person.

V.

Experimental Results

With respect to CSI data collection, two neural networks process the data after a filtering operation and are trained separately: the first one to distinguish among the 4 activities plus the empty room case, the second one to differentiate among the 4 positions. The filtering operation, making use of a median filter and a Hampel filter, is aimed at removing outliers and impulsive noise from the measures, to slightly mitigate the effect of channel noise. The median filter is a nonlinear digital filtering technique often used to remove spikes and noise by replacing each value with the median of neighboring values. The Hampel filter, on the other hand, is a filter which detects and replaces outliers based on the median absolute deviation, preserving underlying trends while eliminating anomalies. The employed tool is the Intel 5300 CSI Tool [15], an experimentation platform which allows acquisition of CSI data. Two PCs mounting three antennas each were placed on the opposite sides of a room, at a distance of approximately 5 meters, working as TX and RX stations, respectively. MIMO measures were gathered using channel 64 (centered at 5.320 GHz) from 6 different people. The acquired data was then split into blocks of varying size $N \times 3 \times 3 \times 30$ (N data samples for 9 antenna couples and 30 subcarriers) and classified using a LSTM neural network. The Long Short-Term Memory Network (LSTM) is a type of recurrent neural network (RNN) specifically designed to learn temporal patterns and dependencies in sequential data. It can effectively retain and utilize information over long time intervals, making it especially suitable for processing time-series data such as CSI sequences.

Once the training phase was completed, tests were conducted using measurements related to the aforementioned classes, providing the network with data blocks containing several seconds of measurements. Intuitively, increasing the measurement time improves classification accuracy, particularly for activity estimation. Whereas the system works properly even with sub-second measures, allowing classification on some seconds of records leads to higher performance. The obtained results demonstrate the feasibility of using CSI for this type of operation, achieving 94% average accuracy in activity classification and 96% average accuracy in localization, as shown in Fig. 3 (four logical positions were tested, identifying 4 different areas of the testing room, in a real scenario they can represent different areas of the patient's home). All data thusly obtained can then be sent to the digital twin using MQTT to enhance its descriptive capabilities regarding an individual's health status and enable monitoring in cases where it is required.

In addition to this, we have realized a testbed to measure the total time for the transmission of various kinds of data from the physical twin to the digital twin. The system has been evaluated by exploiting data on the positioning and vital parameters of monitored patients, transmitted to the digital twin by means of the MQTT protocol. Transmission delay and delivery reliability have been evaluated at various QoS levels using the public broker test.mosquitto.org, which is a test server provided by the Mosquitto project foundation. The physiological values detected were compared with thresholds related to healthy individuals to verify the quality of sensor results and identify any irregularities in transmission or data collection. We were able to replicate authentic remote health monitoring situations using this technique and show that MDT reflected rapid and consistent changes. The tests have been carried out in a controlled laboratory environment, using a stable and reliable connection, to evaluate the basic functionality and performance of the proposed system and to minimize packet loss and ensure consistent measurement conditions. In the following, we present the obtained results.

Fig. 4 shows the total time (expressed in seconds, s) for the delivery of data transmitted through MQTT with different levels of QoS with the aim of quantifying the delay in data delivery to the digital twin for each message sent.

Fig. 5(a) and 5(b) provide more technical details, since different categories of people with disabilities are considered as physical twins and, consequently, data has been sent with different time intervals that have been customized to the condition of the patient under consideration. The continuous line represents the messages constantly sent, while the dots represent the more sporadic messages. Furthermore, we have implemented different transmission techniques according to the criticality of the transmitted information. QoS 2 has been applied to send the most critical data for each disability category every second, such as the case of real-time positioning data for people with motion disability (see Fig. 5(a)), ensuring maximum reliability and transmission frequency. In contrast, QoS 0 has been used to transmit every 10 seconds less critical data, such as vital parameters for people with motion disability (see Fig. 5(a)), allowing for still rapid updates and tolerating occasional packet loss without significant impact.

In detail, Fig. 5(a) shows the results related to a person with motion disabilities who is remotely monitored. In this case, we have sent data about the patient's positioning, detectable through CSI analysis, to the digital twin continuously, while vital parameters, detectable through IoT, have been sent less often. We also used different levels of QoS for transmission based on the higher or lower reliability required for sending data based on the patient's health condition. In the case reported in Fig. 5(a), positioning data, which are the most critical for a person with a motion disability, have been sent with QoS equal to 2, while vital parameters have been sent with a level of QoS equal to 0.

Fig. 5(b) shows the results obtained in the case where the physical twin is a person with a disability with critical clinical implications, such as severe neurological disabilities, complex metabolic or endocrine conditions, or cardiovascular or respiratory diseases. In this case, vital parameters have been sent continuously to the digital twin, while messages with

positioning data are delivered less frequently. Data of highest importance have been sent using QoS 2, while the least critical data has been transmitted with QoS 0.

VI.

Conclusion

In conclusion, the integration of Medical Digital Twins (MDTs) with advanced technologies such as Channel State Information (CSI), Internet of Things (IoT), and edge computing represents a significant step in healthcare to support people with disabilities. In this paper, an architecture involving data collection via wearable IoT devices and CSI is proposed to monitor people with disabilities who are in indoor environments. Vital signs are tracked by wearable devices, while CSI provides information on the person's location and activities involving movement. This data is then transferred to the MDTs of the people being monitored using the MQTT protocol. The proposed system effectively combines vital health data, spatial context, and seamless data transmission to provide a comprehensive overview of the status of an individual. It could support healthcare providers in timely decision-making and empower patients with tools for navigating daily challenges. The integration of emerging sixth-generation (6G) networks and IoT technologies could improve the scalability and performance of such system, potentially making them robust solutions for modern healthcare needs. While challenges remain in addressing the complexity of human behavior and ensuring efficient communication between physical and digital entities, the framework that was presented here describes a promising starting point. Future research should broaden the scope of this conceptual framework to its comprehensive implementation within the system. This includes conducting studies that incorporate the recruitment of individuals with disabilities. Additionally, it is essential to evaluate the framework's capabilities in areas such as recommendation, decision prediction, visualization, and what-if analysis to fully understand its potential and robustness.

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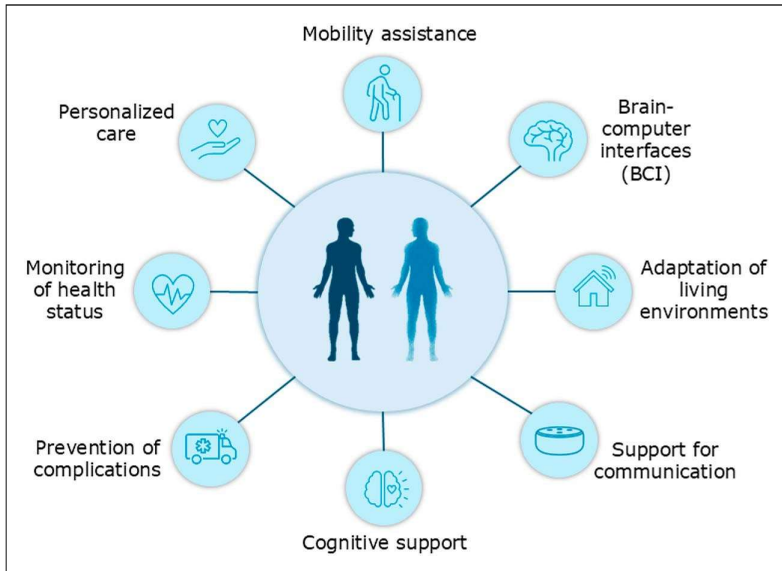


FIG. 1. Possible applications of digital twins in supporting people with disabilities.

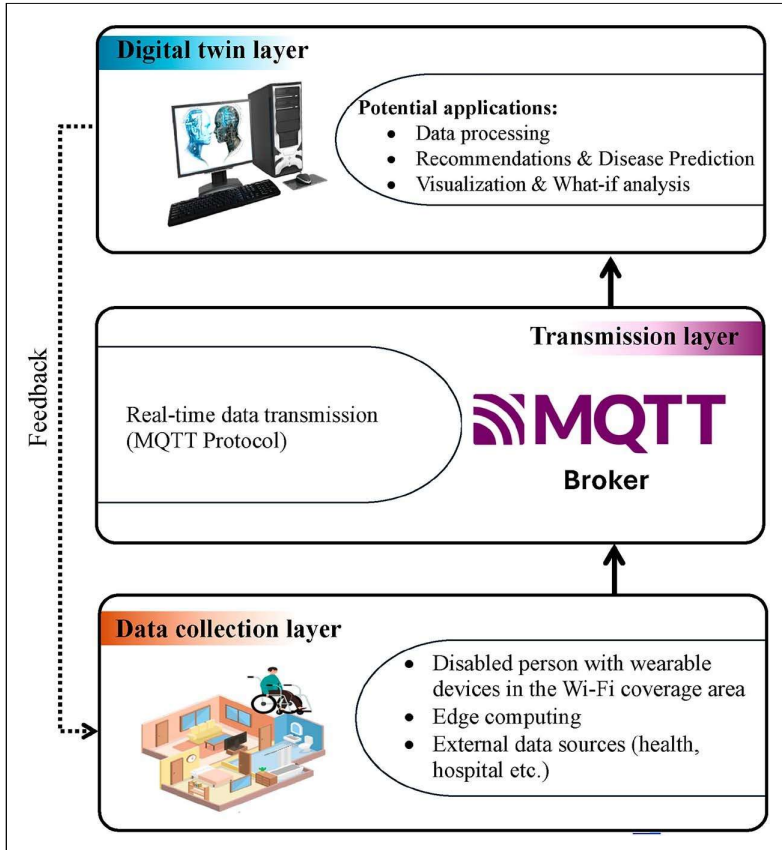


FIG. 2. Conceptual system architecture of medical digital twin.

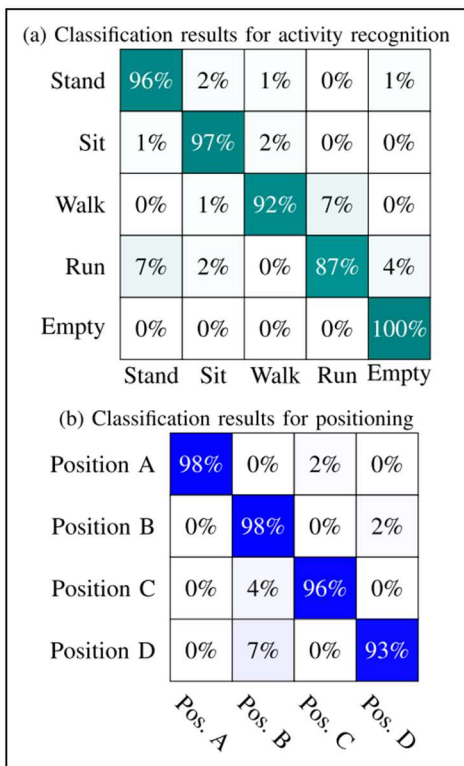


FIG. 3. Classification results.

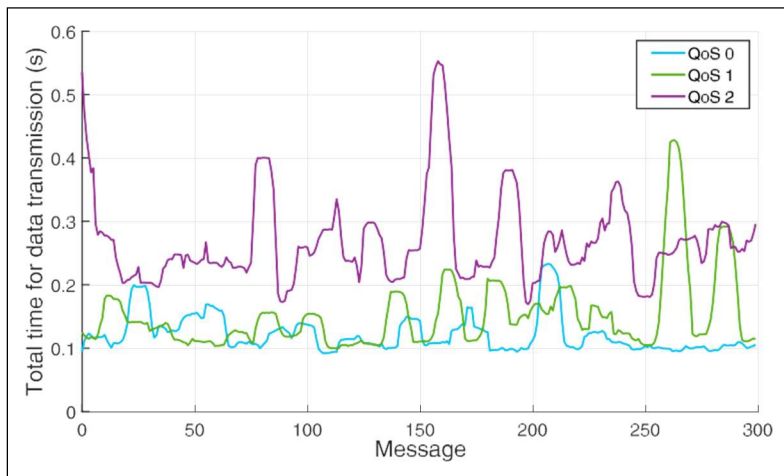


FIG. 4. Total transmission time for the delivery of data with different levels of QoS.

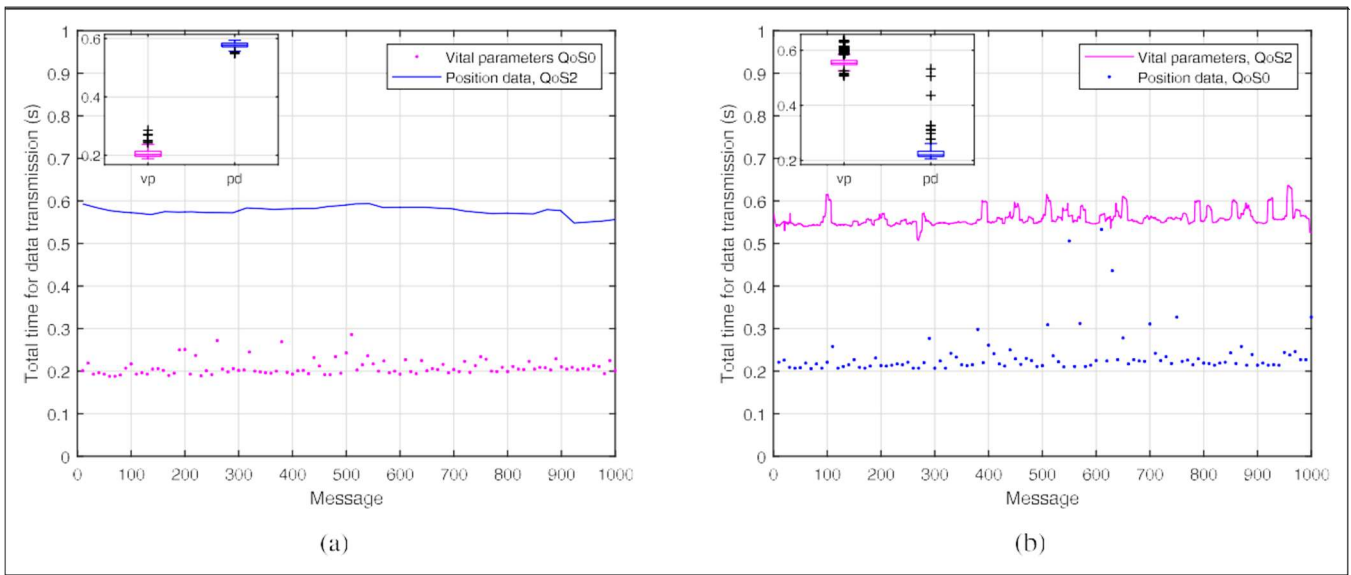


FIG. 5. Total transmission time for the delivery of vital parameters and positioning information related to a person with (a) motion disability and (b) clinical disability.