OCTOPUS: Optimized Cross-border TeleOperated Medicine Pouring Using NextGen Seamless Communication Networks

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***Abstract*—Teleoperated robotic systems have become instrumental in advancing remote healthcare services, especially in tasks that require precision and expert oversight. The advent of cutting-edge telecommunication infrastructures, such as 5G, has amplified interest in these systems, although their full potential remains untapped. This study delves into the effectiveness of teleoperated robotic systems for medicine dispensing, comparing the performance of Wi-Fi and 5G networks in a transnational setup between two cities – Prague and Munich. We focus on the robot's ability to accurately dispense a predefined volume of a syrup-like substance, simulating a delicate healthcare operation, under the guidance of a distant operator. Our research examines the system's holistic performance in real-world implementation across diverse scenarios, encompassing varying network states and feedback methods. Two primary feedback scenarios are considered: one incorporating real-time video streaming and another offering explicit quantitative data on the dispensed volume. Using a blend of quantitative and qualitative methods, we aim to determine the influence of network type and feedback on task efficacy and user satisfaction. This study provides insights into the potential and hurdles of deploying teleoperated robotic systems in crucial healthcare contexts, guiding future advancements in this domain, especially in scenarios, where precision and dependability are crucial.**

***Index Terms*—Teleoperation, Medicine pouring, 5G, Human-Robot Interaction, Experiment, Real-world implementation**

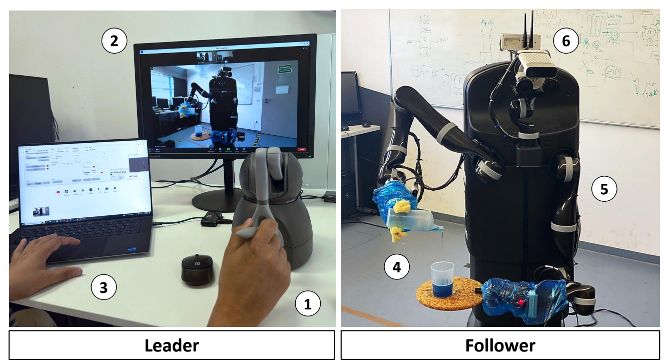

Fig. 1: Medicine Pouring with Kinova® Movo (5) and 3DSystems® Omni (1) using 5G USRP (6): The platforms collaboratively perform a pouring task (4), utilizing force feedback to mimic hand weight and weight gauge (3) next to video (2) feedback to indicate the target container's volume. An external camera provides perspective video feedback of the operation over Zoom® platform.

I. Introduction

The incorporation of robotics into healthcare has expanded avenues for enhanced patient care, especially in tasks that demand precision, reliability, and remote operation capabilities. A notable application emerges in elderly care [1], [2], where precise medicine dispensing is essential for the health and safety of individuals . With the development of sophisticated telecommunication infrastructures, such as the 5G tactile internet, the feasibility of executing robotic operations over networks is under scrutiny [3]. Nonetheless, seamless coordination between robots and these networks for timely healthcare operations warrants in-depth analysis, [4]–[6].

The intricate process of medicine dispensing, especially of liquid medications requiring precise measurements that vary based on viscosity, presents multiple challenges. The consequences of dispensing errors, such as inaccurate dosages or wrong medications, can have severe health implications. While autonomous robotic systems have advanced in diverse fields, the critical nature and variability inherent to medicine dispensing call for human oversight and control. Operations involving liquid medicines impose unique requirements on robots, distinct from handling solid objects, thereby influencing network feedback mechanisms and user control.

As a major novelty and contribution, this study investigates this complex problem by exploring real-world implementation of teleoperated robotic systems as a viable solution for remote,

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precise medicine dispensing as illustrated in Fig. 1. We first evaluate the efficacy of teleoperated robotic medicine pouring, particularly focusing on the impact of network technologies (Wi-Fi and 5G) on task performance and user experience. Then, we perform experiments encompassing teleoperated pouring tasks conducted by 15 individuals and we evaluate the performance across two communication networks, 5G and Wi-Fi, under various feedback modalities, including container weight visualization rate. The results underscore the potential advantages of advanced communication networks like 5G and the importance of feedback modality choice in optimizing teleoperated tasks in healthcare settings.

The remainder of the this paper is as follows. Following this introduction with objectives and significance of the study, Section II delves into related work on developments in teleoperated healthcare robotics and network technologies. Section III elucidates the methodology, detailing the experimental setup, task description, and user study design. Section V presents and discusses the results, both quantitative and qualitative, followed by Section VI concluding the work for future avenues.

II. Related Work

The intersection of robotics, teleoperation, and healthcare has been a focal point of research, driven by the potential to enhance the quality, accessibility, and safety of healthcare services. This section explores pertinent literature and developments in these domains, providing a backdrop against which the present study is positioned [7] [8] [9] [10] [11] [12]. Teleoperated robotic systems have been progressively permeating healthcare, offering solutions that bridge physical distances and enhance capabilities. Notably, teleoperated surgical systems, such as the da Vinci Surgical System [13], have demonstrated the viability and advantages of remote robotic control in healthcare. Studies exploring teleoperation in healthcare have highlighted aspects like latency, reliability, and user experience as critical factors influencing task performance and system usability [14].

In contrast to the related works, our study delves in investigating the challenges in network based teleoperation of robotic pouring, addressing issues like quantity control and spill prevention, with a keen emphasis on the interplay between teleoperation challenges and network performance. In the realm of elderly care, the study centers on the application of teleoperated robotic systems for precise and reliable tasks such as medicine dispensing, recognizing the unique demands of safety and ease of use in this context.

III. Methodology

In this section, we present our methodology for the experimental setup of OCTOPUS. At first, in Section III-A, we describe the system setup at Munich and Prague, then in Section III-B and III-C, we present our approach on the experimentation scenario and the task to be performed in our user-centric study. Finally, in Section III-D, we present our hypotheses for the experimentation.

A. System Setup

The experimental setup is bifurcated into two primary sites connected over the Internet: the robot setup located in Munich and the operator setup in Prague as depicted in Fig. 2.

1) Robot Setup in Munich: The robot, a Kinova® Jaco2 manipulator *, is equipped with a Botasys® FT sensor† , facilitating nuanced control during the pouring task and providing vital force feedback to the operator. The medicine container, simulating a typical medicine bottle, is filled with a syrup-like liquid (350 mPa.s (cP) viscosity), mimicking the viscosity and flow characteristics of certain medicines. The pouring target, a small container, is placed on a tray to act as a precision scale, enabling the accurate measurement of the poured quantity.

2) Operator Setup in Prague: The operator in Prague interfaces with the robot in Munich through a custom-developed control interface, designed to facilitate intuitive control and feedback reception. In this interface, the 3DSystems® Omni device ‡ is employed to provide haptic feedback, translating force data from the robot's sensor into tangible feedback for the operator. Visual feedback is provided via a commercial video streaming service Zoom® on a standard monitor. While the two sites are connected over the Internet, locally, the operator and the robot in the respective labs are connected to the university network either via Wi-Fi or 5G. These two wireless technologies can be switched on demand for different experimental scenarios.

B. Task Description and User Study Design

The primary task necessitates the operator to control the robot to pour a predefined quantity of the liquid (30 ml) into the target container, adhering to specified success criteria such as accuracy of poured quantity and prevention of spills. Task variations are introduced by modulating network conditions and feedback modalities, creating distinct scenarios that test the operator's ability under different conditions.

Our user study design began with defining the participant's criteria, designing the experimental scenarios and procedure, and data metric collection. A diverse cohort of participants is onboarded, ensuring a balanced representation of expertise and familiarity with teleoperated robotic systems. Then, distinct scenarios are defined by different combinations of network conditions (5G and Wi-Fi) and feedback modalities (video streaming and quantitative feedback). Next, we performed each trial to adhere to a standardized procedure, wherein participants were briefed about the task, the feedback modality, and the network condition under which the trial is conducted. Finally, task performance metrics and user subjective feedback data are meticulously collected, ensuring a comprehensive dataset for subsequent analysis [14].

C. Experiment Scenarios

The experiment is structured to explore various scenarios that modulate network conditions and feedback modalities,

* *kinovarobotics.com/product/gen2-robots*
† *botasys.com/force-torque-sensors/sensone*
‡ *3dsystems.com/haptics-devices/touch*

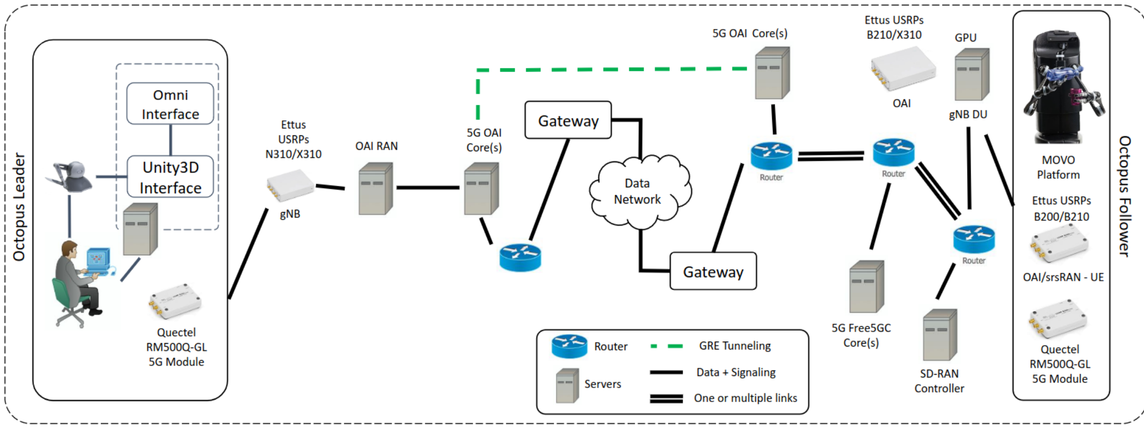

Fig. 2: The overall 5G testbed architecture at Prague and Munich for OCTOPUS.

providing a multifaceted examination of teleoperated medicine pouring. Two primary network conditions (Wi-Fi and 5G) and four feedback modalities (real-time video streaming, single arm haptic and dual arm haptic quantitative feedback at 5Hz and 50 Hz) are employed, systematically exploring all possible combinations of these variables.

In addition to the experimental setup, data collection is pivotal to evaluating the performance and user experience across different scenarios. Key metrics such as accuracy of poured quantity, task completion time are meticulously logged. Post-task surveys and interviews are conducted to gain insights into the user's experience, challenges, and preferences across different scenarios. System data, including network latency and packet loss are recorded to analyze the system's performance under different conditions. We observe and investigate metrics defined in the following subsections for 15 people.

1) Quantitative Metrics:

- Accuracy (ml): Measured as the absolute difference between the target and actual poured quantity: Pouring Error $= |V_{\text{target}} - V_{\text{actual}}|$, where V_{target} is the target volume and V_{actual} is the actual poured volume.
- Task Completion Time (s): Measured from the initiation to the completion of the pouring task.

2) Qualitative Metrics: In our experimentation process, qualitative feedback through surveys is collected from the users. Subjective qualitative metrics Usability (How intuitive is the pouring experience), Stability (How much stable is the connection), Haptic feedback (quality of force feedback on the device) and Robot Control (quality of robot controller) experience are collected for all the modes of OCTOPUS operation on a scale of one (worst) to ten (best).

D. Research Questions

1) *Q1:* Examining the performance of the robotic medicine pouring integrated with our 5G-testbed to extend its application further and see how it outperforms Wi-Fi in terms of pouring error and user experience?
2) *Q2:* In suboptimal networks, is quantitative feedback favored when in non-reliable latency conditions and better intuition of poured liquid volume? Is real-time video feedback preferred in both Wi-Fi and 5G-testbed scenarios?
3) *Q3:* What is the affect of showing the quantitative feedback to users over custom extended 5G-testbeds?

IV. System Architecture

In this section, we first discuss setup for the teleoperation and, then, we outline architectures of the communication networks in Prague and Munich.

A. Teleoperation Setup

The teleoperation system comprises a operator device, the 3DSystems® Omni haptic device, and a remote robot, the Kinova® Jaco2 manipulator. The haptic device allows the operator to send precise position commands to the Jaco2 manipulator and receive force feedback, enabling a haptic interaction with the remote environment. We used the standard Unity3D®[§] plugin driver for the haptic device. Kinova® Jaco2, characterized by its 7 Degrees of Freedom (DOF) and a payload capacity of 2.4 Kg, is employed for executing the pouring task. Our 5G testbeds at both ends play a pivotal role in enabling real-time, reliable teleoperation. The key attributes of 5G, such as ultra-reliable low-latency communication (URLLC) and enhanced Mobile Broadband (eMBB), are harnessed to facilitate seamless interaction between the OCTOPUS leader and the OCTOPUS follower.

Latency, Bit rate, and Reliability: A crucial aspect of teleoperation is minimizing communication latency, L, with a guaranteed bit rate B and reliable connection, R to ensure instantaneous transmission of control and feedback signals with perceptual quality. With 5G, we leverage to achieve a low latency of $L \leq L_{\text{max}}$, ensuring minimum bit rate $B \geq B_{\text{min}}$ with reliability ($R \geq R_{\text{min}}$), where $L_{\text{max}} \approx 100ms$ represents the maximum tolerable latency, $B_{\text{min}} = 25Mbps$ represents guaranteed bit rate with eMBB, and $R_{\text{min}} = 99.9\%$ representing minimum connection reliability for real-time control

§*https://assetstore.unity.com/packages/tools/integration/haptics-direct-for-unity-v1-197034*

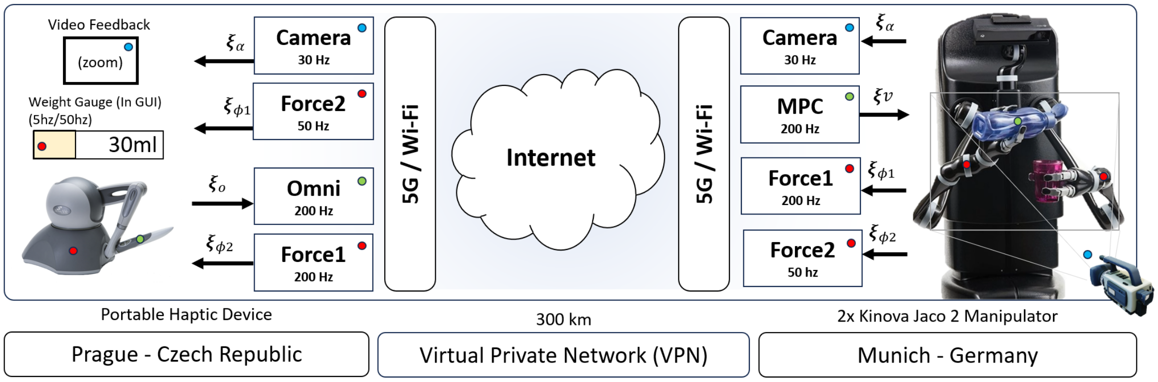

Fig. 3: The overall OCTOPUS Input and Outputs at Prague and Munich Testbeds.

and haptic feedback, ensuring that the delay, data rate, and connection quality in signal transmission does not impede the operator's control and perception.

B. Network Architecture and Features

Our OCTOPUS network architecture as depicted in the Fig. 3, excluding the backbone and core network details, is composed of the components of the 5G core, RAN testbed(s) and internal networks at both ends of Munich and Prague. Primarily, our testbed is developed using OpenAirInterface (OAI) [15] as a baseline and enhanced features in [16], [17]. Currently, our 5G-OCTOPUS testbeds governs the following features:

- End-to-End connections with OAI-Core or Free5GC, OAI-RAN, OAI-UE, and Quectel RM500Q-GL 5G Module.
- Observed stable connection over $5/10/20/40$ MHz bandwidth on our 5G testbed with throughout of up to 120 Mbps in downlink and 25 Mbps in uplink, $\approx$ 29 ms round trip time (RTT) delay between operator/robot and local base station, 10^{-3} packet error rate during mobility. Wi-Fi/WLAN used in part of this experimentation had a throughput up to 65 Mbps in downlink and 20 Mbps in uplink.
- GUI based Dynamic SD-RAN controller.

Through meticulous integration and optimization of these 5G communication attributes, we establish a robust communication framework that substantiates the execution of precision-demanding tasks in teleoperation, validating the capabilities through our proposed liquid pouring task.

C. Manipulator Control Strategy with NMPC-MP

The NMPC-MP (Nonlinear Model Predictive Control with Motion Planning) strategy [9] is pivotal in translating the Cartesian coordinates to joint velocities for the robotic manipulator. This translation ensures that the robotic hand moves with precision and stability, especially during intricate tasks.

Objective Function: The objective function, J, is designed to minimize the discrepancy between the predicted and desired system states and control efforts over the predictive horizon, N. The mathematical formulation can be expressed as:

$$J = \sum_{k=0}^{N} \left(x(k) - x_{\text{rs}}(k)\right)^T Q \left(x(k) - x_{\text{rs}}(k)\right) + Ru^2(k) \quad (1)$$

where $x(k)$ and $x_{\text{rs}}(k)$ are the actual and reference states at time step k, respectively, Q and R are the state and control input weighting matrices, respectively, and $u(k)$ is the control input.

System Model: The system model describes the dynamics of the robotic system. Given the state $x(k)$ and input $u(k)$ at time k, the state at the next time step $k+1$ is given by:

$$x(k+1) = Yx(k) + Zu(k), \quad (2)$$

where Y and Z are the state and input matrices, determined based on the system's dynamics.

Constraints: The constraints ensure that the computed control inputs and predicted states are within permissible limits. If u_{min} and u_{max} represent the minimum and maximum allowable control inputs, and x_{min} and x_{max} represent the state limits, the constraints are formulated as:

$$u_{\text{min}} \leq u(k) \leq u_{\text{max}}, \quad x_{\text{min}} \leq x(k) \leq x_{\text{max}}. \quad (3)$$

Optimization: At each time step, the optimization problem is solved to determine the optimal control input, $u^*(k)$, that minimizes the objective function while adhering to the system constraints.

Through the strategic configuration and application of NMPC-MP [9], we ensure that the teleoperated robot exhibits precise, stable, and predictive behavior. This is particularly crucial in executing tasks where accuracy and control finesse are paramount. The NMPC-MP also boasts dynamic obstacle avoidance capabilities, ensuring safe motion planning. In our experiments, the NMPC-MP demonstrated an average normalized length of 1.0, an average computation time of 0.016 seconds, an average joint velocity of 0.033 radian/second, an average position squared error of 1.10e-3, an average quaternion squared error of 1.90e-3, and a success rate of 1.0.

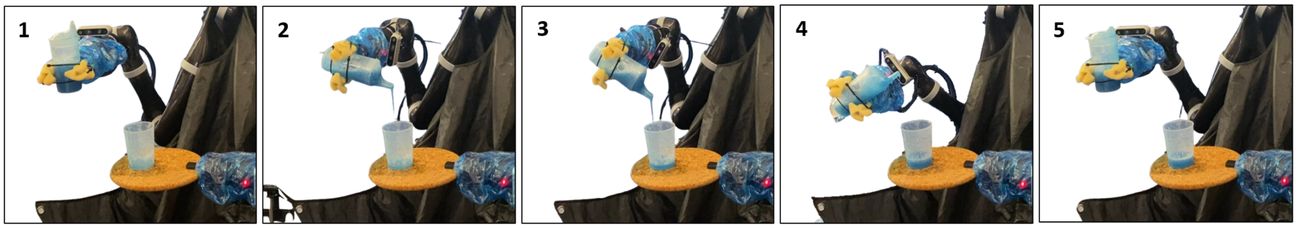

Fig. 4: The demonstration of pouring 30ml medicine in the container.

TABLE I: Average Results for Teleoperated Pouring Experiments using 5G and Wi-Fi performed by 15 people

Type/mode	Usability(10)	Stability(10)	Haptic Feedback(10)	Robot Control(10)	Time(s)	Error(ml)	Latency(ms)	Jitter(ms)	Packet Loss(%)
5G (m1)	8.2	8.4	8	8.1	120	16.89	29	7.8	**0.000**
5G (m2)	8.6	8.5	8.6	8.2	88	13.67	34	8.4	**0.000**
5G (m3)	8.2	8.3	8.4	8.4	84	2.71	28	**7.2**	**0.000**
5G (m4)	**9.1**	**9.3**	**9.2**	**9**	**80**	**2.29**	**25**	7.5	**0.000**
Wi-Fi (m1)	7.1	6.1	7	6.5	144	28.75	90	18.5	0.633
Wi-Fi (m2)	7.5	6.8	7.3	7.1	105	21.50	95	17.8	0.621
Wi-Fi (m3)	8	7.8	8	8.1	96	4.00	92	17.3	0.002
Wi-Fi (m4)	7.7	7.2	7.3	7.6	90	4.25	94	15.4	0.632

V. Results and Discussion

Using our experimental setup, as described in Section III and IV, we performed both quantitative and qualitative system performance under different modes of OCTOPUS operation over 5G and Wi-Fi. Especially in the qualitative experimentation, fifteen unique users have been drawn to perform 120 experimentation scenarios spanning across the four different operations of the OCTOPUS modes.

Conducting a teleoperated pouring task under varied network and feedback conditions necessitates a structured experiment and comprehensive metric measurement to effectively evaluate system performance and user experience. Figure 4 depicts the OCTOPUS Follower setup and further sequential operations.

1) Quantitative Results: In quantitative performance, we have examined the accuracy of pouring, Task completion time, and E2E Latency pertaining to the end-to-end operation. The accuracy of the pouring task is a critical metric in evaluating the efficacy of teleoperated robotic medicine dispensing, while the Task completion time is indicative of the efficiency and fluidity of the teleoperation experience. As depicted from the Table. I, accuracy, low latency, and reduced task completion time in the 5G, implying that the enhanced capabilities of 5G networks contribute to a more responsive and efficient teleoperation experience, has also seen in contributing for the richer qualitative experiment. However, this also puts further statistical analysis needed to validate and explore the significance of these observed trends in qualitative experience.

2) Qualitative Results: Each user is made experimental over 5G and Wi-Fi networks conducted under different modes, namely model 1 ($m1$) with Video only feedback, mode 2 ($m2$) with Follower Arm 1 haptic feedback, mode 3 ($m3$) with including Follower Arm 2 haptic feedback with $5Hz$ weight gauge sensing refresh rate and mode 4 ($m4$) with $m3$ operation over $50Hz$ weight gauge sensing refresh rate, reporting to the OCTOPUS Leader. The participants conduct the pouring task under each mode of operation, and the defined metrics is recorded and analyzed to evaluate the performance and reliability of the OCTOPUS system under each scenario, first in 5G and then in Wi-Fi. This allowed us to reduce the falseness of the metrics data derived due to the hardness imposed on the first-time users. Considering the user feedback, a rich tapestry of insights into the experiential dimensions is observed, with participants often highlighting the perceptual limitations encountered during the Wi-Fi Video scenario, citing delayed visual feedback and resultant difficulties in accurately gauging the poured quantity. Figure 5 showcase the pouring accuracy and Fig. 6 represents the comparative analysis of the network metrics over different modes.

A. Discussion: statistical analysis, implications, comparision and limiting challenges

Through the quantitative and qualitative findings, a nuanced understanding of the interplay between network conditions, feedback modalities, and user experience begins to emerge. The technological superiority of the 5G network is evident in the quantitative metric, especially reduced time to complete the task. The qualitative feedback also provided us with important user metrics such as observed stability, usability, and different feedback improvements in the case of 5G. However, the interplay of Accuracy between the 5G and Wi-Fi on different modes of operation is observed, where mode 4 of operation is well performed in both cases. Comparing to some of the works discussed in [14] reporting that latency, including video feedback is more than 250ms, our OCTOPUS has better user-centric latency performance in Quantitative and Qualitative experimentation.

In addition, robust statistical analysis, employing repeated-measures ANOVA, validates the observed trends in pouring Accuracy and reduced task completion times across scenarios. The findings underscore the significant impact of 5G integration on robotic operations, enhancing latency, system

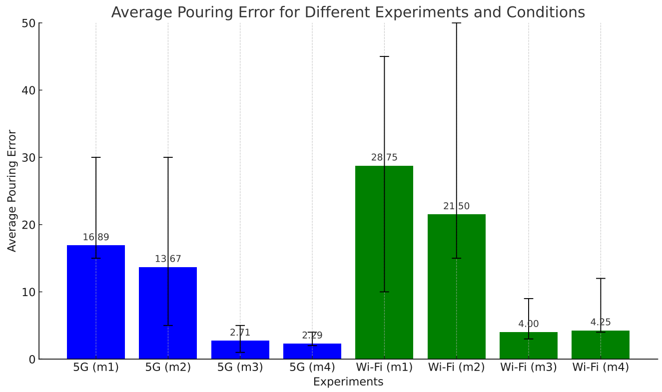

Fig. 5: This chart illustrates the average 'Pouring Error' for teleoperation experiments $m1$ to $m4$ under 5G and Wi-Fi networks. Each bar represents a unique experiment and condition, with lower values indicating better performance.

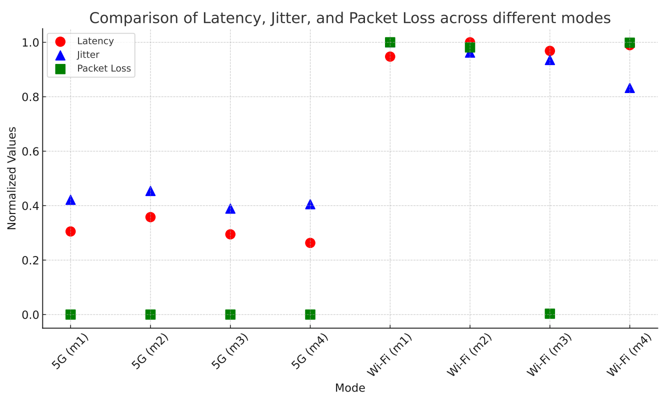

Fig. 6: Comparative Analysis of Normalized Latency, Jitter, and Packet Loss Metrics Across Different Connectivity Modes

stability, and bandwidth while emphasizing the mediating role of usability and feedback modalities.

The user experience, particularly in terms of feedback modality preferences, underscores the importance of providing intuitive and reliable feedback, especially in scenarios where network performance may be suboptimal.

VI. Conclusion

Investigating the impact of network conditions and feedback modalities on teleoperated robotic medicine pouring, this study reveals substantial insights into the intersection of technology and user experience in healthcare robotics. It underscores the paramount role of quantitative weight feedback, which demonstrates notable effectiveness under Wi-Fi conditions and emerges as a more influential factor than video or haptic feedback on the pourer's hand, sustaining system usability even in constrained network environments. Although the system proves functional with Wi-Fi, leveraging video and haptic feedback within a 5G network notably elevates performance, spotlighting the criticality of low-latency communication in teleoperation tasks. The outcomes of this study emphasize the future research is necessary for a user-centric design approach, especially in the event of a more significant error; optimizing 5G in terms of latency and slicing is necessary for global applicability.

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