Touch the Metaverse: Demonstration of Haptic Feedback in Network-Assisted Augmented Reality

Yushan Yang*, MingYu Ma*§, Tung Van Doan*
Thomas Hulin†§, Frank H. P. Fitzek‡§ Giang T. Nguyen*§
*Haptic Communication Systems, TU Dresden, E-mails: {firstname.lastname}@tu-dresden.de
†German Aerospace Center (DLR), Robotics and Mechatronics Center (RMC), Germany, E-mail: thomas.hulin@dlr.de
‡Deutsche Telekom Chair of Communication Networks, TU Dresden, Germany, E-mail: frank.fitzek@tu-dresden.de
§Centre for Tactile Internet with Human-in-the-Loop (CeTI), TU Dresden

***Abstract*—State-of-the-art head-mounted display has brought new momentum to novel augmented/virtual-reality (AR/VR) applications in a metaverse, where people interact with virtual objects. The sense of touch can improve the quality of experience. However, there are several challenges in imitating and realizing the touch sense, communicating haptic feedback, and competing between applications for shared network resources. We developed a haptic gloves with FingerTac to enable the sense of touch and designed a tailor-made communication protocol for the haptic data stream. Additionally, we integrate advanced queue management algorithms to achieve low-delay haptic data. Our demonstration uses an AR game, where we prioritize haptic data transmission for an intuitive experience when users interact with virtual objects.**

***Index Terms*—Metaverse, Tactile Internet, Augmented Reality, Haptic Communication, OpenWrt, CoDel**

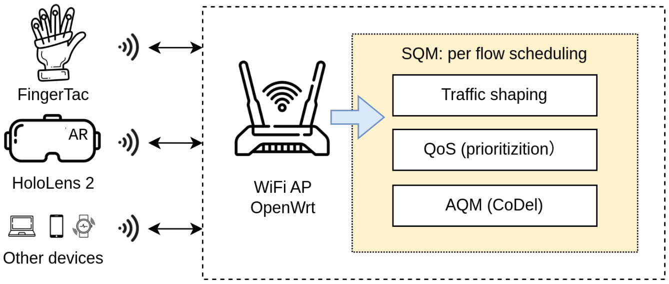

Fig. 1. Network set up - The wireless access point will be configured by the Smart Queue Management (SQM) [4] in OpenWrt system. It mainly includes three parts: traffic shaping, QoS prioritization and active queue management (AQM) like CoDel.

I. INTRODUCTION

The Metaverse, a digital universe, offers a vast and immersive environment where users can meet and interact with each other, digital objects, and computer-generated spaces in perceived real-time [1]. The Metaverse has enabled several potential use cases, such as e-health, immersive classrooms for education, and gaming, strengthened by advanced technologies such as Augmented Reality (AR) and Artificial Intelligence (AI), *e.g.*, to predict hand gestures [2]. Haptic communication is crucial as it provides a sense of touch to improve user experiences. The Tactile Internet [3] is a transformative paradigm shift from content-oriented communication towards control-based communication, enabling people to control real and virtual objects through wireless channels remotely. This concept envisions a network capable of delivering tactile experiences and skills transfer. However, technical challenges exist, *e.g.*, low-latency communication between the virtual and real worlds and the realization of the sense of touch.

The first challenge is creating an intuitive sense of touch, which requires wearable thimble devices with lightweight communication protocols to convey the event of touch and its intensity. Compared to well-established methods for audio and video modalities, there is no straightforward solution for haptic modality. The second challenge is network devices with increasingly large buffers often experience bufferbloat, causing long delays. The third challenge is applications competing for bandwidth resources in access networks. Since current networking protocols and devices are optimized for transferring bulk data, such as high-definition videos, lower-bitrate haptic data streams often suffer from delays, causing unintuitive interaction.

We demonstrate a cross-cutting solution for network-assisted haptic augmented reality applications for the metaverse. We introduce and integrate three innovations: i) FingerTac for three fingertips, ii) a lightweight communication protocol between the FingerTac and the head-mounted device, and iii) the OpenWrt WiFi router with specific algorithm supporting haptic communications. The router leverages highly customizable OpenWrt system and smart queue management to prioritize the haptic data stream and minimize the delay caused by bufferbloat. Via an AR game similar to the famous Angry Bird on smartphones, users can notice the subtle changes in haptic feedback at their fingertips with and without network support. Simultaneously, the audience could observe user performance in the game via a shared live view from the AR headset.

II. TECHNOLOGIES

Our system perfectly integrates Microsoft HoloLens 2, FingerTac haptic gloves, and multi-flow control within an OpenWrt-based wireless access point. Moreover, we extensively explore the complexities of the algorithm implemented on the OpenWrt router, illuminating its central role in optimizing haptic data transmission.

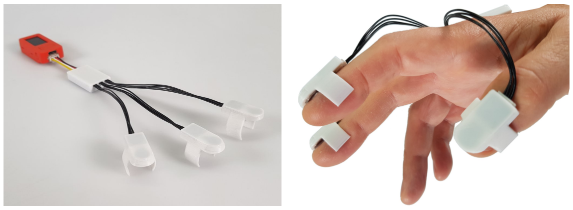

Fig. 2. The tactile device FingerTac provides vibrational feedback at both sides of a finger and thus keeps the finger bottom free of obstruction. Credit: DLR (CC BY-NC-ND 3.0)

A. *FingerTac: Haptic device realizing the sense of touch*

To bridge the divide between the virtual and physical worlds, we integrate the FingerTac [5] into our demo to complement visual immersion. The FingerTac, the haptic gloves, is an augmented haptic device that provides haptic feedback while touching a virtual object. The device uses the limited spatial discrimination capabilities of vibrotactile stimuli of the skin and induces vibrational feedback at both sides of a finger. As shown in Fig. 2, the FingerTac consists of an M5StickC Plus microcontroller (MCU) connected to DRV2605 haptic drivers. They control three Linear Resonant Actuators (LRA) vibration motors, thus providing pre-programmed vibration patterns (or waveforms). We developed a vibration scheme based on an on-off pattern, providing intuitive adjustment of stimulation intensity by simply changing the duration of the off phase as illustrated in Fig. 3. This pattern is inspired by the well-known concept of acoustic parking assistance in cars, where distance information is conveyed by varying the timing between two different beeps. In the case of tactile feedback, the on-off pattern creates a subtle and easily customizable pulsating sensation that provides the user with accurate sensory perception of, for example, distance or intensity.

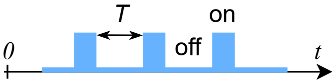

Fig. 3. Realizing the intensity of touch with on/off intervals: Shorter off-intervals represent increased intensity.

B. *Communication between FingerTac and Head-mounted Display: Protocol design and key parameters*

We developed a tailor-made communication protocol between the head-mounted display and the FingerTac with three key design choices. They are transport protocol, message size, and update intervals. We aim to optimize AR and haptic gloves communication by testing the Round Trip Time (RTT) of haptic data under various key parameters. This is crucial to enhance the responsiveness and reliability of AR interactions in real-world applications.

We decided to use TCP instead of UDP or HTTP because TCP demonstrated consistently lower and more consistent RTT across various update intervals, ensuring timely and accurate haptic feedback in our AR demonstration. For UDP, its RTT exhibited escalating inconsistencies as the update intervals varied. The main drawback of HTTP was its significantly higher RTT, ranging between 30 to 70 ms, primarily due to its extensive data format and the necessity to re-establish connections for each message.

TABLE I

RTT BETWEEN AR HEADSET AND HAPTIC GLOVE UNDER VARIOUS UPDATE INTERVALS AND MESSAGE SIZES.

message length	interval (ms)	Round-Trip Time (ms)	
		mean	median
short 2 (Bytes)	5.0	37.1	33.6
	16.0	43.7	33.5
	25.0	54.6	34.6
	100.0	63.6	49.7
long 6 (Bytes)	5.0	34.1	33.4
	16.0	44.6	33.6
	25.0	54.7	34.2
	100.0	71.0	49.8

Given the reliable transport, we fine-tuned the update interval and the message length. Intuitively, shorter intervals and longer messages mean conveying more fine-grain differences promptly. However, there is one constraint. The FingerTac must complete processing one message within one operational cycle. Otherwise, the microcontroller must buffer incoming messages, thereby increasing communication delay, *i.e.*, round-trip time (RTT). We tested the following intervals of 5 ms, 16 ms, 25 ms, and 100 ms. They were selected to be broadly equivalent to the HoloLens' framerates, which are 200 FPS, 60 FPS, 40 FPS, and 10 FPS, respectively. It is worth noting that the 16 ms interval is equivalent to the typical framerate of 60 FPS of the HoloLens. We also tested two message sizes, *i.e.*, small messages of 2 Bytes and large messages of 6 Bytes, and detail the results in table I. To process each message, the MCU needed 1-2 ms for short messages and 4-5 ms for long messages. In comparison, each vibration instruction processing took approximately 1.2 ms.

C. *OpenWrt Gateway*

We implemented the OpenWrt wireless access point (AP) in Fig. 1 to connect devices and manage network traffic with specific customizations. The AP is *Xiaomi AX9000*, which supports the 802.11ax standard with a sufficiently large spectrum width of 160 MHz, which suits our application needs. As illustrated in Fig. 1, we exploited the smart queue management (SQM) in OpenWrt for network traffic, including the following three methods: traffic shaping, QoS prioritization, and Active Queue Management (AQM).

We categorize two types of traffic: normal flows representing background traffic and a higher-priority flow with the haptic data stream. This strategic prioritization minimizes latency and packet loss for haptic data, improving user experience. The traffic shaping and QoS prioritization will ensure network performance for higher priority like haptic streams. We used the AQM algorithm CoDel (Controlled Delay) to combat buffer bloat and maintain low latency. These mechanisms dynamically adjust queue lengths by controlling scheduling and making active drops based on network conditions, effectively reducing latency and enhancing overall throughput.

III. DEMONSTRATION

The primary aim of this demonstration is to showcase an integrated system that addresses two pressing challenges in AR applications: the stringent requirements for haptic data streams and the accurate realization of touch sensations on human hands. Through this demo, we aim to i) highlight the seamless integration of AR and haptic technologies to create a truly immersive gaming experience, showcasing the augmented-reality game as the platform; ii) demonstrate the role of SQM in meeting the high demands of haptic data transmission, thus contributing to the Tactile Internet's requirements for low latency and reliability; and iii) illustrate the use of FingerTac haptic gloves with adjustable vibration patterns to simulate realistic touch sensations.

A. The gameplay as AR application

In this immersive experience, participants wear AR head-mounted devices to embark on an AR game adventure. Once started, player engage by manipulating the slingshot—simply by pulling its band—to dispatch wooden boxes and get scores. The intensity of the interaction is further heightened by the haptic gloves, which deliver varied force feedback responses contingent on the player's actions. In order to simulate real-world physics, the haptic gloves will give more intensive vibration feedback as the player pulls the string further. This innovative combination creates an interactive encounter that seamlessly bridges the gap between the virtual and real worlds.

B. Demo setup

The demo has four main components that work together. The Microsoft HoloLens 2 AR head-mounted display realizes the metaverse and gameplay through holographic overlays, enriching visual and auditory experiences. The FingerTac haptic gloves provide haptic feedback by simulating varying intensities of forces on the fingertips. The SQM algorithms in OpenWrt AP transport background traffic while prioritizing the haptic data stream. Finally, the controller's web interface toggles network support for haptic data streams on or off to prioritize or deprioritize these streams, showcasing the system's ability to adapt to varying levels of network support in real time.

C. Demonstration Workflow

As the game launches, the player is immersed in the AR headset's visual and audio elements. As Fig. 4 shows, the player holds a virtual slingshot with one hand, dragging a virtual rubber band with the other hand, all while aiming their shot at a distant wooden construct. The challenge is multifaceted—nailing shots' accuracy and swiftly accumulating higher scores. While the network ensures smooth visual gameplay, the haptic feedback remains inactive, allowing the player to focus only on the visual cues and game mechanics.

As the player progresses, the central controller turns on the haptic feedback to the game, enriching the gaming experience. The FingerTac gloves come alive when the player interacts with the critical game element slingshot. The further the player pulls the virtual rubber band on the slingshot, the stronger the vibration feedback they receive. This haptic feedback offers cues to guide the player, helping them make more precise shots and achieve higher scores. The tactile sensations, synchronized with in-game actions, add a layer of immersion and realism to the gaming experience. On the flip side, while observing the player's interactions, the audience might also perceive a potential decline in background video quality as the system reallocates resources to prioritize haptic feedback.

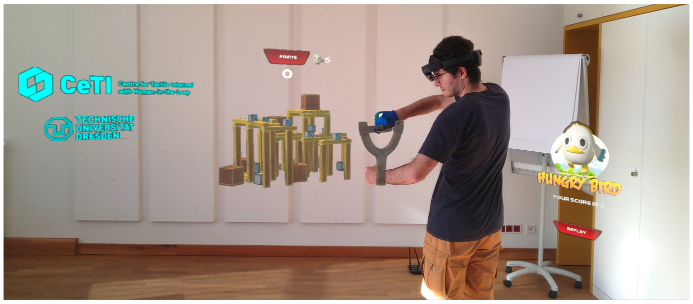

Fig. 4. Spectator view – an augmentation with in-game experience: A player holding a virtual slingshot on one hand and dragging virtual rubber band using the other hand, wearing a glove with the FingerTac targeting the shot at the wooden construct in the front.

In the last stage, the central controller turns off the network assistance like traffic control algorithms, creating a different gameplay environment for the player. The absence of network support becomes evident as the player starts to experience inconsistent haptic feedback. This inconsistency stems from delayed packets of the haptic stream traveling from the AR HMD to the FingerTac gloves. The once-smooth tactile sensations now become delayed, making the player acutely aware of the importance of network assistance in delivering a consistent haptic experience.

ACKNOWLEDGMENT

Funded in part by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universität Dresden and the Federal Ministry of Education and Research of Germany in the programme of "Souverän. Digital. Vernetzt." - Joint project 6G-life - projectID: 16KISK001K.

REFERENCES

[1] J. Yu, A. Alhilal, P. Hui, and D. H. Tsang, "6G mobile-edge empowered metaverse: Requirements, technologies, challenges and research directions," *arXiv preprint arXiv:2211.04854*, 2022.

[2] Schade et al., "On the advantages of hand gesture recognition with data gloves for gaming applications," in *PerCom*, 2023, pp. 313–315.

[3] F. H. Fitzek, S.-C. Li, S. Speidel, and T. Strufe, "Tactile internet with human-in-the-loop: New frontiers of transdisciplinary research," in *Tactile Internet*. Academic Press, 2021, pp. 1–19.

[4] T. B. community, "Smart queue management," https://github.com/tohojo/bufferbloat-net, accessed 2023-12-08.

[5] Hulin et al., "FingerTac – a wearable tactile thimble for mobile haptic augmented reality applications," in *VAMR*, Jul. 2020, pp. 286—298.