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INTRODUCTION

The metaverse refers to immersive environments where users interact through avatars and real-time sensory feedback. In particular, closed-loop haptic interactions demand millisecond-level latency, while the corresponding visual information must be delivered in a synchronized manner [1]. This creates a tradeoff between immersion quality-requiring higher visual payload-communication delay, and radio resource consumption. In this work, we develop a two-time-scale online learning framework that jointly adapts downlink bandwidth and visual payload size to ensure reliable and immersive wireless metaverse interaction.

METHODOLOGY

Two-Time-Scale Control: We decompose the problem into a fast bandwidth allocation (w) at a cycle level and a slow payload adaptation (l) layer at an epoch level.

Fast-Time-Scale Control: Downlink bandwidth is adapted per cycle using a Constrained Online Convex Optimization (COCO) algorithm to minimize spectrum usage while enforcing sublinear cumulative haptic and intermodal delay constraint violations [3].

Slow-Time-Scale Control: The visual payload is selected at the beginning of each epoch using a multi-armed bandit strategy.

NUMERICAL RESULTS

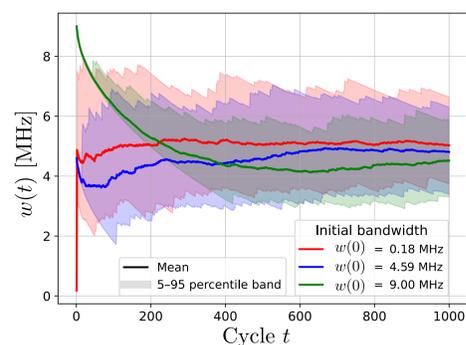


Figure 2: Evolution of the downlink bandwidth allocation over 1000 cycles.

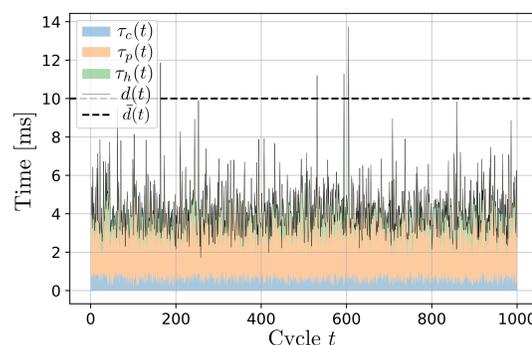


Figure 3: Closed-loop haptic delay decomposition $d(t)$.

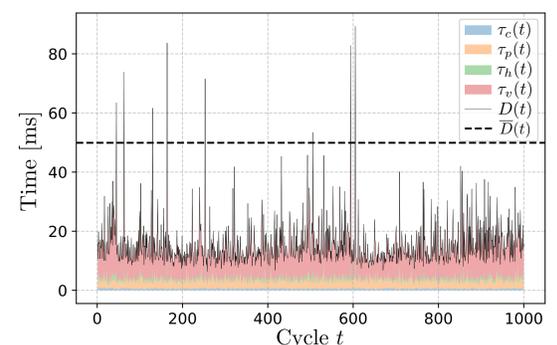


Figure 4: Total visual-haptic delay decomposition $D(t)$.

FUTURE WORK

- Establish the appropriate multi-armed bandit framework for the slow-time-scale control.
- Derive regret bounds for the two-time-scale framework, characterizing the interaction between the fast and slow time-scale algorithms.

REFERENCES

- [1] M. Simsek, et al., "5G-enabled tactile internet," IEEE Journal on Selected Areas in Communications, 2016.
- [2] J. Yu, et al., "Attention-based QoE-aware digital twin empowered edge computing for immersive virtual reality," IEEE TWC, 2024.
- [3] J. Wang, et al., "Doubly-bounded queue for constrained online learning: Keeping pace with dynamics of both loss and constraint," AAAI Conference on Artificial Intelligence, Apr. 2025.

SYSTEM MODEL

A metaverse user interacts with a remote application through a wireless base station. Each communication cycle t consists of an uplink command transmission, application processing, and downlink delivery of haptic and visual information, see Figure 1.

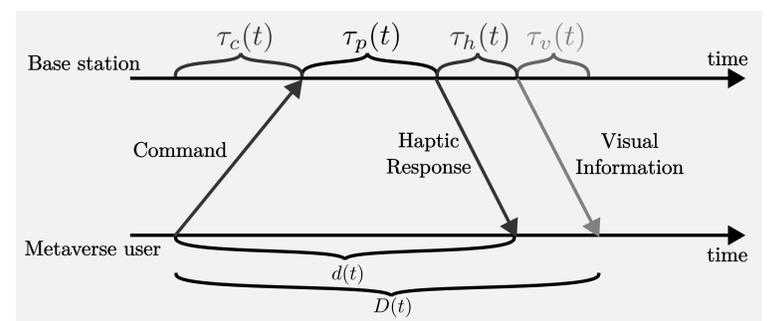


Figure 1: Time evolution of a communication cycle t .

The associated delays are defined as follows:

$$d(t) = \tau_c(t) + \tau_p(t) + \tau_h(t), \quad D(t) = d(t) + \tau_v(t)$$

where

$d(t)$	Closed-loop haptic delay.	$\tau_h(t)$	Haptic transmission delay.
$\tau_c(t)$	Command transmission delay.	$D(t)$	End-to-end cycle delay.
$\tau_p(t)$	Processing delay.	$\tau_v(t)$	Visual transmission delay.

Finally, the performance is evaluated by the following utility [2],

$$U(w, \ell) = \varphi \ln\left(\frac{\ell}{\underline{\ell}}\right) + \gamma(\bar{w} - w)$$

U	Utility.	$\underline{\ell}$	Minimum visual payload.
w	Downlink allocated spectrum.	γ	Cost of allocated spectrum.
ℓ	Visual payload.	\bar{w}	Maximum available spectrum.
φ	Network performance metric.		