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Experimental Investigation of Advanced Metaverse Realms of Experience

By

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I dedicate this thesis to my beloved parents who filled my heart with love and affection and continuously supported me throughout the process.

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Abstract

6G, in contrast to previous generations, is transformative and will revolutionize the wireless evolution from "connected things" to "connected intelligence." 6G will be rather a convergence of the following four applications that will drive the 6G revolution: (i) multisensory extended reality (XR), (ii) connected robotics and autonomous systems, (iii) wireless brain-computer interaction, and (iv) blockchain and distributed ledger technologies. In this doctoral thesis, we elaborate on how the Internet of No Things and its underlying human-intended services may serve as a step toward realizing the 6G far-reaching network vision. The Internet of No Things aims at ushering in the 6G post-smartphone era, where smart wearables are increasingly replacing the functionalities of smartphones. The transition from the current gadgets-based Internet to the gadget-free Internet of No Things is divided into three phases that start from bearables, move toward wearables, and then finally progress to the last phase, termed nearables. This thesis proposes an architecture for the Internet of No Things that integrates the three evolutionary mobile computing stages of ubiquitous, pervasive, and persuasive computing plus all kind of smart wearables to deliver advanced XR experiences. In addition, we integrate the Ethereum blockchain's salient features with the emerging field of robonomics and persuasive robotics to solve problems that machines (robots, AIs) cannot solve well alone. To do so, we investigate the widely studied trust game of behavioral economics in a blockchain context by developing a smart contract to propose a networked N-player trust game and the embodied communications enabled by persuasive robots. Next, we introduce the Multiverse architecture to design advanced XR experiences as the anticipated successor of the Metaverse. The Metaverse and Multiverse have in common to realize the fusion of digital and real worlds. However, while the Metaverse primarily focuses on VR and AR, the Multiverse offers a powerful experience design canvas to uncover hidden XR opportunities by fusing the real and the virtual, thereby creating so-called cross-reality environments. After describing the Multiverse architecture, we gamify and implement all eight Multiverse realms of experience in the context of a single-player origami game and multi-player maze game across our proposed integrated VR/AR HMDs and Amazon Mechanical Turk crowd-of-Oz (CoZ) platform. In the same direction, we adopt the original Wordle game to the Metaverse, including but not limited to VR and AR. Finally, we design and experimentally investigate advanced cognitive cues for playing the Wordle game in the eight different experience realms of the Multiverse, using state-of-the-art smart wearables. In addition, we develop a blockchainized version of the game. Blockchainizing the Wordle game (i) allows remote experts to cooperate with local players benefiting from crowd intelligence, and (ii) allows players to earn tokens and thus naturally realize play-to-earn games by emerging Web 3.0 blockchain technologies.

Keywords: 6G Post-Smartphone Era, Blockchain, Crowd-of-Oz (CoZ), Extended Reality (XR), Gamified Experiences, Head-Mounted Devices (HMDs), Internet of No Things, Metaverse, Multiverse, Smart Wearables, Web 3.0.

Statement of Originality

I hereby certify that this thesis contains original work of the author. Some techniques employed from other authors are properly referenced herein.

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List of Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
6GFP	6Genesis Flagship Program
ABI	Application Binary Interface
AI	Artificial Intelligence
API	Application Programming Interface
APK	Application Package Kit
AR	Augmented Reality
ARGs	Alternate Reality Games
ATIS	Alliance for Telecommunications Industry Solutions
AV	Augmented Virtuality
B5G	Beyond 5G
BCI	Brain-Computer Interactions
BDMA	Beam Division Multiple Access
B-IoT	Blockchain Internet of Things
BSs	Base Stations
CEO	Chief Executive Officer
Cloud-RAN	cloud Radio Access Network
CoMP	Coordinated Multiple transmission/reception cloud Radio Access Network
CoZ	Crowd-of-Oz
CRAS	Connected Robotics and Autonomous Systems
DARPA	Defense Advanced Research Projects Agency
DLT	Distributed Ledger Technology
e-Deliveries	electronic Delivery
EOA	Externally Owned Account
ERC	Ethereum Request for Comments
ESP	Extrasensory Perception
ESPN	Extrasensory Perception Network
EVM	Ethereum Virtual Machine
FDD	Frequency Division Duplex
FGNET-2030	Focus Group Network 2030
GFT	Google Flu Trends
HCI	Human-Computer Interfaces
HIT	Human Intelligence Task
HMDs	Head-Mounted Devices
HO	Human Operator

HSPA	High-Speed Packet Access
HTML	HyperText Markup Language
I2V	Invisible-to-Visible
ICT	Information and Communications Technology
IFrame	Inline Frame
IoE	Internet of Everything
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
LED	Light-Emitting Diode
LTE	Long-Term Evolution
M2M	Machine to machine
MEC	Multi-access Edge Computing
MIMO	Multiple-Input and Multiple-Output
mMTC	Massive Machine Type Communications
MPPs	Mesh Portal Points
MR	Mixed Reality
MRTK	Mixed Reality Toolkit
MTurk	Amazon Mechanical Turk
mULC	massive Ultra-reliable Low-latency Communication
NFTs	Non-Fungible Tokens
NGMN	Next Generation Mobile Networks
OFDM	Orthogona Frequency Division Multiplexing
OLT	Optical Line Terminal
P2P	Peer-to-Peer
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoPE	Quality-of-Physical-Experience
QoS	Quality of Service
RPC	Remote Procedure Call
SDN	Software-Defined Networking
sHRI	social Human-Robot Interaction
SLA	Service Level Agreement
SMS	Short Message Services
SSI	Self-Sovereign Identity
STEM	Science, Technology, Engineering, and Mathematics
TCP	Transmission Control Protocol
TCT	Task Completion Time
TDD	Time Division Duplex
TD-SCDMA	Time-Division Synchronous CDMA
TOR	Teleoperator Robot
TV	Television
UAV	Unmanned Aerial Vehicles
UGC	User-Generated Content
uMBB	Ubiquitous Mobile Broadband
URL	Uniform Resource Locator
URLLC	Ultra-Reliable Low-Latency Communications

USD	Universal Scene Description
VPN	Virtual Private Network
VR	Virtual Reality
WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMR	Windows Mixed Reality
WoZ	Wizard-of-Oz
XML	Extensible Markup Language
XR	Extended Reality
YOLO	You Only Look Once
Z-Tree	Zurich Toolbox for Ready-made Economics

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Chapter 1

Introduction

1.1 Background and Motivation

1.1.1 From 1G to 5G: The Evolution of Wireless Connectivity

The mobile wireless communication system has undergone several evolution stages since MacDonald of Bell Telephone Laboratories introduced the concept of cellular communications in 1979. Over the last four decades, the technology has evolved from the first generation, 1G, followed by 2G, 3G, and 4G, to reach today's threshold of the fifth generation, 5G.

1G was launched in the 1980s to provide voice calls with analog signals with a data rate of 2.4 kbps. However, 1G faced challenges such as low capacity, inconsistent delivery, and lack of security [1]. Therefore, 2G networks were developed based on digital modulation technologies with a data rate of 64 kbps in the 1990s to address 1G shortcomings. In addition, 2G has provided encrypted data services such as short message services (SMS) and traditional voice communications [2]. The 1G and 2G mobile communications systems are built based on a public switched telephone network (PSTN), a combination of several telephone networks, including telephone lines, switching centers, fiber optic networks, cellular networks, and satellite networks.

Around 2000, 3G was introduced to support the increasing demands for multi-data services such as video calls, or internet surfing [3]. As a result, various technologies have been used in 3G networks to support the increasing demands, including wideband code-division multiple access

(WCDMA), time-division synchronous CDMA (TD-SCDMA), time division duplex (TDD), and worldwide interoperability for microwave access (WiMAX) [4]. In addition, 3G networks provide a data rate of up to 284 kbps [5], which is achieved using high-speed packet access (HSPA) technology.

4G was launched in 2009, representing the long-term evolution (LTE) network by operating in the time TDD and frequency division duplex (FDD) modes. Different technologies, such as orthogonal frequency division multiplexing (OFDM), coordinated multiple transmission/reception (CoMP), and multiple-input and multiple-output (MIMO) techniques, have been used in LTE networks [6]. These technologies have been developed to enable a wider transmission bandwidth, achieve a high data rate, and allow wider mobile broadband connections.

5G started in the 2020s outperforming LTE in terms of features and performance. In addition, certain new technologies are proposed and developed for 5G to meet its goals. Software-defined networking (SDN), massive MIMO, mm-Wave, NOMA, cloud radio access network (cloud-RAN), mobile edge computing, M2M communications, ultra-dense networks, wireless caching, and full-duplex communication are just a few of these technologies [7]. Furthermore, beam division multiple access (BDMA) is exploited in 5G networks to increase the system capacity [8]. In this multiplexing technique, an orthogonal beam can be allocated to the users according to their locations [9].

Apart from the mentioned multiplexing techniques, 5G enables the Internet of things (IoT) [10], smart city, massive broadband, virtual reality (VR) [9], augmented reality (AR) [11], and vehicular ad-hoc networks (VANETs) with a maximum data rate of about 20 Gb/s 123 [7]. By increasing the number of IoT devices to reach 25 billion by 2025 [12], it is very challenging for 5G to accommodate such massive devices with its existing multiple access techniques. Specifically, a more robust network must be designed to realize the massive access beyond 5G (B5G) communication systems. Such challenges motivated academia and industry to shift their attention beyond 5G/6G systems to satisfy the future demands for information and communications technology (ICT) in 2030.

1.1.2 The Road to 6G: A General Purpose Technology

Figure 1.1 illustrates an up-to-date tentative roadmap of definition, specification, standardization, and regulation projected on 6G research from representative institutions and countries [13]. Accord-

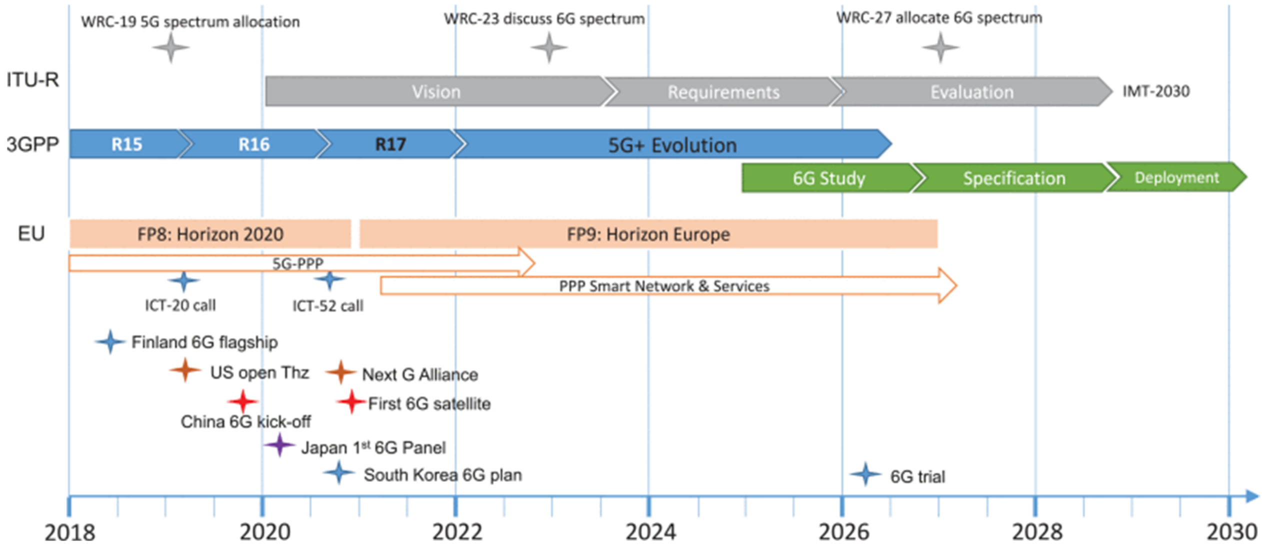


Figure 1.1: Predicted roadmap of research, definition, specification, spectrum regulation, development, and deployment for 6G mobile systems [13].

ing to this roadmap, a focus group called Technologies for Network 2030 within the International Telecommunication Union (ITU-T) standardization sector was established in July 2018 to study the capabilities of networks for 2030 and beyond [14]. This group mentioned that future mobile networks will enable novel applications such as holographic calls, avatar robotics applications, flying networks, and teleoperated driving [15]. However, the massive amount of data requires tremendous computation and communication resources from edge servers. Thus, the huge gap between users' requirements and what the edge servers can provide is a significant challenge for 5G systems in delivering massive data traffic demands for emerging and new applications, as mentioned above.

To mitigate the aforementioned challenges, 6G networks are envisioned to enhance the conventional wireless communications systems further, improve the quality of service (QoS), and support the massive data traffic demands [16]. As a result, 6G will provide enhanced services, ubiquitous mobile broadband (uMBB), and ultra-reliable low-latency broadband communication (ULBC). Furthermore, 6G provides massive ultra-reliable low-latency communication (mULC) to support several new disruptive applications, most notably XR, multi-sense experience, pervasive intelligence, and digital twin [13]. Moreover, an extremely high data rate above 100 Gbps with an end-to-end delay of less than 1ms may be supported by 6G [1]. In terms of concept and definitions, the ITU will complete 6G standardizations by the end of 2030, whereas 3GPP will finalize its standardization of 6G [17].

Apart from new standards, 6G technology will have a more comprehensive business scope than 5G by optimizing industry operations and creating new products and innovations to unlock new opportunities [4]. The COVID-19 pandemic has shown that video communication has enabled people, businesses, governments, medical professionals, and their patients to remain in virtual contact, avoiding the need for travel while remaining socially, professionally, and commercially active. While educational institutions were closed, online education was possible via video communication, and we expect many such developments to stay active, even in the post-COVID-19 era. Although the 5G technology emphasizes the interconnection of all things and the connectivity between essential Internet services [16], 6G will change and disrupt the traditional business models and ecosystem roles of digital service providers. According to 6G white paper released by Samsung, 6G will bring the next hyper-connected experience to every corner of our life [15] to open the market for key stakeholders. Likewise, the China Mobile Research Institute for 6G is working to realize ubiquitous intelligence and fully connect all things based on artificial intelligence mechanisms [4].

Similar to China and Samsung, the European Commission sponsored beyond 5G research activities to accelerate investments in Europe's "Gigabit Connectivity." This investment aims to connect all main socio-economic drivers, including schools, universities, research centers, transport hubs, hospitals, public administrations, and companies, with gigabit connectivity access to shape Europe's digital future [4]. As early as 2016, the U.S. Defense Advanced Research Projects Agency (DARPA) established a cooperative industry-university to jumpstart 6G systems and develop technologies for future cellular infrastructure. In November 2019, China understood the importance of 6G and officially kicked off 6G technology research and development work. The Ministry of Science and Technology and five other ministries or national institutions coordinate all the development works. A promotion working group from the government that is in charge of management and coordination and an overall expert group that is composed of 37 experts from universities, research institutes, and industry were established at this event. Later, it was announced that China aims to form 6G overall development ideas by the end of 2020.

In early 2020, the Japanese government set up a dedicated panel, including representatives from the private sector and academia, to discuss technological development, potential use cases, and policy. In addition, Japan reportedly intends to dedicate around $2 billion to encourage private-sector research and development for 6G technology [18]. Furthermore, in October 2020, the Alliance for Telecommunications Industry Solutions (ATIS) announced the launch of the "Next G Alliance." The aim is to advance North American mobile technology leadership in 6G and beyond over the next decade. Moreover, the Next G Alliance will encompass the comprehensive research and development lifecycle, manufacturing, standardization, and market readiness [19]. The founding members include AT&T, T-Mobile, Verizon, Qualcomm, Ericsson, Nokia, Apple, Samsung, Google, Facebook, Microsoft, etc.

In the same direction, in October 2020, the Next Generation Mobile Networks (NGMN) launched its new "6G Vision and Drivers" project to provide early and timely direction for global 6G activities. Furthermore, based on the roadmap, in November 2020, China launched what it claimed is the first 6G experimental satellite to test communications from space using a high-frequency terahertz spectrum [20]. Next, in February 2020, the Radio Communication sector of ITU decided to start the study on future technology trends for the future evolution of International Mobile Telecommunications (IMT) [1]. Finally, the Academy of Finland announced 6Genesis to conceptualize 6G under the University of Oulu’s Centre for Wireless Communications to satisfy all the expectations not met with 5G, as well as new ones to be defined later [21]. To this end, in late 2020, the government of South Korea confirmed a plan to carry out a 6G trial in 2026 and is expected to spend approximately $169 million over five years to develop 6G technology. The trial aims to achieve 1 Tbps in data transmission speeds and latency reduction to one-tenth of current 5G services. Toward this end, the government of South Korea will initially push for tasks in six key areas (hyper-performance, hyper-bandwidth, hyper-precision, hyper-space, hyper-intelligence, and hyper-trust) to preemptively secure next-generation technology.

1.1.3 6G: Key Driving Applications

Figure 1.2 identifies the applications, trends, and disruptive technologies that will drive 6G revolution. This vision will delineate new 6G services and provide a concrete research roadmap and recommendations to facilitate the leap from current 5G systems toward 6G [22]. While traditional applications, such as live multimedia streaming, will remain central to 6G, the key determinants of the system performance will be four new application domains. In this thesis, we only focused on 6G driving applications ranging from smart wearables to integrated headsets and innovative body implants, potentially driving a majority of 6G use cases known as the 6G post smartphone era.

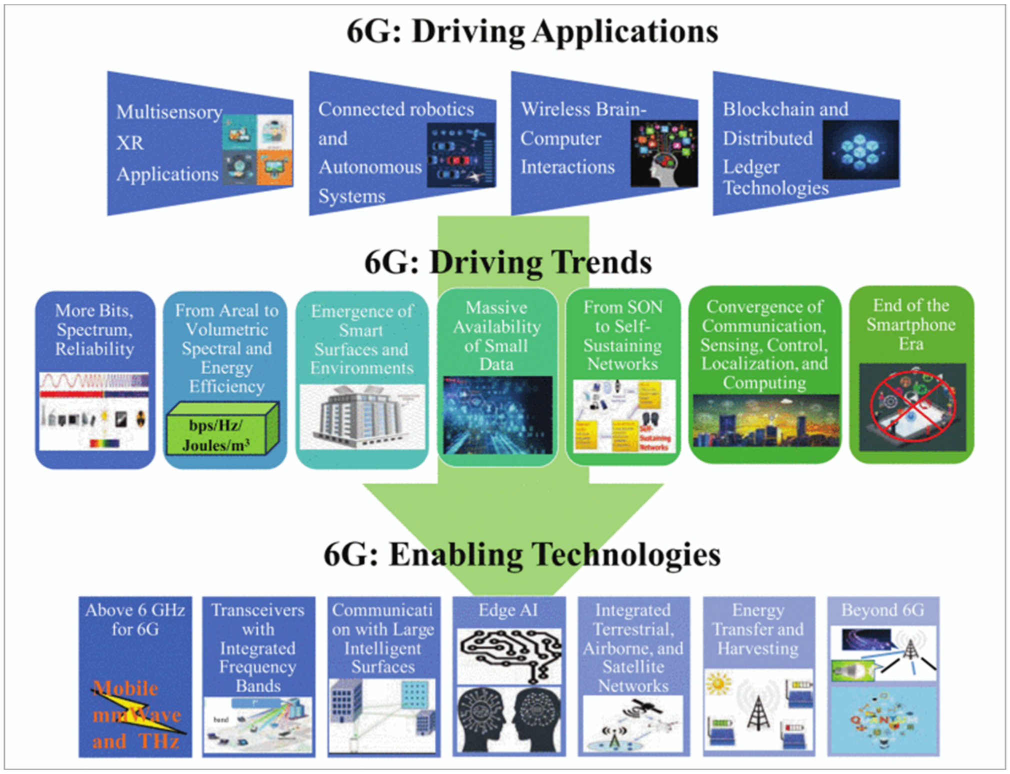


Figure 1.2: 6G vision: applications, trends, and technologies [22].

- **Multisensory XR Applications:** Future wireless services will improve quality of life by enabling various applications, such as XR applications. Multisensory XR applications with underlying services will yield many killer applications for 6G by allowing us to merge digital and physical worlds [23]. Although upcoming 5G systems still fail to provide a complete immersive XR experience, 6G networks aim to meet ever-increasing demands. A truly immersive AR/MR/VR experience requires a joint design integrating not only engineering requirements but also perceptual requirements stemming from human senses, cognition, and physiology. Therefore, developing new metrics such as quality-of-physical-experience (QoPE) is necessary to meet the mentioned requirements. QoPE can combine quality-of-service (QoS), Quality-of-Experience (QoE), and human perceptions, including XR and holographic communication, to perceive a realistic experience [24]. In the same direction, in [25] demonstrated that visual and haptic perceptions are crucial to maximizing QoPE with incorporated perceptual factors that 6G must support.

- **Connected Robotics and Autonomous Systems (CRAS):** A primary driver behind 6G systems is the imminent deployment of CRAS, including Drone-delivery systems, autonomous cars, autonomous drones, vehicle platoons, and autonomous robotics. Autonomous robotic devices rely on innovative communication technologies that use fixed and moving platforms to achieve consistent connectivity. Such devices require constant and reliable connectivity to maintain adequate QoS. Moreover, communication between mobile robots in swarm scenarios plays a significant role in many real-world scenarios, such as search and rescue, battlefield communication, and unmanned aerial vehicles (UAV) swarm [26]. Different requirements for these applications introduce new trends and research directions toward 6G. For instance, holographic communications are bandwidth intensive and thus need to open up new and wider spectrums, such as terahertz (THz) bands [27]. On the other hand, other use cases involve communications between multiple small devices that mainly work on batteries, setting the trend for energy sustainability. Toward this end, CRAS is perhaps a prime use case that requires stringent requirements across the rate-reliability-latency spectrum, a balance that is not yet available in 5G.

- **Wireless Brain-Computer Interactions (BCI):** BCI is an approach for controlling appliances used daily in smart societies, especially appliances used at home and in medical systems. People will use wireless BCI technologies by establishing a direct communication path between the brain and external devices instead of smartphones. BCI acquires the brain signals that transmit to a digital device and analyze and interprets the signals into further commands or actions [28]. Similar to empathic and haptic communications and XR, wireless BCI services need high rates, ultra-low latency, and high reliability. However, they are much more sensitive than XR to physical perceptions and necessitate QoPE guarantees.

- **Blockchain and Distributed Ledger Technologies (DLT):** Blockchain and distributed ledger technology are one of the most disruptive technology enablers to address most of the current limitations and facilitate the operational standards of 6G to meet the complex requirements of network slicing for vertical applications [14]. 6G network leverages superior performance in enhanced reliability, especially ubiquitous communication. However, it is highly necessary to effectively manage the resource allocation process that arises due to the scarcity of spectrum resources to meet all the increasing requirements of modern digital communication. Furthermore, by growing data volume and stringent data privacy requirements in 6G, blockchain is a promising technology to mitigate technical security challenges by providing transparency and efficiency in a decentralized blockchain-based system [29].

1.1.4 The Metaverse: A Successor of Today's Internet

The evolution of 5G to B5G and, as many want to call it, 6G offers us another surprise called Metaverse. The term "Metaverse" was coined in Neal Stephenson's science fiction novel Snow Crash in 1992 [30]. The name refers to a world where virtual and reality interact and create value through various social activities. Metaverse is a compound word of transcendence meta (i.e., beyond) and the universe. It refers to a three-dimensional virtual world where avatars engage in political, economic, social, and cultural activities to provide immersive, interactive, realistic, and augmented digital experiences with a broad spectrum of consumer and industrial applications. The novel describes a virtual world detached from the real world, but parallels with the real world interact and are always online. It is widely used in the sense of a virtual world based on daily life where both the real and the unreal coexist [31]. As the scope of the Metaverse is wide and continuously growing, various definitions and similar concepts exist.

The advent of the metaverse boom in 2021 indicates that new changes will take place in the way of human society and communication [32]. People join the virtual world with their digital identity. In the Metaverse, they are free and independent. People's image in the virtual world is not necessarily the same as in the real world. People can create a new digital identity for themselves. The world of Metaverse pays more attention to the sense of experience, which will bring people a better world. The underlying technologies of the Metaverse are AI, network and computing technology, VR technology, 6G networks, cloud computing, visualization, and digital twins. However, the front-end devices include smart wearable head-mounted devices (HMDs), interactive controllers, and neural devices [32].

According to [33], the term Metaverse currently has no consensus definition or consistent description. Most industry leaders define it to fit their worldviews according to their companies' capabilities. In [34], the authors described the Metaverse as a shared and persistent online 3D virtual-reality space, which integrates various technologies, such as sensing, communication, and computing, and emphasizes the integration of virtual and reality. Users access the Metaverse through smart devices, such as virtual and AR headsets, smart glasses, wearables, and even human-computer interfaces (HCI), which interact with a computer-generated environment and other users flexibly for both work and personal purposes. Undoubtedly, the Metaverse is one of the most concerned and promising innovative applications in the next generation of wireless network intelligent applications. The goal of the Metaverse is to simulate real existing circumstances and more. The programmers of the Metaverse are millions of users around the world. They create themselves as avatars in the Metaverse and entire worlds in which they operate. The worlds are virtual where each person, thing, or other entity will simultaneously exist within multiple synchronized realities opening up new spaces of possibilities [35].

The Metaverse is the outcome of the AR/VR evolution toward interconnected virtual worlds [1]. In addition, the Metaverse leverages the latest achievements of AI and blockchain technologies to achieve a truly immersive user experience with synchronized realities [36, 37]. Currently, metaverses are mainly limited to virtual worlds, where users can be engaged only through the VR headset and purchase virtual items as unique non-fungible tokens (NFTs). However, a VR-based metaverse is expected to converge in the foreseeable future with AR glasses, wearable devices, and existing IoT infrastructure to synchronize virtual and physical realities. Based on [38], the Metaverse differs from AR and VR in three ways. First, while VR-related studies focus on a physical approach and rendering, Metaverse has a vital aspect as a service with more sustainable content and social meaning. Second, the Metaverse does not necessarily use AR and VR technologies. Third, even if the platform does not support VR and AR, it can be a Metaverse application. Finally, the Metaverse has a scalable environment that can accommodate many people is essential to reinforce social meaning.

The Metaverse: Applications and Challenges

In this section, we summarize the unprecedented playgrounds imposed by Metaverse applications and then describe the main challenges of the envisioned supporting infrastructure and challenges.

- **Social:** The Metaverse is known as human-centric and social interactions constitute the human world using the metaphor of the real world without its physical limitations. Equipped with smart wearable devices, humans can interact and control their digital avatars to play, work, socialize, and interact with other avatars or virtual entities in the Metaverse via HCI and XR technologies [39]. Metaverse can revolutionize our society and enable immersive social applications such as virtual lives, virtual shopping, virtual dating, virtual chatting, global travel, and even space/time travel. For example, Lil Nas X held a virtual concert on Roblox in 2020, with over 30 million fans participating. In addition, players can unlock particular

Lil Nas X goods in the digital store, e.g., commemorative items and emotions. Furthermore, due to the COVID-19 situation, UC Berkeley celebrated graduation festivities virtually in Minecraft in 2020 by digitally copying the campus scenery. Besides, Tencent developed a Digital Palace Museum 4 in 2018, which allows tourists to freely visit the palace museum and its exhibitions with a panoramic and immersive view by wearing VR helmets in their homes.

- **Gaming:** Game is the current hottest metaverse application. Games are an excellent way to explore the Metaverse considering the technological maturity, user matching, and content adaptability. The Metaverse introduces more realistic and interactive games by accelerating efforts on physical world digitization and enabling multisensory experiences. The games such as Horizon Worlds, Roblox, and Fortnite have become widely popular, and movies like Ready Player On and Free Guy envision a more interactive mixed-reality world in future Metaverse games. Furthermore, metaverses offer a flexible game-based learning platform, which facilitates the creation of new educational contexts. We list some representative examples of Metaverse games. The sandbox game Second Life1 offers a modifiable 3D virtual world where players can join in as avatars and create their virtual architectures and sell them, as well as participate in social activities such as art shows and even political gatherings visiting an embassy. Roblox 2 is a global user-created game platform where players can create games and design items such as skins and clothes. It proposes eight critical features of the Metaverse: identity, friends, immersion, anywhere, diversity, low latency, economy, and civilization [40]. Finally, Fortnite 3 is a massively multiplayer online (MMO) shooter game designed by Epic Games, where players can build buildings and bunkers and construct islands. At the same time, the platform can only develop in-game items such as skins.

- **Simulation and Design:** Another promising application is a 3D simulation, modeling, and architectural design on the Metaverse. For example, NVIDIA has built its open platform Omniverse7 to support multi-user real-time 3D simulation and visualization of physical objects and attributes in a shared virtual space for industrial applications, e.g., automotive design. Besides, Omniverse can be compatible with Disney Pixart's open-source platform Universal Scene Description (USD). In industrial applications, the Metaverse can increase productivity along multiple phases of a product's life cycle. First, product design can be conducted in the Metaverse running accurate simulations at a lower cost and a faster pace. Second, the Metaverse can use digital twins to enhance operational efficiency and reduce quality control risks in the manufacturing process. Finally, the Metaverse provides a communal space where providers and customers can have real-time interactions, increasing the efficiency and agility of the product design and development life cycle.

- **Collaboration:** Metaverse also opens new possibilities for immersive virtual collaboration where people can create a personalized workspace or virtual office, a more flexible working environment to facilitate cooperation regardless of geographical restrictions. In addition, digital assets representing people (e.g., avatars) and objects can be incorporated into the 3D space, giving a new dimension to today's online meetings. For example, Horizon Workroom5 is an office collaboration software (run in Oculus Quest 2) released by Meta (parent company of Facebook), which allows people in any physical location to work and meet together in the same virtual room. In addition, Microsoft Mesh6 is an MR platform supported by Azure. It enables users working from multiple sites to cooperate virtually via holographic presence and shared experience from anywhere in a digital copy of their office.

- **Health:** The Metaverse also enables essential applications in the healthcare industry, including telemedicine, augmented fitness, and in particular, remote surgery. When provided with highly realistic environments, remote doctors can perform high-precision operations on a patient's body. Besides, real-time patient physical conditions can enrich displayed content to help doctors' decision-making. Education: The Metaverse transforms the way knowledge is presented. Students can be exposed to visual 3D models with improved clarity in descriptive or explanatory courses compared to any precedent media. In training courses, students can practice their skills in realistic environments and enjoy efficient, low-risk.

However, there are some challenges associated with the application of Metaverse mentioned as follows:

- **Security and Privacy:** From the perspective of Metaverse companies, developers, and users, a natural question is how the Metaverse will guarantee their security and privacy. The data collected or generated by wearable devices and users/avatars may suffer from threats in terms of data tampering, false data injection, low-quality user-generated content (UGC), ownership/provenance tracing, and intellectual property violations in the Metaverse. Thus, metaverse-oriented cryptography mechanisms are open proposals for privacy preservation in the Metaverse, which could mean violation of their privacy, potential identity theft, and other types of fraud [41]. Furthermore, the Metaverse has the same digital information security issues as the real world. For example, Metaverse can potentially monitor users' physiological responses and body movements, thereby leaking sensitive personal information such as user habits and their physiological characteristics to third parties. In addition, in the virtual world, evil users can imitate other users to obtain other people's personal information. In large-scale online games, some matters, such as user harassment and theft of other people's finances, threaten users' privacy and security all the time [42].

- **Delay:** One of the characteristics of the Metaverse is an immersive virtual experience for users. However, a high-speed and low-latency network connection is essential for improving the user experience. In the virtual world created by the basic digital technology, the user may experience visual jitter or delay and other undesirable phenomena, which seriously affect the user's immersive experience due to insufficient network bandwidth.

- **Computing and Communication Resource Allocation:** In the Metaverse, many users must interact through high-performance computing and networks. Hence computing power, i.e., calculation, storage, and transmission of data, is much-needed support for its implementation. On the other side, the Metaverse consists of multiple heterogeneous networks to realize a cyber town is equipped with various opportunities. For managing this gigantic cyber city, efficient dynamic resource provisioning algorithms are necessary to provide QoS networks by avoiding the different kinds of transient bottlenecks involved in the network.

1.1.5 The Metaverse: Prior Art and Recent Progress

Figure 1.3 shows the development timeline of the Metaverse [43]. Since 2002, the development of digital twin technology has made constructing the Metaverse platform possible. At this time, the American Linden Laboratory developed the Second Life online game. In this game, players can make whatever they want in their field. However, due to the lack of immersion in Second Life, it is only an initial foray into the realm of the Metaverse.

With the birth of Bitcoin in 2008 and blockchain technology in 2009, the Metaverse established an independent economic system. In 2014, the development of VR technology realized the transformation of the Metaverse from "planar, passive and one-way" to "three-dimensional, active and

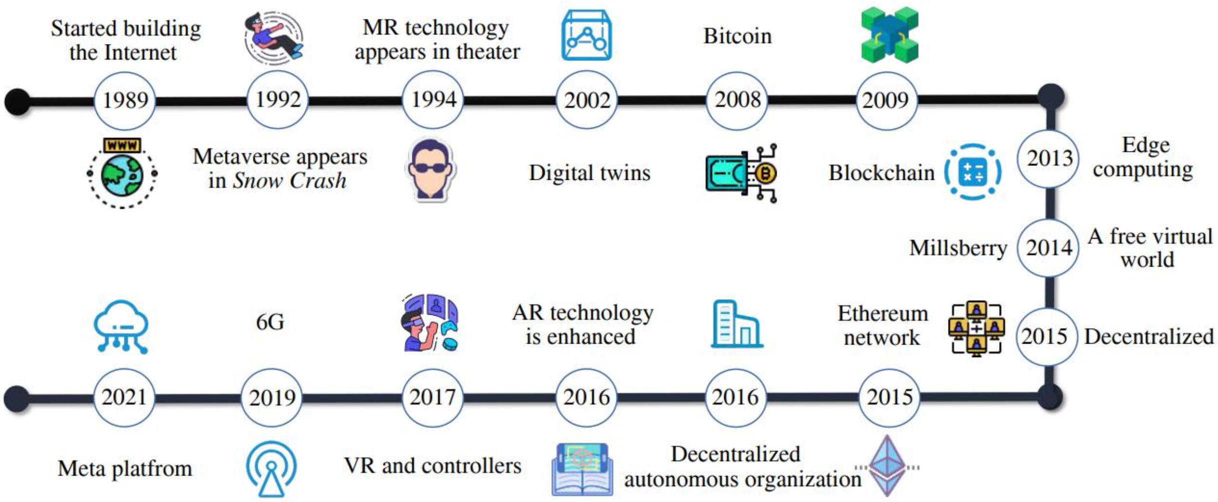


Figure 1.3: The development in the Metaverse from the perspective of technological updates [43].

interactive." Significantly since 2016, by emerging VR technologies (i.e., Oculus and HTC Vive), the sensory stimuli generated by the user's avatar in Metaverse can be transformed into reality through VR equipment and somatosensory. These VR devices enhance the user's sensory experience, thereby greatly enhancing the user's sense of immersion. In the same year, the maturity of decentralization technology also caused some companies to shift from developing centralized architecture Metaverse platforms to decentralized Metaverses. In 2019, the continuous development of network communication technology and AI has reduced the communication overhead of VR devices and the delay of user interaction in the real-virtual world, greatly enhancing the user's immersive experience. In 2021, Roblox wrote the Metaverse concept into its prospectus and successfully landed on the New York Stock Exchange. Meanwhile, Facebook founder Mark Zuckerberg announced that the company would be renamed, Meta. Since then, the development of the Metaverse has ushered in another wave.

Advanced XR Technologies: Fusing of Digital and Real Worlds

The Metaverse concept is increasingly becoming adopted into everyday society with ubiquitous applications from daily living and working scenarios to customized forms of social activities enhancing a connectedness of experiences. In [44], the authors consider the Metaverse as a virtual environment constructed by the Internet, Web technologies, and XR toward a hybrid physical and virtual space. In this sense, XR is a promising technology of the Internet of No Things to extend

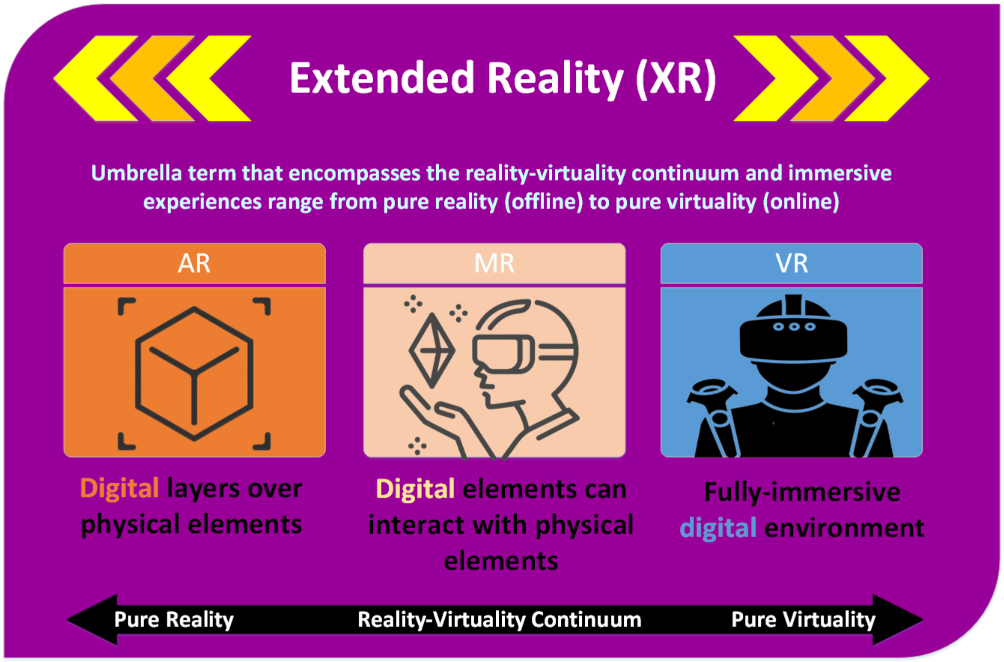


Figure 1.4: The reality-virtuality continuum, ranging from pure reality (offline) to pure virtuality (online).

humans' abilities to develop human-robot/avatar interaction. Furthermore, XR is an expanded field of fluid space that enables the visualization of Metaverse content in both immersive virtual and hybrid environments. As illustrated in Fig. 1.4, XR is an umbrella term for Virtual Reality VR, AR, and MR of the virtuality continuum concept, which is a mixture of the presentation of objects from real-to-virtual displays [45]. In addition, XR refers to the combination of physical and virtual environments where "X" represents the spatial future of unforeseen computing technologies connecting virtual and physical spaces [44].

AR tools such as Facebook's innovative lenses and filters, Google's ARCore, Apple's ARKit, and cloud-based platforms have further accelerated the development of AR content and consumer experiences [46]. For instance, Shopify's ARKit allows smartphones to place 3D models of physical items and see how they would look in real life. An illustrative AR example is an aircraft maintenance engineer, who can visualize a real-time model, often referred to as a digital twin, of an engine that may be thousands of kilometers away. Finally, Microsoft's HoloLens 2 is a flagship MR device that helps bridge the gap between real and virtual environments where user interaction occurs [47].

With the maturity of miniaturized sensors, embedded technology, and XR technology, XR devices such as HMDs are expected to be the main terminal for entering the metaverse. In particular, wearable XR devices perform fine-grained human-specific information perception, as well as ubiquitous sensing for objects and surroundings, with the assistance of indoor smart devices (e.g., cameras). In this manner, the user/avatar interactivity will no longer be limited to mobile inputs (e.g., handheld phones and laptops) but all kinds of interactive devices connected to the Metaverse. Besides, low-latency edge computing systems and AI-empowered real-time rendering can resolve negative experiences such as dizziness in wearing XR HMDs [22]. Moreover, XR service requirements blend traditional URLLC and eMBB with incorporated perceptual factors that 6G must support. To this end, to successfully operate XR and connected autonomous systems, a wireless system must simultaneously deliver high reliability, low latency, and high data rates for heterogeneous devices across uplink and downlink [22].

1.2 Objectives

The objectives of this thesis are as follows:

- XR is a promising technology of the Internet of No Things to extend the abilities of humans to develop human-robot/avatar interaction. XR acts as an umbrella term that encompasses AR, VR, and MR. While AR integrates virtual and real objects in real time, VR allows users to control and navigate their movements in a simulated world. The first objective of the thesis is to explain the fundamental concepts of the emerging XR technology and its network infrastructure requirements. Moreover, we aim to discuss the current recent progress and open challenges of integrating XR technology in the human-robot/avatar ecosystem. Finally, an important objective of this thesis is to provide insights into how XR makes it possible to transition from pure reality to pure virtuality to extend humans' experiences, including the support of human-machine interaction.
- Apart from V/AR, one of the objectives of the thesis is how we can develop advanced XR experiences to provide a cross-reality environment to involve all five human senses, pervasive connectivity, robotics, and haptic communications. Another objective of the thesis is to explore how we can exploit the convergence of XR with smart wearables, artificial intelligence-enhanced multi-access edge computing, and intelligent mobile robots. This convergence helps

us to realize the Internet of No Things as an essential stepping stone toward ushering in 6G post-smartphone era.

- 6G is anticipated to become more human-centered than 5G and should not only explore more spectrum at high-frequency bands but, more importantly, converge driving technological trends such as blockchain and connected robotics. One of the objectives of the thesis is to focus on the emerging field of robonomics, which studies the sociotechnical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society. After identifying open research challenges of blockchain, we investigate the widely studied trust game of behavioral economics in a blockchain context, paying close attention to the importance of developing efficient cooperation and coordination technologies. Another objective of the thesis is to extend the classical two-player trust game to a networked N-players trust game benefiting advanced blockchain technologies.

- In 6G, there is also a strong notion that the nature of mobile terminals will change, whereby smart cars and intelligent mobile robots are anticipated to play a more important role. Mobile robots assist human users through social interactions. These robots encourage humans to general positive behavior changes like reducing energy consumption. Persuasive robots will be less like tools and more like partners. Their role or function will be increasingly human-centric, where human interaction is not a means to an end but rather the end itself. Another objective is to explore how humans can help social robots in many aspects like nonverbal behaviors such as gaze, body language, gestures, facial expressions, and communicative cues to realize reliable human-robot persuasive systems. Furthermore, we will study proper mechanisms to increase the social power of robots to make them more persuasive to increase their capabilities during complex tasks.

- Various fundamental technologies need to be integrated into 6G to drive the implementation of the next Internet, referred to as the Metaverse. The Metaverse will utilize HMDs and XR as the medium to connect avatars and users in the real world. Furthermore, the Metaverse provides an immense innovation space for human-in-the-loop (HITL) hybrid-augmented intelligence. Specifically, cloud robotics and AR are among the fastest growing commercial applications for enhancing an individual's intelligence in multi-robot collaborative systems. One of the main objectives is to develop methods that allow robots to learn from massive training

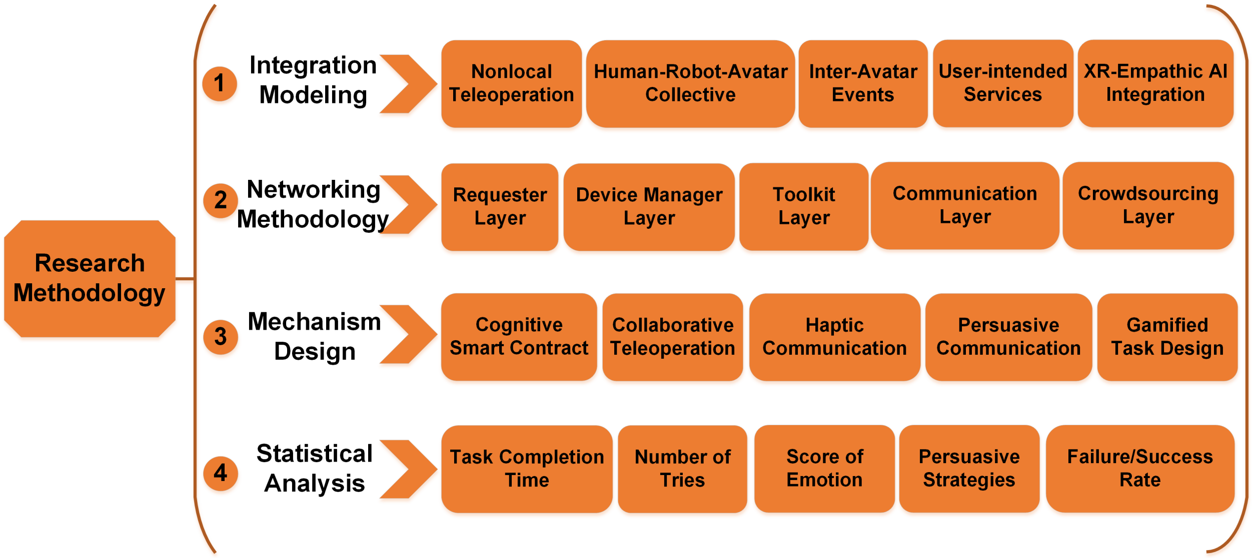


Figure 1.5: Research methodology.

samples and human knowledge to accomplish highly intelligent tasks via shared intelligence among different robots and humans.

- The Metaverse is supposed to provide gamified experiences around emerging Web 3.0 technologies, VR and AR. Gamification will encompass the activity and story around emerging Web 3.0 blockchain technologies. An important objective of this thesis is adopting the original Wordle game to the Metaverse, including but not limited to VR and AR. Another goal is designing and experimentally investigating advanced cognitive cues for playing the Wordle game in the eight different experience realms of the so-called Multiverse, the anticipated successor of the Metaverse, using state-of-the-art smart wearables. Another objective of the thesis is to develop a blockchainized version of the game that allows remote experts to play-to-earn tokens and cooperate with local players by providing them with cognitive assistance while accomplishing a task.

1.3 Research Methodology

The research methodology applied in this thesis includes integration modeling, network methodology, mechanism design, and statistical analysis, as summarized in Fig. 1.5 and briefly described in the following.

- Integration modeling: We integrated several components, including XR-empathic AI services, user-intended services, non-local teleoperation, inter-avatar events, and human-robot-avatar collective, to provide a cross-reality environment. We adopted a novel teleoperation technique such as Crowd of Oz (CoZ) to let teleoperators remotely control Softbank's social robot Pepper gestures placed in front of a human user and have a real-time dialogue via web-based text-to-speech translation. By integrating the aforementioned mechanisms and the CoZ platform with Microsoft HoloLens 2, a human user can experience XR with the CoZ platform, which combines data from real robots and the perception and abilities of a human operator. Moreover, we can visualize the current robot state and the extended human vision, leading to a rising percentage of the HITL workplace. Such XR is an anywhere service and will increase the skill and accuracy of human users.

- Network methodology: We adopted a layered approach to design our platform for realizing all the eight realms of Multiverse architecture. Each layer has components that are logically or physically related to each other. Designing a layered architecture provides improved scalability and simplified administration, troubleshooting, and maintenance. The developed services, interfaces, and protocols are structured into five layers: Requester Layer, Device Manager Layer, toolkit Layer, Communication Layer, and Crowdsourcing Layer.

- Mechanism design: Novel algorithmic mechanisms are presented throughout the thesis to address the aforementioned objectives. These mechanisms include collaborative task design, collaborative teleoperation, haptic communication, persuasive communication, and task gamifying.

- Statistical analysis: In this thesis, Task Completion Time, Number of Tries, Score of Emotions, Success/Failure rate, and persuasive strategies have been leveraged to conduct performance evaluations. All of the abovementioned metrics are comprehensively investigated for our different experimental setups in two ways: (i) laboratory experiment and (ii) Amazon Mechanical Turk (MTurk). Several laboratory experiments are adopted in our research to find relevant and reliable data. Further, we used MTurk, recently popular among experimental and social scientists, as a source of survey and experimental data. Furthermore, MTurk participants are slightly more representative of the world population than standard Internet samples and are significantly more diverse than typical laboratory experiment samples. In addition, the compensation of anonymous MTurk workers in our experiment does not affect data quality. Also, the data obtained are more reliable than those obtained via traditional methods.

1.4 Contributions of the Thesis

This thesis is a compilation of four journal publications published or submitted for publication in high-caliber IEEE journals. The key contributions of the thesis are briefly discussed in the following.

1.4.1 The Internet of No Things: Making the Internet Disappear and "See the Invisible"

The outcome of this research has been published in the following journal article and the main contributions of this work are summarized below:

- M. Maier, A. Ebrahimzadeh, S. Rostami, and A. Beniiche, The Internet of No Things: Making the Internet Disappear and "See the Invisible", *IEEE Communications Magazine*, vol. 58, no. 11, pp. 76-82, November 2020.

After introducing the concepts of the Internet of No Things, we proposed our architecture for the Internet of No Things integrates bearables, wearables, nearables, and three evolutionary stages of mobile computing: (i) ubiquitous, (ii) pervasive, and (iii) persuasive computing. Next, we exploit the so-called Multiverse concept to design cross-reality environments that help fuse the real and the virtual in networked human-avatar/robot collectives. The Multiverse is an architecture of advanced XR experiences containing three dimensions, six variables, and eight realms. The Multiverse aims to realize the fusion of the digital and real worlds. However, while the Metaverse primarily focuses on VR and AR, the Multiverse offers eight types of advanced XR experience realms, spanning the entire reality-virtuality continuum. Finally, we demonstrated the average empathic AI score measurements of the four positive emotions detected by IBM Watson's tone analyzer. Our results clearly illustrate that the users become increasingly more confident and emotionally less tentative after transiting from reality to virtuality, thus confirming the beneficial impact of the Proteus effect experienced in virtual inter-avatar events.

1.4.2 Robonomics in the 6G Era: Playing the Trust Game With On-Chaining Oracles and Persuasive Robots

The outcome of this research has been published in the following journal article and the main contributions of this work are summarized below:

- A. Beniiche, S. Rostami, and M. Maier, Robonomics in the 6G Era: Playing the Trust Game With On-Chaining Oracles and Persuasive Robotics, *IEEE Access*, vol. 9, pp. 46949-46959, Mar. 2021.

We investigated robonomics as an emerging sociotechnical field of interdisciplinary research that integrates behavioral economics, advanced blockchain technologies, and persuasive robotics. Then we widely studied the trust game of behavioral economics in a blockchain context to identify open research challenges of blockchain-enabled implementations. In this work, we first develop a smart contract that replaces an experimenter between trustor and trustee. Next, we presented an on-chaining oracle architecture for a networked N-player trust game that involves a third type of human agent to track the players' investment and reciprocity. Finally, we experimentally demonstrate that mixed logical-affective persuasive strategies for social robots significantly improve trustees' trustworthiness and reciprocity. In addition, these beneficial characteristics of social robots represent a promising solution for enhancing the performance of the trust game. This work was the first to implement blockchain techniques in behavioral and economic game experiments, such as the trust game.

1.4.3 The Metaverse and Beyond: Implementing Advanced Multiverse Realms With Smart Wearables

The outcome of this research has been published in the following journal article and the main contributions of this work are summarized below:

- S. Rostami and M. Maier, "The Metaverse and Beyond: Implementing Advanced Multiverse Realms With Smart Wearables," *IEEE Access*, vol. 10, pp. 110796-110806, Oct. 2022.

In this paper, we first provide a comprehensive description of the current Metaverse vision(s). Next, we mentioned that the Multiverse appears to be predestined to help usher in the Metaverse via novel experiences and the advanced social and interactive user engagement that results from them. Then, we provide a comprehensive investigation of all the Multiverse realms by introducing related examples of them in our real life. In the remainder of this paper, we introduced our multi-layered architecture to integrate VR/AR HMDs and the Amazon MTurk platform to enable the crowdsourcing-based remote control of the social humanoid robot Pepper and its virtual avatar. Finally, in the rest of this paper, we've extended the Metaverse's primary focus on VR/AR to Multiverse's eight distinct XR realms of experience and experimentally compared their performance in terms of TCT and failure/success rate for a single-player origami game and a multiplayer maze game, played in both offline and online (i.e., networked) mode. To our best knowledge, this is the first time such a comprehensive study of the Multiverse realms of experience has been conducted.

1.4.4 Blockchainizing the Wordle Game in Advanced Metaverse Realms Using Smart Wearables

The outcome of this research has been published in the following conference and the main contributions of this work are summarized below:

- S. Rostami, A. Beniiche, L. Gouiran, and M. Maier, Blockchainizing the Wordle Game in Advanced Metaverse Realms Using Smart Wearables, *Proc., IEEE International Conference on Metaverse*, accepted for publication.

This paper investigated the role of 6G that enables the intelligentization and blockchainization of future mobile networks based on decentralized Web 3.0 technologies. After presenting the envisioned Metaverse, we then elaborated on gamified experiences where it encompasses the activity and story around emerging Web 3.0 blockchain technologies. Furthermore, this paper focuses on adopting the original Wordle game to the Metaverse, including but not limited to VR and AR. Specifically, we design and experimentally investigate advanced cognitive cues for playing the Wordle game in the eight different experience realms of the Multiverse using state-of-the-art smart wearables. Moreover, we introduce a multiplayer version of the game by developing a blockchain cognitive smart contract that allows remote experts to play-to-earn tokens and cooperate with local players by providing them with cognitive assistance via smart wearables.

1.5 List of Publications

Publications included in this thesis

In summary, this thesis includes materials extracted from the following four publications:

Journals

[J1] M. Maier, A. Ebrahimzadeh, S. Rostami, and A. Beniiche, The Internet of No Things: Making the Internet Disappear and "See the Invisible", *IEEE Communications Magazine,* vol. 58, no. 11, pp. 76-82, Nov. 2020.

[J2] A. Beniiche, S. Rostami, and M. Maier, Robonomics in the 6G Era: Playing the Trust Game With On-Chaining Oracles and Persuasive Robotics, *IEEE Access,* vol. 9, pp. 46949-46959, Mar. 2021.

[J3] S. Rostami and M. Maier, "The Metaverse and Beyond: Implementing Advanced Multiverse Realms With Smart Wearables," *IEEE Access*, vol. 10, pp. 110796-110806, Oct. 2022.

[J4] M. Maier, A. Beniiche, and S. Rostami, "Metaverse as the New Eleusis 2.0: Are We in the Midst of the Next Renaissance?," *IEEE Communications Magazine,* submitted.

Conference

[J5] S. Rostami, A. Beniiche, L. Gouiran, and M. Maier, Blockchainizing the Wordle Game in Advanced Metaverse Realms Using Smart Wearables, *Proc., IEEE International Conference on Metaverse,* accepted for publication.

Publications not included in this thesis

For completeness, we mention that the following publications have also been published or submitted during my doctoral studies, though their content is not included in this thesis.

[J6] A. Beniiche, S. Rostami, and M. Maier, Society 5.0: Internet as if People Mattered, *Proc., IEEE Wireless Communications Magazine,* accepted for publication.

[J7] M. Maier, A. Ebrahimzadeh, A. Beniiche, and S. Rostami, The Art Of 6G (TAO 6G): How To Wire Society 5.0 [Invited], *IEEE/OSA Journal of Optical Communications and Networking,* OFC 2021 Special Issue, vol. 14, no. 2, pp. A101-A112, Feb. 2022.

1.6 Thesis Outline

The thesis is organized into six chapters to present a consistent overview of the research conducted during the doctoral studies. The remainder of this thesis is structured as follows.

In Chapter 2, we elaborate on how the Internet of No Things with its underlying human-intended services may serve as a useful stepping stone toward realizing the far-reaching vision of future 6G networks, ushering in the 6G post-smartphone era. After briefly reviewing the 6G vision, we explain the reality-virtuality continuum in more detail and introduce the Multiverse for the design of advanced extended reality (XR) experiences, ranging from conventional VR to more sophisticated cross-reality environments known as third spaces. We also explore how the full potential of multisensory XR experiences may be unleashed in Multiverse cross-reality environments. We exploit the convergence of artificial-intelligence-enhanced multi-access edge computing, intelligent mobile robots, and blockchain technologies to help realize the Internet of No Things as an important stepping stone toward ushering in the 6G post-smartphone era. We then elaborate on the recently emerging invisible-to-visible (I2V) technology concept, which we use together with other key enabling network technologies to tie both online and offline worlds closer together in an Internet of No Things and make it “see the invisible” through the awareness of non-local events in space and time. In our experiments, we consider locally connected human-avatar/robot collectives and investigate our proposed extrasensory perception network, which integrates the three evolutionary mobile computing stages of ubiquitous, pervasive, and persuasive computing. As an illustrative example of advanced XR experiences, we study the delivery of sixth-sense perceptions that transverse the boundary between Multiverse realms in order to mimic the quantum realm.

Chapter 3 focuses on the emerging field of robonomics, which studies the sociotechnical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society. We also investigate the widely studied trust game of behavioral economics in a blockchain context, paying close attention to the importance of developing efficient cooperation and coordination technologies. After identifying open research challenges of blockchain-enabled implementations of the trust game, we first develop a smart contract that replaces the experimenter in the middle between trustor and trustee. We then present an on-chaining oracle architecture for a networked N-player trust game that involves a third type of human agents called observers, who track the players' investment and reciprocity.

Chapter 4 focuses on the anticipated 6G post-smartphone era, where smart wearables such as VR/AR HMDs are increasingly replacing the functionalities of smartphones. Our contributions are threefold: (i) we first extend Metaverse's primary focus on VR/AR to Multiverse's advanced XR realms of experience. Next, we gamify and implement all eight Multiverse realms of experience using Oculus Quest 2 and Microsoft HoloLens 2 as state-of-the-art VR/AR HMDs, experimentally investigating and comparing the performance of a (ii) single-player origami game and (iii) multi-player maze game across our proposed integrated VR/AR HMD and Amazon Mechanical Turk crowd-of-Oz (CoZ) platform.

Chapter 5 focuses on the Wordle game, which was developed during Covid-19 lockdowns and became a worldwide Internet phenomenon. In this chapter, we adopt the original Wordle game to the Metaverse, including but not limited to VR and AR. Specifically, we design and experimentally investigate advanced cognitive cues for playing the Wordle game in the eight different experience realms of the so-called Multiverse, the anticipated successor of the Metaverse, using state-of-the-art smart wearables. In addition, we develop a blockchainized version of the game that allows remote experts to play-to-earn tokens and cooperate with local players by providing them with cognitive assistance via smart wearables.

Finally, Chapter 6 concludes the thesis by summarizing the major findings of the thesis and outlining potential avenues for future research that may build upon this work.

Chapter 2

The Internet of No Things: Making the Internet Disappear and "See the Invisible"

This chapter contains material extracted from the following publication:

- M. Maier, A. Ebrahimzadeh, S. Rostami, and A. Beniiche, The Internet of No Things: Making the Internet Disappear and "See the Invisible", *IEEE Communications Magazine*, vol. 58, no. 11, pp. 76-82, November 2020.

In the following, my key contributions in the publication mentioned above are explained in greater detail: (1) I proposed the idea for demonstrating eternalism in locally connected human-avatar/robot collectives illustrated in Fig. 2.3, (2) I implemented the experimental set-up, using Pepper robot, IBM Tone analyzer, avatar, and Oculus Rift, (3) I developed a multi-language chat interface using Google Translate APK and integrated it with Pepper, avatar, and IBM Tone analyzer (4) I conducted the experimental works to obtain and analyze all the results demonstrated in Fig. 2.5.

2.1 Introduction

At the 2015 World Economic Forum, Eric Schmidt famously stated that "the Internet will disappear" given that there will be so many things that we are wearing and interacting with that we won't even sense the Internet, although it will be part of our presence all the time. Although at first this might sound a bit surprising, it is actually what profound technologies do in general. In "The Computer for the 21st Century," Mark Weiser argued that the most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it [48].

An interesting recent approach to make the Internet disappear is the so-called Naked world vision that aims at paving the way to an *Internet of No Things* by offering all kinds of human-intended services without owning or carrying any type of computing or storage devices [49]. The term Internet of No Things nicely resonates with Eric Schmidt's aforementioned statement. The Naked world envisions Internet services to appear from the surrounding environment when needed and disappear when not needed. The transition from the current gadgets-based Internet to the Internet of No Things is divided into three phases; *bearables* (e.g., smartphone), *wearables* (e.g., Google and Levi's smart jacket or Amazon's recently launched voice-controlled Echo Loop ring, glasses, and earbuds), and then finally *nearables*. Nearables denote nearby surroundings or environments with embedded computing/storage technologies and service provisioning mechanisms that are intelligent enough to learn and react according to user context and history in order to provide user-intended services.

Some of the most interesting 5G applications most notably, *virtual reality (VR)* and the *Tactile Internet* seem to evolve in the same direction. To see this, note that according to [50], VR systems will undergo three evolutionary stages, similar to the aforementioned Internet of No Things. The first evolutionary stage includes current VR systems that require a wired connection to a PC or portable device because current 4G or even pre-5G wireless systems cannot cope with the massive amount of bandwidth and latency requirements of VR. At the second evolutionary stage, VR devices are wirelessly connected to a fog/edge server located at the base station for local computation and caching. The third and final evolutionary stage envisions ideal (fully interconnected) VR systems, where no distinction between real and virtual worlds are made in human perception. Similarly, the Tactile Internet allows for the tactile steering and control of not only virtual but also real objects (e.g., teleoperated robots) as well as processes. Thus, the Tactile Internet may be viewed as an extension of immersive VR from a virtual to a physical environment. Recently, in [51], we showed that the human-centric design approach of the Tactile Internet helps extend the capabilities of humans through the Internet by supporting them in the coordination of their physical and digital co-activities with robots and software agents by means of artificial intelligence (AI) enhanced multi-access edge computing (MEC).

The above discussion shows that future fully interconnected VR systems and the Tactile Internet seem to evolve toward common design goals. Most notably, the boundary between virtual (i.e., online) and physical (i.e., offline) worlds is to become increasingly imperceptible, while both digital and physical capabilities of humans are to be extended via edge computing variants, ideally with embedded AI capabilities. In this chapter, we elaborate on how the Internet of No Things with its underlying human-intended services may serve as a useful stepping stone toward realizing the far-reaching vision of future 6G networks, ushering in the *6G post-smartphone era*. After briefly reviewing the 6G vision, we explain the reality-virtuality continuum in more detail and introduce the Multiverse for the design of advanced *extended reality (XR)* experiences, ranging from conventional VR to more sophisticated cross-reality environments known as third spaces. We then elaborate on the recently emerging *invisible-to-visible (I2V)* technology concept, which we use together with other key enabling network technologies to tie both online and offline worlds closer together in an Internet of No Things and make it "see the invisible" through the awareness of non-local events in space and time.

2.2 6G Vision: Putting (Internet of No) Things in Perspective

The authors of [52] provided a roadmap to 6G, which envisions that, in contrast to previous generations, 6G will be transformative and will revolutionize the wireless evolution from "connected things" to "connected intelligence." The authors of [53] argue that 6G will provide an ICT infrastructure that enables end users to perceive themselves as surrounded by a huge artificial brain offering virtually zero-latency services, unlimited storage, and immense cognitive capabilities. In 6G, there is also a strong notion that the nature of mobile terminals will change, whereby smart cars and intelligent mobile robots are anticipated to play a more important role [54].

6G is anticipated to allow for the inclusion of additional human sensory information. The International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) Focus Group on Technologies for Network 2030 (FG NET-2030) was established in July 2018 to study and advance the capabilities of the networks for 2030 and beyond. Among others, FG NET-2030 envisions user experiences to go from well-explored audio-visual communications to the delivery of all five human senses as well as *other senses* in line with the IEEE Digital Senses Initiative. In [2], the authors advocate that 6G should embrace a new mode of thinking from the get-go and argue that 6G services that could *predict future events* for the user and provide good advice would certainly be appreciated.

Finally, the authors of [22] observed that the ongoing deployment of 5G cellular systems is exposing their inherent limitations compared to the original premise of 5G as an enabler for the Internet of Everything (IoE). They argue that 6G should not only explore more spectrum at high-frequency bands but, more importantly, converge driving technological trends, thereby ushering in the 6G post-smartphone era. Specifically, they claim that there will be the following four driving applications behind 6G: (i)*multisensory XR applications*, (ii) *connected robotics* and autonomous systems, (iii) wireless brain-computer interaction (a subclass of *human-machine interaction*), and (iv) *blockchain* and distributed ledger technologies. Among other 6G driving trends and enabling technologies, they emphasize the importance of haptic and empathic communications, edge AI, the emergence of smart surfaces/environments and new human-centric service classes, as well as the end of the smartphone era, given that smart wearables are increasingly replacing the functionalities of smartphones. They also expect that research on the *quantum realm* will intersect with 6G toward its end of standardization.

According to the world's first 6G white paper published by the 6Genesis Flagship Program (6GFP) in September 2019, 6G will become more human-centered than 5G, which primarily focused on industry verticals. One of the currently most compelling visions of the future life and digital society on the other side of the 2030s was recently outlined in [17]. Among others, it anticipates the creation of digital twin worlds that enable new *super-human capabilities* and a resultant *network with the sixth sense*.

The Internet of No Things with its underlying human-intended services and nonlocal extension of human "sixth-sense" experiences in both space and time may serve as a useful stepping stone toward realizing the far-reaching 6G vision above, as explained in technically greater detail in the remainder of the article.

2.3 Extended Reality: Unleashing its Full Potential

In this section, we further elaborate on the recently emerging term XR and how its full potential can be unleashed.

2.3.1 The Reality-Virtuality Continuum

According to Qualcomm, XR will be the next-generation mobile computing platform that brings the different forms of reality together in order to realize the entire reality-virtuality continuum for the extension of human experiences, including the support of human-machine interaction. In fact, according to a recent ABI Research and Qualcomm white paper, "Augmented and Virtual Reality: the First Wave of 5G Killer Apps," some of the most exciting XR use cases include remotely controlled devices and the Tactile Internet. According to this white paper, wireless connectivity has to become faster and cost less, especially considering the visually intensive data used for immersive experiences. It will heavily depend on the following three primary wireless network attributes: (i) high capacity, (ii) low latency, and (iii) uniform experience, even at cell edges. Supporting all three simultaneously is critical to enabling today's VR and future XR uses cases under the same network. More specifically, Qualcomm estimates that sustained wireless network performance providing a very high per-user throughput of 200 to 5000 Mb/s and an ultra-low latency of 1 ms is required for XR mass adoption.

The reality-virtuality continuum ranges from pure reality (offline) to pure virtuality (online), as created by VR. Both reality and virtuality may be augmented, leading to augmented reality (AR) on one side of the continuum and augmented virtuality (AV) on the other. AR enables the live view of a physical, real-world environment, whose elements are augmented by computer-generated perceptual information, ideally across multiple sensory modalities. In doing so, AR alters one's perception of the real-world environment, as opposed to VR, which replaces the real-world environment with a simulated one. Conversely, AV occurs in a virtual environment, where a real object is inserted into a computer-generated environment.

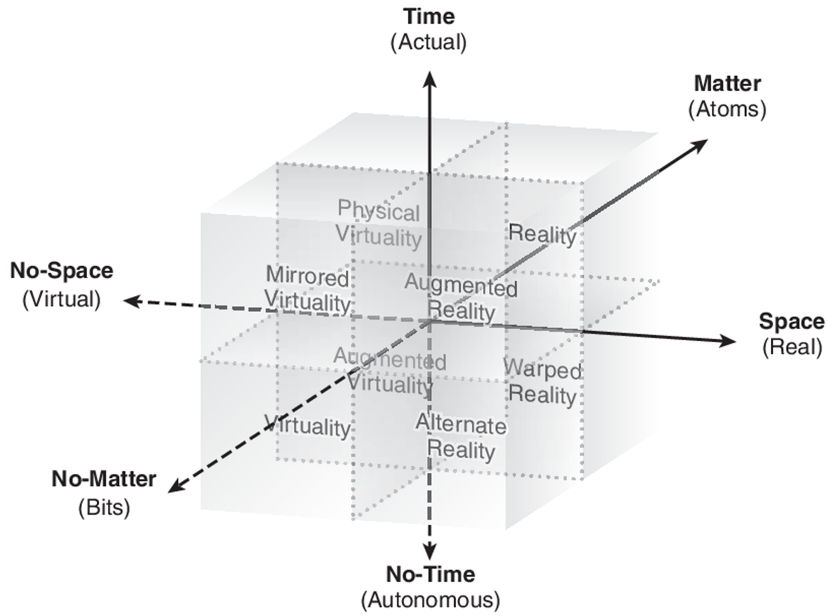


Figure 2.1: The Multiverse as an architecture of advanced XR experiences: three dimensions, six variables, and eight realms.

The term mixed reality (MR) includes AR, AV, and mixed configurations thereof, blending representations of virtual and real-world elements together in a single user interface. MR helps bridge the gap between real and virtual environments, whereby the difference between AR and AV reduces to where the user interaction takes place. If the interaction happens in the real world, it is considered AR. By contrast, if the interaction occurs in a virtual space, it is considered AV. The areas where most industries apply XR is in remote guidance systems for performing complex tasks such as maintenance and assembly[55].

2.3.2 The Multiverse: An ArchItecture of Advanced XR Experiences

Apart from VR/AR/MR, future XR technologies may realize novel, unprecedented types of reality. Thus, X may be rather viewed as a placeholder for future yet unforeseen developments on the digital frontier. An interesting attempt to charter the unknown territory is the *Multiverse*, which may serve as an architecture of advanced XR experiences [56]. As shown in Fig. 2.1, the Multiverse consists of the following architectural components [56].

- **Dimensions:** There are the three well-known physical dimensions Space, Time, and Matter that constitute our physical reality.

- **Variables:** In addition, there are three non-physical dimensions referred to as *No-Space*, *No-Time*, and *No-Matter* that make up the virtual world. Unlike their physical counterparts, these three digital dimensions are not subject to the constraints imposed by physical space, time, and matter. Thus, in total there are six variables that can be exploited for the design of advanced XR experiences.

- **Realms:** Given that there are three (3) pairs of variables, each with two (2) opposite physical/digital dimensions, we have a total of 2^3=8 possible realms. Each realm creates a diff erent type of reality, ranging from conventional AR/AV to more sophisticated types of reality, for example, mirrored virtuality, warped reality, and alternate reality. *Mirrored virtuality* absorbes the real world into the virtual and creates a virtual expression of reality that unfolds as it actually happens, providing a particular bird's eye view. *Warped reality* plays with time in any way possible by taking an experience firmly grounded in reality and shifting it from actual to autonomous time. *Alternate reality*, on the other hand, creates an alternative view of the real world by constructing a digital experience and superimposing it onto a real place. Unlike AR, however, alternate reality manipulates time and allows looking to the future freed from the bonds of actual time.

According to [56], the Multiverse with its different variables and realms offers a powerful experience design canvas to uncover hidden XR opportunities by fusing the real and the virtual, thereby creating cross-reality environments, also known as third spaces. Third spaces are created whenever one transverses the boundary between realms within any given experience. It is worthwhile to mention that, in [48], Mark Weiser seems to have had something similar in mind when describing what he initially called *embodied virtuality*, which is now more widely referred to as ubiquitous computing.

In the subsequent section, we explore how the above concepts (No-Space, No-Time, No-Matter, realms, cross-reality environments) can be used to tie both online and off line worlds closer together in an Internet of No Things and make it "see the invisible."

2.4 Internet of No Things: Invisible-to-Visible Technologies

Future fully interconnected VR systems will leverage on the growing number of drones, robots, and self-driving vehicles. A very interesting example of future connected car technologies that merges real and virtual worlds to help drivers "see the invisible" is Nissan's recently unveiled *invisible-to-visible (I2V)* technology concept [57]. By merging information from sensors outside and inside the vehicle with data from the cloud, I2V enables the driver and passengers not only to track the vehicle's immediate surroundings but also to anticipate what's ahead, for example, what's behind a building or around the corner. Although the initial I2V proof-of-concept demonstrator used AR headsets (i.e., wearables), Nissan envisions turning the windshield (i.e., nearables) of future self-driving cars into a portal to the virtual world.

I2V maps a 360-degree virtual space and gives guidance in an interactive, human-like way, such as through avatars that appear inside the car. It can also connect passengers to people in the Metaverse virtual world that is shared with other users. In doing so, people may appear inside the car as AR avatars to provide assistance or company. Clearly, I2V opens up endless opportunities by tapping into the virtual world.

According to [58], the vastly progressing smart wearables such as exoskeletons and VR/AR devices effectively create real-world avatars, that is, tactile robots connected to human operators via smart wearables, as a central physical embodiment of the Tactile Internet. More specifically, the authors of [58] argue that the Tactile Internet creates the new paradigm of an immersive coexistence between humans and robots in order to achieve tight physical human-robot interaction (pHRI) and entanglement between man and machine in future locally connected *human-avatar/robot collectives*. In addition, many studies have shown that the physical presence of robots benefit a variety of social interaction elements such as persuasion, likeability, and trustworthiness.

In the following, we build on the I2V technology concept and explore how emerging multisensory XR technologies in conjunction with AI-enhanced MEC, intelligent mobile robots, and blockchain technologies may be combined to usher in the Internet of No Things as an important stepping stone toward realizing the 6G vision outlined earlier.

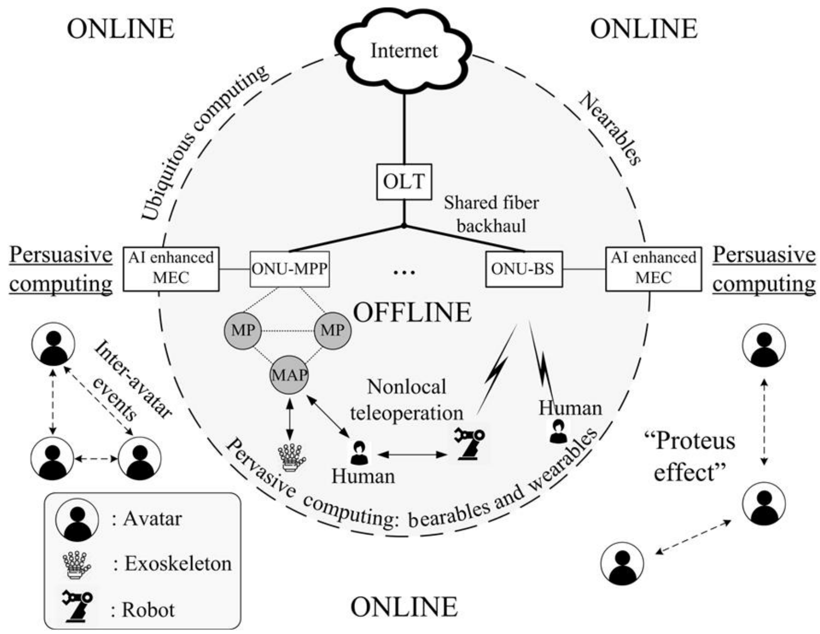


Figure 2.2: Extrasensory perception network architecture integrating ubiquitous, pervasive, and persuasive computing.

2.4.1 Extrasensory Perception Network

Let our point of departure be Joseph A. Paradiso's pioneering work on extrasensory perception (ESP) in an IoT context at MIT Media Lab [59]. In a sensor-driven world, network-connected sensors embedded in anything function as extensions of the human nervous system and enable us to enter the long-predicted era of ubiquitous computing, as envisioned by Mark Weiser more than a quarter of a century ago. In [59], the authors showed that network-connected sensors and computers make it possible to virtually travel to distant environments and "be" there in real time. Interestingly, the authors concluded that future technologies will fold into our surroundings that help us to get our noses off the smartphone screens and back into our environments, thus making us more (rather than less) present in the world around us. Clearly, this human-centric outlook on future technologies may materialize in the 6G post-smartphone era.

Recall that XR will be the next-generation mobile computing platform for the extension of human experiences, including the support of human-machine interaction. Figure 2.2 depicts the architecture of our proposed *extrasensory perception network (ESPN)*, which integrates the following three evolutionary stages of mobile computing: (i)ubiquitous, (ii)pervasive, and (iii)persuasive computing. Ubiquitous computing is embedded in the things surrounding us (i.e., nearables), while pervasive computing involves our bearables and wearables. Persuasive computing aims at changing the behavior of users through social infl uence. An interesting phenomenon for changing behavior in an online virtual environment is known as the "Proteus effect," where the behavior of individuals is shaped by the characteristics and traits of their virtual avatars, especially through interaction during inter-avatar events. We exploit AI-enhanced MEC to realize persuasive computing, as described in more detail shortly.

We have seen previously that some of the most exciting XR use cases include remotely controlled devices and the Tactile Internet. Recently, we studied the Tactile Internet as one of the most interesting 5G low-latency applications enabling novel immersive experiences by means of haptic communications [51]. The underlying physical network infrastructure, which is illustrated in Fig. 2, consisted of a fi ber backhaul shared by WLAN mesh portal points (MPPs) and cellular base stations (BSs) that are collocated with optical network units (ONUs), which in turn are connected to the central optical line terminal (OLT) of the fiber backhaul. Based on real-world haptic traces, we studied the use case of nonlocal teleoperation between a human operator (HO) and teleoperator robot (TOR), which are both physical (i.e., offline) entities (2.2). We showed that AI-enhanced MEC helps decouple haptic feedback from the impact of extensive propagation delays by forecasting delayed or lost haptic feedback samples. This enables humans to perceive remote task environments in real time at a 1 ms granularity.

2.4.2 Nonlocal Awareness of Space and Time: Mimicking the Quantum Realm

As an illustrative example of advanced XR experiences, we study the delivery of extrasensory human perceptions, that is, senses other than the five human senses, as envisioned by the IEEE Digital Senses Initiative and ITU-T FG NET-2030.

It is interesting to note that the term ESP actually refers to a widely known phenomenon that allows humans to have nonlocal experiences in space and time. According to Wikipedia, ESP is also called *sixth sense*, which includes claimed reception of information not gained through the recognized five physical senses, but sensed with the mind. There are different types of ESP, including clairvoyance (i.e., viewing things or events at remote locations) and precognition (i.e., viewing future events before they happen). While clairvoyance may be viewed as the ability to perceive the hidden present, precognition is a forecast (not prophecy) of events to come about in the future unless one does something to change them based on the perceived information. In contemporary physics, there is the "principle of nonlocality," also referred to as quantum-interconnectedness of all things by quantum physicists such as David Bohm, which transcends spatial and temporal barriers. Nonlocality occurs due to the phenomenon of entanglement, where a pair of particles have complementary properties when measured, and might be the cause of ESP.

Note that despite reports based on anecdotal evidence, there has been no convincing scientific evidence that ESP exists after more than a century of research. However, instead of rejecting ESP as pseudoscience, in this article we argue that with the emergence of XR it might become possible to disrupt the old impossible/possible boundary and mimic the quantum realm. Toward this end, we are going to design the following two advanced XR experiences that transverse the boundary between the aforementioned Multiverse realms in order to realize awareness of nonlocal events in space and time.

Precognition: To achieve precognition, we extend our aforementioned AI-enhanced MECbased haptic feedback sample forecasting scheme in [51] for realizing persuasive computing. Recall from above that in nonlocal teleoperation, the HO and TOR are physical entities, that is, both reside in the realm *reality* characterized by space, time, and matter. In addition, we let the HO have access to the realm *augmented virtuality* (i.e., No-Space, Time, No-Matter) by observing a digital twin of the remote TOR via a wearable head-mounted display. Our AI-enhanced MEC forecasting scheme was trained by using haptic traces obtained from application-specific teleoperation experiments. It was shown in [51] that a high forecasting accuracy (mean squared error below 1 percent) can be achieved in the considered scenarios. In general, however, the training may become irrelevant in changing or unstructured real-world environments, resulting in decreased forecasting accuracy. How can the HO know when or even before this happens and be persuaded to make an informed decision?

To quantify the decreasing effectiveness, our AI-enhanced MEC computes the metric regret, which measures the future regret the HO will have after *blindly* relying on a presumably intact haptic feedback sample forecasting scheme. We define regret as the difference between the achievable and optimum physical task execution times of the TOR. Note that the metric regret is used to influence the HO's decision to abort the teleoperation before unintended consequences might occur. It is displayed in his/her head-mounted wearable to "make him/her see" the AI becoming less trustworthy. Later we highlight some illustrative results.

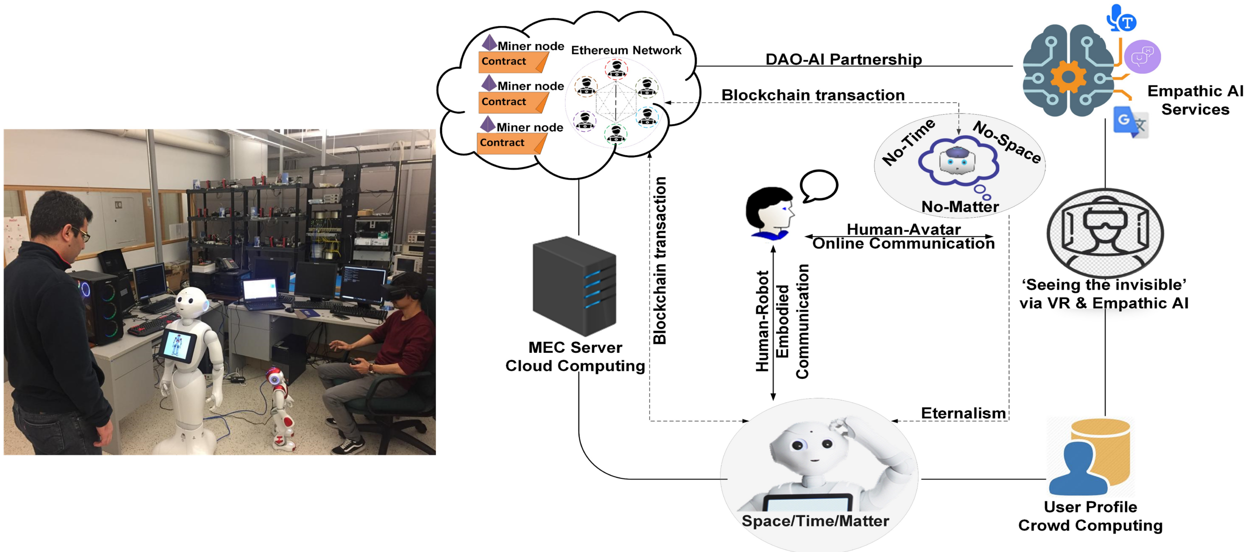


Figure 2.3: Experimental setup for demonstrating eternalism in locally connected human-avatar/robot collectives.

Eternalism: Next, we also consider the transition from the time to no-time dimension of the Multiverse in Fig. 2.1. In physics, the two most important theories on the nature of time have been *presentism* and *eternalism*. Presentism states that only the present is real. By contrast, eternalism states that the past and future are equally as real as the present. Under eternalism, "now" is to time as "where" is to space, whereby time is a dimension much like space, one in which the past and future are as real as locations north and south (i.e., unlike presentism, eternalism thus lends itself to time travel). Today, most physicists view eternalism as the order of time. Figure 2.3 illustrates our experimental set-up for demonstrating eternalism locally where time is better viewed as space in the sense that you are in the present but also could simultaneously move to the past and future. This is a human-avatar/robot collective where several human operators can remotely communicate with a student through Pepper robot[1]. Moreover, all operators can receive/send messages based on their native languages. To do so, we integrate Google Translate API[2] to translate different types of languages, and finally, Pepper transfers all the messages in English to the student who communicates with Pepper physically. In this set-up, the student engages in embodied communication with Pepper via voice, gesture, and Pepper's tablet. Moreover, the student taps into the No-Time as a variable of the nonphysical Multiverse to access the avatar.

[1] `https://www.softbankrobotics.com/emea/en/pepper`
[2] `https://cloud.google.com/translate`

To do so, we established an experiment that lasted 15 minutes and was repeated five times, and each time involving a different student. The experiment had two parts including reality and virtuality. In the initial reality part, the student first engages with Pepper for an interactive audio-visual tour of INRS. In this audio-visual tour, Pepper presents INRS University. Then Pepper shows a list of professors on her tablet. The students select one of them and Pepper shows more details of the selected professor on the tablet and starts to speak about the professor. Moreover, Pepper was able to perform emotion recognition using facial expressions for students (e.g., happiness, sadness, fear, anger, and surprise). After that Pepper shows students' pictures on the tablet. Subsequently, the student is allowed to ask Pepper any arbitrary question about INRS, whereby Pepper's responses are provided by a remote human operator via speech-to-text and text-to-speech conversion.

Next, Pepper invites the student to continue the experiment in the virtuality part, where the student can virtually walk through INRS[3]. We used an Oculus Rift VR headset to let the student accesses a virtual avatar. The student, guided by an avatar acting as an omniscient oracle. The oracle relies on a remote human operator, who can monitor the student's detected emotions in real-time. We exploit IBM Watson's empathic AI services, most notably, IBM's Tone analyzer[4] for detecting emotions in written text exchanged during human-robot/avatar online communication. A TCP server calls the IBM Tone analyzer and forwards the received message. The output of the IBM Tone analyzer is a JSON file, which contains the scores extracted from the received message. In the middle, a user profile is maintained to record each human-robot interaction. Next, the TCP server calls the logger server, which stores all messages and scores in separate user profiles. Finally, the TCP server receives an acknowledgment from the logger server and sends the data to Google Translate API. In the subsequent section, we highlight a use case of exploiting VR and empathic AI to *make emotions visible* and nudge the human toward experiencing eternalism.

Let us consider an HO-TOR pair carrying out a given physical task that can be decomposed into 100 operations. To achieve the optimum task execution time, the AI-enhanced MEC forecasting scheme outsources certain operations to another crowdsourced HO, who is located 20 s away from the physical task point. Let f_H and f_R denote the capability (given in number of operations per second) of the HO and TOR to execute the physical task, respectively. The HO decides to abort teleoperation when he/she observes the digital twin starting to produce failures, and the ratio of

[3] `https://www.youtube.com/watch?v=W6OsRODQbXk&ab_channel=omarAlexandergelvezparada`
[4] `https://cloud.ibm.com/docs/tone-analyzer?topic=tone-analyzer-about`

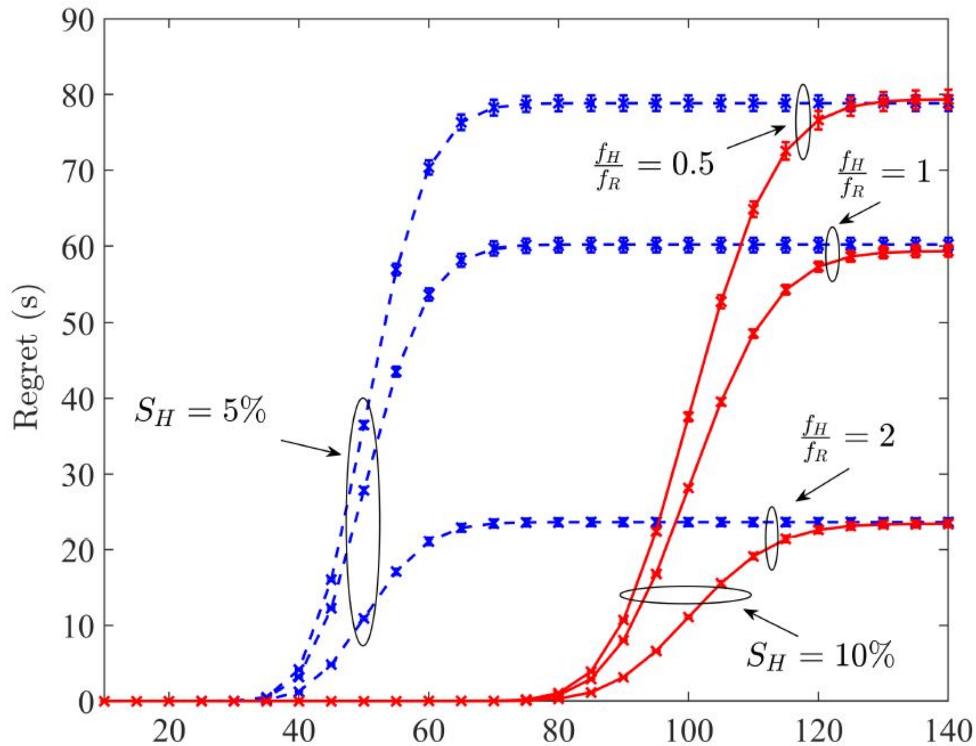


Figure 2.4: Regret (given in seconds) vs. misforecast sample rate λ_f lf for different ratios of human and robot capabilities $f_H/f_R \in$ 0.5, 1, 2 with human decision threshold $S_H \in$ 5% , 10% (shown with 95 percent confidence intervals).

misforecast samples to total number of received haptic feedback samples exceeds a certain threshold S_H. Subsequently, the crowdsourced HO traverses to the physical task point to finalize all remaining operations.

2.5 Results

Figure 2.4 depicts the average regret vs. misforecast sample rate λ_f lf for different ratio f_H/f_R and S_H with 95 percent confidence intervals. We note that the shown confidence intervals deviate from the corresponding average value not more than 1.6 percent. It highlights the beneficial role of crowdsourcing a capable assistant HO with increased f_H/f_R in compensating for unreliable AI and completing the physical task failure-free. In our sensitivity analysis, we found that the design of a properly operating AI-enhanced MEC forecasting scheme with smaller λ_f lf have a bigger impact on reducing regret than crowdsourcing human individuals with a higher f_H/f_R.

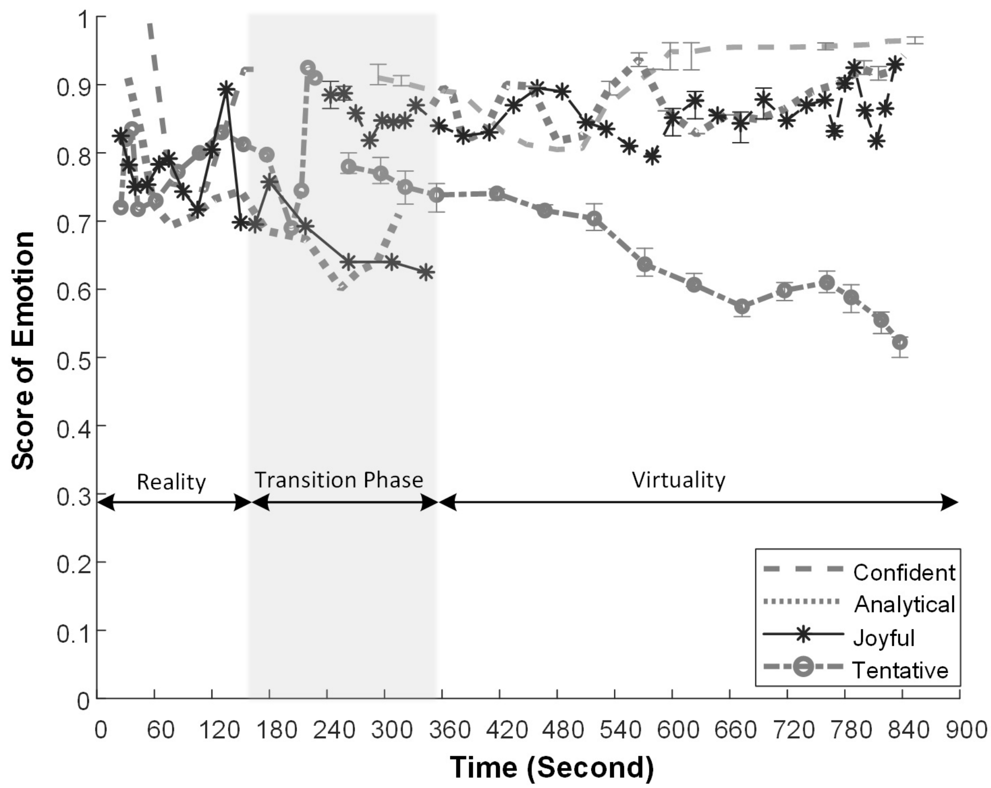


Figure 2.5: Average empathic AI score of four different positive emotions experimentally detected during time travel from reality to virtuality (shown with minimum-to-maximum measured score intervals).

Note that the above digital twin is synchronized with the remote TOR, both operating in the actual time dimension of Fig. 2.1. Next, we also tap into the no-time dimension of VR environments during the following time travel experiment from reality to virtuality. The experiment lasted 15 minutes and was repeated five times, each time involving a different student. In the initial reality part, the student first engages with Pepper for an interactive audio-visual tour of INRS (the students' university). Subsequently, the student is given the opportunity to ask Pepper any arbitrary question about INRS, whereby Pepper's responses are provided by a remote HO via speech-totext and text-to-speech conversion. Next, Pepper invites the student to continue the experiment in the virtuality part, where the student can virtually walk through INRS guided by an avatar acting as an omniscient oracle. The oracle relies on a remote human operator, who is able to monitor the student's detected emotions in real time. By leveraging on the Proteus effect experienced in inter-avatar events (Fig. 2.2), the oracle gives advice to the student on how to gradually reach a desirable future situation at INRS, which is characterized by higher levels of confidence and emotional engagement.

Figure 2.5 shows the average empathic AI score of the four positive emotions detected by IBM Watson's tone analyzer during the various human-robot/avatar speech-to-text and text-to-speech exchanges of the experiment. It clearly illustrates that the students become increasingly more confident and emotionally less tentative after transiting from reality to virtuality, thus confirming the beneficial impact of the "Proteus effect". Our experiment confirms the Proteus effect in that the oracle advises the student on how to gradually reach a desirable future situation at INRS, which is characterized by higher levels of confidence and emotional engagement.

2.6 Conclusions

Our proposed ESPN architecture integrates ubiquitous, pervasive, and persuasive computing to enable the delivery of extrasensory sixth-sense human perceptions via advanced XR experiences in a future Internet of No Things, which will be increasingly based on wearables (e.g., VR headsets) and nearables (e.g., intelligent mobile robots) in an anticipated 6G post-smartphone era. We exploit the so-called Multiverse concept to design cross-reality environments that help fuse the real and the virtual in networked human-avatar/robot collectives. By means of simulation and experiment, we studied two illustrative cross-reality use cases to make humans see AI becoming less trustworthy and to exploit empathic AI services making human emotions visible.

Chapter 3

Robonomics in the 6G Era: Trust Game with On-Chaining Oracles and Robots

This chapter contains material extracted from the following publication:

- A. Beniiche, S. Rostami, and M. Maier, Robonomics in the 6G Era: Playing the Trust Game With On-Chaining Oracles and Persuasive Robotics, *IEEE Access*, vol. 9, pp. 46949-46959, Mar. 2021.

In the following, my key contributions in the aforementioned publication are explained in greater detail: (1) I developed and implemented the experimental set-up for realizing N-player Trust game with persuasive robots in Section 3.5, (2) I proposed the idea of exploring social cues of robonomics and implemented the persuasive robotics strategies scripts using CoZ platform for controlling the gestures of Softbank's social robot Pepper in Section 3.5.3, (3) I implemented a real-time video streaming and embedded it in the CoZ user interface where an observer can watch the trustee's environment through Pepper's eyes. (4) I contributed in conducting all the experimental works to obtain results demonstrated in Fig. 3.6.

3.1 Introduction

In the last chapter, we mentioned that artificial-intelligence-enhanced multi-access edge computing, intelligent mobile robots, and blockchain technologies are the key technologies that help us to realize the Internet of No Things as an essential stepping stone toward ushering in the 6G post-smartphone era. 6G is anticipated to become more human-centered than 5G and should not only explore more spectrum at high-frequency bands but, more importantly, converge driving technological trends such as blockchain technologies and connected robotics. This chapter focuses on the emerging field of robonomics, which studies the sociotechnical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society.

A major limitation of the conventional blockchain is its inability to interact with the "outside world" since smart contracts can only operate on data that is on the blockchain. In the emerging B-IoT, sensors are typically deployed to bring sensor measurement data onto the blockchain [60]. Advanced blockchain technologies enable the *on-chaining* of blockchain-external off-chain information stemming also from real users, apart from sensors and other data sources only, thus leveraging also on human intelligence rather than machine learning only. To overcome this limitation, smart contracts may make use of so-called *oracles*, which are trusted decentralized blockchain entities whose primary task is to collect off-chain information and bring it onto the blockchain as trustworthy input data to smart contracts. Several decentralized oracle systems exist that rely on *voting-based games*, e.g., ASTRAEA [61].

Blockchain-external data sources imply the risk that the on-chained data may be unreliable, maliciously modified, or untruthfully reported. Typically, various game-theoretical mechanisms are used to incentivize truthful provisioning of data. According to [62], however, those approaches address only partial aspects of the larger challenge of assuring *trustworthiness* in data on-chaining systems. A key property of trustworthy data on-chaining systems is truthfulness, which means that no execution of blockchain state transition is caused by untruthful data provisioning, but instead data is always provisioned in a well intended way. The challenge that derives from truthfulness is the building of incentive compatible systems, where participants are assumed to act as rational self-interest driven *homini oeconomici*, whose primary goal is to maximize their individual utility via monetary rewards and penalties for their actions and behavior.

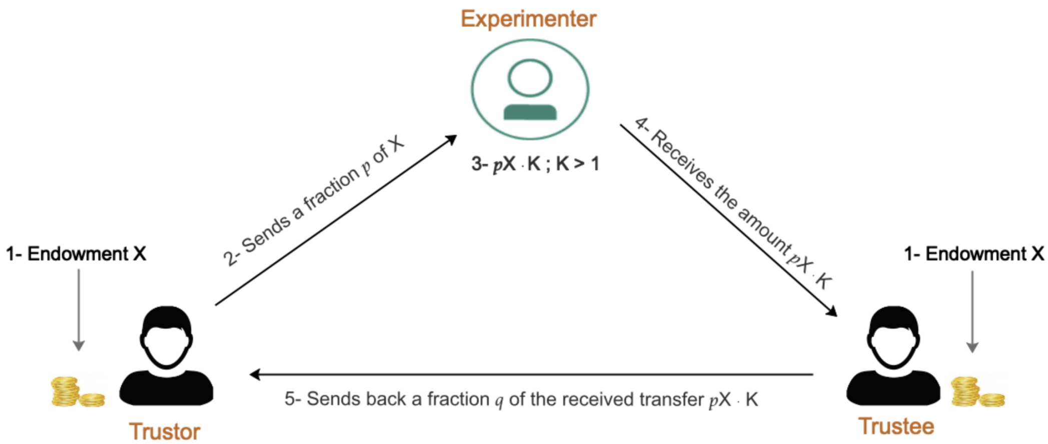


Figure 3.1: Classical trust game involving two human players (trustor and trustee) and one experimenter in the middle.

In this chapter, we focus on the *trust game* widely studied in behavioral economics. The trust game hasn't been investigated in a blockchain context yet, though it allows for a more systematic study of not only trust and trustworthiness but also reciprocity between human actors [63]. Next, we present a networked version of the trust game leveraging the beneficial characteristics of the social robots in changing players' behavior. Toward this end, we elaborate on the emerging field of *robonomics*, which studies the sociotechnical impact of blockchain technologies on social human-robot interaction. The classical trust game involves only two human players referred to as trustor and trustee, who are paired anonymously and are both endowed with a certain amount X of monetary units. Fig. 3.1 illustrates the sequential exchange between trustor and trustee. The trustor can transfer a fraction $0 \leq p \leq 1$ of her/his endowment to the trustee. The experimenter then multiplies this amount by a factor $K > 1$, e.g., doubled or tripled. The trustee can transfer a fraction $0 \leq q \leq 1$ of the received amount directly back to the trustor without going through the experimenter. Note that the trust game captures any generic economic exchange between two actors. According to [64], the trust game will remain an important instrument for the study of social capital and its relation to economic growth for many years to come, whereby research on efficient cooperation and coordination technologies will be of particular interest.

The remainder of the chapter is structured as follows. In Section 3.2, we first briefly review the 6G vision of future mobile networks, followed by a discussion of the challenges and benefits of blockchain in 6G networks paying close attention to the anticipated role of blockchain oracles and persuasive robots. In Section 3.3, we identify open research challenges of realizing a blockchain-enabled trust game, including its social efficiency performance and the design of suitable reward and penalty mechanisms. We then delve into the technical issues of implementing a smart-contract based decentralized version of the classical trust game by applying basic blockchain technologies and validating them experimentally. Section 3.4 explores advanced blockchain technologies, most notably on-chaining oracles, to facilitate equitable social efficiency in a networked N-player (i.e., multiplayer) trust game. In Section 3.5, we put the N-player trust game in the context of robonomics leveraging the beneficial characteristics of robot persuasive strategies to foster prosocial human behavior. Finally, Section 3.6 concludes the chapter.

3.2 6G Vision: Blockchains and Robots

3.2.1 Blockchain Benefits for 6G

Blockchain is used to generate the large-scale index as a security measure for all network communication. It serves as a mutual, collective, and common ledger. Blockchain performs the transition from client-server to a trusted peer-to-peer network. According to [22], blockchain and DLT may be viewed as the next generation of distributed sensing services, whose need for connectivity will require a synergistic mix of URLLC and mMTC to guarantee low-latency, reliable connectivity, and scalability [54]. A combination of blockchain technologies and 6G communications network yield the following benefits:

- **Intelligent Resource Management:** According to [2], network resource management and sharing play a significant role in 6G. Resource management operations such as spectrum sharing, orchestration, and decentralized computation have to be compatible with massive infrastructure volumes. Toward this end, blockchain and smart contracts are anticipated to play a major role for self-organizing network resource management. Further, smart contracts help handle and automate the relationship between operators and end-users.

- **Security and Privacy Features:** Another important benefit is the sophisticated use of all 6G network resources, services, and user data without compromising user security and privacy [2]. In this regard, security and privacy-preserving solutions based on blockchain such as decentralized authentication and access control, data ownership, integrity, traceability, and monitoring as well as the self-sovereign identity (SSI) paradigm, have been emerging to provide users with mechanisms that enable them to become anonymous, secure, and take control of their personal data during digital transactions.

- **Trustworthy 6G Communications:** 6G will fuse the digital and physical worlds for the purpose of sensing the real world and integrate far-reaching applications, ranging from autonomous systems to extended reality [2]. The opportunities for exploiting blockchain in 6G network infrastructures enhance the trustworthiness and performance gains of new services. For instance, blockchain can enable a trusted charging and billing without centralized intermediaries. In addition, blockchain helps establish trusted and decentralized service level agreement (SLA) management given that, similar to 5G, 6G builds on virtualized and sliced network architectures. However, these solutions still need to be implemented at an extremely large scale. As a result, 6G is expected to support a very wide range of use cases with diverse SLA guarantees that need to be managed in a trusted manner.

3.2.2 Blockchains and Robots

The authors of [22] observed that the ongoing deployment of 5G cellular systems is exposing their inherent limitations compared to the original premise of 5G as an enabler for the Internet of Everything (IoE). They argue that 6G should not only explore more spectrum at high-frequency bands but, more importantly, converge driving technological trends. Among others, they claim that there will be the following three driving applications behind 6G: (*i*) blockchain and distributed ledger technologies, (*ii*) connected robotics and autonomous systems, and (*iii*) wireless brain-computer interaction (a subclass of human-machine interaction). In fact, in 6G, there is a strong notion that the nature of mobile terminals will change, whereby intelligent mobile robots are anticipated to play a more important role [54]. More specifically, in [2], the authors argue that 6G services that could provide human users with good advice would certainly be appreciated. According to the world's first 6G white paper published by the 6Genesis Flagship Program (6GFP) in September 2019, 6G will become more human-centered than 5G, which primarily focused on industry verticals.

This brief review of the 6G vision shows that blockchain technologies and robots are anticipated to play a central role in future mobile networks, which will become more human-centered than previous generations of cellular networks. Advanced blockchain technologies such as oracles that enable the on-chaining of blockchain-external off-chain information stemming from human users hold promise to leverage also on human intelligence rather than machine learning only. Similarly, intelligent mobile robots interacting with human users appear a promising solution to not only give physical and/or emotional assistance, but also to nudge human behaviour by benefitting from persuasive robots.

3.3 Blockchain-Enabled Trust Game

In this section, we first identify open research challenges, then, we develop a blockchain-enabled implementation of the classical trust game using Ethereum and experimentally investigate the beneficial impact of a simple yet effective blockchain mechanism known as *deposit* on enhancing both trust and trustworthiness as well as increasing social efficiency.

3.3.1 Open Research Challenges

The use of decentralized blockchain technologies for the trust game should tackle the following research challenges:

- **Social Efficiency:** Recall from above that the trust game allows the study of social capital for achieving economic growth. Towards this end, the closely related term *social efficiency* plays an important role. Social efficiency is defined as the optimal distribution of resources in society, taking into account so-called externalities as well. In general, an externality is the cost or benefit that affects third parties other than the voluntary exchange between a pair of producer and consumer. We will study the impact of externalities below, when we extend the classical trust game to multiplayer games.

  We measure social efficiency as the ratio of the achieved total payoff of both trustor and trustee and the maximum achievable total payoff, which is equal to $X(K+1)$. A social efficiency of 100% is achieved if the trustor sends her/his full endowment X (i.e., $p=1$), which is then multiplied by K, and the trustee reciprocates by sending back the received amount XK fully or in part, translating into a total payoff of $q \cdot XK + (1-q) \cdot XK + X = X(K+1)$. Note that maximizing the total payoffs requires to set $p=1$ for a given value of K, though q may be set to any arbitrary value. The parameter q, however, plays an important role in controlling the (equal or unequal) distribution of the total payoffs between trustor and trustee, as discussed in more detail shortly. Conversely, if the trustor decides to send nothing (i.e., $p=0$) due to the lack of trust (on the trustor's side) and/or lack of trustworthiness (on the trustee's side), both are left with their endowment X and the social efficiency equals $2X/X(K+1) = 2/(K+1)$. How to improve social efficiency in an equitable fashion in a blockchain-enabled trust game is an important research challenge.

- **Trust and Trustworthiness in N-Player Trust Game:** In the past, games of trust have been limited to two players. In [65], the authors introduced a new N-player trust game that generalizes the concept of trust, which is normally modeled as a sequential two-player game to a population of multiple players that can play the game concurrently. According to [65], evolutionary game theory shows that a society with no untrustworthy individuals would yield maximum wealth to both the society as a whole and the individual in the long run. However, when the initial population consists of even the slightest number of untrustworthy individuals, the society converges to zero trustors. The proposed N-player trust game shows that the promotion of trust is an uneasy task, despite the fact that a combination of trustors and trustworthy trustees is the most rational and optimal social state.

  It's important to note that the N-player trust game in [65] was played in an unstructured environment, i.e., the population was not structured in any specific spatial topology or social network. In [66], the authors investigated whether a *networked* version of the N-player trust game would promote higher levels of trust and global net wealth (i.e., total payoffs) in the population than that of an unstructured population. To do so, players were mapped to a spatial network structure, which restricts their interactions and cooperation to local neighborhoods. Unlike [65], where the existence of a single untrustworthy individual would eliminate trust completely and lead to zero global net wealth, the authors of [66] discovered the importance of establishing network structures for promoting trust and global net wealth in the N-player trust game in that trust can be promoted despite a substantial number of untrustworthy individuals in the initial population. Clearly, the development of appropriate communication network solutions for achieving efficient cooperation and coordination among players with different strategies in a networked N-player trust game represents an interesting research challenge.

- **Reward & Penalty Mechanism Design:** For the implementation of desirable social goals, the theory of *mechanism design* plays an important role. According to [67], the theory of mechanism design can be thought of as the "engineering" side of economic theory. While the economic theorist wants to explain or forecast the social outcomes of mechanisms, the mechanism design theory reverses the direction of inquiry by identifying first the social goal and then asking whether or not an appropriate mechanism could be designed to attain that goal. And if the answer is yes, what form that mechanism might take, whereby a mechanism may be an institution, procedure, or game for determining desirable outcomes.

An interesting example of mechanism design is the so-called *altruistic punishment* to ensure human cooperation in multiplayer public goods games [68]. Altruistic punishment means that individuals punish others, even though the punishment is costly and yields no material gain. It was experimentally shown that altruistic punishment of defectors (i.e., untrustworthy participants) is a key motive for cooperation in that cooperation flourishes if altruistic punishment is possible, and breaks down if it is ruled out. The design of externalities such as third-party punishment and alternative reward mechanisms for incentivizing human cooperation in multiplayer public goods games in general and N-player trust game in particular is of great importance.

- **Decentralized Implementation of Economic Experiments:** A widely used experimental software for developing and conducting almost any kind of economic experiments, including the aforementioned public goods games and our considered trust game, is the *Zurich Toolbox for Ready-made Economics (z-Tree)* [69]. The z-Tree software is implemented as a client-server application with a central server application for the experimenter, called z-Tree, and a remote client application for the game participants, called z-Leaf. It is available free of charge and allows economic experiments to be conducted via the Internet. On the downside, however, z-Tree does not support peer-to-peer (P2P) communications between players, as opposed to a decentralized blockchain-enabled implementation.

3.3.2 Experimenter Smart Contract

First, we develop a smart contract that replaces the experimenter in the middle between trustor and trustee (see Fig. 3.1). The development process makes use of the Truffle framework[1], a decentralized application development framework. The resultant experimenter smart contract is written in the programming language Solidity. We then compile the experimenter smart contract into Ethereum EVM byte code. Once the experimenter smart contract is compiled, it generates the EVM byte code and Application Binary Interface (ABI). Next, we deploy the experimenter smart contract on Ethereum's official test network Ropsten. It can be invoked by using its address and ABI.

[1] `https://www.trufflesuite.com/`

More specifically, in our experimenter contract, we use the following global variables: (i) *msg.value*, which represents the transaction that is sent, and (ii) *msg.sender*, which represents the address of the player who has sent the transaction to the experimenter smart contract, i.e., trustor or trustee. Both trustor and trustee use their Ethereum Externally Owned Account (EOA), which uses public and private keys to interact and invoke each function of our experimenter smart contract. In the following, we provide a brief overview of the core functions and parameters of our experimenter smart contract:

- **Function investFraction():** This function allows the trustor to invest a portion p of her endowment X. Once called, it takes the received msg.value p from the trustor, multiplies it by factor K using the contract balance, and transfers it directly to the trustee's account. The trustee receives $msg.value \cdot K$.
- **Function splitFraction():** This function allows the trustee to split a portion q of the received investment from the trustor. Once called, it takes the set split amount from the trustee's account and sends it to the trustor's account.
- **Parameter Onlytrustor (modifier type):** This modifier is applied to the *investFraction()* function. Thus, only the trustor can invoke this function of the experimenter smart contract.
- **Parameter Onlytrustee (modifier type):** This modifier is applied to the *splitFraction()* function. Thus, only the trustee can invoke this function of the experimenter smart contract.

We note that after the execution of each function of the experimenter smart contract, an event is used to create notifications and saved logs. Events help trace and notify both players about the current state of the contract and activities.

3.3.3 Blockchain Mechanism Deposit

The use of one-way security deposits to provide trust for one party with respect to the other is quite common, particularly for the exchange of goods and services via e-commerce and crowdsourcing platforms. In the context of blockchains, a deposit is an agreement smart contract that defines the arrangement between parties, where one party deposits an asset with a third party. An interesting use case of the blockchain mechanism deposit can be found in [70]. In this paper, the authors propose a new protocol that achieves the fulfillment of all the desired properties of a registered electronic Delivery (e-Deliveries) service using blockchain. In the proposed protocol, the authors included a deposit mechanism with the aim to encourage the sender to avoid dishonest behavior and fraud attempts, and also to conclude the exchange in a predefined way following the phases of the protocol. The deposit will be returned to the sender if he finishes the exchange according to the protocol. In our work, we propose to add an optional function *deposit*() to our experimenter smart contract to improve trust and trustworthiness between both players. Towards this end, we make the following two modifications:

- **Function deposit():** This function allows the trustee to submit an amount of $2 \leq D \leq X$ monetary units (i.e., Ether in our considered case of Ethereum) as a deposit to the experimenter smart contract. The deposit is returned to the trustee only if a transaction with $q > 0$ is completed. Otherwise, with $q = 0$, the trustee loses the deposit. It should be noted that the aforementioned *Onlytrustee()* modifier is also applied to this function.
- **Function splitFraction():** We make a modification to this function to allow the trustee to split the received amount (i.e., $q > 0$). Otherwise, the transaction is rejected until the trustee splits the received amount. Once this happens, the function transfers the amount to the trustor's account and returns the deposit D to the trustee's account.

3.3.4 Experimental Setup

Next, we investigate the impact of the deposit as an effective pre-commitment mechanism on the trust game performance (i.e., social efficiency and normalized reciprocity) via Ethereum-based blockchain experiments. We set $K = 2$ in our experimenter smart contract and consider different deposit values of $D = \{0, 2, 5, X\}$ Ether, whereby $D = 0$ denotes the classical trust game without any deposit. The experiment was conducted with two graduate students from different universities. The rationale behind the selection of only two students is to first focus on the conventional trust game that by definition involves only two players. This allows us to be more certain that the effects of the deposit mechanism are real. In addition, conducting our experiment with the same two participating students allows us to better observe the behavior change during the rounds of the game. As for our inclusion criteria, we note that the students didn't know each other's identity, which was important to ensure anonymity between them. Further, the students hadn't conducted any behavioral research experiment before. Nor did either participant had any prior knowledge or experience with the trust game or any other investment game experiments. The two participating students were male and their age was 23 and 25 years, respectively.

At the beginning of the experiment, both trustor and trustee were given an endowment of $X = 10$ Ether. We ran the experiment four times, each time for a different value of D. Each of the four experiments took five rounds. We note that for the experiment with $D = 10$ Ether, the trustee put her full endowment X into the deposit, thus $D = X$ Ether. All experiments were run across the Internet. Both participants interacted with our experimenter smart contract using their Ethereum accounts. We note that both the trustor and the trustee need to pay a gas fee. Gas price refers to the pricing value, required to successfully conduct a transaction or execute a function in a smart contract on the Ethereum blockchain platform. Priced in small fractions of the cryptocurrency Ether, commonly referred to as Gwei. Each Gwei is equal to 0.000000001 ETH (10^{-9} Ether). Given its lowest cost, we considered transaction fees associated with deploying the smart contract and sending transactions negligible compared to the amounts invested and split.

3.3.5 Results

Fig. 3.2 depicts the average social efficiency and normalized reciprocity (both given in percent) vs. deposit $D = \{0, 2, 5, X\}$ (given in Ether). We define normalized reciprocity as the ratio of q/p as a measure of the trustee's reciprocity, q, in response to the trustor's generosity, p. Note that the normalized reciprocity is useful to gauge the fair distribution of total payoffs from trustee to trustor, and vice versa, for a given achievable social efficiency. Note that Fig. 3.2 also shows the interval between minimum and maximum measured score for each value of D.

We make the following interesting observations from Fig. 3.2. First, the social efficiency continually grows for an increasing deposit D until it reaches the maximum of 100% for $D = X$. Thus, the social efficiency performance of the classical trust game can be maximized by applying the blockchain chain mechanism of deposit properly with $D = X$. This is due to the fact that the trustor sends her full endowment (i.e., $p = 1$) after the trustee has put in her maximum deposit. In doing so, a maximum total payoff of 30 Ether is achieved, translating into a social efficiency of 100%. It is worthwhile to mention that this was the case in all five rounds of the experiment. Second, the average normalized reciprocity improves significantly for increasing deposit D compared

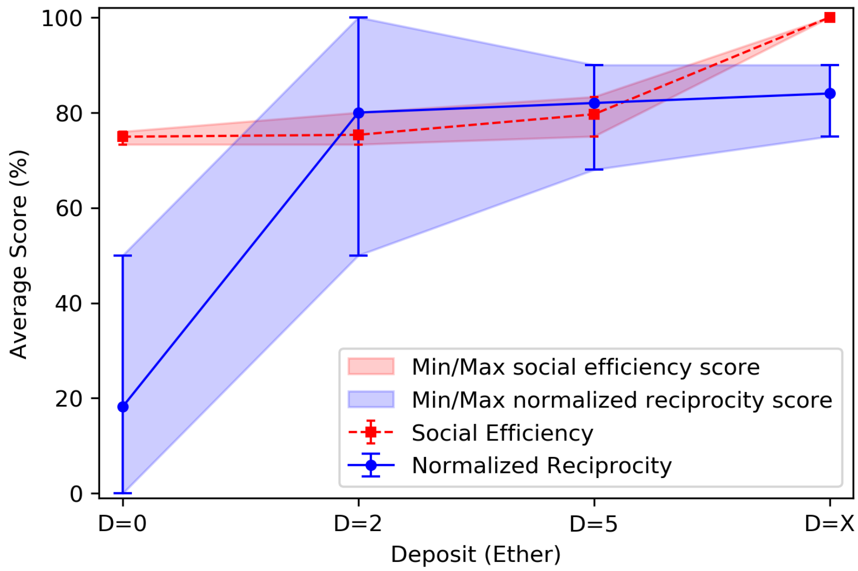


Figure 3.2: Average social efficiency and normalized reciprocity q/p vs. deposit $D = \{0, 2, 5, X\}$ Ether using experimenter smart contract with $K = 2$ and $X = 10$ (shown with minimum-to-maximum measured score intervals).

to the classical trust game without any deposit ($D = 0$). Specifically, in the classical trust game, the average normalized reciprocity is as low as 18%. By contrast, for a deposit of as little as $D = 2$ Ether, the average normalized reciprocity rises to 80%. Interestingly, further increasing D does not lead to sizeable additional increases, e.g., average normalized reciprocity equals 83% for $D = X$. Hence, the amount of the deposit does not change the normalized reciprocity significantly with $q/p \approx 80\%$ for $D > 0$. Finally, Fig. 3.2 illustrates that for an increasing deposit D, the behaviour of the two players become more consistent, as indicated by the decreasing intervals of minimum to maximum measured scores.

In the subsequent section, we extend the classical two-player trust game to a networked N-player trust game and study how advanced blockchain technologies, most notably on-chaining oracles, drive the behaviour of players by means of different reward and penalty mechanisms. Among others, we seek to understand whether an increased normalized reciprocity is achievable without sacrificing social efficiency.

3.4 On-Chaining Oracle for Networked N-Player Trust Game

3.4.1 Architecture of Oracle

Fig. 3.3 depicts the architecture of our proposed on-chaining oracle for the networked N-player trust game. The proposed architecture comprises a set of clusters or pools. Each cluster contains three types of agent: (*i*) trustors, (*ii*) trustees, and (*iii*) observers. The difference between observers and players (trustors/trustees) is that observers don't play, but track and evaluate trust and trustworthiness criteria such as investment (p) and split (q). Players interact with the experimenter smart contract using their public-private keys through a DApp. The different rounds of the game are monitored remotely by the observers using *Etherscan*[2], an Ethereum blockchain explorer that uses the experimenter contract address and shows the different transactions between each pair of trustor and trustee in real-time. We note that alternatively one may use *Alethio*[3], a monitoring tool that allows observers to send and receive alerts to and from any on-chain address, activity, or function.

The design of a third-party punishment and reward mechanism for incentivizing player cooperation in our networked N-player trust game is based on crowdsourcing. Specifically, observers provide their collective human intelligence to the nudge contract in order to punish a cluster or an individual player, who demonstrates inappropriate behaviour, or provide a positive reward for good behaviour. The nudge contract manages the reward-penalty mechanism in the form of loyalty points. A trustor can earn loyalty points for a honest transaction, investment, and engagement in the game and redeem earned points for rewards. Similarly, the trustee is rewarded for generous reciprocity. Loyalty points keep the players engaged and aware of the overall goals, i.e., increase of total payoff, social efficiency, and normalized reciprocity. In addition, the players have a score profile associated with their public key, whereby players earn 1 point for every honest action and loose 1 point if their action is dishonest. The scoring profile is managed by the nudge contract. Trustor and trustee can check the status of their loyalty reward points by calling the function *getTrustorLoyalty*() and *getTrusteeLoyalty*(), respectively. Furthermore, an incentive strategy was designed to incorporate principles of behavioural psychology using economic outcomes to render the system more effective in changing the players' behaviour. Players earn a monetary reward in the form of Ether after reaching a certain number of loyalty reward points in the game, e.g., 10 points

[2] `https://etherscan.io`
[3] `https://reports.aleth.io/`

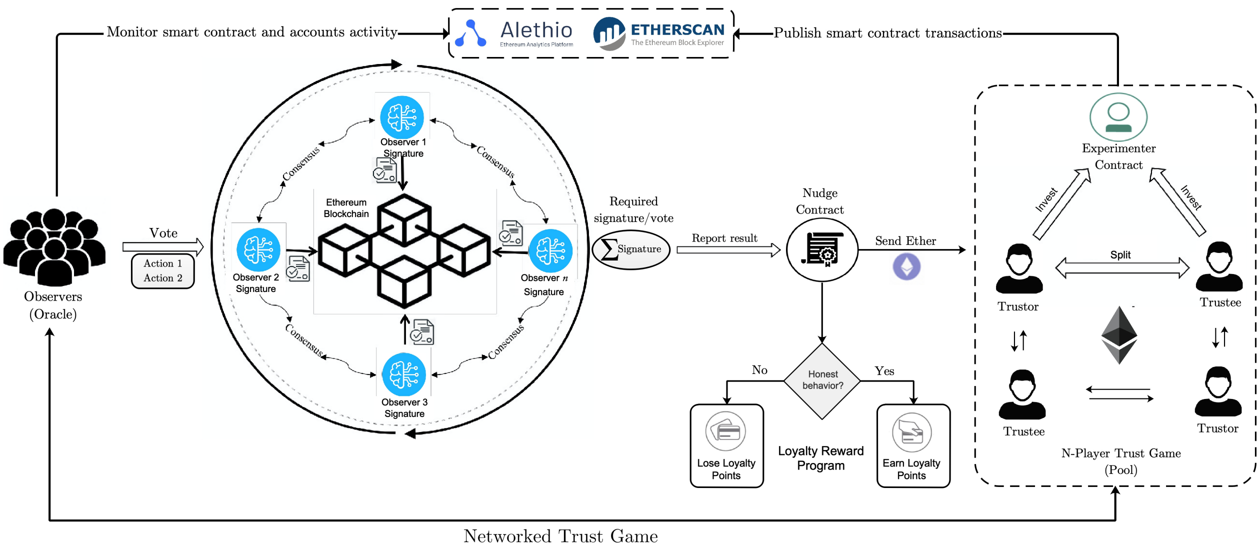


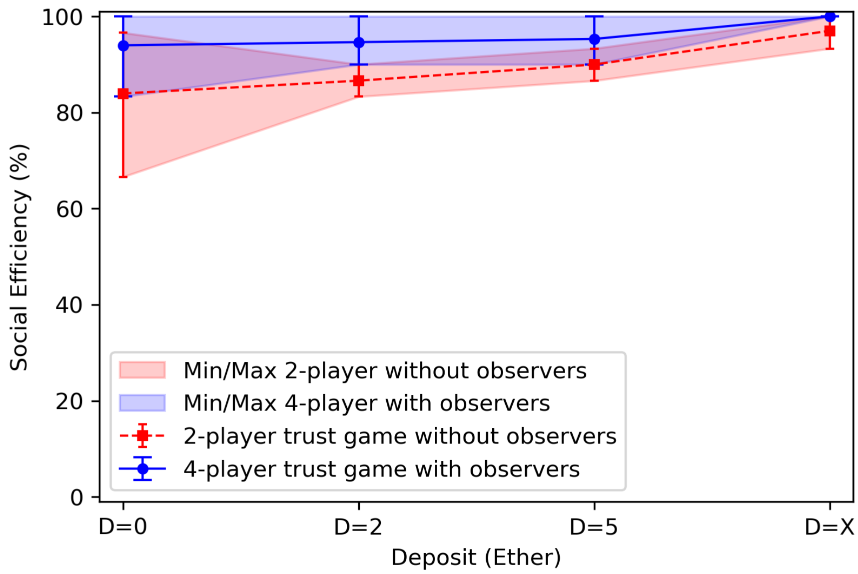
Figure 3.3: Architecture of on-chaining oracle for networked N-player trust game.

= 1 Ether. The Ethers earned are added to the player's endowment X, which will be used for the investment and payoff in future rounds of the game. We note that there are more advanced schemes to compute score/reputation of users, e.g., [71, 72].

3.4.2 On-Chaining of Voting-based Decisions

In our oracle implementation, we assigned predetermined public keys to both players and observers. The creation of each key pair can be accomplished by using several options, including Ethereum wallets and online/offline Ethereum address generators, e.g., Vanity-ETH [4]. All public keys are declared in the nudge contract, whose purpose is to allow only registered observers to vote while automatically rejecting malicious voters. To facilitate the formation of a majority, the number of possible voting options is restricted to the four following functions on the nudge contract: *VOTE_RewardTrustor*, *VOTE_RewardTrustee*, *VOTE_PunishTrustor*, and *VOTE_PunishTrustee*. Recall that a function is a code that resides at a specific smart contract address on the Ethereum blockchain. Further, to ensure a trustworthy on-chaining decision, a k-out-of-M threshold signature is used to reach a consensus on the function to be executed. A k-out-of-M threshold signature scheme is a protocol that allows any subset of k players out of M players to generate a signature, and disallows the creation of a valid signature if fewer than k players should participate. The right decision is determined as

[4] `https://vanity-eth.tk/`



t]

Figure 3.4: Average social efficiency vs. deposit $D = \{0, 2, 5, X\}$ Ether for 2-player trust game without observers and 4-player trust game with observers (shown with minimum-to-maximum measured score intervals).

the one that has received the desired number of votes. Once the function is executed, the nudge contract allocates the reward or punishment loyalty points to each player who behaved in a trusted or untrusted way, respectively.

3.4.3 Results

We compare the performance of our proposed on-chaining oracle for the multiplayer N-player trust game with the conventional two-player baseline experiment. Towards this end, we invited the same two students, who have played the classical two-player trust game before, and asked them to play the game again, i.e., without any observers. Next, we invited them to play the game in the presence of two observers. The two players were informed that their account is associated with loyalty reward points, which will be increased if they act honestly. Otherwise, they will be punished and loose 1 loyalty point. Both players were aware that they will be rewarded with 1 Ether for each 10 accumulated loyalty reward points. In addition, they are notified that the decision will be made by two observers, who will monitor their online transactions in order to make their independent reward/penalty decisions. All four participants interact anonymously via the Internet.

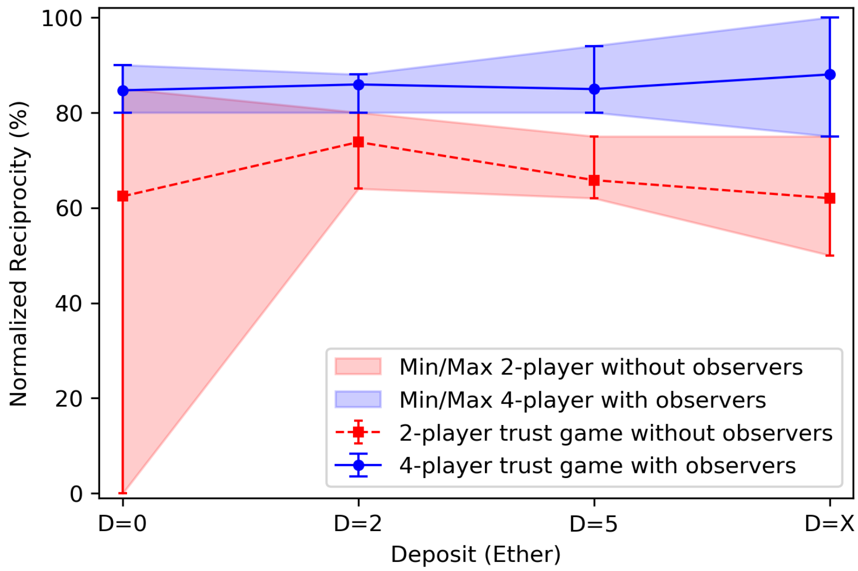


Figure 3.5: Average normalized reciprocity q/p vs. deposit $D = \{0, 2, 5, X\}$ Ether for 2-player trust game without observers and 4-player trust game with observers (shown with minimum-to-maximum measured score intervals).

Fig. 3.4 compares the average social efficiency of the two-player trust game without observers with that of the four-player trust game with observers. The figure clearly demonstrates the beneficial impact of the presence of observers on social efficiency for all values of D. Note that with observers the instantaneous social efficiency reaches the maximum of 100% for all values of D, as opposed to the two-player trust game where this occurs requiring the full deposit of $D = X$ Ether. As for the normalized reciprocity achievable with and without observers things are similar, as shown in Fig. 3.5. However, while the presence of observers helps raise the average (and instantaneous) normalized reciprocity consistently above 80% (compared to below 80% in Fig. 3.2), there still remains room for further improvement, especially for $0 \leq D < X$.

3.5 Robonomics: Playing the N-Player Trust Game with Persuasive Robots

3.5.1 Robonomics: Key Principles

Many studies have shown that the physical presence of robots benefits a variety of social interaction elements such as persuasion, likeability, and trustworthiness. Thus, leveraging these beneficial characteristics of social robots represents a promising solution towards enhancing the performance of the trust game. Social robots connected with human operators form a physical embodiment that creates the new paradigm of an immersive coexistence between humans and robots, whereby persuasive robots aim at changing the behaviour of users through social influence. Importantly, these robots are less like tools and more like partners, whose persuasive role in a social environment is mainly human-centric [73].

Recently, in [74], an experimental pilot study with 5 participants adapted the trust game from its original human-human context to a social human-robot interaction (sHRI) setting using a humanoid robot operated in a *Wizard-of-Oz (WoZ)* manner, where a person controls the robot remotely. The obtained findings suggest that people playing the sHRI trust game follow a human-robot trust model that is quite similar to the human-human trust model. However, due to the lack of common *social cues* present in humans (e.g., facial expressions or gestures) that generally influence the initial assessment of trustworthiness, almost all participants started investing a lower amount and increased it after actively exploring the robot's behaviour and trustworthiness through social experience.

In the following, we focus on the emerging field of *robonomics*, which studies the sociotechnical impact of blockchain technologies on sHRI, behavioral economics, behavioral game theory, and cryptocurrencies (both coins and tokens) for the social integration of robots into human society [75]. Robonomics involves persuasive robotics, whereby a physical or virtual robotic agent is used as enforcer or supervisor of human behavior modification via psychological rewards in addition to tangible rewards. In a recent exploratory sHRI study [76], ten multimodal *persuasive strategies* were compared with regard to their effectiveness of social robots attempting to influence human behavior. It was experimentally shown that two particular persuasive strategies—affective and logical strategies—achieved the highest persuasiveness and trustworthiness.

3.5.2 Persuasive Robotics Strategies

Similar to [77], we developed a *Crowd-of-Oz (CoZ)* platform for letting observers remotely control the gestures of Softbank's social robot Pepper placed in front of the trustee and have a real-time dialogue via web-based text-to-speech translation. The CoZ user interface is built using a Django[5] web server. The trustee can communicate with Pepper through voice and Pepper's tactile tablet. To support voice communication, we implemented a web-based speech-to-text tool. When text is extracted from voice, the trustee can see his/her message on Pepper's tablet in order to verify it. Next, the speech-to-text function calls another function to add additional fields to the main message (extracted text), including *sequence_ID*, *sender_ID*, *message_type*, and *time* to make the message distinguishable on the Django server. The called function executes a marshaling process and sends the message to the Django server through the OOCSI middleware[6]. The OOCSI middleware is a message-based connectivity layer and is platform-independent inspired by the concept of RPC (Remote Procedure Call) for connecting web clients.

In our developed CoZ system, there are two types of message: information and control. The information messages are created by the observers. This type of message is multicast to all observers and the trustee through Pepper to update them, but not the trustor. The trustee can see all the information messages on Pepper's tablet. Moreover, Pepper uses a text-to-speech function to transfer the observers' messages to the trustee. The control messages are used for important functionalities of the CoZ architecture, e.g., performing a gesture on Pepper. When an observer presses a social cue button, the CoZ web-interface invokes a JavaScript method to call a new event on the Django server. The invoked method sets all the related joints' angles plus the Light-Emitting Diode (LED) colors of Pepper's eyes. Given that two or more observers may press the same or different social cue buttons simultaneously, the Django server implemented a queue to synchronize all issued commands. While Pepper is performing a gesture, the Django server puts the next gesture in the queue and sends it to Pepper back-to-back.

Further, our CoZ user interface provides a section, where an observer can watch the trustee's environment through Pepper's eyes. To implement this part, we used OpenCV[7], Flask[8], and CV2[9]

[5] `https://www.djangoproject.com/`
[6] `https://oocsi.id.tue.nl/`
[7] `https://opencv.org/`
[8] `https://flask.palletsprojects.com/en/2.0.x/`
[9] `https://pypi.org/project/opencv-python/`

tools. The Django server invokes a method on Pepper called "ALVideoDevice" to start recording videos. Next, the Flask server stores the sequence of produced videos with a valid Uniform Resource Locator (URL). To make live video streams accessible over the Internet we used Virtual Private Network (VPN). Moreover, in our CoZ interface, we used an IFrame (Inline Frame) tag to demonstrate live video streaming using the valid URL. An IFrame is an HyperText Markup Language (HTML) document embedded inside another HTML document on a website. The IFrame HTML element is often used to insert content from another source, such as a camera, into a Web page. In our CoZ user interface, we also realized four buttons to turn Pepper's head to left, right, up, and down. When an observer presses one of these buttons, the CoZ interface invoke a method to create a control message, marshaling process, and send it to the Django server. Upon reception, the Django server performs unmarshaling to extract the main message and then invokes the "ALMotion" along with initializing some parameters like speed, angle, and joint name. For each invocation, Pepper turns her head by ten degrees.

The user CoZ inteface also displays nine social cue buttons to prevent possible typos and save time for observers to fill communication gaps. The nine social cue buttons were as follows: "Gain time", "Tell me about it", "Good job", "Hi", "Bye", "Open arms", "Taunting hands", "No", and "Ask for attention". Observers may press to perform different gestures of Pepper during conversation and thereby influence the trustee's behavior. In addition, we drafted two scripts, one for a logical persuasive strategy appealing to the left side of the brain (i.e., logics) and another one for an affective persuasive strategy appealing to the right side of the brain (i.e., emotions) of the trustee. Each script contains pre-specified sentences stored in pull-down menus in the CoZ interface, from which observers may choose in order to nudge the trustee's behavior toward reciprocity via real-time text-to-speech messages. The different persuasive robot strategies operate as follows:

- **Logical Strategy**: Contains a set of reward and punishment mechanisms. In addition, Pepper performs some economical and technical advice via text-to-speech through the above described CoZ platform.

- **Affective Strategy**: Contains a set of reward/punishment mechanisms and Pepper uses text-to-speech encouragement messages through the CoZ platform. In addition, Pepper shows social cues by means of gestures and embodied communications toward the trustee.

Table 3.1: Social Cues used by Pepper in Mixed Persuasive Strategy

Round number	Trusted behavior action	Untrusted behavior action
Round 1	*Text-to-speech:* Trust Game is a cooperative investment game. You all play together to get the best total payoff!	Untrusted behavior will be shown in Round 2
Round 2	*Text-to-speech:* Awesome! That's a split worth celebrating! *Embodied communication:* Open arm gesture.	*Text-to-speech:* If this behavior is repeated, you will receive a punishment from the observers. *Embodied communication:* Taunting hand gesture.
Round 3	*Text-to-speech:* If this good behavior is repeated, your partner will invest more in the next round. *Embodied communication:* Open arm gesture.	*Text-to-speech:* Weak reciprocity can cause costly punishment for you. *Embodied communication:* Taunting hand gesture.
Round 4	*Text-to-speech:* Incredible! Your partner must be impressed! *Embodied communication:* Open arm gesture.	*Text-to-speech:* With such a behavior, the punishment will be executed next round. *Embodied communication:* Taunting hand gesture.
Round 5	*Text-to-speech:* Congrats! Your good behavior toward your partner has provided you with an incremental total payoff over all rounds of the game. *Embodied communication:* Open arm gesture.	*Text-to-speech:* Your bad behavior translated into a very weak total payoff. *Embodied communication:* Taunting hand gesture.

- **Mixed Strategy**: Combines the above logical and affective strategies into one mixed strategy. It contains a set of reward/punishment mechanisms and Pepper provides not only economical and technical advice but also encouragement via text-to-speech messages through the CoZ platform. In addition, Pepper shows social cues by means of gestures and embodied communications toward the trustee.

For illustration, Table 3.1 lists the social cues used by Pepper in our proposed mixed logical-affective persuasive strategy. In this strategy, one observer plays the logical strategy and the other observer plays the affective strategy such that the trustee receives mixed messages and mixed embodied communications. Depending on the trustee's behavior, the observers carry out the "Trusted behavior action" or the "Untrusted behavior action" in each round of the experiment. The social cues in Table 3.1 enable the observers to control Pepper's text-to-speech and embodied communications using our developed CoZ platform.

3.5.3 Experimental Setup

We ran large-scale experiments involving 20 students to measure the effectiveness of our developed persuasive robotics strategies (i.e., logical, affective, and mixed strategies). Similar to our last experiment in the two players' trust game, the participating students didn't know each other's identity. Also, students hadn't conducted any behavioral research experiment before. The age of the selected students was between 24 and 32 years. Three students were female and seventeen students were male. The experiment was divided into four trials: baseline, logical, affective, and mixed strategy. Each trial involved 5 rounds. We first conducted a baseline trust-game experiment, where trustees didn't interact with Pepper, as done previously, followed by experiments exposing

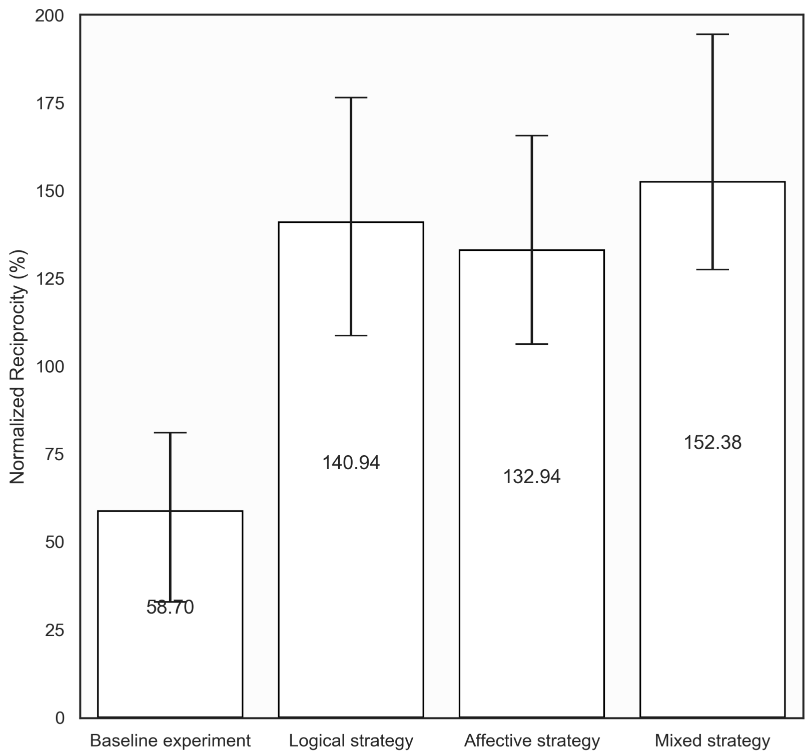


Figure 3.6: Average normalized reciprocity q/p without (baseline experiment) and with using logical, affective, and mixed logical-affective persuasive strategies for $D = 0$ (shown with minimum-to-maximum measured score intervals).

trustees to Pepper's logical, affective, and mixed logical-affective persuasive strategies. Both trustor and trustee interacted via a blockchain account with the experimenter's smart contract. The trustor played the game from a separate room, while the trustee was in the lab alone with Pepper. Pepper was controlled via our CoZ platform remotely by the observer. We used the same parameter settings, i.e., endowment $X = 10$ Ether for the trustor and $K = 2$. Further, in all persuasive strategies, we didn't use any deposit mechanism (i.e., $D = 0$).

3.5.4 Results

Fig. 3.6 demonstrates the superior effectiveness of our persuasive strategies, especially mixed ones appealing to both sides of the brain, resulting in average normalized reciprocity well above 100%. In all the experiment steps, all the players were fully aware of all the rules mentioned in the smart contract. Further, to better reveal the differences among the persuasive strategies, we have calculated the measurement range for the four strategies. The measurement range for the baseline experiment is 48.2 (Max=81, Min=32.8), while for the logical strategy it is 67.8 (Max=176.4, Min=108.6), for the affective strategy it is 59.4 (Max=165.6, Min=106.2), and the mixed strategy it is 67 (Max=194.4, Min=127.4). As the results show, the baseline experiment has the smallest measurement range. Next, we computed the standard deviation for the baseline experiment as well as logical, affective, and mixed strategies, which is equal to 15.6, 21.75, 21.10, and 22.73, respectively. The results show that the baseline experiment has the smallest standard deviation among all considered strategies, while the mixed strategy has the largest one. Finally, we have computed the variance for the persuasive strategies under consideration. The calculated variance equals 245.83, 473.17, 445.25, and 517.03 for the baseline, logical, affective, and mixed strategy, respectively. Based on the gathered results, we observe that the baseline experiment has the smallest and the mixed strategy has the largest variance.

3.6 Conclusions

Robonomics is a recently emerging sociotechnical field of interdisciplinary research that integrates behavioral economics with advanced blockchain technologies and persuasive robotics. Given its prominent role in behavioral economics and the relevance of trust in blockchains, we focused on the trust game, including its networked multiplayer extension. We experimentally demonstrated the beneficial impact of the blockchain mechanisms deposit and on-chaining oracle on improving both social efficiency and reciprocity significantly. Our experimental results show that the presence of third parties such as human observers and in particular social robots play an important role in a blockchain-enabled trust game. While the trust game's central experimenter may be easily replaced with our presented experimenter smart contract, the peer pressure executed by on-chaining oracles and especially the embodied communications enabled by persuasive robots were shown to have a potentially greater social impact than monetary incentives such as deposit, opening up new research avenues for future work.

Chapter 4

The Metaverse and Beyond: Implementing Advanced Multiverse Realms With Smart Wearables

This chapter contains material extracted from the following publication:

- S. Rostami and M. Maier, The Metaverse and Beyond: Implementing Advanced Multiverse Realms With Smart Wearables, *IEEE Access*, vol. 10, pp. 110796-110806, Oct. 2022.

In the following, my key contributions to the publication mentioned above are explained in greater detail: (1) I largely contributed to writing the whole manuscript, (2) I proposed the idea of layered experimental set-up for realizing the Multiverse realms via integrated state-of-the-art VR/AR HMDs, Amazon MTurk, and CoZ platform demonstrated in Fig. 4.2, (3) I identified the challenges of integrating smart HMDs, avatar, AI algorithms, and robots for realizing all the Multiverse realms in Section 4.4, (4) I proposed the idea of the multi-player version of the maze game using MTurk workers and CoZ in Section 4.5 (5) I developed and implemented the proposed experimental set-up using Pepper robot and A* algorithm for the baseline scenario in Section 4.5.1, (6) I conducted all the experimental works, and (7) I obtained and analyzed all the results demonstrated in Figs. 4.3, 4.4, and table 4.1.

4.1 Introduction

In the last chapter, we explained the emerging field of robonomics, which studies the sociotechnical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society in the context of the Trust game. In this chapter, we gamify and implement all eight Multiverse realms, the anticipated successor of the *Metaverse*, using Oculus Quest 2[1], Microsoft HoloLens 2[2], SoftBank Mobile's Pepper robot, and Pepper's virtual avatar in the context of origami and maze games. With the mass digital adoption of remote work and online social activities accelerated by a global pandemic, we may finally find ourselves on the verge of something big and potentially paradigm-shifting: The Metaverse, the next step after the Internet, similar to how the mobile Internet expanded and enhanced the early Internet in the 1990s and 2000s[78].

Unlike earlier Metaverse approaches, e.g., Linden Lab's Second Life, the current Metaverse, most notably Facebook's recent announcement on October 28 2021, is based on the social value of Generation Z that online and offline selves are not different [38]. The younger generation considers the social meaning of the virtual world as important as that of the real world, since they think that their identity in virtual space and reality is the same. Metaverse applications are mostly aimed at *games* as well as research and marketing simulations, and some office applications. At present, games (e.g., Fortnite and Roblox) are the most common platforms in the popularization of the Metaverse, including so-called serious games. *Extended reality (XR)* is the medium that connects avatars in the Metaverse and users in the real world. According to [38], the Metaverse will utilize the following hardware and software components: Hand- and non-handbased input devices, scene/object/sound/speech recognition and synthesis, motion rendering, and last but not least *head-mounted devices (HMDs)*.

The authors of [79], one of the most recent books on the Metaverse, consolidated various perspectives to give the following central definition of the Metaverse: "The Metaverse represents the top-level hierarchy of persistent virtual spaces that may also interpolate in real life, so that social, commercial, and personal experiences emerge through Web 3.0 technologies." According to [79], the Metaverse isn't meant to exist in a vacuum. Whether through virtual reality (VR), augmented

[1] `https://store.facebook.com/ca/quest/products/quest-2/?utm_source=www.google.com&utm_medium=oculusredirect`

[2] `https://www.microsoft.com/en-us/hololens/hardware`

reality (AR), or a smartphone, the Metaverse and the experiences inside it can connect to the real world. Importantly, in addition to incentivizing transactions, the Metaverse should provide what the authors call *gamified experiences*, given that gamification [80] will encompass the activity and story around emerging Web 3.0 non-fungible tokens (NFTs).

According to [81], the Metaverse will be the precursor of the so-called Multiverse. The Metaverse and Multiverse have in common that they aim at realizing the fusion of digital and real worlds, which is the driving theme for the Network 2030 vision of ITU-T Focus Group Network 2030 (FG-NET-2030)[82]. However, while the Metaverse primarily focuses on VR and AR, the Multiverse offers eight different types of advanced XR experience realms, including but not limited to VR and AR, as illustrated in Fig. 3.1 and explained in more detail shortly. With the rise of the Metaverse, the Internet will no longer be at arm's length. Instead, it will surround us and will be a network of interconnected experiences and devices far beyond mere VR. The Metaverse will be about being inside the Internet rather than simply looking at it from a phone or computer screen.

This chapter builds on our recent work on the so-called Internet of No Things for the *6G post-smartphone era*, where smart wearables such as VR/AR HMDs are increasingly replacing the functionalities of smartphones [47, 83] . Our novel contributions are threefold: (i) we first extend Metaverse's primary focus on VR/AR to Multiverse's advanced XR realms of experience. Next, we gamify and implement all eight Multiverse realms of experience using Oculus Quest 2 and Microsoft HoloLens 2 as state-of-the-art VR/AR HMDs. More specifically, we experimentally investigate the (ii) single-player offline Multiverse implementation playing an origami game and (iii) multi-player online Multiverse implementation playing a networked maze game across our proposed integrated VR/AR HMD and Amazon Mechanical Turk *crowd-of-Oz (CoZ)* platform [77], which enables the crowdsourcing based remote control of SoftBank Mobile's *Pepper*, a state-of-the-art social humanoid robot, as well as its virtual avatar, and compare their performance in terms of task completion time and failure/success rate as our metrics of interest.

The remainder of the chapter is structured as follows. In Section 4.2, we first provide a comprehensive description of the current Metaverse vision(s). In Section 4.3, we describe the eight different Multiverse realms of experience in technically greater detail. In Section 4.4, we describe the single-player offline implementation of the Multiverse realms of experience for playing an origami game with Quest 2 and HoloLens 2, followed by the description of the multiplayer online implementation for playing a networked maze game (beside the origami game) across our proposed integrated VR/AR HMD and Amazon Mechanical Turk (MTurk) CoZ platform in Section 4.5. Section 4.6 presents the comparison of our obtained experimental results. Finally, Section 4.7 concludes the chapter.

4.2 Current Metaverse Vision(s)

In his long anticipated and recently published book “The Metaverse: And How It Will Revolutionize Everything,” Canadian writer Matthew Ball argues that one of the most exciting aspects of the Metaverse is how poorly understood it is today [33]. Ball observes that for all the fascination with the Metaverse, the term has no consensus definition or consistent description. Most industry leaders define it in the manner that fits their own worldviews and/or the capabilities of their companies. For instance, Microsoft’s CEO Satya Nadella has described the Metaverse as a platform that turns the entire world into an app canvas which could be augmented by cloud software and machine learning. No surprise, Microsoft already had a technology stack which was a natural fit for the not-quite-here Metaverse and spanned the company’s operating system Windows, cloud computing offering Azure, communications platform Microsoft Teams, augmented reality headset HoloLens, gaming platform Xbox, professional network LinkedIn, and Microsoft’s own Metaverses including Minecraft, Microsoft Flight Simulator, and even the space-faring first-person shooter Halo. Conversely, Mark Zuckerberg’s articulation focused on immersive virtual reality as well as social experiences that connect individuals who live far apart. Notably, Facebook’s Oculus division is the market leader in VR in both unit sales and investment, while its social network is the largest and most used globally. Furthermore, the Washington Post characterized Epic’s vision of the Metaverse as an expansive, digitized communal space where users can mingle freely with brands and one another in ways that permit self-expression and spark joy, a kind of online playground where users could join friends to play a multiplayer game like Epic’s Fortnite one moment, watch a movie via Netflix the next and bring their friends to test drive a new car that’s crafted exactly the same in the real world as it would be in this virtual one. It would not be the manicured, ad-laden news feed presented by platforms like Facebook. Facebook hasn’t said whether or not the Metaverse can be privately operated, but the company does say that there can be only one Metaverse - just as there is “the Internet,” not “an Internet” or “the Internets.” In contrast, Microsoft and Roblox talk about “Metaverses.”

According to Ball, the Metaverse is still only a theory. It is an intangible idea, not a touchable product. As a result, it's difficult to falsify any specific claim, and inevitable that the Metaverse is understood within the context of a given company's own capabilities and preferences. However, he notes that the sheer number of companies which see potential value in the Metaverse speaks to the size and diversity of the opportunity for widespread disruption. Far from disproving it, confusion and uncertainty are features of disruption. While there are competing definitions and a great deal of confusion, Ball believes that it is possible to offer a clear, comprehensive, and useful definition of the term, even at this early point in the history of the Metaverse. Ball provides the following useful working definition of the Metaverse:

> A massively scaled and interoperable network of real-time rendered 3D virtual worlds that can be experienced synchronously and persistently by an effectively unlimited number of users with an individual sense of presence, and with continuity of data, such as identity, history, entitlements, objects, communications, and payments.

Simply put, according to [33], the Metaverse is envisioned as a parallel plane for human leisure, labor, and existence more broadly. So it should come as no surprise that the extent to which the Metaverse succeeds will depend, in part, on whether it has a thriving economy. Towards this end, payment rails are an important requirement to achieve a flourishing and fully realized Metaverse. Ball argues that's why so many Metaverse-focused founders, investors, and analysts see blockchains and cryptocurrencies as the first digitally native payment rail and the solution to the problems plaguing the current virtual economy. Ball argues that what matters is that blockchains are programmable payment rails. That is why many position them as the first digitally native payment rails, while contending PayPal, Venmo, WeChat, and others are little more than facsimiles of legacy ones.

According to Ball, ultimately, the Metaverse will be ushered in through *experiences*. Millions if not billions of users and dollars will be drawn to the new experiences and transformations that result. He argues that the very idea of the Metaverse means that more of our lives, labor, leisure, time, spending, wealth, happiness, and relationships will go online. Actually, they will exist online, rather than just be put online like a Facebook post or Instagram upload. Ball advocates that shifting any of the time passively consumed thru today's lean-back entertainment to *social, interactive, and more engaged entertainment* is likely a positive outcome, not a negative one. Hence, the

Multiverse with its eight different types of advanced XR experience realms, including but not limited to conventional VR and AR, appears to be predestined to help usher in the Metaverse via novel experiences and the advanced social and interactive user engagement that results from them. Given its apparent importance to the emerging Metaverse, we provide a comprehensive investigation of all the Multiverse realms of experience in the remainder of this paper. To our best knowledge, this is the first time such a comprehensive study of the Multiverse realms of experience is conducted.

4.3 The Multiverse Realms of Experience

In chapter 2 we introduced the Multiverse as an architecture for the design of advanced XR experiences[56]. As shown in Fig. 2.1, the Multiverse consists of three pairs of variables, each with two opposite physical/ digital dimensions Space/No-Space, Time/No-Time, and Matter/No-Matter, which give rise to a total of eight realms, each offering a different type of reality. It encompasses the multiple ways for *when* [Time $\leftrightarrow$ No-Time] experiences happen, *where* [Space $\leftrightarrow$ No-Space] they occur, and what [Matter $\leftrightarrow$ No-Matter] they act on. Each combination of the six variables yields a distinct realm, spanning the entire reality-virtuality continuum. In the following, we describe each realm in greater detail:

- **Reality:** The realm Reality consists of the variables Time/Space/Matter. An equivalent way of looking at it is Actual/Real/Atoms, see Fig. 2.1.We experience Reality as the realm of physical experiences through the age-old medium of *real life*. It is of course the realm with which we are most familiar.

- **Virtuality:** Virtuality lies exactly opposite Reality in the realm of No-Time/No-Space/No-Matter, consisting of Autonomous/Virtual/Bits. Virtuality is not subject to the physical laws of the real world. Virtuality together with Reality anchor the Multiverse. The name of each of the other realms relates directly to the two anchors in that the names of each realm on the right half of Fig. 2.1 denote their Reality-based nature, whereas the names of each realm on the left half of the Multiverse denote their Virtuality-based nature. These six other realms enhance, extend, or amend either our Reality- or Virtuality-based experiences. Therefore, they hold out greater possibility for value creation. A prime example of VR HMD is *Oculus Quest 2*.

- **Augmented Reality:** Of these, surely the most familiar is AR, characterized by the variables Time/Space/No-Matter. In the realm AR, digital technology is employed to enhance our experience of the physical world. The flagship AR HMD is *Microsoft HoloLens 2*.
- **Augmented Virtuality:** If bits can augment Reality, then logically atoms should be able to augment Virtuality. This is exactly what happens in the opposite realm of Augmented Virtuality (AV) characterized by the variables No-Time/No-Space/Matter, which is widely used for realizing digital twins. AV effectively flips a Virtuality experience from No-Matter to Matter, from Bits to Atoms. That means we're taking something material and tactile and using it to augment an otherwise virtual offering, resulting in an Autonomous/Virtual/Atoms experience. A popular example is *Nintendo's Wii*, where, for the first time, players at home could get physically, materially engaged in computer games, removing the experience from one residing primarily between the fingers and the brain to one involving the whole body.
- **Alternate Reality:** The shift from actual to autonomous events distinguishes Alternate Reality from the adjacent realm of the aforementioned AR, which both share the variables of digital substance and physical place. That means that if you can take the technology used to augment reality and then add a dimension of playing with time in some way, you can use that very same technology to alter people's view of the reality before them. Alternate Reality comprises the variables No-Time/Space/No-Matter. Its essence lies in constructing a digital experience and superimposing it onto a real place to create an alternate view of the physical reality. Alternate Reality derives its name from *alternate reality games (ARGs)* [84]. Such games have become increasingly popular in marketing circles as platforms for reaching the online gaming crowd.
- **Physical Virtuality:** Where Alternate Reality takes an otherwise virtual experience and plays it out in the real world, its opposite, Physical Virtuality, takes realworld objects (Atoms residing in Actual Time) and designs them virtually. Such a Time/No-Space/Matter experience occurs when virtually designed artifacts take material shape. *3D printing* perhaps best captures the Actual/Virtual/Atoms nature of Physical Virtuality. Here, as another example, we can propose wearable haptic sleeves encompassing human arm, wrist, and elbow joints to send feedback from the virtual environment to the real environment.
- **Warped Reality:** The last realm on the Real side of the Space dimension, Warped Reality, consists of the variables No-Time/Space/Matter. As opposed to Augmented and Alternate Re-

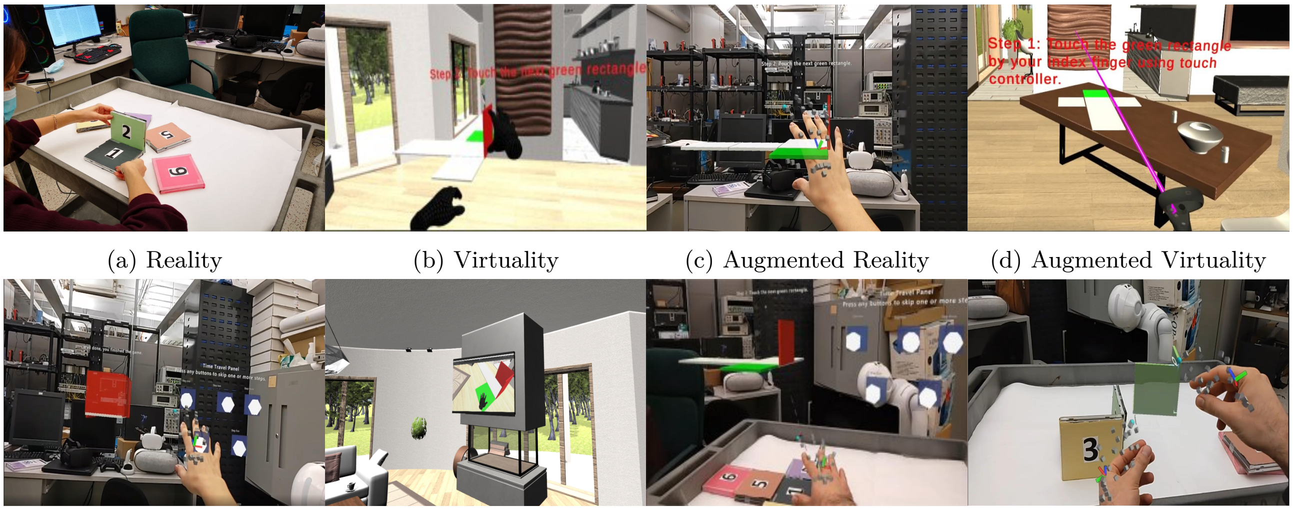
ality, this realm isn't about embracing digital technology or bringing virtual places into the real world. Rather, it takes an experience firmly grounded in Reality and shifts only one variable, moving the event from Actual to Autonomous Time. This realm of Autonomous/Real/Atoms is not infused with the digital technology of No-Matter, nor does it reside in the virtual arena of No-Space. It just requires the offering to play with or manipulate time in some way that makes it clearly distinct and different from normal experience. Such reality-based time travel happens whenever experiences simulate another time in the past or future (albeit a fictional future), e.g., *living history museums or Star Trek conventions.*

- **Mirrored Virtuality:** Finally, Mirrored Virtuality, characterized by the variables Time/No-Space/No-Matter, is the exact opposite toWarped Reality, where Virtuality is tied to Real Time. Inside Virtuality, operating via some sort of avatar, you generally remain free to do whatever you wish to do, whereas inside Mirrored Virtuality you inexorably remain tied into what is happening in the real world, in real time, moment by moment. This realm derives its name from the term MirrorWorlds coined by Yale computer scientist David Gelernter in 1991 [85]. The use of any sort of online tracking tool, e.g., *Google Flu Trends (GFT)*, qualifies as Mirrored Virtuality since this realm offers a real-time view, a mirrored perspective, of what is going on out there, in the world.

4.4 Single-player Offline Implementation: Playing Origami Game with State-of-the-Art VR/AR HMDs

4.4.1 Origami Game Design

The authors of[86] argue that the need for engineering based careers has been steadily rising. To prepare our future work force, they developed a novel curriculum that integrates arts into STEM (Science, Technology, Engineering, and Mathematics) education, which gets students to think outside the box through interactive games. More specifically, to provide students with the addition of art, the authors applied the ancient Japanese craft of *origami*, which folds paper into geometric structures. According to [86], through the art of origami, students can be introduced to engineering concepts. Origami was shown to improve their spatial thinking and cognitive skills.



(a) Reality (b) Virtuality (c) Augmented Reality (d) Augmented Virtuality

(e) Alternate Reality (f) Physical Virtuality (g) Warped Reality (h) Mirrored Virtuality

Figure 4.1: Single-player offline implementation: Creating an origami cube in the eight different Multiverse realms.

To provide an apt environment for children to learn, origami was deployed as a tangible interaction tool in a HoloLens based mixed-reality system [87]. The proposed tangible user interface system uses hand tracking with Kinect to overcome the limitations of HoloLens gestures and make the interaction more natural. The reported user study showed that mixed reality makes the origami process clearer and easier to understand, resulting in higher usability scores.

In this chapter, we design a simple *cube origami game* for all eight realms of the Multiverse using Oculus Quest 2 and Microsoft HoloLens 2, two state-of-the-art VR/AR HMDs. As a cube has six sides, our origami game involves six steps to create the folded cube. Players are asked to successfully finish the cube origami game in each Multiverse realm within the shortest possible time. Depending on the specific variables of the Multiverse realm, players wear a different HMD and may use their actual hands, virtual hands, haptic controllers, and/or cognitive assistance, as explained next.

4.4.2 Implementation Using Quest 2 and Hololens 2

Quest 2 and HoloLens 2 are the two flagship HMDs providing industry-leading solutions to deliver immersive singleand multi-user VR and AR experiences, respectively. The VR/AR experiences may be enhanced by the reliability, security, and scalability of Microsoft Azure[3] and IBM Watson[4] cloud AI services. Furthermore, both Quest 2 and HoloLens 2 provide several key design upgrades to their previous version, including an increased field of view, improved ergonomics, and more importantly, novel interaction modes that allow users to touch, grasp, and move virtual/holographic objects in ways that feel natural and intuitive.

While implementing the two Multiverse realms Virtuality and AR is straightforward with Quest 2 and HoloLens 2, the realization of the remaining Multiverse realms, apart from Reality grounded in real life, is more challenging since they require the use of virtual hands, haptic controllers, and additional support mechanisms, as we will see shortly. For illustration, Fig. 4.1 provides an overview of our implementation of all eight different Multiverse realms, which we describe in technically greater detail in the following.

To begin with, Fig. 4.1(a) shows how our cube origami game is played in the realm Reality by using six physical squares, each numbered and colored differently. Note that in this realm, the player is not given any cognitive assistance since it is rather obvious how to build a physical origami cube. Next, Fig. 4.1(b) shows the realm Virtuality using the aforementioned Quest 2 as VR goggles. Unlike in Reality, the player interacts with virtual squares to fold a virtual origami cube. Given that a player wearing VR goggles cannot see his own physical hands, we designed virtual hands that follow the player's physical hand movements in real time. Further, we embedded a text board in the virtual scene to give written instructions for each step. In addition, we give visual cues by coloring the next virtual square to be touched by the player in green. Once the player folded the square, its color changes to red and the subsequent virtual square is highlighted in green[5]. By replacing Quest 2 with HoloLens 2, the realm Augmented Reality is realized, where the player interacts with holographic squares instead of virtual ones. Note that, unlike in Reality, here the player uses his own physical hands to interact with the holographic squares, as illustrated in Fig. 4.1(c). Similar to Virtuality, we embedded a holographic text board to give written instructions for each step and also used the same green/red coloring of (holographic) squares. After augmenting Reality, let us now augment Virtuality. Fig. 4.1(d) depicts the realm Augmented Virtuality. The player wears Quest 2, but has to tap into Matter instead of No-Matter. To do so, the player is provided with haptic feedback via a hand-held Oculus touch controller to update her about the right or wrong performed

[3] https://azure.microsoft.com/en-ca/
[4] https://www.ibm.com/watson
[5] https://www.youtube.com/watch?v=Y6qu7017KNw&ab_channel=SajjadRostami

action while folding the virtual origami cube. Similar to the realm Virtuality, a virtual text board is embedded in the scene for nudging the player to perform the right actions during the game. In addition, a laser beam (see pink line in Fig. 4.1(d)) guides the player to select the folding a virtual object by pressing a button on the touch controller. For each successful step, the player feels a short haptic vibration in her hands. Next, to implement the realm Alternate Reality in Fig. 4.1(e), the player wears HoloLens 2 to access the holographic objects. Unlike in Augmented Reality, however, we need to realize the No-Time variable by embedding a holographic time travel panel to let the player jump forward to a specific step, backward, or replay it. Hence, the player is able to skip one or more intermediate steps by using the time travel panel. The player creates the physical origami cube immediately afterwards. The player can take advantage of an additional text board embedded on top of the holographic objects, which autonomously updates the player about the right decision. Fig. 4.1(f) depicts the implementation of the realm Physical Virtuality, where the player first wears Quest 2 to watch a short step-by-step tutorial on a virtual TV screen. At the end of the tutorial, the player is asked to take off Quest 2 and build the cube physically. To experience No-Time while creating a physical cube in the realm Warped Reality, the player wears HoloLens 2 to gain access to the aforementioned holographic time travel panel. As shown in Fig. 4.1(g), the player is able to virtually move back and forth in time to see the folding of the holographic cube and then creates one physically. Finally, Fig. 4.1(h) illustrates our implementation of the realm Mirrored Virtuality, where the player wears HoloLens 2. While the player is building the physical origami cube, HoloLens 2 updates the status of the holographic cube according to the player's recent progress. Moreover, the player may perform additional actions on the holographic cube, e.g., rotating, relocating, and resizing.

4.5 Multi-player Online Implementation: Playing Maze Game with Social Humanoid Robot Pepper via Integrated State-of-the-Art VR/AR HMDs and Amazon MTurk CoZ Platform

In this section, we describe the multiplayer online implementation for playing a networked maze game across our proposed integrated VR/AR HMD and Amazon MTurk CoZ platform. Note that our proposed CoZ platform may be also used to play the aforementioned cube origami game, provided that a human is involved in lieu of the the social humanoid robot Pepper in order to compensate for Pepper's limited dexterity, as explained in more detail next.

4.5.1 Maze Game Design

Instead of the previous origami cube game, we select a maze game since Pepper's hands were not designed for folding objects. In our maze game, a group of online MTurk[6] workers try to remotely steer Pepper to a hidden object (a book in our case) placed in an array of cubicles. To do so, Pepper first performs simultaneous localization and mapping (SLAM) to explore the physical environment autonomously by leveraging its built-in navigation sensors[7]. Pepper merges all the data obtained from its navigation sensors to create a 2D map of the physical environment. Upon the successful completion of SLAM, Pepper uses the 2D map to find the approximately shortest path to the hidden object's location using the well-known A* search algorithm [88, 89], one of the best techniques used in path-finding and graph traversals. For real-time object detection, we use Pepper's native NAOqi[8] modules and adopt a supervised learning approach based on a convolutional neural network to train our light dataset using ImageAI[9] and YOLO V3[10]. Using these techniques to let Pepper find the hidden object autonomously (i.e., without any support from local or remote human players) defines our *baseline* experiment.

Unlike in the baseline experiment, the maze game environment is dynamically changed by adding an obstacle in Pepper's path. Due to the fact that the physical environment is not the same as explored in the SLAM phase, Pepper's built-in sensors immediately abort its operation. As a result, Pepper freezes and cannot continue the assigned task. To help Pepper bypass the obstacle, workers may use our developed CoZ platform for navigating Pepper in the eight different Multiverse realms [11]. Specifically, we realize the realm Virtuality using a local human player wearing Quest 2 to visually enable MTurk workers to remotely steer Pepper's avatar in a virtual version of the maze game environment. Note that the virtual avatar could jump over the obstacle quickly without passing around it [12] . Further, we define a holographic border based on the output of the A*

[6] `https://www.mturk.com/`
[7] `https://www.youtube.com/watch?v=Jf-b2SRyhko&t=43s&ab_channel=SajjadRostami`
[8] `http://doc.aldebaran.com/2-5/index_dev_guide.html`
[9] `http://imageai.org/`
[10] `https://pypi.org/project/yolo/`
[11] `https://www.youtube.com/watch?v=xpDmiaFAfeg&t=81s&ab_channel=SajjadRostami`
[12] `https://www.youtube.com/watch?v=59RX9MyLMCE&ab_channel=SajjadRostami`

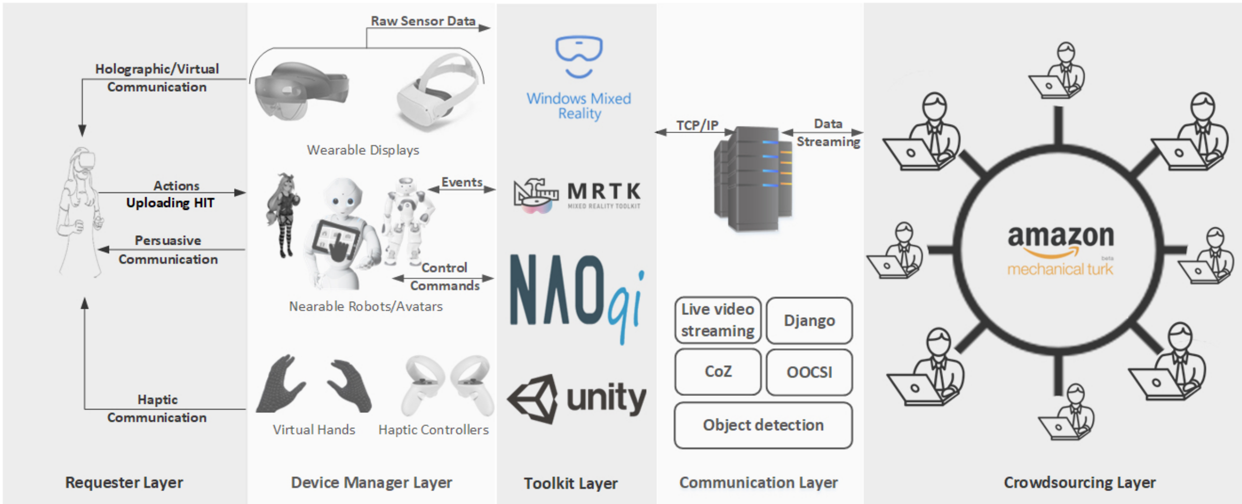


Figure 4.2: High-level architecture of our developed CoZ platform integrating Quest 2, HoloLens 2, social humanoid robot Pepper, and crowdsourced Amazon MTurk workers.

search algorithm for realizing the realm Augmented Reality. The border augments MTurk workers to steer Pepper without crossing the border[13]. Next, we integrate haptic controllers with Quest 2 to realize the tangible aspects of Augmented Virtuality. If the avatar crosses the virtual border, the requester feels a haptic vibration in her hands and moves the avatar backward within the border. To tap into No-Time, we use HoloLens 2 and break down the maze game into four distinct steps for realizing Alternate Reality[14]. In Physical Virtuality, the workers first watch a video on a virtual TV via Quest 2 to find out about the essential clues of the game in advance[15]. In the realm Warped Reality, the requester wears HoloLens 2 to access a holographic time travel panel and an avatar that appears one step ahead in the path where Pepper has to move next[16]. Finally, we realize the realm Mirrored Virtuality using Quest 2, where we synchronize Pepper with the avatar by sending a copy of every command, issued by the MTurk workers to Pepper, to the virtual avatar, thus mimicking Pepper's movements in the virtual world [17].

4.5.2 Implementation Integrating Quest 2 and Hololens 2 with Social Humanoid Robot Pepper and Amazon Mechanical Turk

Figure 4.2 depicts the high-level architecture of our developed CoZ platform, which integrates Quest 2, HoloLens 2, and Pepper with Amazon MTurk for crowdsourcing online workers/players. We apply a layered approach to design our platform, which provides improved scalability and simplified administration, troubleshooting, and maintenance. The developed services, interfaces, and protocols are structured into the following five layers:

- **Requester Layer:** A requester defines a human intelligence task (HIT) to recruit several online MTurk workers to accomplish a designated task. According to Amazon MTurk, a HIT represents a virtual task created by a requester and one or more workers can submit a proper answer. If the requester accepts the submitted answer, the involved worker(s) will receive a pre-defined reward. We applied CoZ to assist Pepper during the game to enable a real-time dialogue between the requester and worker(s). In addition, the requester uses Pepper to access the CoZ interface for defining and uploading a HIT using via Pepper's in-built tablet.

- **Device Manager Layer:** We use a pointer mediator library to be able to interact with holographic objects, including 3D rendering and collision detection in this layer. This library provides two types of interactions: (i) touching/grabbing holographic objects and (ii) detecting hand events. We also equip our virtual game objects with a so-called Collider and ImixedRealityPointerHandeler as intractable script to receive pointer laser beam events created by the haptic controllers.

- **Toolkit Layer:** We use several tools and libraries to handle all the events, motion commands, and processing of raw sensor data. Specifically, we used the Windows Mixed Reality (WMR)[18] library to blend AR and MR experiences with compatible HMDs. In addition, we used Microsoft's Mixed Reality Toolkit (MRTK)[19] to accelerate cross-platform MR application development. Furthermore, we apply Pepper's NAOqi to execute the received commands on

[13] https://www.youtube.com/watch?v=OW-dcBSX-wE&t=4s&ab_channel=SajjadRostami
[14] https://www.youtube.com/watch?v=N2mWDEIjgiE&ab_channel=SajjadRostami
[15] https://www.youtube.com/watch?v=CzWEir7XsPA&ab_channel=SajjadRostami
[16] https://www.youtube.com/watch?v=wuEGfavbXFY&t=85s&ab_channel=SajjadRostami
[17] https://www.youtube.com/watch?v=2Ok6dfXJg1I&t=82s&ab_channel=SajjadRostami
[18] https://docs.microsoft.com/en-us/windows/mixed-reality/discover/mixed-reality
[19] https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05

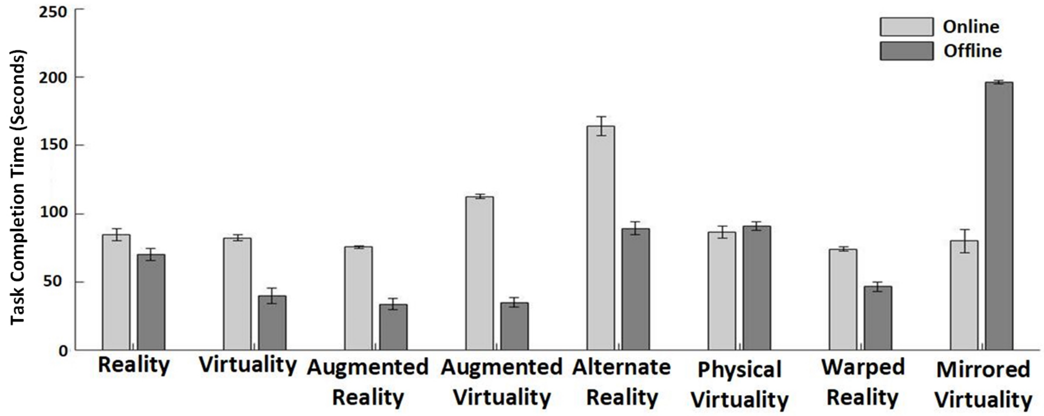


Figure 4.3: Experimental average task completion time (TCT) of cube origami game with and without using crowdsourced Amazon MTurk workers in different realms of the Multiverse (each shown with minimum-to-maximum TCT intervals).

the robot. We use the Unity 3D[20] game engine to fine-tune the relationship between head tracking, virtual avatar, and virtual hands.

- **Communication Layer:** The CoZ server is built using a Django web server and OOCSI Python middleware to create connections among the components and web clients. First, to join the toolkit layer with the CoZ platform, we implement a local TCP/IP socket. Next, we use Python libraries, including OpenCV, Flask, and CV2, to provide live video streams accessible over the Internet via Pepper's built-in cameras. Finally, to upload a HIT onto MTurk, we use Amazon Boto3.5[21] to integrate it with the CoZ server by converting a live HTML into XML format, which is a valid input format for the MTurk platform.

- **Crowdsourcing Layer:** Crowdsourcing Layer: The crowd workers use the CoZ interface to be able to have a real-time conversation with the requester through Pepper or HMDs, using a text-to-speech AI service to achieve more precise results. In addition, the CoZ has several social cue buttons to perform physical gestures and vocal cues on Pepper via embodied communication. Further, our CoZ user interface provides a section where workers can watch the physical environment through Pepper/HoloLens 2/Quest 2 cameras. Finally, we embed four directional buttons in the CoZ interface where the MTurk worker(s) can turn Pepper's head and move it in four different directions.

[20] `https://unity.com/`
[21] `https://pypi.org/project/boto3/`

4.6 Experimental Results

Similar to [90], we use *task completion time (TCT)* as our primary metric of interest for the comparison of different XR environments, including but not limited to VR and AR. Fig. 4.3 compares the experimental average TCT results of playing the cube origami game with five online (MTurk workers) and five offline (local human) players in each Multiverse realm. All the recruited players, aged 25 to 32, had no experience with HoloLens and Quest. The recruited players entered our lab freely and willingly, unaware of the study being conducted. Before starting the experiments, we trained all players in the same manner how to use the hand-held controllers, HoloLens, and Quest. For fair comparison, we did not recruit the same player to build the origami cube in two different realms in order to avoid biased players. Furthermore, we isolated the players from each other to create a distraction-free area during each experiment. Likewise, we avoided methods like standing next to the players while measuring TCT. Instead, in our experiment set-up, we used the Unity game engine that calculated the TCT score of each player automatically. This way, the players felt comfortable while playing the game and overcoming the task's challenges without feeling any external influence.

Let us first consider the Reality realm, where both online and offline players had no access to cognitive assistance. The players were supposed to build an origami cube based on their previous knowledge in this realm. The difference between achieved TCTs for offline and online players is 10 seconds. Conversely, in the Virtuality realm, the players had access to a virtual text board. Hence, they did not need to figure out how to build an origami cube based on their own knowledge. Instead, they could accomplish the task only by following the instructions on the virtual board and visual cues.

We observe from Fig. 4.3 that the offered virtual assistance is effective in that the players achieve a lower TCT than in the Reality realm. In the Augmented Reality realm, the players had the same visual cues and cognitive assistance, though a holographic version of them. Hence, players could use their real hands to manipulate the holographic game components. In doing so, they achieve an even lower TCT than in the Virtuality realm, where they had to use a virtual version of their hands. However, unlike the Virtuality realm, in the Physical virtuality realm the players could take advantage of the provided haptic feedback via the hand-held Oculus touch controller to give players real-time feedback about their performed actions while folding the virtual origami cube. We observe that the achieved TCT in this realm is lower than the TCT score in the virtuality realm. This result shows that haptic feedback is effective to enable the players to perform the right action on the virtual cube.

In the Alternate Reality realm, we observed that the players adopted an interesting approach, even though the players could use the time travel panel to build the origami cube by skipping one or more steps. More specifically, we observed that most of the offline players preferred to build the origami cube on their own to rather than skipping several steps and finishing the game as soon as possible. Only one of the offline players skipped several steps to jump to step five of the game using the panel and perform the last step on her own. This is the reason for the considerable difference between the achieved TCT of offline and online players in this realm.

Next, the Physical Virtuality realm applies the same scenario as the Reality realm, except that the players in the Physical Virtuality realm could watch a video on a virtual TV via Quest 2 to find out about the essential clues of the game in advance. This is the main reason that both online and offline players could finish the game almost with the same TCT. Without watching the video, the achieved TCT is lower than in the Reality realm, because players benefitted from the essential cues in advance to build the origami cube.

In the Warped Reality realm, the players had access to the time travel panel while building the origami cube. In this realm, the online players achieved the lowest TCT among all online scenarios. Conversely, the offline players achieved a lower TCT compared to the Reality realm. Moreover, although the offline players experienced the highest TCT in the Mirrored Virtuality realm, we witnessed that it was the most exciting realm for the offline players. This is due to the fact that they could see a synchronized holographic cube in real-time that allow them to resize, relocate, or turn the holographic components. In contrast, the online players preferred to accomplish the game as soon as possible to gain the offered reward.

Next, let us consider the maze game. Table 4.1 shows that the first three realms achieve a lower TCT than in the baseline experiment, which achieved a TCT of 34 seconds requiring 0 commands. This is due to the following reasons. First, unlike with the Pepper, physical limitations don't limit its avatar from passing a dynamic obstacle by simply jumping over it. Second, the virtual/holographic border helps workers issue fewer duplicated yet more effective commands. And third, the time travel panel provides players with the opportunity to finish the maze game with only three commands in

Table 4.1: Experimental results on TCT and number of issued commands for playing maze game with online MTurk workers.

Multiverse Name	TCT (seconds)	Issued Commands
Alternate Reality	9	3
Augmented Virtuality	23	9
Virtuality	27	13
Baseline	34	0
Physical Virtuality	68	26
Mirrored Virtuality	128	15
Warped Reality	134	17
Augmented Reality	171	21
Reality	237	31

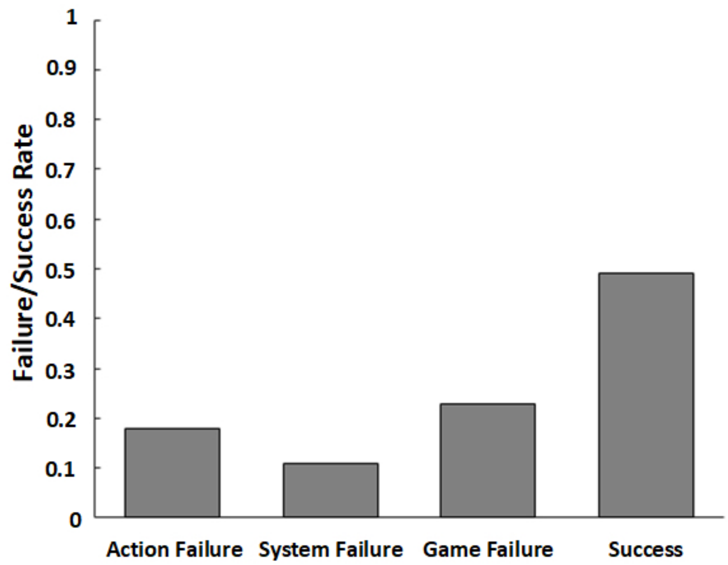


Figure 4.4: Experimental failure and success rates of origami and maze games.

the realm Alternate Reality. Conversely, the realm Reality achieves the highest TCT since Pepper can not bypass the dynamic obstacle autonomously by only relying on the previously acquired SLAM information. Further, in this realm, workers can not access any cognitive assistance such as our virtual/holographic border.

In total, we have submitted 128 HITs to Amazon MTurk, resulting in 61 recruited online workers to conduct our experiments. At least two MTurk workers were involved in each Multiverse realm during the maze game. As shown in Fig. 4.4, we had an action failure rate of 0.18 (or 18 percent), where the players did not make the right decision during the maze game. Furthermore, in 11 percent of the maze game instances, we encountered system failures, which in most cases were due

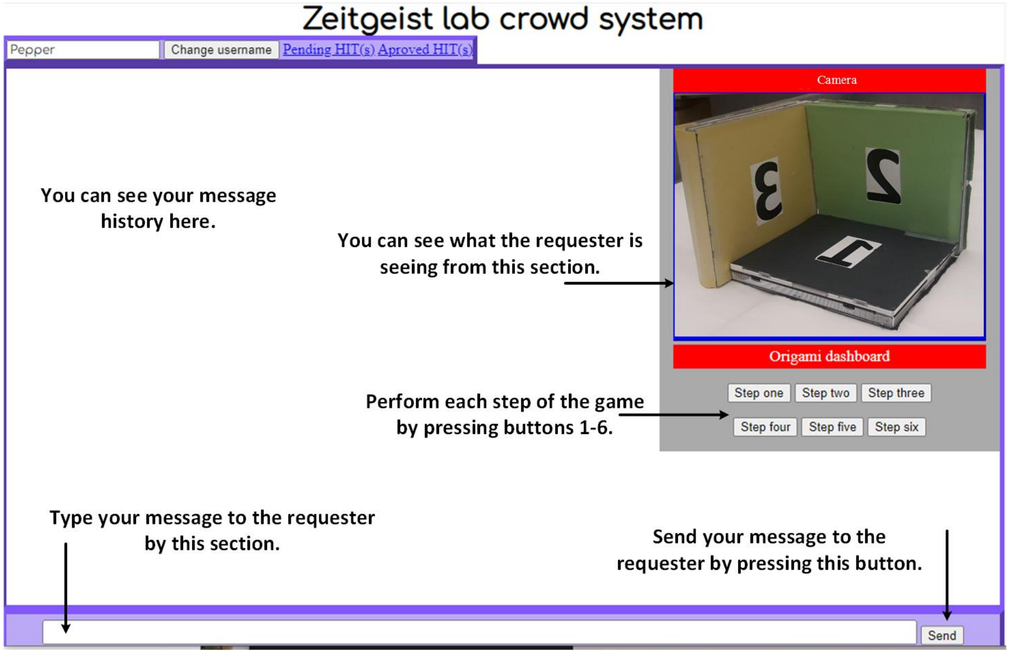


Figure 4.5: An overview of the CoZ user interface console, including real-time video streaming, origami steps, defining new HIT, view submitted HITs, and the message box.

to the lack of Internet connectivity and HoloLens 2 interruption. Game failure rate accounted for 23 percent of our encountered failures, where the inability to find a worker to continue the game or lack of practical knowledge of workers were typical game failures. Finally, we observed that the remaining 48 percent of the submitted HITs were successfully completed in the sense that the workers performed all steps without facing any of the aforementioned failures.

To reduce the number of submitted HITs, we were inspired by several previous studies done by researchers, as discussed in more detail in the following. The design of tasks, workflows, motivation, and incentives, as well as the selection of suitable workers and their training are possible solutions that task owners can adopt to make their submission of HITs more effective [91, 92, 93]. Moreover, gamification is another technique used in crowdsourcing systems that may be adopted by task owners to increase the workers' intrinsic motivation to accept a task and participate actively [94, 95, 96]. By choosing gamification-based titles helped us get our HITs accepted sooner. Furthermore, we created a short user manual that explains the game rules along with a CoZ interface tutorial and an illustrative image of the CoZ platform to train the workers before starting the game, as shown in Fig. 4.5. Our CoZ interface design focused on training workers by offering them a gratifying task rather than simply filtering out unprofessional workers by submitting several back-to-back HITs.

Note that generally the lack of direct communication between workers and requesters is one of the main issues in crowd systems to keep the workers motivated [97, 98]. We tackled this shortcoming by establishing a peer communication link through our designed CoZ interface that makes it more manageable and feasible for workers to accomplish tasks. The CoZ platform provided this facility in that workers and requesters can communicate directly via text during the game. Hence, the hired workers were not supposed to accomplish a task independently. Instead, the requester could support the workers by providing immediate feedback during the decision-making process. The aforementioned approaches allowed us to recruit suitable workers and keep them interested till the end of the game. Keeping the workers motivated prevents them from aborting a given task unpredictably, resulting in improved HIT success rates.

4.7 Conclusions and Future Work

At present, games such as Fortnite and Roblox are the most common platforms in the popularization of the Metaverse. The emerging Metaverse should provide gamified experiences, including serious games, and is anticipated to be the precursor of the Multiverse's advanced XR realms of experiences going beyond conventional VR and AR. In this paper, we presented our integrated VR/AR HMD and Amazon MTurk CoZ platform, which uses Quest 2 and HoloLens 2 to enable the crowdsourcing based remote control of social humanoid robot Pepper and its virtual avatar. We've extended the Metaverse's primary focus on VR/AR to Multiverse's eight distinct XR realms of experience and experimentally compared their performance in terms of task completion time (TCT) and failure/success rate for a single-player origami game and a multiplayer maze game, played in both offline and online (i.e., networked) mode. Our obtained experimental results aim at providing insights into understanding the pros and cons of different types of reality and selecting the most suitable one to realize gamified experiences with the lowest TCT at acceptable failure/success rates. Taking the specific TCT requirements and failure tolerance of a given gamified experience into account, game designers may select their preferred single type of reality that satisfies the performance requirements. Alternatively, game designers may combine two or more types of reality in order to create cross-reality environments, in which players can cross or transverse multiple Multiverse realms within a given gamified experience, resulting in integrated physical-virtual environments whose respective weaknesses are mitigated and respective strengths are multiplied. In Section 5.5, we provided more detail on how we achieved this goal using blockchain technology in the Wordle game context.

Leveraging on our obtained results, future research efforts may adapt collective intelligence mechanisms for nudging players to accomplish their assigned tasks faster and more successfully. Towards this end, the full potential of blockchains should be explored by exploiting the crowd intelligence in a cooperative game world. Blockchains allow players to earn tokens and thus help realize play-to-earn games, where players can earn or exchange cryptocurrencies or non-fungible tokens (NFTs). Using emerging Web 3.0 blockchain technologies, remote expert players can cooperate with local novice players across the Internet in different Multiverse realms to jointly perform complicated tasks faster and more accurately.

Chapter 5

Blockchainizing the Wordle Game in Advanced Metaverse Realms Using Smart Wearables

This chapter contains material extracted from the following publication:

- S. Rostami, A. Beniiche, L. Gouiran, and M. Maier, Playing the Blockchainized Wordle Game in Advanced Metaverse Realms With Smart Wearables, *Proc., IEEE International Conference on Metaverse*, accepted for publication.

In the following, my key contributions to the publication mentioned above are explained in greater detail: (1) I proposed different ideas for adapting the original version of the Wordle game in each realm of the Multiverse using smart HMDs in Section 5.4, (2) I proposed a multi-player version of the Wordle game by inspiring the play-to-earn blockchain games in Section 5.5, (3) I implemented our customized web version of the Wordle game to obtain the results demonstrated in Table 5.1, (4) I developed and implemented the Wordle game in all the Multiverse realms using smart HMDs, (5) I conducted all the experimental works, obtained and analyzed all the results demonstrated in Figs. 5.3 and 5.4.

Figure 5.1: NSF's view on Next G research: Near-, mid-, and long-term objectives, including the Metaverse [99].

5.1 Introduction

In Chapter 4, we have seen that the Metaverse will utilize HMDs and XR as the medium to connect avatars and users in the real world. Moreover, the Metaverse provides gamified experiences around emerging Web 3.0 technologies to be the precursor of the so-called Multiverse and serve as an architecture of advanced XR experience beyond conventional VR and AR. The Metaverse is the next step after the Internet, similar to how the mobile Internet expanded and enhanced the early Internet in the 1990s and 2000s [78]. Figure 5.1 illustrates NSF's view on near- to long-term Next G research objectives, including many of the emerging and future key enabling 6G technologies such as the Metaverse [99]. Recently, in [34], the authors outlined a roadmap to the Metaverse. In their presented framework, they discussed the fundamental technologies that need to be integrated in 6G in order to drive the implementation of the Metaverse, including digital twin, edge computing, and blockchain, whereby the latter one is considered a key enabling technology to achieve decentralized network management, improved interoperability between different systems of the Metaverse, and community integration. In one of the most recent books on the Metaverse [79], the authors consolidated various perspectives to give the following central definition of the Metaverse: “The Metaverse represents the top-level hierarchy of persistent virtual spaces that may also interpolate in real life, so that social, commercial, and personal experiences emerge through Web

3.0 technologies." Whether through virtual reality (VR), augmented reality (AR), or a smartphone, the Metaverse and the experiences inside it can connect to the real world. Importantly, in addition to incentivizing transactions, the Metaverse should provide what the authors call gamified experiences, given that gamification will encompass the activity and story around emerging Web 3.0 blockchain technologies.

Serious games have become a useful remote teaching tool, especially during Covid-19 lockdowns. Another type of game that has received particular attention during the Covid-19 pandemic are so-called blockchain games, which allow players to earn a livelihood in the form of cryptocurrencies or nonfungible tokens (NFTs). Here, we consider the Wordle game, which was developed during pandemic lockdowns and became a worldwide Internet phenomenon. The Wordle game provides players with cognitive cues in form of color-coded keys to help them find a secret word as well as earn points and share them online. In this paper, we adopt the original Wordle game to the Metaverse, including but not limited to VR and AR. Specifically, we design and experimentally investigate advanced cognitive cues for playing the Wordle game in the eight different experience realms of the so-called Multiverse, the anticipated successor of the Metaverse, using state-of-the-art smart wearables. In addition, we develop a blockchainized version of the game that allows remote experts to play-to-earn tokens and cooperate with local players by providing them with cognitive assistance via smart wearables.

The remainder of the Chapter is structured as follows. Section 5.2 describes the original Wordle game. Section 5.3 reviews recent progress on serious games, play-to-earn blockchain games, and cooperative game worlds that leverage crowd intelligence for community integration. After introducing the Multiverse, Section 5.4 presents our advanced cognitive cues using Oculus Quest 2 and HoloLens 2, while Section 5.5 explains how to blockchainize the Wordle game. Section 5.6 presents our experimental results. Finally, Section 5.7 concludes the Chapter.

5.2 Original Wordle Game

In 2021, software engineer Josh Wardle has invented a word game for his girlfriend, who in turn called it Wordle, a melange of "word" and her boyfriend's last name. Given his girlfriend's excitement, he decided to publish the Wordle game on the Internet. A few weeks later, a worldwide craze started

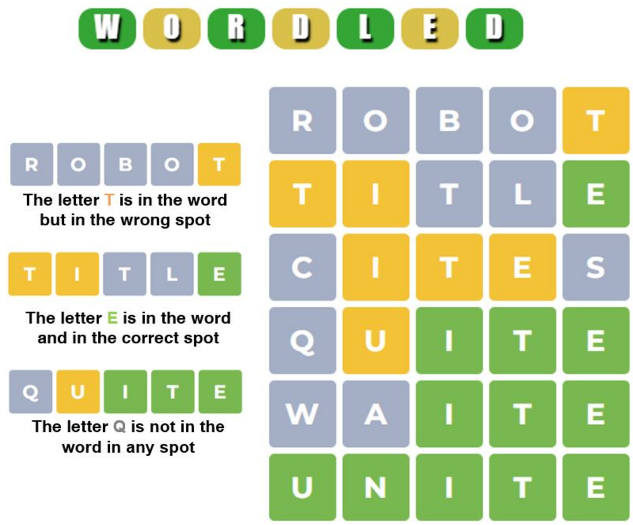


Figure 5.2: Original Wordle game finding the secret word UNITE within six tries benefitting from cues given as color-coded keys.

engaging millions of players. Due to its enormous success, in January 2022, the New York Times bought the game for millions of dollars and transformed it into a daily changing challenge to solve via app or browser [100]. The Wordle game is easy to understand and works as follows. The goal of the game is to find a secret word consisting of exactly five letters within six tries. For illustration, Fig. 5.2 shows the Wordle game played for the secret word UNITE. In this illustrative example, the player succeeds after six tries benefitting from cognitive cues in form of colored keys he or she has received in each of the previous five attempts. After each attempt, the keys change color (green, yellow, or default grey) to indicate the significance of each of the five letters chosen in each round of the game. Specifically, a green key indicates that the letter is correct and at the right spot, while a yellow key indicates that the letter is present in the secret word but at the wrong spot. A default grey key indicates that the letter is not in the secret word. Depending on the number of required tries, a player earns points that can be shared with other players online. The earned points are added to the total score of previous days.

5.3 From Serious Games to Play-to-Earn Blockchain Games & Cooperative Game Worls

The concept of serious games was introduced in the 1970s by Clark C. Abt as a new way to learn while having fun. Serious games have been on the rise and are used in different fields, e.g., a mixed reality (MR) based smartphone app for remote intergenerational storytelling [101] or a VR based immersive English learning platform for everyday-life scenes[102]. According to Wikipedia, blockchain games are video games that are based on blockchain technologies, in which players can earn or exchange cryptocurrencies or NFTs. Therefore, they are also called play-to-earn games. Play-to-earn games are still in their preliminary stages and face a number of challenges, e.g., interoperability and asset management across multiple games and blockchain platforms, to facilitate a crosschain gaming experience [103]. Further, private and sensitive information may be accessed through blockchain games, giving rise to security issues. In [104], the authors discussed possible attack methods based on blockchain game architecture and described how to avoid these vulnerabilities.

The authors of [105] surveyed the state of the art by categorizing 23 representative blockchain games from various blockchain platforms. Different from traditional games, blockchain game players should register an address in the corresponding blockchain before they start their gaming sessions. Typically, this blockchain address is a public key, which can be accessed by a wallet program. Further, the game server should offload some core functions, e.g., the ones managing the player's virtual assets, to the blockchain as smart contracts. Among other blockchain platforms, Ethereum and EOS provide strong support for smart contract execution, allowing for the implementation of novel blockchain games as well as opening up new research directions, e.g., gamified crowdsourcing.

An interesting example of building cooperative game worlds on blockchains with reciprocal crowdsourcing was presented in [106]. Reciprocal crowdsourcing is a special crowdsourcing platform, where participants are not only the data contributors but also the beneficiaries. In their proposed cell evolution blockchain game, the authors developed a gameplay to collect the individual player's intelligence, represented as cell data, to form the crowd intelligence of the game world and build an entire community. Cell evolution consists of multiple smart contracts, which contain the specific rules of the blockchain game.

5.4 Playing the Wordle Game in Advanced Metaverse Realms with Smart Wearables

5.4.1 Advanced Metaverse Realms

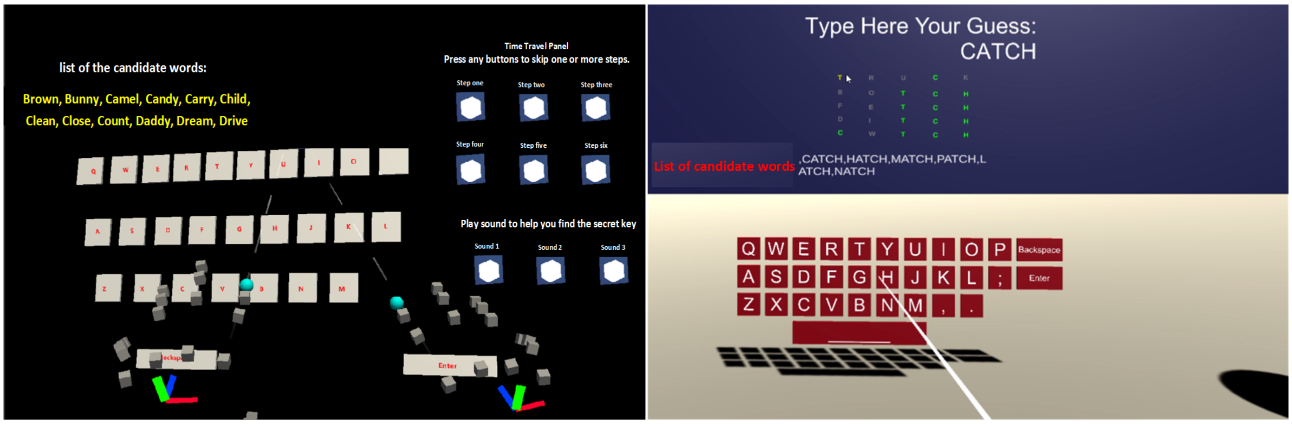
According to [81], the Metaverse will be the precursor of the so-called Multiverse. Both have in common that they aim at realizing the fusion of digital and real worlds. However, while the Metaverse primarily focuses on VR and AR, the Multiverse offers eight different types of advanced extended reality (XR) experience realms, spanning the entire reality-virtuality continuum. More specifically, the Multiverse consists of three pairs of variables, each with two opposite physical/digital dimensions Space/No-Space, Time/No-Time, and Matter/No-Matter, which give rise to a total of eight realms, each offering a different type of reality. It encompasses the multiple ways for when [Time ↔ No-Time] experiences happen, where [Space ↔ No-Space] they occur, and what [Matter ↔ No-Matter] they act on. Each combination of the six variables yields a distinct experience realm and different type of XR reality. For further information about the Multiverse, we refer the interested reader to [107].

5.4.2 Implementation of Cognitive Cues Using Smart Wearables

As illustrated in Fig. 5.3, we adapt the original Wordle game to the distinct experience realms of the Multiverse using Oculus Quest 2 and Microsoft HoloLens 2, two state-of-the-art VR/AR smart wearables). In our implementation, we pay particular attention to the development of advanced cognitive cues for playing the Wordle game in each of the following eight Multiverse realms:

- **Reality:** Players could play the Wordle across the Internet with the same dataset as the original version plus embedded color-coded keys as cognitive cues.
- **Virtuality:** We connect Quest 2 and its controllers to a cognitive cues board containing a list of candidate words. The list updates in each step based on player guesses and database SQL filtering mechanisms[1].

[1] `https://www.youtube.com/watch?v=jBRTQkec01M&t=15s&ab_channel=SajjadRostami`



(a) (b)

Figure 5.3: Single-player offline implementation: Playing the original Wordle game in the different Multiverse realms using holographic/virtual keyboard, time travel panel, list of candidate words, vocal assistance, laser beam pointer, and embedded color-coded keys as cognitive cues. (a) demonstrated all the HoloLens 2 associated cognitive cues, and (b) illustrated all the Quest 2 cognitive cues.

- **Augmented Reality:** Players could access the mentioned list through HoloLens 2 along with several sound buttons in the scene to bring other human senses apart from eyesight to find the secret key in a shorter time.

- **Augmented Virtuality:** Players are given haptic feedback via Oculus controllers to update them about their wrong guesses by feeling a short vibration in their hands in the presence of the list of the candidate words.

- **Alternate Reality:** We embed a panel to let the players jump forward to a specific step, backward, or replay it. It was accessible via HoloLens 2 and proposed some fiveletter words containing several green or yellow letters.

- **Physical Virtuality:** Players first wear Quest 2 to watch a tutorial on a virtual TV to ensure they fully understand the game's rules. Then, we asked them to play the game using the original version without cognitive cues.

- **Warped Reality:**Players wear HoloLens 2 to access the panel while playing the original Wordle game. The panel proposed the best candidate words, and the players could apply them to finish the game in a shorter time.

- **Mirrored Virtuality:** HoloLens 2 updates the status of the holographic Wordle game according to the players' recent progress using a PC by connecting players to the candidate word list.

5.5 Blockchainizing the Wordle Game

Given that blockchain is also known as the world computer, in this section, we explore the potential of blockchain to leverage crowd intelligence in our designed cooperative game world. Blockchainizing the Wordle game (i) allows remote experts to cooperate with local players benefiting from crowd intelligence, and (ii) allows players to earn tokens and thus naturally realize play-to-earn games by emerging Web 3.0 blockchain technologies. The players perform the Wordle game and share cognitive assistance to earn tokens in two Multiverse realms, i.e., Physical Virtuality (has the longest TCT) and Warped Reality (has the shortest TCT) to decrease the TCT value for the Physical Virtuality realm.

According to color-coded keys, we consider each letter of the English alphabet as a financial asset (reward), while the Scrabble game initializes the value of each letter. If a player guessed a word containing more letters in green, he would earn more points than guessing a word with all gray letters. During the game, remote experts can change their earned points to have tokens for an exchange rate mentioned in a cognitive smart contract.

We introduced a multiplayer version of the game by implementing a cognitive smart contract to enable a remote expert to transfer a whole or a part of his earned tokens to local players. Furthermore, remote experts can send remote assistance in words to other players to collect a reward. An ERC-20 smart contract represents the tokens, and during the game, the players could exchange them with the five-letter words containing some of the secret key's characters as NFTs based on the Scrabble game. We deployed both smart contracts on Ethereum's official test network Ropsten. The cognitive smart contract can be invoked using its public key and Application Binary Interface (ABI).

Moreover, our smart contract contains two main variables: msg.value, which indicates a submitted transaction, and msg. sender represents the player's address who has sent a transaction to remote experts. We also implemented two functions for providing shearing mechanisms: UpdateAssistanceFunction and Word-Function. UpdateAssistanceFunction allows remote experts to define a new word where it takes a msg.value in a string and transfers it to the experts' account. WordFunction allows local players to receive the word(s) defined by the remote experts. After each function's

Table 5.1: Experimental results for playing the Wordle game in the Multiverse realm Reality across the Internet.

TRAIN	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Tries	2	5	4	4	5	6	6	6	6	5	6	4	3	3	3
TCT	45	230	139	150	183	300	420	37	428	97	112	52	105	63	90
AHINT	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Tries	6	6	3	6	6	5	6	-	-	5	3	4	6	-	-
TCT	673	309	133	262	355	233	366	-	-	55	37	154	79	-	-

execution, an event is used to create notifications and saved logs which further help remote and local players with the game's current state and activities.

5.6 Experimental Results

We considered task completion time (TCT) given in seconds and number of required tries as the two performance metrics of interest for comparing the different Multiverse realms. We recruited 15 online players, involving novices (labeled #1 to #9) and experts (labeled #10 to #15), depending on whether (s)he has already played the Wordle game and acquired some strategies. All participants played the game twice, once for a common five-letter secret word (TRAIN) and once for an uncommon one (AHINT).

Table 5.1 shows our measured average TCT and number of tries. Interestingly, note that the expert players require a comparable average TCT for finding both the common and uncommon secret words (86.05 seconds for TRAIN and 80.25 seconds for AHINT), whereas the average TCT of the novice players has increased significantly (214.67 seconds for TRAIN versus 333 seconds for AHINT). This is due to the fact that the experts have developed a strategy that works independently from the actual secret word. We observed that they choose candidate words that have at least two vowels and the most frequent letters such that they can reduce the number of unsuccessful tries. Fig. 5.4 compares the experimental average TCT results of playing the Wordle game for the secret word TRAIN in the seven remaining Multiverse realms with five offline players in our laboratory, using our designed advanced cognitive provided by smart wearables. We observe that Physical Virtuality exhibits the highest TCT value due to the time it takes to watch the introductory tutorial video and subsequently to play the game without further cognitive assistance.

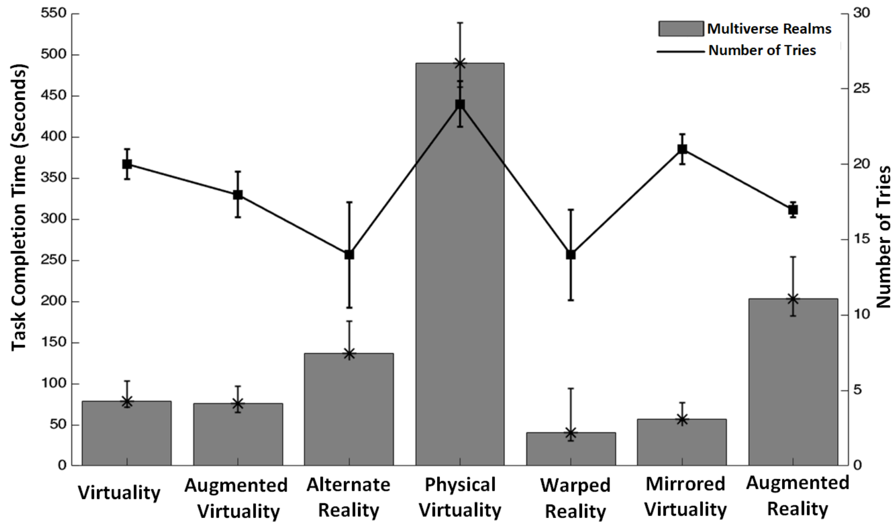


Figure 5.4: Experimental results for playing the Wordle game for secret word TRAIN in the seven remaining Multiverse realms using our smart wearable enabled advanced cognitive cues (shown with minimum-to-maximum intervals).

Further, we observe that the TCT value in Augmented Reality is better than Reality (see Table 5.1), since the players had access to the candidate words list. Note that the TCT value is significantly lower in the realm Virtuality, because we observed that the players find it easier to interact with the virtual keyboard than a holographic one. Note that the smallest TCT values were measured for the realms Warped Reality and Mirrored Virtuality. In Warped Reality, players could use the time travel panel and a real keyboard at the same time. Figure 5.5 aims at combining the experiments reported in Table 5.1 (only remote players, both experts and novices) and Fig. 5.4 (only local players), where remote experts in the Reality realm could send cognitive assistance across the Internet to local players in the Physical Virtuality realm using blockchain smart contracts to reduce TCT value and number of tries.

To experimentally verify the effectiveness of our advanced cognitive cue design, we examined the realm Virtuality also for the secret word AHINT. The measured average TCT value was equal to 66.8 seconds. Note that this is less than that of the expert players in the realm Reality. Interestingly, the TCT value was comparable to the one for the common secret word TRAIN, indicating that our designed cognitive cue works independently from the secret word's actual level of difficulty.

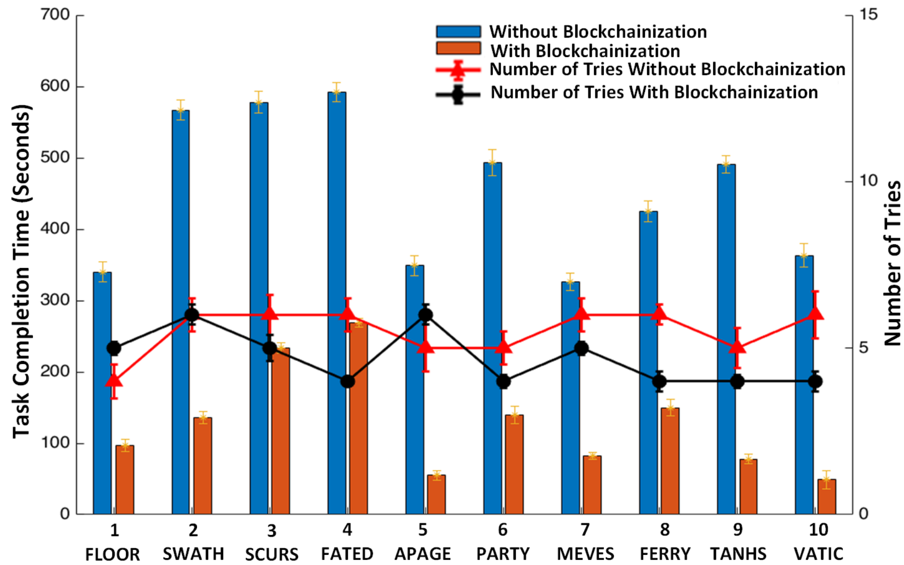


Figure 5.5: Experimental results for a multiplayer version of the Wordle game with/without blockchainization with ten words selected randomly from Wordle's database of five-letter secret words (shown with minimum-to-maximum intervals).

5.7 Conclusion

In this Chapter, we integrated the original Wordle game with advanced cognitive cues to be played in the Multiverse realms with smart wearables. Furthermore, we blockchainized the game to introduce a multiplayer version where remote experts play the game to earn tokens and cooperate with local players by providing them with advanced cognitive assistance via smart HMDs and blockchain smart contracts. Our experimental results show that players could accomplish the game successfully with the lowest TCT value and fewer tries.

Chapter 6

Conclusions

This chapter summarizes the important contributions of the dissertation and outlines possible directions for future work.

6.1 Summary

This thesis introduced the Internet of No Things as an important stepping stone toward ushering in the 6G post-smartphone era. We argued that while 5G was supposed to be about the Internet of Everything, to be transformative, 6G might be just about the opposite of Everything, that is, Nothing or, more technically, No Things. The Internet of No Things offers all kinds of human-intended services without owning or carrying any computing or storage devices. Instead, it envisions Internet services appearing from the surrounding environment when needed and disappearing when not needed. The transition from the current gadgets-based Internet to the Internet of No Things is divided into three phases: (i) bearables, (ii) wearables, and then finally (iii) nearables.

Based on the above discussion, the boundary between virtual (i.e., online) and physical (i.e., offline) worlds is becoming increasingly indistinguishable. In the meantime, humans' digital and physical capabilities will extend via the edge computing variants, ideally with embedded AI capabilities. This thesis also elaborated on how the Internet of No Things and its underlying human-intended services may serve as a step toward realizing the 6G far-reaching network vision. This is the start of the 6G era after post-smartphones.

This doctoral thesis is built based on the XR as a promising technology of the Internet of No Things to extend the abilities of humans to develop human-robot/avatar interaction in the 6G post smartphone era. Chapter 2 explained that multisensory XR applications are one of the four driving applications behind 6G to revolutionize the wireless evolution from “connected things” to “connected intelligence.” We also pointed out that XR is the next generation of mobile computing platforms combining the different forms of reality to realize the entire reality-virtuality continuum for the extension of human experiences. Apart from VR/AR/MR, future XR technologies may discover novel, unprecedented types of reality. Thus, X may be viewed as a placeholder for future yet unforeseen developments on the digital frontier.

In Chapter 2, we also elaborated on the Multiverse as an exciting attempt to charter the unknown territory, which may serve as an architecture of advanced XR experiences. The Multiverse also explains how we can realize novel and unprecedented types of reality in more detail. Toward this end, we illustrated our experimental setup for demonstrating eternalism in locally connected human-avatar/robot collectives. Our proposed setup deployed Ethereum to interconnect all human operators, real and virtual robots, and empathic AI services in a decentralized autonomous organization (DAO) to share skills and help solve complex problems. Finally, we experimentally illustrated that the users become increasingly more confident and emotionally less tentative after transiting from reality to virtuality, thus confirming the beneficial impact of the Proteus effect experienced in virtual inter-avatar events.

In Chapter 3, we first briefly reviewed the 6G vision of future mobile networks. Then, we mentioned that 6G is anticipated to become more human-centered than 5G, where it converges driving technological trends such as blockchain technologies and connected robotics. We also pointed out the challenges and benefits of blockchain in 6G networks by paying close attention to the sociotechnical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society. Furthermore, we identified open research challenges of realizing a blockchain-enabled trust game by paying close attention to the importance of developing efficient cooperation and coordination technologies. We then delved into the technical issues of implementing a smart-contract-based decentralized version of the classical trust game by applying basic blockchain technologies and validating them experimentally. We put the N-player trust game in the context of robonomics leveraging the beneficial characteristics of persuasive robot strategies to foster prosocial human behavior. Finally, we experimentally demonstrate that mixed logical-affective persuasive strategies for social robots significantly improve trustees' trustworthiness and reciprocity. We have shown that up to 100% social efficiency can be achieved by using deposits to enhance trust and trustworthiness.

In Chapter 4, we mentioned that the Metaverse utilizes HMDs and XR as the medium to connect avatars and users in the real world. In addition, the Metaverse is supposed to provide gamified experiences around emerging Web 3.0 technologies beyond conventional VR and AR. In this chapter, we focused on the 6G post-smartphone era, where smart wearables such as VR/AR HMDs are increasingly replacing the functionalities of smartphones. Next, we proposed different scenarios for gamifying and implementing all eight Multiverse realms. To do so, we applied Oculus Quest 2 and Microsoft HoloLens 2 as state-of-the-art VR/AR HMDs by extending the Metaverse's primary focus on VR/AR to Multiverse's eight distinct XR realms of experience. Next, we introduced our layered setup for integrating Quest 2, HoloLens 2, and Pepper with Amazon MTurk to recruit online workers/players. We also proposed scenarios for adapting a single-player origami game and a multi-player maze game across our proposed layered platform. Finally, we experimentally compared players' performance in terms of TCT and failure/success rate in offline and online (i.e., networked) modes. Then, we briefly discussed our adapted strategies for increasing the HIT acceptance rate and keeping the workers motivated while accomplishing a task. Our obtained experimental results provide insights into understanding the pros and cons of different types of reality and selecting the most suitable one to realize gamified experiences with the lowest TCT at acceptable failure/success rates.

In Chapter 5, we explained various fundamental technologies that need to be integrated into 6G to drive the implementation of the Metaverse, known as the next Internet. Metaverse provides gamified experiences to incentivize transactions using emerging Web 3.0 blockchain technologies. Similar to serious games, blockchain games received particular attention during the Covid-19 pandemic, where players play the game to earn NFTs. We adopted the original Wordle game for all eight Multiverse realms, the anticipated successor of the Metaverse, using state-of-the-art smart wearables in this chapter. Next, we explored the potential of blockchain to leverage crowd intelligence in our designed cooperative game world. Blockchainizing the Wordle game (i) allows remote experts to cooperate with local players benefiting from crowd intelligence, and (ii) allows players to earn tokens and thus naturally realize play-to-earn games by emerging Web 3.0 blockchain technologies. In this game version, the players performed the Wordle game and shared cognitive assistance to earn tokens for an exchange rate mentioned in a smart cognitive contract. Finally, we introduced a multiplayer version of the game by implementing a cognitive smart contract that allows remote experts to play-to-earn tokens and cooperate with local players by providing them with cognitive assistance via smart wearables. Our experimental results demonstrated that players could accomplish the game successfully with the lowest TCT value and fewer tries in the presence of online remote players.

6.2 Future Work

As explained in Chapter 4, our proposed CoZ platform has the potential to explore the beneficial characteristics of social robots to address the user acceptability and trust issues of human-intended services using persuasive computing via social robotics. So, there is this opportunity to integrate other nearable or wearable gadgets into our CoZ platform to investigate embodied communication via social robots. Our designed CoZ enables us to develop sophisticated social robotic applications, including user attention models, natural language understanding functions, and access to crucial robot functions such as motion and gesture expression. In addition, the implemented CoZ supports a robust and scalable backend architecture to support the future dialog flow of the robot using state machines and to provide low-latency complex interactions. This CoZ interface can be integrated with external Cloud AI services like Google Cloud and Microsoft Azure Ethereum blockchain to deliver cognitive services for complicated tasks.

Creating a smart environment is another aspect of the Internet of No Things. We will integrate the CoZ platform with Microsoft Surface Hub 2S, a nearable all-in-one digital whiteboard, meetings platform, and collaborative computing device with multi-touch interfaces. This technology can connect people who wouldn't otherwise be able to contribute and create more authentic group experiences, even for remote team members. It also allows collaboration among devices from anywhere, turning any space into a team space. For example, remote team members can contribute to the digital whiteboard and add to it from anywhere on multiple bearables such as phones, tablets, and laptops. By integrating the aforementioned nearable gadgets and the CoZ platform with Microsoft Hololens 2, a human user can experience XR with the CoZ platform, which combines data from real robots and the perception and abilities of a human operator.

Moreover, we can visualize the current robot state and the extended human vision, leading to a rising percentage of the HITL workplace. Such XR is an anywhere service and will increase the skill and accuracy of human users. Toward this end, our designed CoZ platform also has the potential to be integrated with Quest 2 HMD to realize haptic teleoperations. Teleoperators can use Quest 2 touch controllers to drive Pepper's robot indirectly through an avatar as Pepper's successor in the virtual world via the Quest headset.

In this study, we performed several experiments with gamified scenarios. Nevertheless, in future works, the players can take advantage of other haptic wearable technologies (i.e., haptic gloves) to interact with virtual/holographic objects and touch them during the game. In addition, olfaction is another human sense that allows users to perceive the odor from VR/AR environment. Therefore, it is anticipated that equipping the Multiverse realms with the mentioned hardware will increase players' performance and accuracy. Moreover, we used Unity Chan as a general avatar without considering the personal characteristics of the players. Since the Metaverse provides an alternative platform for human interaction in the virtual world, the avatar's appearance should be considered. Users should be able to control their avatars' movements by responding to them to create a more customized and realistic experience. Furthermore, there are other aspects that we have to consider in future scenarios for designing an avatar character, including appearance, clothing and attachments, locomotion, facial expressions, emotion, and personality. By applying the abovementioned phenomenons as embodiment, users seriously feel virtually present in their virtual world by attaching their avatars to themselves.

According to our best knowledge, this is the first research study that used the Multiverse architecture to realize gamified experience using smart wearables, blockchain, and social robots in the 6G context. So, we did not have this opportunity to extend other research or compare our achieved results with prior investigations. Therefore, to have a concert or more quantifiable results, we highly encourage other researchers first create a testbed for 6G on a lab scale and then perform their experiment based on it. This way, they will have more opportunities to compare gathered results with other technologies, such as 5G.

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Appendix A

Extended Synopsis in French

Enquête Expérimentale sur les Domaines d'expérience Avancés du Métaverse

Introduction

La 6G, contrairement aux générations précédentes, est transformatrice et révolutionnera l'évolution sans fil des "objets connectés" vers "l'intelligence connectée". Les réseaux 6G devraient intégrer les derniers développements en matière d'infrastructure de réseau et les avancées technologiques émergentes. La 6G exploitera non seulement plus de spectre à partir des bandes haute fréquence, mais convergera également sur les tendances technologiques, y compris (i) la réalité étendue multi-sensorielle (XR), (ii) la robotique connectée et les systèmes autonomes, (iii) l'interaction cerveau-ordinateur sans fil, et (iv) les technologies de blockchain et de grand livre distribué. Dans cette thèse de doctorat, nous expliquons comment l'Internet of No Things et ses services sous-jacents destinés à l'homme peuvent servir d'étape vers la réalisation de la vision du réseau de grande envergure 6G. Ensuite, nous proposons une architecture pour l'Internet of No Things qui intègre les trois étapes évolutives de l'informatique mobile, à savoir l'informatique omniprésente, omniprésente et persuasive, ainsi que toutes sortes de dispositifs portables intelligents pour offrir des expériences XR avancées. De plus, nous intégrons les principales caractéristiques de la blockchain Ethereum au domaine émergent de la robonomique et de la robotique persuasive pour résoudre des problèmes que les machines (robots, IA) ne peuvent pas résoudre seules. Pour ce faire, nous étudions le jeu de confiance largement étudié de l'économie comportementale dans un contexte de blockchain en développant un contrat intelligent pour proposer un jeu de confiance en réseau à N joueurs et les communications incarnées permises par des robots persuasifs. Ensuite, nous introduisons l'architecture Multiverse pour concevoir des expériences XR avancées en tant que successeur anticipé du Métavers. Le Métavers et le Multivers visent en commun à réaliser la fusion des mondes numérique et réel. Cependant, alors que le métaverse se concentre principalement sur la réalité virtuelle et la réalité augmentée, le Multivers offre un canevas de conception d'expérience puissant pour découvrir les opportunités cachées de XR en fusionnant le réel et le virtuel, créant ainsi des environnements dits de réalité croisée. Après avoir décrit l'architecture Multivers, nous gamifions et mettons en œuvre les huit domaines d'expérience Multivers dans le contexte d'un (ii) jeu d'origami à un joueur et (iii) jeu de labyrinthe multijoueur à travers nos HMD VR/AR intégrés proposés et Amazon Mechanical Turk. plate-forme crowd-of-Oz (CoZ). Dans le même sens, nous adoptons le jeu Wordle original au Métavers, y compris, mais sans s'y limiter, la VR et l'AR. Enfin, nous concevons et étudions expérimentalement des signaux cognitifs avancés pour jouer au jeu Wordle dans les huit domaines d'expérience différents du Multivers, en utilisant des dispositifs portables intelligents à la pointe de la technologie. De plus, nous développons une version blockchain du jeu. Blockchainiser le jeu Wordle (i) permet à des experts distants de coopérer avec des acteurs locaux bénéficiant de la crowd intelligence, et (ii) permet aux joueurs de gagner des jetons et ainsi de réaliser naturellement des jeux jouer pour gagner par les technologies blockchain émergentes du Web 3.0.

Objectifs

Le premier objectif de la thèse est d'expliquer les concepts fondamentaux de la technologie XR émergente et ses exigences en matière d'infrastructure réseau. De plus, nous visons à discuter des progrès récents actuels et des défis ouverts de l'intégration de la technologie XR dans l'écosystème humain-robot/avatar. Ensuite, nous visons à fournir des informations sur la manière dont la XR permet de passer de la réalité pure à la virtualité pure pour étendre les expériences humaines, y compris le support de l'interaction homme-machine. Ensuite, nous expliquerons comment nous pouvons développer des expériences XR avancées pour fournir un environnement de réalité croisée impliquant les cinq sens humains, la connectivité omniprésente, la robotique et les communications haptiques. Un autre objectif de la thèse est d'explorer comment nous pouvons exploiter la convergence de XR avec des appareils portables intelligents, l'informatique de pointe multi-accès améliorée par l'intelligence artificielle et les robots mobiles intelligents. Cette convergence nous aide à réaliser l'Internet of No Things comme un tremplin essentiel vers l'entrée dans l'ère post-smartphone 6G. Puisque la 6G est plus centrée sur l'humain que la 5G, dans cette thèse, nous nous concentrerons sur le domaine émergent de la robonomique, qui étudie l'impact sociotechnique des technologies blockchain sur l'interaction sociale homme-robot et l'économie comportementale pour l'intégration sociale des robots dans la société humaine. . Diverses technologies fondamentales doivent être intégrées à la 6G pour piloter la mise en œuvre du prochain Internet, appelé métaverse. Le Métavers utilisera les HMD et XR comme moyen de connecter les avatars et les utilisateurs dans le monde réel. L'un des principaux objectifs est de développer des méthodes permettant aux robots d'apprendre à partir d'échantillons d'entraînement massifs et de connaissances humaines pour accomplir des tâches hautement intelligentes via une intelligence partagée entre différents robots et humains. Le Métavers est censé fournir des expériences ludiques autour des technologies Web 3.0 émergentes, VR et AR. La gamification englobera l'activité et l'histoire autour des technologies émergentes de blockchain Web 3.0. Un objectif important de cette thèse est d'adopter le jeu Wordle original au métaverse, y compris, mais sans s'y limiter, la réalité virtuelle et la réalité augmentée. Un autre objectif est de concevoir et enquêter expérimentalement sur des signaux cognitifs avancés pour jouer au jeu Wordle dans les huit domaines d'expérience différents du soi-disant Multivers, le successeur prévu du métaverse, en utilisant des dispositifs portables intelligents à la pointe de la technologie. Un autre objectif de la thèse est de développer une version blockchainisée du jeu qui permette à des experts distants de jouer pour gagner des jetons et de coopérer avec des joueurs locaux en leur fournissant une assistance cognitive tout en accomplissant une tâche.

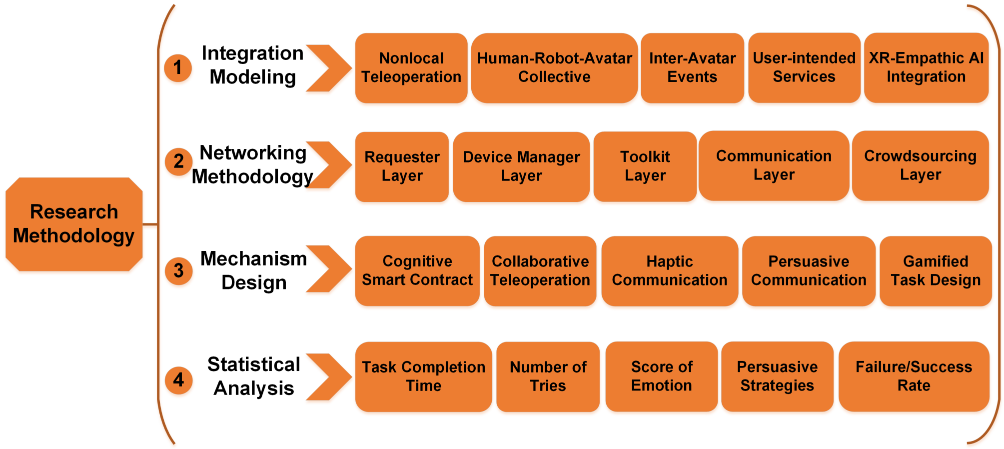


Figure A.1: Méthodologie de la recherche.

Méthodologie

La méthodologie de recherche appliquée dans cette thèse comprend la modélisation d'intégration, la méthodologie de réseau, la conception de mécanismes et l'analyse statistique, comme résumé dans la Fig. A.1 et brièvement décrit dans ce qui suit. Nous avons intégré plusieurs composants, notamment des services d'IA empathique XR, des services destinés aux utilisateurs, une téléopération non locale, des événements inter-avatars et un collectif humain-robot-avatar, pour fournir un environnement de réalité croisée. De plus, nous avons adopté une nouvelle technique de téléopération telle que Crowd-of-Oz (CoZ) pour permettre aux téléopérateurs de contrôler à distance les gestes du robot social Pepper de Softbank placés devant un utilisateur humain et d'avoir un dialogue en temps réel via une messagerie texte-à- traduction de la parole. En intégrant les mécanismes susmentionnés et la plate-forme CoZ avec Microsoft HoloLens 2, un utilisateur humain peut expérimenter XR avec la plate-forme CoZ, qui combine les données de vrais robots et la perception et les capacités d'un opérateur humain. De plus, nous pouvons visualiser l'état actuel du robot et la vision humaine étendue, ce qui entraîne une augmentation du pourcentage du lieu de travail humain dans la boucle (HITL). Un tel XR est un service n'importe où et augmentera les compétences et la précision des utilisateurs humains. Nous avons également adopté une approche en couches pour concevoir notre plate-forme afin de réaliser les huit royaumes de l'architecture Multivers. Chaque couche a des composants qui sont logiquement ou physiquement liés les uns aux autres. La conception d'une architecture en couches offre une évolutivité améliorée et une administration, un dépannage et une maintenance simplifiés. Les services, interfaces et protocoles développés sont structurés en cinq couches: couche demandeur, couche gestionnaire de périphériques, couche boîte à outils, couche communication et couche crowdsourcing. Pour ce faire, nous avons appliqué de nouveaux mécanismes algorithmiques pour répondre aux objectifs susmentionnés. Ces mécanismes comprennent la conception de tâches collaboratives, la téléopération collaborative, la communication haptique, la communication persuasive et la gamification des tâches. Enfin, le temps d'exécution des tâches, le nombre d'essais, le score d'émotions, le taux de réussite/d'échec et les stratégies de persuasion ont été mis à profit pour effectuer des évaluations de performance. Toutes les mesures susmentionnées sont étudiées de manière approfondie pour nos différentes configurations expérimentales de deux manières: (i) expérience en laboratoire et (ii) Amazon Mechanical Turk (MTurk). Plusieurs expériences de laboratoire sont adoptées dans notre recherche pour trouver des données pertinentes et fiables. De plus, nous avons utilisé MTurk, récemment populaire parmi les scientifiques expérimen-

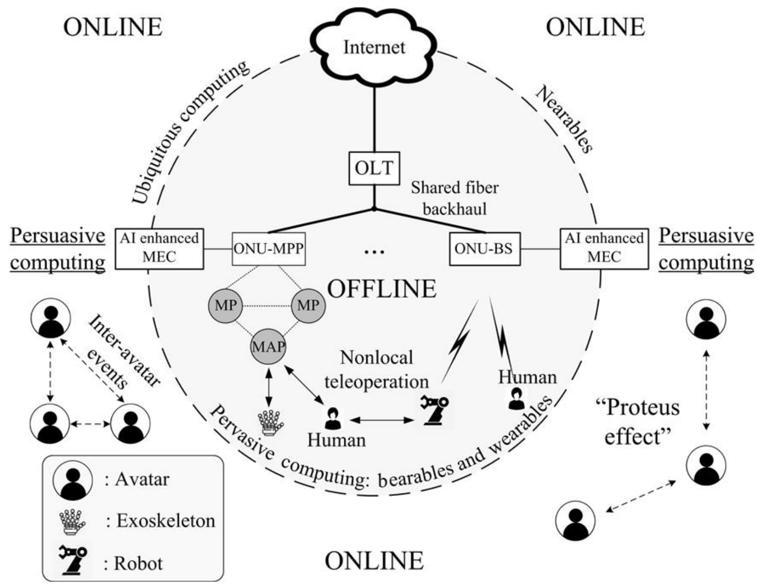


Figure A.2: Architecture de réseau de perception extrasensorielle intégrant l'informatique ubiquitaire, omniprésente et persuasive.

taux et sociaux, comme source d'enquête et de données expérimentales. De plus, les participants à MTurk sont légèrement plus représentatifs de la population mondiale que les échantillons Internet standard et sont nettement plus diversifiés que les échantillons d'expériences de laboratoire typiques. De plus, la rémunération des travailleurs anonymes de MTurk dans notre expérience n'affecte pas la qualité des données. De plus, les données obtenues sont plus fiables que celles obtenues par les méthodes traditionnelles.

Contributions de la thèse

Cette thèse est une compilation de quatre publications (3 articles de revues et un article de conférence) publiées ou soumises pour publication dans des revues IEEE de haut calibre. Les principales contributions de la thèse sont brièvement discutées ci-dessous.

L'Internet of No Things: Faire Disparaître Internet et "Voir le Invisible"

Les futures technologies de communication émergentes devraient s'intégrer à notre environnement, ce qui nous aidera à sortir notre nez des écrans de smartphone et à revenir dans notre environnement environnant. Ce faisant, ils vont nous aider à être plus présents dans le monde qui nous entoure. Lors du Forum économique mondial de 2015, Eric Schmidt a déclaré que "l'Internet va disparaître". Cependant, Internet fera partie de notre présence tout le temps. Bien que cette première puisse sembler un peu surprenante, c'est dans la nature des technologies. Dans "L'ordinateur du 21e siècle", Mark Weiser a soutenu que les technologies les plus profondes sont celles qui disparaissent. Ils se tissent dans le tissu de la vie quotidienne jusqu'à ce qu'ils en soient indiscernables.

Une approche intéressante pour faire disparaître Internet est la soi-disant vision du monde nu qui vise à ouvrir la voie à l'Internet du rien. Le fondateur de Demos Helsinki, Roope Mokka, a inventé le terme Internet of No Things en 2015. Le terme signifie qu'un utilisateur peut vivre sans avoir à transporter de gadgets (c'est-à-dire nu) mais peut accéder aux services numériques en cas de besoin, et après cela, l'interface utilisateur du les services vont disparaître. La figure A.2 illustre l'architecture générique de l'Internet of No Things. L'architecture proposée intègre les portables, les portables, les proches et trois étapes évolutives de l'informatique mobile: (i) omniprésente, (ii) omniprésente et (iii) informatique persuasive. L'informatique omniprésente est intégrée dans les choses qui nous entourent (c'est-à-dire les objets proches), tandis que l'informatique omniprésente implique nos supports et nos objets portables. L'informatique persuasive vise à modifier le comportement des utilisateurs par l'influence sociale. Un phénomène intéressant pour modifier le comportement dans un environnement virtuel en ligne est connu sous le nom d'"effet Proteus", où le comportement des individus est façonné par les caractéristiques et les traits de leurs avatars virtuels, notamment par l'interaction lors d'événements inter-avatars.

L'infrastructure de réseau physique sous-jacente, qui est illustrée à la Fig. A.2, consiste en une liaison de fibre partagée par des points de portail maillés WLAN (MPP) et des stations de base cellulaires (BS) qui sont colocalisées avec des unités de réseau optique (ONU), qui à leur tour sont connecté au terminal de ligne optique central (OLT) du backhaul fibre. Sur la base de traces haptiques du monde réel, nous avons étudié le cas d'utilisation de la téléopération non locale entre un opérateur humain (HO) et un robot téléopérateur (TOR), deux entités physiques, c'est-à-dire hors ligne.

L'Internet of No Things comporte trois phases. La première phase concerne les supportables d'aujourd'hui. Dans cette phase, les utilisateurs peuvent accéder à des services numériques via des composants tels que des tablettes, des PC, des montres connectées, des smartphones, etc. La deuxième phase concerne les wearables émergents. Au cours de cette phase, les utilisateurs peuvent accéder à des services numériques (par exemple, la veste intelligente de Google et Levi ou la bague, les lunettes et les écouteurs Echo Loop à commande vocale récemment lancés par Amazon). La phase finale est qualifiée de proches. Les objets proches désignent des environnements ou des environnements proches avec des technologies informatiques/de stockage intégrées et des mécanismes de fourniture de services suffisamment intelligents pour apprendre et réagir en fonction du contexte et de l'historique de l'utilisateur afin de fournir les services souhaités par l'utilisateur. Le développement de l'Internet of No Things est un défi. Outre les problèmes techniques, il existe d'autres défis tels que l'état d'esprit commercial et social en raison de l'acceptabilité et de la confiance requises par les utilisateurs.

Certaines des applications 5G les plus intéressantes, notamment la Réalité Virtuelle (VR) et l'Internet Tactile, semblent évoluer dans le même sens. Les systèmes VR subiront trois étapes évolutives, comme l'Internet of No Things susmentionné. La première étape évolutive concerne les systèmes VR actuels qui nécessitent une connexion filaire à un PC ou un appareil portable. En effet, les systèmes sans fil 4G ou même pré-5G actuels ne peuvent pas satisfaire l'énorme quantité de bande passante et les exigences de latence de la réalité virtuelle. Au deuxième stade évolutif, les appareils VR sont censés être connectés sans fil à un serveur fog/edge situé à la station de base pour le calcul et la mise en cache locaux. La troisième et dernière étape évolutive envisage des systèmes VR idéaux (entièrement interconnectés), où aucune distinction entre les mondes réel et virtuel n'est faite dans la perception humaine. L'Internet tactile, connu sous le nom de groupe de travail standard IEEE P1918.1, permet également la direction et le contrôle tactiles d'objets

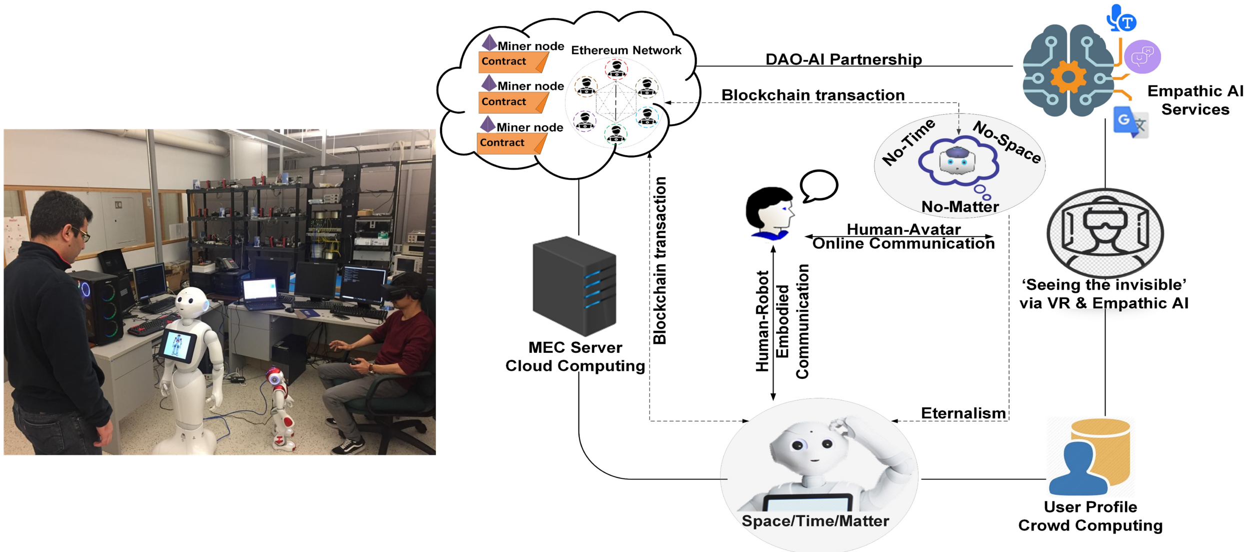


Figure A.3: Dispositif expérimental pour démontrer l'éternalisme dans des collectifs humains-avatars/robots connectés localement.

non seulement virtuels mais aussi réels (par exemple, des robots de téléopération) ainsi que des processus. Ainsi, l'Internet tactile peut être considéré comme une extension de la réalité virtuelle immersive d'un environnement virtuel à un environnement physique.

La figure A.3 illustre notre configuration expérimentale pour démontrer l'éternalisme localement où le temps est mieux considéré comme un espace dans le sens où vous êtes dans le présent mais que vous pouvez également vous déplacer simultanément vers le passé et le futur. Il s'agit d'un collectif humain-avatar/robot où plusieurs opérateurs humains peuvent communiquer à distance avec un élève via le robot Pepper. De plus, tous les opérateurs peuvent recevoir/envoyer des messages en fonction de leur langue maternelle. Pour ce faire, nous intégrons l'API Google Translate pour traduire différents types de langues, et enfin, Pepper transfère tous les messages en anglais à l'étudiant qui communique physiquement avec Pepper. Dans cette configuration, l'étudiant s'engage dans une communication incarnée avec Pepper via la voix, le geste et la tablette de Pepper. De plus, l'étudiant puise dans le Non-Temps comme une variable du Multivers non physique. Comme illustré sur la Fig. A.4, le multivers est une architecture d'expériences XR avancées qui contient : trois dimensions, six variables et huit domaines. À l'aide d'environnements de réalité virtuelle, l'étudiant fait également l'expérience d'un voyage dans le temps qui, basé sur le Multivers, signifie passer des dimensions matière, temps et espace (réalité) aux dimensions Non-Matière, Non-Temps et Non-Espace (virtualité).

Pour ce faire, nous avons mis en place une expérience qui a duré 15 minutes et a été répétée cinq fois, impliquant à chaque fois une réalité et une virtualité différentes. Dans la partie réalité initiale, l'étudiant s'engage d'abord avec Pepper pour une visite audiovisuelle interactive de l'INRS. Dans cette visite audiovisuelle, Pepper présente l'Université INRS. Puis Pepper montre une liste de professeurs sur sa tablette. Les étudiants en sélectionnent un et Pepper montre plus de détails sur le professeur sélectionné sur la tablette et commence à parler du professeur. De plus, Pepper a pu effectuer une reconnaissance des émotions à l'aide d'expressions faciales pour les élèves (par exemple, bonheur, tristesse, peur, colère et surprise). Après cela, Pepper montre les photos des élèves sur la tablette. Par la suite, l'étudiant est autorisé à poser à Pepper toute question arbitraire sur

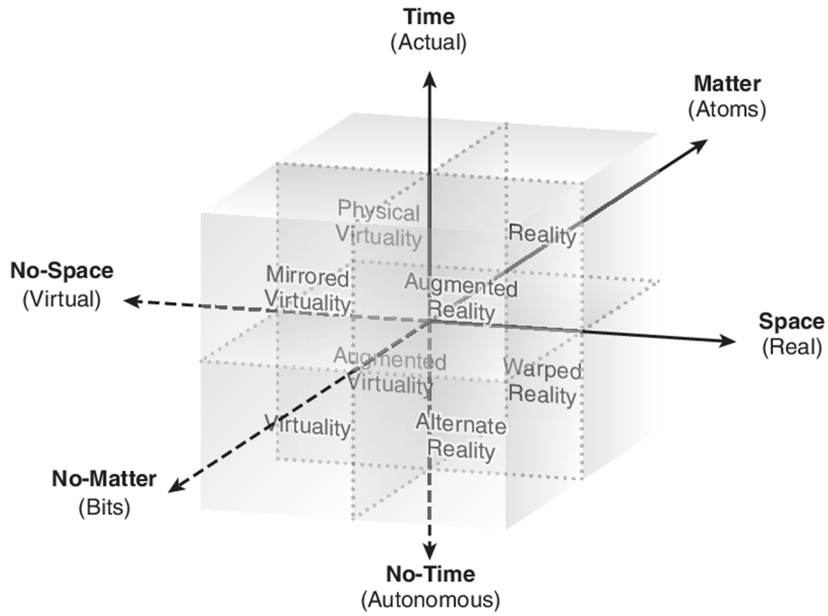


Figure A.4: Le Multivers en tant qu'architecture d'expériences XR avancées : Trois dimensions, six variables et huit domaines.

l'INRS, les réponses de Pepper étant fournies par un opérateur humain distant via une conversion parole-texte et texte-parole.

Ensuite, Pepper invite l'étudiant à poursuivre l'expérience dans la partie virtualité, où l'étudiant peut parcourir virtuellement l'INRS. Nous avons utilisé un casque Oculus Rift VR pour permettre à l'élève d'accéder à un avatar virtuel. L'étudiant, guidé par un avatar faisant office d'oracle omniscient. L'oracle s'appuie sur un opérateur humain à distance, qui peut surveiller les émotions détectées de l'élève en temps réel. Nous exploitons les services d'intelligence artificielle empathique d'IBM Watson, notamment l'analyseur de tonalité d'IBM pour détecter les émotions dans les textes écrits échangés lors d'une communication en ligne homme-robot/avatar. Un serveur TCP appelle l'analyseur de tonalité IBM et transfère le message reçu. La sortie de l'analyseur IBM Tone est un fichier JSON, qui contient les scores extraits du message reçu. Au milieu, un profil utilisateur est maintenu pour enregistrer chaque interaction homme-robot. Ensuite, le serveur TCP appelle le serveur de journalisation, qui stocke tous les messages et scores dans des profils utilisateur distincts. Enfin, le serveur TCP reçoit un accusé de réception du serveur de journalisation et envoie les données à l'API Google Translate.

La figure A.5 montre le score d'IA empathique moyen des quatre émotions positives détectées par l'analyseur de tonalité d'IBM Watson lors des différents échanges parole-texte et texte-parole humain-robot/avatar de l'expérience. Il illustre clairement que les étudiants deviennent de plus en plus confiants et émotionnellement moins hésitants après avoir transité de la réalité à la virtualité, confirmant ainsi l'impact bénéfique de l'effet Proteus. Notre expérience confirme l'effet Protée dans la mesure où l'oracle conseille l'étudiant sur la manière d'atteindre progressivement une situation future souhaitable à l'INRS, caractérisée par des niveaux plus élevés de confiance et d'engagement émotionnel.

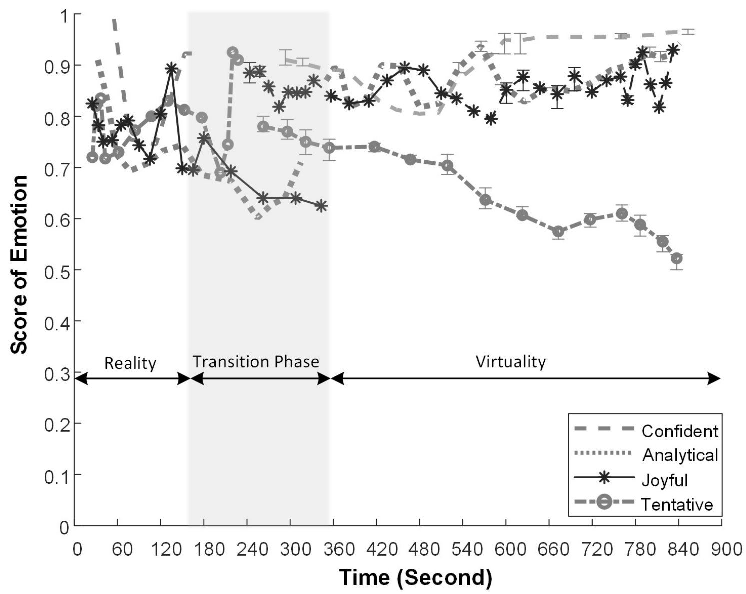


Figure A.5: Score moyen d'IA empathique de quatre émotions positives différentes détecté expérimentalement pendant le voyage dans le temps de la réalité à la virtualité (illustré avec des intervalles de score mesurés minimum à maximum).

La Robonomique à L'ère de la 6G: Jouer au Jeu de la Confiance Avec des Oracles en Chaîne et des Robots Persuasifs

Dans la dernière section, nous avons mentionné que l'informatique de pointe multi-accès améliorée par l'intelligence artificielle et les technologies de blockchain sont les technologies clés qui nous aident à réaliser l'Internet of No Things comme un tremplin essentiel vers l'introduction de la 6G, l'ère post-smartphone. La 6G devrait devenir plus centrée sur l'humain que la 5G et devrait non seulement explorer plus de spectre dans les bandes haute fréquence, mais, plus important encore, converger vers des tendances technologiques telles que les technologies de blockchain et la robotique connectée. Ce chapitre se concentre sur le domaine émergent de la robonomique, qui étudie l'impact sociotechnique des technologies blockchain sur l'interaction sociale homme-robot et l'économie comportementale pour l'intégration sociale des robots dans la société humaine.

Une limitation majeure de la blockchain conventionnelle est son incapacité à interagir avec le "monde extérieur" puisque les contrats intelligents ne peuvent fonctionner que sur les données de la blockchain. Dans le B-IoT émergent, les capteurs sont généralement déployés pour amener les données de mesure des capteurs sur la blockchain. Les technologies avancées de blockchain permettent le chaînage d'informations hors chaîne externes à la blockchain provenant d'utilisateurs réels, à l'exception des capteurs et d'autres sources de données uniquement, tirant ainsi également parti de l'intelligence humaine plutôt que de l'apprentissage automatique. Pour surmonter cette limitation, les contrats intelligents peuvent utiliser des soi-disant oracles, des entités de chaîne de blocs décentralisées de confiance dont la tâche principale est de collecter des informations hors chaîne et de les intégrer à la chaîne de blocs en tant que données d'entrée fiables pour les contrats intelligents. Il existe plusieurs systèmes oracle décentralisés qui reposent sur des jeux basés sur le vote, par exemple ASTRAEA.

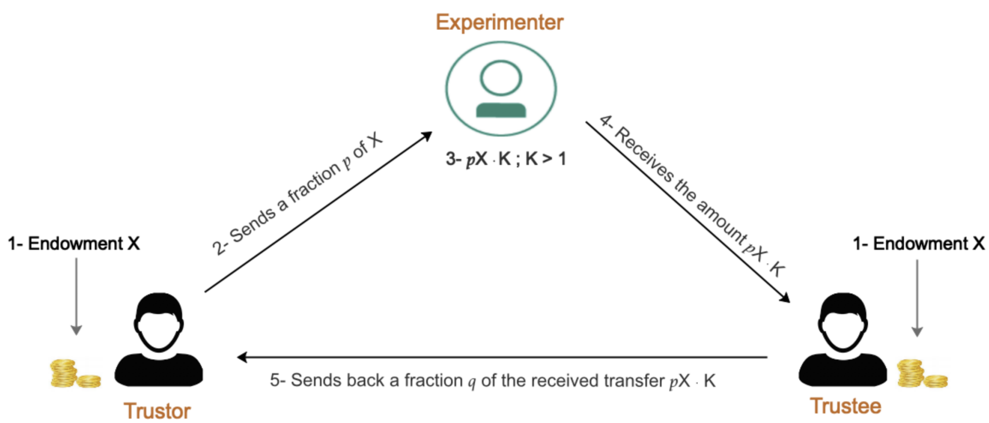


Figure A.6: Jeu de confiance classique impliquant deux joueurs humains (trustor et trustee) et un expérimentateur au milieu.

Cette section se concentre sur le jeu de la confiance largement étudié en économie comportementale. Le jeu de la confiance n'a pas encore été étudié dans un contexte de blockchain. Cependant, il permet une analyse plus systématique étude de la confiance, de la loyauté et de la réciprocité entre les acteurs humains. Le jeu de confiance classique implique seulement deux joueurs humains, trustor et trustee, qui se sont jumelés anonymement et sont tous deux dotés d'un certain nombre X d'unités monétaires. La figure A.6 illustre l'échange séquentiel entre trustor et trustee. Le constituant peut transférer une fraction $0 \leq p \leq 1$ de sa dotation au fiduciaire. L'expérimentateur multiplie ensuite cette quantité par un facteur $K > 1$, par exemple doublé ou triplé. Le dépositaire peut transférer une fraction $0 \leq q \leq 1$ du montant reçu directement au dépositaire sans passer par l'expérimentateur. Notez que le jeu de la confiance capture tout échange économique générique entre deux acteurs.

La figure A.7 décrit l'architecture de notre oracle de chaînage proposé pour le jeu de confiance en réseau à N joueurs. L'architecture proposée comprend un ensemble de clusters ou pools. Chaque cluster contient trois types d'agents: (i) les trusteurs, (ii) les trustees et (iii) les observateurs. La différence entre les observateurs et les joueurs (trustors/trustees) est que les observateurs ne jouent pas mais suivent et évaluent les critères de confiance et de fiabilité tels que l'investissement (p) et la répartition (q). Les joueurs interagissent avec le contrat intelligent de l'expérimentateur en utilisant leurs clés publiques-privées via une application décentralisée (DApp). Les différents tours de jeu sont suivis à distance par les observateurs via Etherscan.io. Cet explorateur de blockchain Ethereum utilise l'adresse du contrat de l'expérimentateur et affiche les différentes transactions entre chaque paire de trustor et trustee en temps réel. Nous notons qu'en alternative, on peut utiliser Alethio.io, un outil de surveillance qui permet aux observateurs d'envoyer et de recevoir des alertes vers et depuis n'importe quelle adresse, activité ou fonction en chaîne. La conception d'un mécanisme tiers de punition et de récompense pour inciter la coopération des joueurs dans notre jeu de confiance en réseau à N-joueurs est basée sur le crowdsourcing. Plus précisément, les observateurs fournissent leur intelligence humaine collective au contrat de coup de pouce pour punir un cluster ou un joueur individuel qui démontre un comportement inapproprié ou fournir une récompense positive pour un bon comportement. Le contrat de nudge gère le mécanisme de récompense-malus sous forme de points de fidélité. Un trustor peut gagner des points de fidélité pour une transaction honnête, un investissement et un engagement dans le jeu et échanger des points gagnés contre des récompenses. De même, le fiduciaire est récompensé pour sa généreuse réciprocité.

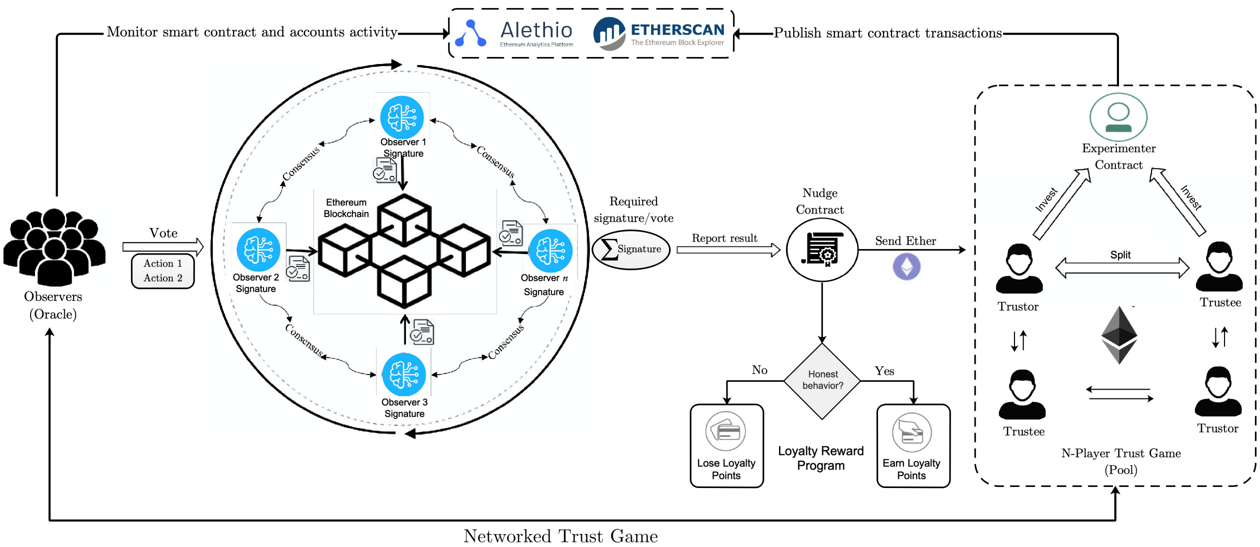


Figure A.7: Architecture des réseaux mobiles améliorés FiWi avec MEC équipé par l'IA pour des applications Internet tactiles immersives.

Les points de fidélité maintiennent les joueurs engagés et conscients des objectifs généraux, c'est-à-dire l'augmentation du gain total, l'efficacité sociale et la réciprocité normalisée. De plus, les joueurs ont un profil de score associé à leur clé publique, selon lequel les joueurs gagnent 1 point pour chaque action honnête et perdent 1 point si leur action est malhonnête. Le contrat nudge gère le profil de scoring. Trustor et le trustee peuvent vérifier l'état de leurs points de fidélité en appelant respectivement la fonction *getTrustorLoyalty*() et *getTrusteeLoyalty*(). De plus, une stratégie incitative a été conçue pour incorporer les principes de la psychologie comportementale en utilisant les résultats économiques pour rendre le système plus efficace pour changer le comportement des joueurs. Les joueurs gagnent une récompense monétaire sous forme d'Ether après avoir atteint un certain nombre de points de fidélité dans le jeu, par exemple, 10 points = 1 Ether. Les Ethers gagnés sont ajoutés à la dotation X du joueur, qui sera utilisée pour l'investissement et le gain lors des prochains tours de jeu.

Nous avons développé une plate-forme CoZ pour permettre aux observateurs de contrôler à distance les gestes du robot social Pepper de Softbank placé devant l'administrateur et d'avoir un dialogue en temps réel via une traduction texte-parole basée sur le Web. L'interface utilisateur de CoZ est construite à l'aide d'un serveur Web Django. Le syndic peut communiquer avec Pepper par la voix et la tablette tactile de Pepper. Pour prendre en charge la communication vocale, nous avons mis en place un outil Web de conversion de la parole en texte. Lorsque le texte est extrait de la voix, le dépositaire peut voir son message sur la tablette de Pepper pour le vérifier. Ensuite, la fonction de synthèse vocale appelle une autre fonction pour ajouter des champs supplémentaires au message principal (texte extrait), y compris *sequence_ID*, *sender_ID*, *message_type*, et *time* pour rendre le message distinct sur le serveur Django. La fonction appelée exécute un processus de marshaling et envoie le message au serveur Django via le middleware OOCSI.

Notre système CoZ développé a deux types de messages: information et contrôle. Les observateurs créent les messages d'information. Ce type de message est multidiffusé à tous les observateurs et au trustee via Pepper pour les mettre à jour, mais pas au trustor. Le syndic peut voir tous les messages d'information sur la tablette de Pepper. De plus, Pepper utilise une fonction de synthèse

Table A.1: Indices sociaux utilisés par Pepper dans une stratégie de persuasion mixte.

Round number	Trusted behavior action	Untrusted behavior action
Round 1	*Text-to-speech:* Trust Game is a cooperative investment game.	Untrusted behavior will be shown in Round 2
	You all play together to get the best total payoff!	
Round 2	*Text-to-speech:* Awesome! That's a split worth celebrating!	*Text-to-speech:* If this behavior is repeated,
		you will receive a punishment from the observers.
	Embodied communication: Open arm gesture.	*Embodied communication:* Taunting hand gesture.
Round 3	*Text-to-speech:* If this good behavior is repeated,	*Text-to-speech:* Weak reciprocity can cause
	your partner will invest more in the next round.	costly punishment for you.
	Embodied communication: Open arm gesture.	*Embodied communication:* Taunting hand gesture.
Round 4	*Text-to-speech:* Incredible! Your partner must be impressed!	*Text-to-speech:* With such a behavior,
		the punishment will be executed next round.
	Embodied communication: Open arm gesture.	*Embodied communication:* Taunting hand gesture.
Round 5	*Text-to-speech:* Congrats! Your good behavior	*Text-to-speech:* Your bad behavior
	toward your partner has provided you with an incremental	translated into a very weak total payoff.
	total payoff over all rounds of the game.	
	Embodied communication: Open arm gesture.	*Embodied communication:* Taunting hand gesture.

vocale pour transférer les messages des observateurs à l'administrateur. Les messages de contrôle sont utilisés pour des fonctionnalités importantes de l'architecture CoZ, par exemple, effectuer un geste sur Pepper. Lorsqu'un observateur appuie sur un bouton de repère social, l'interface Web CoZ invoque une méthode JavaScript pour appeler un nouvel événement sur le serveur Django. La méthode invoquée définit tous les angles des articulations associées ainsi que les couleurs des LED des yeux de Pepper. Étant donné que deux observateurs ou plus peuvent appuyer simultanément sur le même bouton de repère social ou sur des boutons différents, le serveur Django a mis en place une file d'attente pour synchroniser toutes les commandes émises. Pendant que Pepper effectue un geste, le serveur Django place le geste suivant dans la file d'attente et l'envoie dos à dos à Pepper.

De plus, notre interface utilisateur CoZ fournit une section où un observateur peut observer l'environnement de l'administrateur à travers les yeux de Pepper. Nous avons utilisé les outils OpenCV, Flask et CV2 pour implémenter cette partie. Le serveur Django invoque une méthode sur Pepper appelée "ALVideoDevice" pour commencer à enregistrer des vidéos. Ensuite, le serveur Flask stocke la séquence de vidéos produites avec une URL valide. Pour rendre les flux vidéo en direct accessibles sur Internet, nous avons utilisé un VPN. De plus, notre interface CoZ a utilisé une balise IFrame pour démontrer le streaming vidéo en direct en utilisant l'URL valide. Un IFrame est un document HTML intégré dans un autre document HTML sur un site Web. L'élément HTML IFrame est souvent utilisé pour insérer du contenu provenant d'une autre source, telle qu'une caméra, dans une page Web. Notre interface utilisateur CoZ a également réalisé quatre boutons pour tourner la tête de Pepper vers la gauche, la droite, le haut et le bas. Lorsqu'un observateur appuie sur l'un de ces boutons, l'interface CoZ invoque une méthode pour créer un message de contrôle, un processus de marshaling, et l'envoyer au serveur Django. Dès réception, le serveur Django effectue un démarquage pour extraire le message principal, puis invoque le "ALMotion " avec des paramètres d'initialisation tels que la vitesse, l'angle et le nom de l'articulation. A chaque invocation, Pepper tourne la tête de dix degrés.

De plus, nous avons rédigé deux scénarios, un pour une stratégie de persuasion logique faisant appel au côté gauche du cerveau (c'est-à-dire la logique) et un autre pour une stratégie de persuasion affective faisant appel au côté droit du cerveau (c'est-à-dire les émotions) du curateur. Chaque script contient des phrases pré-spécifiées stockées dans des menus déroulants dans l'interface CoZ, à partir desquelles les observateurs peuvent choisir de pousser le comportement de l'administrateur vers la réciprocité via des messages texte-parole en temps réel. Les différentes stratégies de robot persuasives sont appliquées, y compris la stratégie logique, la stratégie affective et la stratégie mixte.

À titre d'illustration, le tableau A.1 répertorie les indices sociaux utilisés par Pepper dans notre proposition de stratégie de persuasion mixte logique-affective. Dans cette stratégie, un observateur joue la stratégie logique et l'autre observateur joue la stratégie affective de sorte que l'administrateur reçoive des messages mixtes et des communications incarnées mixtes. Selon le comportement du trustee, les observateurs exécutent l'action "Trusted behavior" ou "Untrusted behavior action" à chaque tour de l'expérience. Les signaux sociaux du tableau A.1 permettent aux observateurs de contrôler la synthèse vocale et les communications incarnées de Pepper à l'aide de notre plate-forme CoZ développée. Nous avons mené des expériences à grande échelle impliquant 20 étudiants pour mesurer l'efficacité de nos stratégies de robotique persuasive développées. Semblable à notre dernière expérience dans le jeu de confiance entre deux joueurs, les étudiants participants ne connaissaient pas l'identité de l'autre. De plus, les étudiants n'avaient mené aucune expérience de recherche comportementale auparavant. L'âge des étudiants sélectionnés était compris entre 24 et 32 ans. Trois étudiants étaient des femmes et dix-sept étudiants étaient des hommes. L'expérience a été divisée en quatre essais : ligne de base, stratégie logique, affective et mixte. Chaque essai comportait 5 tours. Nous avons d'abord mené une expérience de jeu de confiance de base, où les fiduciaires n'interagissaient pas avec Pepper, comme cela avait été fait précédemment, suivie d'expériences exposant les fiduciaires aux stratégies de persuasion logiques, affectives et mixtes logiques-affectives de Pepper. Le trustor et le trustee ont tous deux interagi via un compte blockchain avec le contrat intelligent de l'expérimentateur. Le trustor a joué le jeu depuis une pièce séparée, tandis que le trustee était seul dans le laboratoire avec Pepper. Pepper était contrôlé à distance via notre plateforme CoZ par l'observateur. Nous avons utilisé les mêmes réglages de paramètres, c'est-à-dire la dotation $X = 10$ Ether pour le donneur de confiance et $K = 2$. De plus, dans toutes les stratégies persuasives, nous n'avons utilisé aucun mécanisme de dépôt (c'est à dire., $D = 0$).

La figureFig. A.8 démontre l'efficacité supérieure de nos stratégies de persuasion, en particulier celles mixtes faisant appel aux deux côtés du cerveau, résultant en une réciprocité normalisée moyenne bien supérieure à 100 %. De plus, pour mieux révéler les différences entre les stratégies persuasives, nous avons calculé la plage de mesure pour les quatre stratégies. La plage de mesure pour l'expérience de base est de 48.2 (Max=81, Min=32.8), tandis que pour la stratégie logique, elle est de 67.8 (Max=176.4, Min=108,6) et pour la stratégie affective, elle est de 59.4 (Max=165.6, Min=106.2), et la stratégie mixte c'est 67 (Max=194.4, Min=127.4). Comme le montrent les résultats, l'expérience de base a la plus petite plage de mesure. Ensuite, nous avons calculé l'écart type pour l'expérience de base ainsi que les stratégies logiques, affectives et mixtes, qui est égal à 15.6, 21.75, 21.10 et 22.73, respectivement. Les résultats montrent que l'expérience de base a le plus petit écart-type parmi toutes les stratégies considérées, tandis que la stratégie mixte a le plus grand. Enfin, nous avons calculé la variance pour les stratégies de persuasion considérées. La variance calculée est égale à 245.83, 473.17, 445.25 et 517.03 pour la stratégie de base, logique, affective et mixte, respectivement. Sur la base des résultats recueillis, nous observons que l'expérience de base a la plus petite variance et que la stratégie mixte a la plus grande variance.

Le Métaverse et Au-delà: Implémentation de Royaumes Multivers Avancés avec des Appareils Portables Intelligents

Dans ce chapitre, nous gamifions et implémentons les huit royaumes Multivers, le successeur prévu du métaverse, en utilisant Oculus Quest 2, Microsoft HoloLens 2, le robot Pepper de SoftBank Mobile et l'avatar virtuel de Pepper dans le contexte des jeux d'origami et de labyrinthe. Nous avons introduit le Multivers comme architecture pour la conception d'expériences XR avancées. Comme le montre la Fig. A.4, le Multivers se compose de trois paires de variables, chacune avec deux dimensions physiques/numériques opposées Espace/Non-Espace, Temps/Non-Temps et Matière/Non-

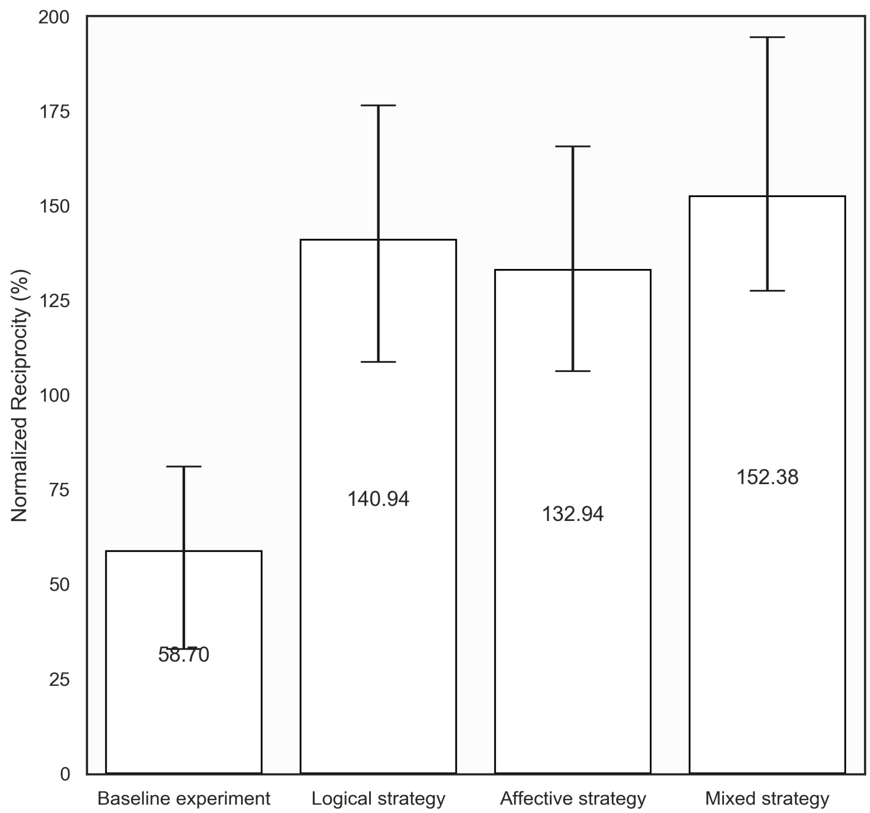


Figure A.8: Réciprocité normalisée moyenne q/p sans (expérience de base) et avec l'utilisation de stratégies de persuasion logiques, affectives et mixtes logique-affectives pour $D = 0$ (montré avec des intervalles de score mesurés minimum à maximum).

Matière, qui donnent lieu à un total de huit royaumes, chacun offrant un type de réalité différent. Il englobe les multiples façons dont les expériences [Temps↔Non-Temps] se produisent, où [Espace ↔ Non-Espace] elles se produisent et sur quoi [Matière ↔ Non-Matière] elles agissent. Chaque combinaison des six variables produit un domaine distinct, couvrant l'ensemble du continuum réalité-virtualité. Dans ce qui suit, nous décrivons chaque domaine plus en détail:

- **Réalité:** Le domaine Réalité se compose des variables Temps/Espace/Matière. Une façon équivalente de voir les choses est Réel/Réel/Atomes, voir Fig. A.4. Nous expérimentons la Réalité comme le domaine des expériences physiques à travers le médium séculaire de la vie réelle. C'est bien sûr le domaine avec lequel nous sommes le plus familiers.
- **Virtualité:** La virtualité se trouve exactement à l'opposé de la réalité dans le domaine du sans-temps/sans-espace/sans-matière, consistant en Autonome/Virtuel/Bits. La virtualité n'est pas soumise aux lois physiques du monde réel. La virtualité et la réalité ancrent le Multivers. Le nom de chacun des autres royaumes est directement lié aux deux ancres en ce que les noms de chaque royaume sur la moitié droite de la Fig. A.4 indiquent leur nature basée sur la Réalité, tandis que les noms de chaque royaume sur la moitié gauche du Multivers indiquent leur nature basée sur la virtualité. Ces six autres domaines améliorent, étendent ou modifient nos expériences basées sur la réalité ou la virtualité. Par conséquent, ils offrent une plus grande possibilité de création de valeur. Un excellent exemple de VR HMD est Oculus Quest 2.

- **Réalité Augmentée:** Parmi celles-ci, la plus familière est sûrement la réalité augmentée, caractérisée par les variables Temps/Espace/Non-Matière. Dans le domaine AR, la technologie numérique est utilisée pour améliorer notre expérience du monde physique. Le produit phare AR HMD est Microsoft HoloLens 2.

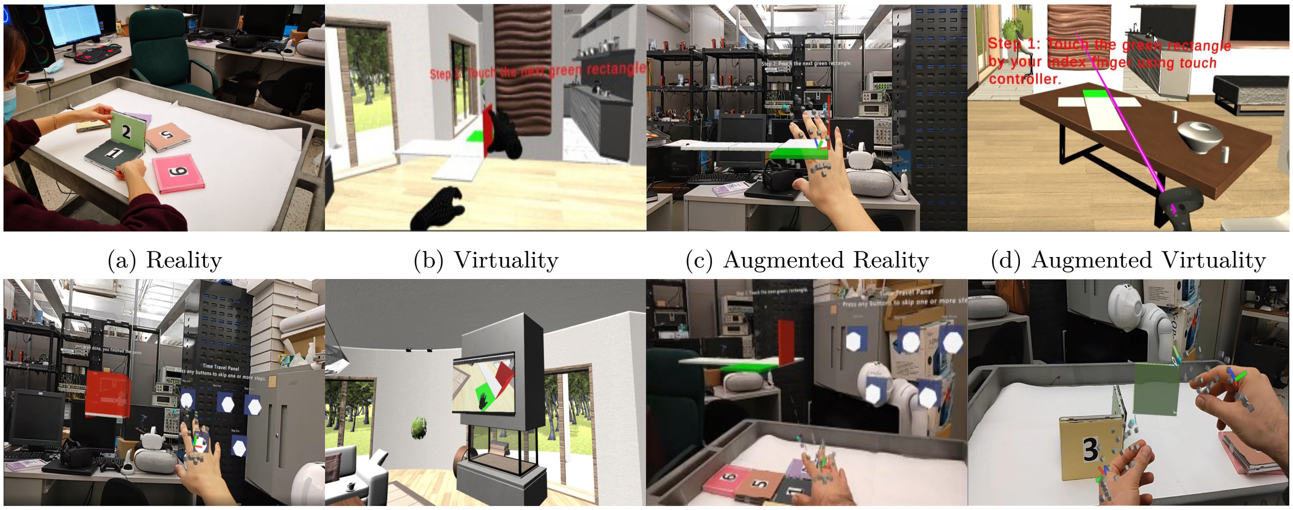
- **Virtualité Augmentée:** Si les bits peuvent augmenter la réalité, alors logiquement les atomes devraient être capables d'augmenter la virtualité. C'est exactement ce qui se passe dans le domaine opposé de la Virtualité Augmentée (VA) caractérisée par les variables Non-Temps/Non-Espace/Matière, qui est largement utilisée pour réaliser des jumeaux numériques. AV fait basculer efficacement une expérience de virtualité de No-Matter à Matter, de Bits à Atoms. Cela signifie que nous prenons quelque chose de matériel et de tactile et que nous l'utilisons pour augmenter une offre autrement virtuelle, résultant en une expérience Autonome/Virtuelle/Atoms. Un exemple populaire est la Wii de Nintendo, où, pour la première fois, les joueurs à la maison pouvaient s'engager physiquement et matériellement dans des jeux informatiques, supprimant l'expérience d'un jeu résidant principalement entre les doigts et le cerveau à un jeu impliquant tout le corps.

- **Réalité Alternative:** Le passage d'événements réels à des événements autonomes distingue la réalité alternative du domaine adjacent de l'AR susmentionné, qui partagent tous deux les variables de la substance numérique et du lieu physique. Cela signifie que si vous pouvez prendre la technologie utilisée pour augmenter la réalité, puis ajouter une dimension de jeu avec le temps d'une manière ou d'une autre, vous pouvez utiliser cette même technologie pour modifier la vision que les gens ont de la réalité devant eux. La réalité alternative comprend les variables Non-Temps/Non-Espace/Non-Matière. Son essence réside dans la construction d'une expérience numérique et sa superposition sur un lieu réel pour créer une vision alternative de la réalité physique. Alternate Reality tire son nom des jeux de réalité alternative. Ces jeux sont devenus de plus en plus populaires dans les cercles marketing en tant que plateformes pour atteindre la foule des joueurs en ligne.

- **Virtualité Physique:** Là où la réalité alternative prend une expérience autrement virtuelle et la joue dans le monde réel, son opposé, la virtualité physique, prend des objets du monde réel (des atomes résidant dans le temps réel) et les conçoit virtuellement. Une telle expérience Temps/Non-Temps/Matière se produit lorsque des artefacts conçus virtuellement prennent une forme matérielle.

- **Réalité Déformée:** Le dernier domaine du côté réel de la dimension spatiale, Réalité Déformée, se compose des variables Non-Temps/Espace/Matière. Contrairement à la réalité augmentée et alternative, ce domaine ne consiste pas à adopter la technologie numérique ou à faire entrer des lieux virtuels dans le monde réel. Au contraire, cela prend une expérience fermement ancrée dans la réalité et ne déplace qu'une seule variable, déplaçant l'événement du temps réel au temps autonome. Ce royaume d'Autonomous/Real/Atoms n'est pas imprégné de la technologie numérique de Non-Matière, ni ne réside dans l'arène virtuelle de Non-Espace. Cela nécessite simplement l'offre de jouer avec ou de manipuler le temps d'une manière qui le rend clairement distinct et différent de l'expérience normale. Un tel voyage dans le temps basé sur la réalité se produit chaque fois que des expériences simulent une autre époque dans le passé ou dans le futur (bien qu'un futur fictif), par exemple, les musées d'histoire vivante ou les conventions de Star Trek.

- **Virtualité en Miroir:** Enfin, la Virtualité en miroir, caractérisée par les variables Temps/Non-Espace/Non-matière, est l'exact opposé de la Réalité déformée, où la Virtualité est liée au



(a) Reality (b) Virtuality (c) Augmented Reality (d) Augmented Virtuality

(e) Alternate Reality (f) Physical Virtuality (g) Warped Reality (h) Mirrored Virtuality

Figure A.9: Implémentation hors ligne pour un joueur : Création d'un cube en origami dans les huit royaumes Multivers différents.

> Temps réel. À l'intérieur de Virtuality, opérant via une sorte d'avatar, vous restez généralement libre de faire ce que vous voulez, alors qu'à l'intérieur de Mirrored Virtuality, vous restez inexorablement lié à ce qui se passe dans le monde réel, en temps réel, à chaque instant. Ce domaine tire son nom du terme MirrorWorlds inventé par l'informaticien de Yale David Gelernter en 199. L'utilisation de tout type d'outil de suivi en ligne, par exemple Google Flu Trends (GFT), est qualifiée de virtualité miroir puisque ce domaine offre un temps réel vue, une perspective en miroir, de ce qui se passe là-bas, dans le monde.

Alors que la mise en œuvre des deux domaines Multivers, Virtuality et AR, est simple avec Quest 2 et HoloLens 2, la réalisation des domaines Multivers restants, à l'exception de la réalité ancrée dans la vie réelle, est plus difficile car ils nécessitent l'utilisation de mains virtuelles, de contrôleurs haptiques, et des mécanismes de soutien supplémentaires, comme nous le verrons bientôt. Pour illustration, Fig. A.9 donne un aperçu de notre implémentation des huit domaines Multivers différents, que nous décrivons plus en détail techniquement dans ce qui suit.

Pour commencer, la Fig. A.9(a) montre comment notre jeu d'origami de cube est joué dans le royaume de la Réalité en utilisant six carrés physiques, chacun numéroté et coloré différemment. Notez que dans ce domaine, le joueur ne reçoit aucune aide cognitive puisqu'il est assez évident de construire un cube d'origami physique. Ensuite, la Fig. A.9(b) montre le domaine Virtuality en utilisant la quête 2 susmentionnée comme lunettes de réalité virtuelle. Contrairement à Reality, le joueur interagit avec des carrés virtuels pour plier un cube d'origami virtuel. Étant donné qu'un joueur portant des lunettes VR ne peut pas voir ses propres mains physiques, nous avons conçu des mains virtuelles qui suivent les mouvements physiques des mains du joueur en temps réel. De plus, nous avons intégré un tableau de texte dans la scène virtuelle pour donner des instructions écrites pour chaque étape. De plus, nous donnons des repères visuels en colorant en vert le prochain carré virtuel à toucher par le joueur. Une fois que le joueur a plié le carré, sa couleur passe au rouge et le carré virtuel suivant est surligné en vert. En remplaçant Quest 2 par HoloLens 2, le royaume de la réalité augmentée est réalisé, où le joueur interagit avec des carrés holographiques au lieu de carrés virtuels. Notez que, contrairement à Reality, ici le joueur utilise ses propres mains physiques pour interagir avec les carrés holographiques, comme illustré sur la Fig. A.9(c). Semblable à Virtuality, nous avons intégré un tableau de texte holographique pour donner des instructions écrites pour chaque étape et avons également utilisé la même coloration vert/rouge des carrés (holographiques). Après avoir augmenté la Réalité, augmentons maintenant la Virtualité. La Fig. A.9(d) décrit le domaine de la virtualité augmentée. Le joueur porte Quest 2, mais doit puiser dans Matière au lieu de Non-Matière. Pour ce faire, le joueur reçoit un retour haptique via un contrôleur tactile Oculus portable pour l'informer de la bonne ou de la mauvaise action effectuée lors du pliage du cube d'origami virtuel. Semblable au royaume Virtuality, un tableau de texte virtuel est intégré dans la scène pour inciter le joueur à effectuer les bonnes actions pendant le jeu. De plus, un faisceau laser (voir la ligne rose sur la Fig. A.9(d)) guide le joueur pour sélectionner le pliage d'un objet virtuel en appuyant sur un bouton du contrôleur tactile.

Pour chaque étape réussie, le joueur ressent une courte vibration haptique dans ses mains. Ensuite, pour implémenter le domaine Alternate Reality dans la Fig. A.9(e), le joueur porte HoloLens 2 pour accéder aux objets holographiques. Contrairement à la réalité augmentée, cependant, nous devons réaliser la variable Non-Temps en intégrant un panneau de voyage dans le temps holographique pour permettre au joueur d'avancer vers une étape spécifique, de revenir en arrière ou de la rejouer. Par conséquent, le joueur peut sauter une ou plusieurs étapes intermédiaires en utilisant le panneau de voyage dans le temps. Le joueur crée le cube origami physique immédiatement après. Le joueur peut profiter d'un tableau de texte supplémentaire intégré au-dessus des objets holographiques, qui informe de manière autonome le joueur de la bonne décision. La Fig. A.9(f) illustre la mise en œuvre du royaume Physical Virtuality, où le joueur porte d'abord Quest 2 pour regarder un court didacticiel étape par étape sur un écran de télévision virtuel. À la fin du didacticiel, le joueur est invité à décoller la quête 2 et à construire physiquement le cube. Pour découvrir No-Time tout en créant un cube physique dans le royaume Réalité Déformée, le joueur porte HoloLens 2 pour accéder au panneau de voyage dans le temps holographique susmentionné. Comme le montre la Fig. A.9(g), le joueur est capable de se déplacer virtuellement dans le temps pour voir le pliage du cube holographique, puis en crée un physiquement. Enfin, la Fig. A.9(h) illustre notre implémentation du domaine Mirrored Virtuality, où le joueur porte HoloLens 2. Lors de la construction du cube origami physique, HoloLens 2 met à jour l'état du cube holographique en fonction des progrès récents du joueur. De plus, le joueur peut effectuer des actions supplémentaires sur le cube holographique, par exemple, faire pivoter, déplacer et redimensionner.

La figure A.10 illustre l'architecture de haut niveau de notre plate-forme CoZ développée, qui intègre Quest 2, HoloLens 2 et Pepper avec Amazon MTurk pour le crowdsourcing des travailleurs/joueurs en ligne. Nous appliquons une approche en couches pour concevoir notre plateforme, qui offre une évolutivité améliorée et une administration, un dépannage et une maintenance simplifiés. Les services, interfaces et protocoles développés sont structurés selon les cinq couches suivantes:

- **Couche Demandeur:** Un demandeur définit une tâche de renseignement humain (HIT) pour recruter plusieurs travailleurs MTurk en ligne pour accomplir une tâche désignée. Selon Amazon MTurk, un HIT représente une tâche virtuelle créée par un demandeur et un ou plusieurs travailleurs peuvent soumettre une réponse appropriée. Si le demandeur accepte la réponse soumise, le ou les travailleurs concernés recevront une récompense prédéfinie. Nous avons appliqué CoZ pour assister Pepper pendant le jeu afin de permettre un dialogue en temps réel entre le demandeur et le ou les travailleurs. De plus, le demandeur utilise Pepper

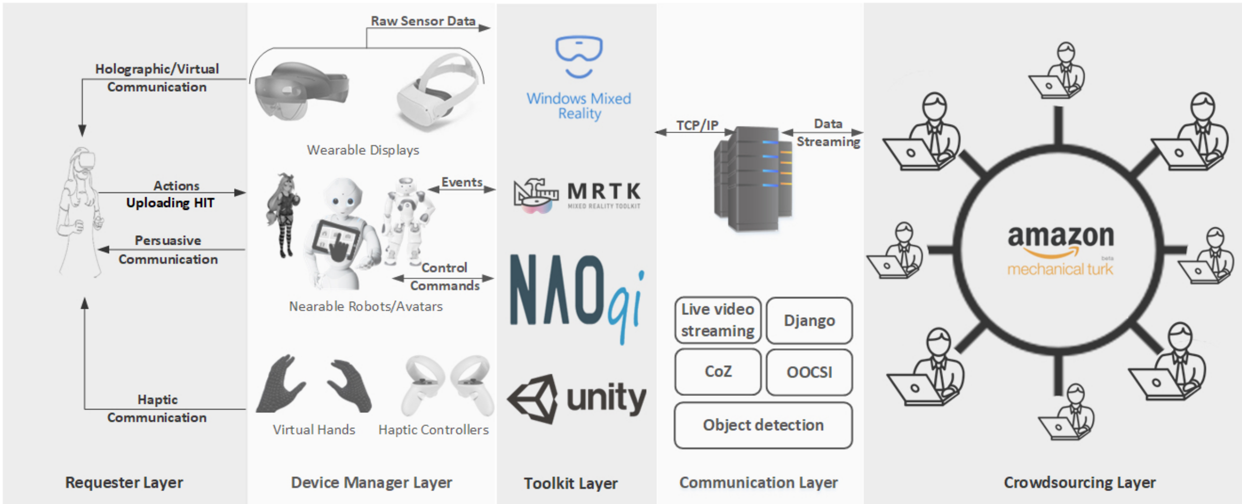


Figure A.10: Architecture de haut niveau de notre plate-forme CoZ développée intégrant Quest 2, HoloLens 2, le robot humanoïde social Pepper et les travailleurs Amazon MTurk externalisés.

pour accéder à l'interface CoZ afin de définir et de télécharger un HIT à l'aide de la tablette intégrée de Pepper.

- **Couche Device Manager:** Nous utilisons une bibliothèque de médiateurs de pointeurs pour pouvoir interagir avec des objets holographiques, y compris le rendu 3D et la détection de collision dans cette couche. Cette bibliothèque fournit deux types d'interactions : (i) toucher/saisir des objets holographiques et (ii) détecter des événements de main. Nous équipons également nos objets de jeu virtuels d'un soi-disant Collider et ImixedRealityPointerHandeler en tant que script insoluble pour recevoir les événements de faisceau laser de pointeur créés par les contrôleurs haptiques.

- **Couche Toolkit:** Nous utilisons plusieurs outils et bibliothèques pour gérer tous les événements, les commandes de mouvement et le traitement des données brutes des capteurs. Plus, précisément, nous avons utilisé la bibliothèque Windows Mixed Reality (WMR) pour combiner les expériences AR et MR avec des HMD compatibles. De plus, nous avons utilisé le Mixed Reality Toolkit (MRTK) de Microsoft pour accélérer le développement d'applications RM multiplateformes. De plus, nous appliquons le NAOqi de Pepper pour exécuter les commandes reçues sur le robot. Nous utilisons le moteur de jeu Unity 3D pour affiner la relation entre le suivi de la tête, l'avatar virtuel et les mains virtuelles.

- **Couche de Communication:** Le serveur CoZ est construit à l'aide d'un serveur Web Django et d'un middleware Python OOCSI pour créer des connexions entre les composants et les clients Web. Tout d'abord, pour joindre la couche toolkit avec la plate-forme CoZ, nous implémentons un socket TCP/IP local. Ensuite, nous utilisons les bibliothèques Python, notamment OpenCV, Flask et CV2, pour fournir des flux vidéo en direct accessibles sur Internet via les caméras intégrées de Pepper. Enfin, pour télécharger un HIT sur MTurk, nous utilisons Amazon Boto3.512 pour l'intégrer au serveur CoZ en convertissant un HTML en direct au format XML, qui est un format d'entrée valide pour la plateforme MTurk.

- **Couche de Crowdsourcing:** Les travailleurs de la foule utilisent l'interface CoZ pour pouvoir avoir une conversation en temps réel avec le demandeur via Pepper ou HMD, en utilisant

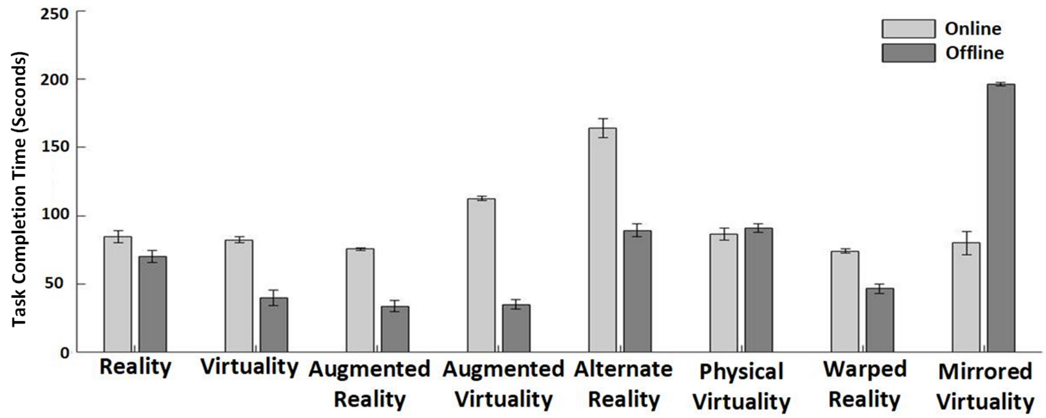


Figure A.11: Temps d'exécution moyen expérimental des tâches (TCT) du jeu d'origami de cube avec et sans l'utilisation de travailleurs Amazon MTurk externalisés dans différents domaines du Multivers (chacun illustré avec des intervalles TCT minimum à maximum).

un service d'IA de synthèse vocale pour obtenir des résultats plus précis. De plus, le CoZ dispose de plusieurs boutons de signaux sociaux pour effectuer des gestes physiques et des signaux vocaux sur Pepper via une communication incarnée. De plus, notre interface utilisateur CoZ fournit une section où les travailleurs peuvent surveiller l'environnement physique via les caméras Pepper/HoloLens 2/Quest 2. Enfin, nous intégrons quatre boutons directionnels dans l'interface CoZ où le ou les travailleurs MTurk peuvent tourner la tête de Pepper et la déplacer dans quatre directions différentes.

Nous utilisons le temps d'exécution des tâches (TCT) comme principale mesure d'intérêt pour la comparaison de différents environnements XR, y compris, mais sans s'y limiter, la réalité virtuelle et la réalité augmentée. La figure A.11 compare les résultats TCT moyens expérimentaux du jeu d'origami de cube avec cinq joueurs en ligne (travailleurs MTurk) et cinq joueurs hors ligne (humains locaux) dans chaque domaine Multivers. Tous les joueurs recrutés, âgés de 25 à 32 ans, n'avaient aucune expérience avec HoloLens et Quest. Les joueurs recrutés sont entrés dans notre laboratoire librement et volontairement, sans être au courant de l'étude en cours. Avant de commencer les expériences, nous avons formé tous les joueurs de la même manière à l'utilisation des contrôleurs portables, HoloLens et Quest. Pour une comparaison équitable, nous n'avons pas recruté le même joueur pour construire le cube origami dans deux royaumes différents afin d'éviter les joueurs biaisés. De plus, nous avons isolé les joueurs les uns des autres pour créer une zone sans distraction lors de chaque expérience. De même, nous avons évité des méthodes comme se tenir à côté des joueurs tout en mesurant le TCT. Au lieu de cela, dans notre configuration expérimentale, nous avons utilisé le moteur de jeu Unity qui calculait automatiquement le score TCT de chaque joueur. De cette façon, les joueurs se sont sentis à l'aise tout en jouant au jeu et en surmontant les défis de la tâche sans ressentir aucune influence extérieure.

Considérons d'abord le domaine de la réalité, où les joueurs en ligne et hors ligne n'avaient pas accès à l'assistance cognitive. Les joueurs étaient censés construire un cube en origami basé sur leurs connaissances antérieures dans ce domaine. La différence entre les TCT obtenus pour les joueurs hors ligne et en ligne est de 10 secondes. À l'inverse, dans le domaine Virtualité, les joueurs avaient accès à un tableau de texte virtuel. Par conséquent, ils n'ont pas eu besoin de comprendre comment construire un cube d'origami en se basant sur leurs propres connaissances. Au lieu de cela, ils ne pouvaient accomplir la tâche qu'en suivant les instructions sur le tableau virtuel et les repères visuels. Nous observons sur la Fig. A.11 que l'assistance virtuelle offerte est efficace car les joueurs obtiennent un TCT plus faible que dans le domaine de la Réalité. Les joueurs avaient les mêmes repères visuels et assistance cognitive dans le domaine de la réalité augmentée, bien qu'une version holographique de ceux-ci. Par conséquent, les joueurs pouvaient utiliser leurs vraies mains pour manipuler les composants du jeu holographique. Ce faisant, ils obtiennent un TCT encore plus bas que dans le domaine de la virtualité, où ils devaient utiliser une version virtuelle de leurs mains. Cependant, contrairement au domaine de la virtualité, dans le domaine de la virtualité physique, les joueurs peuvent profiter du retour haptique fourni via le contrôleur tactile Oculus portable pour donner aux joueurs un retour en temps réel sur leurs actions effectuées tout en pliant le cube d'origami virtuel. Nous observons que le TCT atteint dans ce domaine est inférieur au score TCT dans le domaine de la virtualité. Ce résultat montre que le retour haptique est efficace pour permettre aux joueurs d'effectuer la bonne action sur le cube virtuel.

Dans le domaine de la réalité alternative, nous avons observé que les joueurs adoptaient une approche intéressante, même si les joueurs pouvaient utiliser le panneau de voyage dans le temps pour construire le cube origami en sautant une ou plusieurs étapes. Plus, précisément, nous avons observé que la plupart des joueurs hors ligne préféraient construire eux-mêmes le cube origami plutôt que de sauter plusieurs étapes et de terminer le jeu le plus rapidement possible. Un seul des joueurs hors ligne a sauté plusieurs étapes pour passer à l'étape cinq du jeu en utilisant le panneau et effectuer la dernière étape par elle-même. C'est la raison de la différence considérable entre le TCT atteint des joueurs hors ligne et en ligne dans ce domaine. Ensuite, le royaume virtualité physique applique le même scénario que le royaume Reality, sauf que les joueurs du royaume Physical Virtuality pourraient regarder une vidéo sur une TV virtuelle via Quest 2 pour connaître à l'avance les indices essentiels du jeu. C'est la principale raison pour laquelle les joueurs en ligne et hors ligne pourraient terminer le jeu presque avec le même TCT. Sans regarder la vidéo, le TCT obtenu est inférieur à celui du royaume Reality car les joueurs ont bénéficié à l'avance des repères essentiels pour construire le cube origami.

Dans le royaume réalité déformée, les joueurs avaient accès au panneau de voyage dans le temps tout en construisant le cube en origami. Dans ce domaine, les joueurs en ligne ont atteint le TCT le plus bas parmi tous les scénarios en ligne. À l'inverse, les joueurs hors ligne ont obtenu un TCT inférieur à celui du domaine Reality. De plus, bien que les joueurs hors ligne aient connu le TCT le plus élevé dans le domaine de la virtualité en miroir, nous avons constaté que c'était le domaine le plus excitant pour les joueurs hors ligne. Cela est dû au fait qu'ils pouvaient voir un cube holographique synchronisé en temps réel qui leur permettait de redimensionner, déplacer ou tourner les composants holographiques. En revanche, les joueurs en ligne ont préféré accomplir le jeu le plus tôt possible pour gagner la récompense offerte.

Ensuite, considérons le jeu de labyrinthe. Le tableau A.2 montre que les trois premiers domaines atteignent un TCT inférieur à celui de l'expérience de base, qui a atteint un TCT de 34 secondes nécessitant 0 commande. Cela est dû aux raisons suivantes. Tout d'abord, contrairement au Pepper, les limitations physiques n'empêchent pas son avatar de franchir un obstacle dynamique en sautant simplement par-dessus. Deuxièmement, la frontière virtuelle/holographique aide les travailleurs à émettre moins de commandes dupliquées mais plus efficaces. Et troisièmement, le panneau de voyage dans le temps offre aux joueurs la possibilité de terminer le jeu de labyrinthe avec seulement trois commandes dans le domaine réalité alternative. À l'inverse, le domaine réalité atteint le TCT le plus élevé puisque Pepper ne peut pas contourner l'obstacle dynamique de manière autonome

Table A.2: Résultats expérimentaux sur TCT et nombre de commandes émises pour jouer au jeu de labyrinthe avec des travailleurs MTurk en ligne.

Multiverse Name	TCT (seconds)	Issued Commands
Alternate Reality	9	3
Augmented Virtuality	23	9
Virtuality	27	13
Baseline	34	0
Physical Virtuality	68	26
Mirrored Virtuality	128	15
Warped Reality	134	17
Augmented Reality	171	21
Reality	237	31

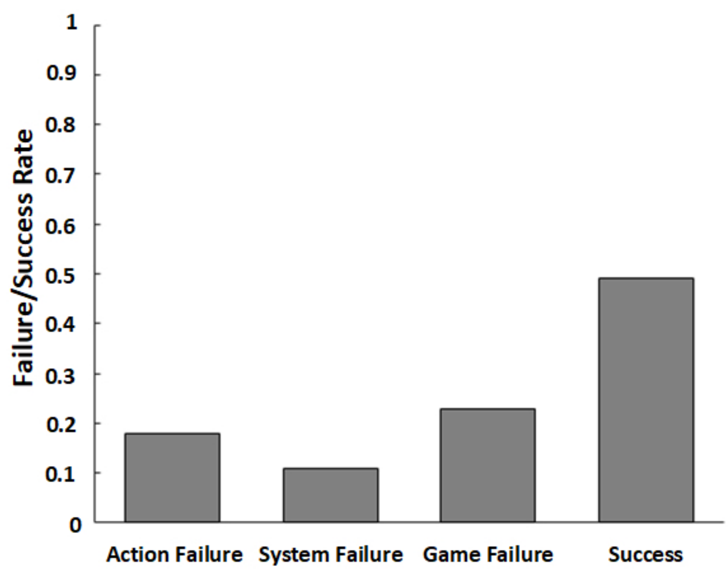


Figure A.12: Experimental failure and success rates of origami and maze games.

en s'appuyant uniquement sur les informations SLAM précédemment acquises. De plus, dans ce domaine, les travailleurs ne peuvent accéder à aucune assistance cognitive telle que notre frontière virtuelle/holographique.

Comme illustré sur la Fig. A.12, au total, nous avons soumis 128 HIT à Amazon MTurk, ce qui a permis de recruter 61 travailleurs en ligne pour mener nos expériences. Au moins deux travailleurs de MTurk étaient impliqués dans chaque royaume Multivers pendant le jeu de labyrinthe. Comme le montre la figure 4.4, nous avons eu un taux d'échec d'action de 0,18 (ou 18 %), où les joueurs n'ont pas pris la bonne décision pendant le jeu de labyrinthe. De plus, dans 11 % des cas de jeux de labyrinthe, nous avons rencontré des défaillances du système, qui dans la plupart des cas étaient dues au manque de connectivité Internet et à l'interruption de HoloLens 2. Le taux d'échec du jeu représentait 23 % de nos échecs rencontrés, où l'incapacité de trouver un travailleur pour continuer le jeu ou le manque de connaissances pratiques des travailleurs étaient des échecs de jeu typiques. Enfin, nous avons observé que les 48 % restants des HIT soumis ont été complétés avec succès

Figure A.13: Le point de vue de la NSF sur la recherche G suivant : Objectifs à court, moyen et long terme, y compris le métaverse.

dans le sens où les travailleurs ont effectué toutes les étapes sans faire face à aucun des échecs susmentionnés.

Blockchainiser le Jeu Wordle dans les Royaumes Métavers Avancés à L'aide de Dispositifs Portables Intelligents

Nous avons vu que le Métavers utilisera les HMD et XR comme moyen de connecter les avatars et les utilisateurs dans le monde réel. De plus, le Métavers fournit des expériences gamifiées autour des technologies Web 3.0 émergentes pour être le précurseur du soi-disant Multiverse et servir d'architecture d'expérience XR avancée au-delà de la VR et de la RA conventionnelles. Le Métavers est la prochaine étape après Internet, similaire à la façon dont l'Internet mobile a étendu et amélioré l'Internet des débuts dans les années 1990 et 2000. La Fig. A.13 illustre le point de vue de la NSF sur les objectifs de recherche G suivant à court et à long terme, y compris bon nombre des technologies 6G clés émergentes et futures telles que le métaverse. Le métaverse représente la hiérarchie de haut niveau des espaces virtuels persistants qui peuvent également s'interpoler dans la vie réelle, de sorte que des expériences sociales, commerciales et personnelles émergent grâce aux technologies Web 3.0. Que ce soit par le biais de la VR, de la AR ou d'un smartphone, le métaverse et les expériences qu'il contient peuvent se connecter au monde réel. Il est important de noter qu'en plus d'inciter les transactions, le Métavers devrait fournir ce que les auteurs appellent des expériences gamifiées, étant donné que la gamification englobera l'activité et l'histoire autour des technologies émergentes de la blockchain Web 3.0.

Les jeux sérieux sont devenus un outil d'enseignement à distance utile, en particulier pendant les confinements liés au Covid-19. Un autre type de jeu qui a fait l'objet d'une attention particulière pendant la pandémie de Covid-19 sont les jeux dits blockchain, qui permettent aux joueurs de gagner leur vie sous la forme de crypto-monnaies ou de jetons non fongibles (NFT). Ici, nous considérons le

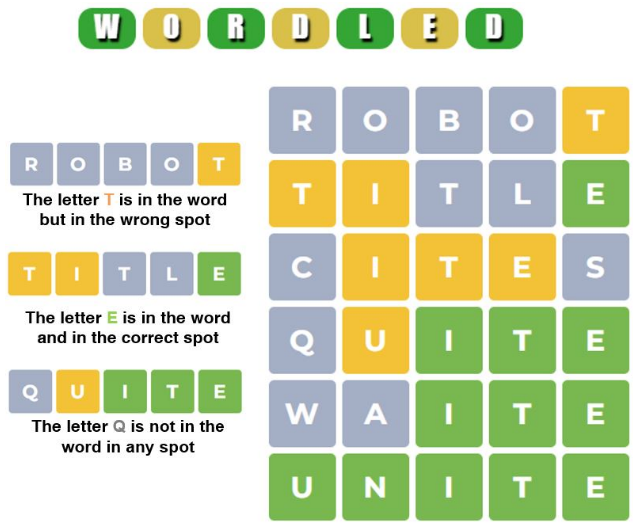


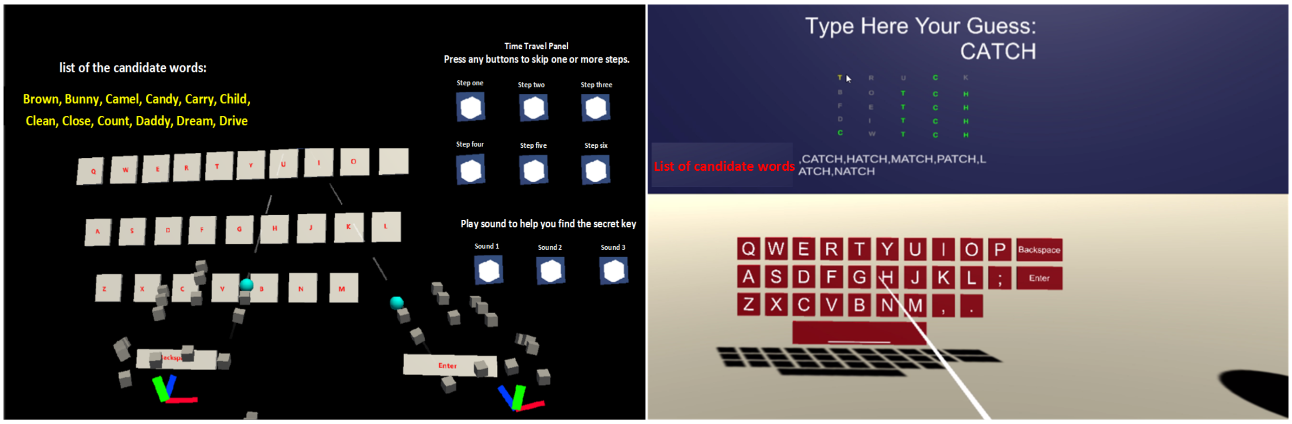
Figure A.14: Jeu Wordle original trouvant le mot secret UNITE en six essais bénéficiant d'indices donnés sous forme de clés à code couleur.

jeu Wordle, qui a été développé pendant les fermetures pandémiques et est devenu un phénomène Internet mondial. En 2021, l'ingénieur logiciel Josh Wardle a inventé un jeu de mots pour sa petite amie, qui l'a à son tour appelé Wordle, un mélange de "mot" et du nom de famille de son petit ami. Devant l'excitation de sa petite amie, il a décidé de publier le jeu Wordle sur Internet. Quelques semaines plus tard, un engouement mondial a commencé engageant des millions de joueurs.

En raison de son énorme succès, en janvier 2022, le New York Times a acheté le jeu pour des millions de dollars et l'a transformé en un défi quotidien changeant à résoudre via une application ou un navigateur. Le jeu Wordle est facile à comprendre et fonctionne comme suit. Le but du jeu est de trouver un mot secret composé d'exactement cinq lettres en six essais. A titre d'illustration, la Fig. A.14 montre le jeu Wordle joué pour le mot secret UNITE. Dans cet exemple illustratif, le joueur réussit après six essais en bénéficiant d'indices cognitifs sous la forme de clés colorées qu'il a reçues lors de chacune des cinq tentatives précédentes. Après chaque tentative, les touches changent de couleur (verte, jaune ou grise par défaut) pour indiquer la signification de chacune des cinq lettres choisies à chaque tour de jeu. Concrètement, une clé verte indique que la lettre est correcte et au bon endroit, tandis qu'une clé jaune indique que la lettre est présente dans le mot secret mais au mauvais endroit. Une touche grise par défaut indique que la lettre n'est pas dans le mot secret. En fonction du nombre d'essais requis, un joueur gagne des points qui peuvent être partagés avec d'autres joueurs en ligne. Les points gagnés sont ajoutés au score total des jours précédents.

Comme illustré à la Fig. A.15, nous adaptons le jeu Wordle original aux domaines d'expérience distincts du Multivers en utilisant Oculus Quest 2 et Microsoft HoloLens 2, deux appareils portables intelligents VR/AR à la pointe de la technologie). Dans notre implémentation, nous accordons une attention particulière au développement d'indices cognitifs avancés pour jouer au jeu Wordle dans chacun des huit domaines Multivers suivants:

- **Réalité:** Les joueurs pouvaient jouer au Wordle sur Internet avec le même ensemble de données que la version originale, plus des clés à code couleur intégrées comme indices cognitifs.



(a) (b)

Figure A.15: Mise en œuvre hors ligne pour un seul joueur : Jouer au jeu Wordle original dans les différents royaumes Multivers à l'aide d'un clavier holographique/virtuel, d'un panneau de voyage dans le temps, d'une liste de mots candidats, d'une assistance vocale, d'un pointeur à faisceau laser et de touches à code couleur intégrées comme indices cognitifs. (a) a démontré tous les signaux cognitifs associés à HoloLens 2, et (b) a illustré tous les signaux cognitifs Quest 2.

- **Virtualité:** Nous connectons Quest 2 et ses contrôleurs à un tableau d'indices cognitifs contenant une liste de mots candidats. La liste est mise à jour à chaque étape en fonction des suppositions des joueurs et des mécanismes de filtrage SQL de la base de données.
- **Réalité Augmentée:** Les joueurs pouvaient accéder à la liste mentionnée via HoloLens 2 ainsi que plusieurs boutons sonores dans la scène pour mettre d'autres sens humains en dehors de la vue pour trouver la clé secrète en un temps plus court.
- **Virtualité Augmentée:** Les joueurs reçoivent un retour haptique via les contrôleurs Oculus pour les mettre à jour sur leurs mauvaises suppositions en ressentant une courte vibration dans leurs mains en présence de la liste des mots candidats.
- **Réalité Alternative:**: Nous intégrons un panneau pour permettre aux joueurs d'avancer vers une étape spécifique, de reculer ou de la rejouer. Il était accessible via HoloLens 2 et proposait quelques mots de cinq lettres contenant plusieurs lettres vertes ou jaunes.
- **Virtualité Physique:** Les joueurs portent d'abord Quest 2 pour regarder un didacticiel sur une télévision virtuelle afin de s'assurer qu'ils comprennent parfaitement les règles du jeu. Ensuite, nous leur avons demandé de jouer au jeu en utilisant la version originale sans repères cognitifs.
- **Réalité Déformée:** Les joueurs portent HoloLens 2 pour accéder au panneau tout en jouant au jeu Wordle original. Le panel proposait les meilleurs mots candidats, et les joueurs pouvaient les appliquer pour terminer le jeu en un temps plus court.
- **Virtualité en Miroir:** HoloLens 2 met à jour l'état du jeu Wordle holographique en fonction aux progrès récents des joueurs à l'aide d'un PC en connectant les joueurs à la liste de mots candidats.

Nous avons introduit une version multijoueur du jeu en mettant en place un contrat intelligent cognitif pour permettre à un expert distant de transférer tout ou partie de ses jetons gagnés à

Table A.3: Résultats expérimentaux pour jouer au jeu Wordle dans le domaine multivers de la réalité sur Internet.

TRAIN	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Tries	2	5	4	4	5	6	6	6	6	5	6	4	3	3	3
TCT	45	230	139	150	183	300	420	37	428	97	112	52	105	63	90

AHINT	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
Tries	6	6	3	6	6	5	6	-	-	5	3	4	6	-	-
TCT	673	309	133	262	355	233	366	-	-	55	37	154	79	-	-

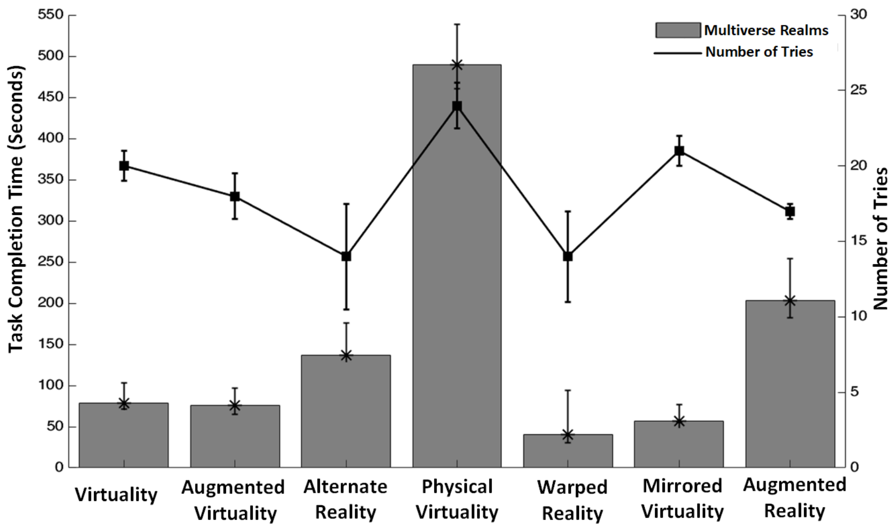


Figure A.16: Résultats expérimentaux pour jouer au jeu Wordle pour le mot secret TRAIN dans les sept royaumes multivers restants en utilisant nos repères cognitifs avancés activés par portable intelligent (affichés avec des intervalles minimum à maximum).

des joueurs locaux. De plus, les experts à distance peuvent envoyer une assistance à distance en mots à d'autres joueurs pour collecter une récompense. Les jetons sont représentés par un contrat intelligent ERC-20. Nous avons déployé les deux contrats intelligents sur le réseau de test officiel d'Ethereum, Ropsten. Le contrat intelligent cognitif peut être invoqué à l'aide de sa clé publique et de l'interface binaire d'application (ABI). De plus, notre contrat intelligent contient deux variables principales: msg.value, qui indique une transaction soumise, et msg.value. sender représente l'adresse du joueur qui a envoyé une transaction à des experts distants. Nous avons également implémenté deux fonctions pour fournir des mécanismes de cisaillement: UpdateAssistanceFunction et Word-Function. UpdateAssistanceFunction permet aux experts distants de définir un nouveau mot où il prend un msg.value dans une chaîne et le transfère sur le compte des experts. WordFunction permet aux acteurs locaux de recevoir le(s) mot(s) défini(s) par les experts distants. Après l'exécution de chaque fonction, un événement est utilisé pour créer des notifications et des journaux enregistrés qui aident davantage les joueurs distants et locaux avec l'état et les activités actuels du jeu.

Nous avons considéré le temps d'achèvement des tâches (TCT) donné en secondes et le nombre d'essais requis comme le deux mesures de performance intéressantes pour comparer les différents

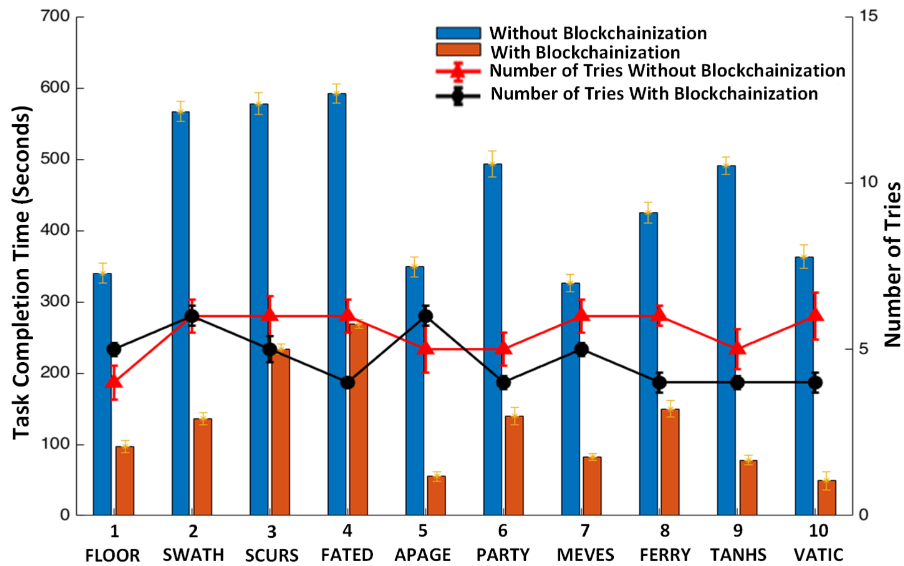


Figure A.17: Résultats expérimentaux pour une version multijoueur du jeu Wordle avec/sans blockchainisation avec dix mots sélectionnés au hasard dans la base de données Wordle de mots secrets de cinq lettres (affichés avec des intervalles minimum à maximum).

domaines Multivers. Nous avons recruté 15 joueurs en ligne, impliquant des novices (labellisés #1 à #9) et des experts (labellisés #10 à #15), selon qu'il a déjà joué au jeu Wordle et acquis quelques stratégies. Tous les participants ont joué deux fois au jeu, une fois pour un mot secret commun de cinq lettres (TRAIN) et une fois pour un mot inhabituel (AHINT). Le tableau A.3 montre notre TCT moyen mesuré et le nombre d'essais. Il est intéressant de noter que les joueurs experts ont besoin d'un TCT moyen comparable pour trouver les mots secrets communs et peu communs (86.05 secondes pour TRAIN et 80.25 secondes pour AHINT), alors que le TCT moyen des joueurs novices a augmenté de manière significative (214.67 secondes pour TRAIN contre 333 secondes pour AHINT). Cela est dû au fait que les experts ont développé une stratégie qui fonctionne indépendamment du mot secret réel. Nous avons observé qu'ils choisissent des mots candidats qui ont au moins deux voyelles et les lettres les plus fréquentes de manière à réduire le nombre d'essais infructueux. La Fig. A.16 compare les résultats moyens expérimentaux du TCT en jouant au jeu Wordle pour le mot secret TRAIN dans les sept royaumes Multivers restants avec cinq joueurs hors ligne dans notre laboratoire, en utilisant notre cognitif avancé conçu fourni par des dispositifs portables intelligents. Nous observons que la virtualité physique présente la valeur TCT la plus élevée en raison du temps nécessaire pour regarder la vidéo du didacticiel d'introduction et par la suite pour jouer au jeu sans autre assistance cognitive. De plus, nous observons que la valeur TCT en réalité augmentée est meilleure que la réalité (voir tableau A.3), puisque les joueurs avaient accès à la liste des mots candidats. Notez que la valeur du TCT est significativement plus faible dans le domaine Virtualité, car nous avons observé que les joueurs trouvent plus facile d'interagir avec le clavier virtuel qu'avec un clavier holographique. Notez que les plus petites valeurs de TCT ont été mesurées pour les domaines réalité déformée et virtualité en miroir. Dans réalité déformée, les joueurs pouvaient utiliser le panneau de voyage dans le temps et un vrai clavier en même temps. La figure. A.17 vise à combiner les expériences rapportées dans le tableau A.3 (uniquement les acteurs distants, experts et novices) et la Fig. A.16 (uniquement les acteurs locaux), où les experts distants du domaine de la réalité pourraient envoyer une assistance cognitive via Internet aux acteurs locaux du domaine. Domaine de virtualité physique utilisant des contrats intelligents blockchain pour réduire la valeur TCT et le nombre d'essais. Pour vérifier expérimentalement l'efficacité de notre conception avancée d'indices cognitifs, nous avons également examiné le domaine Virtuality pour le mot secret AHINT. La valeur TCT moyenne mesurée était égale à 66,8 secondes. A noter que c'est moins que celui des joueurs experts dans le domaine Reality. Fait intéressant, la valeur TCT était comparable à celle du mot secret commun TRAIN, ce qui indique que notre signal cognitif conçu fonctionne indépendamment du niveau de difficulté réel du mot secret.

Conclusion

Cette thèse a présenté l'Internet of No Things comme un tremplin important vers l'avènement de l'ère post-smartphone 6G. Nous avons fait valoir que si la 5G était censée concerner l'Internet de Tout, pour être transformatrice, la 6G pourrait être à peu près l'opposé de Tout, c'est-à-dire Rien ou, plus techniquement, Aucune chose. L'Internet of No Things offre toutes sortes de services destinés à l'homme sans posséder ni transporter d'appareils informatiques ou de stockage. Au lieu de cela, il envisage des services Internet apparaissant de l'environnement environnant en cas de besoin et disparaissant lorsqu'ils ne sont pas nécessaires. Cette thèse de doctorat est construite sur la base du XR en tant que technologie prometteuse de l'Internet of No Things pour étendre les capacités des humains à développer l'interaction homme-robot/avatar à l'ère des smartphones post 6G. Le chapitre 2 a expliqué que les applications XR multisensorielles sont l'une des quatre applications motrices derrière la 6G pour révolutionner l'évolution sans fil des "objets connectés" à "l'intelligence connectée". Nous avons également souligné que XR est la prochaine génération de plates-formes informatiques mobiles combinant les différentes formes de réalité pour réaliser l'ensemble du continuum réalité-virtualité pour l'extension des expériences humaines. Dans le chapitre 3, nous plaçons le jeu de confiance à N joueurs dans le contexte de la robonomique en tirant parti des caractéristiques bénéfiques des stratégies robotiques persuasives pour favoriser un comportement humain prosocial. Ensuite, le chapitre 4 se concentre sur les huit domaines d'expérience XR distincts de VR / AR de Multiverse. Ensuite, nous avons proposé des scénarios pour adapter un jeu d'origami à un joueur et un jeu de labyrinthe à plusieurs joueurs sur notre plate-forme en couches proposée. Enfin, au chapitre 5, nous avons adopté le jeu Wordle original pour les huit royaumes multivers, le successeur prévu du métaverse, en utilisant des dispositifs portables intelligents à la pointe de la technologie dans ce chapitre. Ensuite, nous avons exploré le potentiel de la blockchain pour tirer parti de l'intelligence des foules dans notre monde de jeu coopératif conçu. Blockchainiser le jeu Wordle (i) permet à des experts distants de coopérer avec des acteurs locaux bénéficiant de la crowd intelligence, et (ii) permet aux joueurs de gagner des jetons et ainsi de réaliser naturellement des jeux play-to-earn par les technologies blockchain émergentes du Web 3.0.