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Design and Investigation of Advanced Human-Centered Blockchain Technologies for the 6G Era

By

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To my parents, sister, family, and friends.
To the memory of my grandmother,
and to all my teachers.

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Abstract

The sixth-generation (6G) of wireless cellular networks is expected to incorporate the latest developments in network infrastructure and emerging advances in technology. 6G will not only explore more spectrum at high-frequency bands but also converge driving technological trends, including connected robotics, artificial intelligence (AI), and blockchain technologies. There is also a strong notion that the nature of mobile terminals will change, whereby intelligent mobile robots are anticipated to play a more important role. Importantly, 6G will become more human-centered than 5G, which primarily focused on industry verticals. In this thesis, we aim at exploring the human-centeredness of blockchain technologies for the 6G era, in which we leverage advanced blockchain technologies alongside human beings while leveraging emerging technologies. After briefly reviewing recent progress on blockchain Internet of Things (BIoT), we explore the symbiosis of blockchain with other key technologies such as AI and robots, while putting our focus on the emerging Tactile Internet for advanced human-to-machine interaction. Our interest is in exploiting the concept of the decentralized autonomous organization (DAO), which executes smart contracts and requires the involvement of humans to perform certain tasks that autonomous AI-based software agents and robots themselves cannot do. In our search for synergies between human-agent-robot teamwork (HART) and the complementary strengths of the DAO, AI, and robots, we decentralize the Tactile Internet by leveraging mobile end-user equipment via partially or fully decentralized multi-access edge computing. We then introduce the concept of the nudge contract for crowdsourcing of human expertise to decrease the completion time of physical tasks in the event of unreliable feedback forecasting of teleoperated robots or unskilled decentralized members of the DAO. Next, we investigate the widely studied trust game of behavioral economics in a blockchain context. 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 experimentally investigate the impact of the mechanism of deposit on the trust game performance. In addition, we present an on-chaining oracle architecture for a networked N-player trust game that involves a third type of human agent called observers. Further, we study the emerging field of *robonomics*, which integrates behavioral economics with advanced blockchain technologies and persuasive robotics. We show then that the embodied communications enabled by persuasive robots have a potentially greater social impact than monetary incentives such as deposits. Finally, this doctoral thesis describes the evolution from industry 4.0 to human centric cyber-physical-social systems (CPSS) and a future Supersmart *Society 5.0*. After introducing our CPSS based bottom-up multilayer token engineering framework for Society 5.0, a reflection on the role of bioligization in Industry 5.0 is presented. Finally, we experimentally demonstrate how the collective human intelligence of a blockchain-enabled DAO can be enhanced via purpose-driven tokens.

Keywords: 6G, Blockchain, Behavioral Economics, Collective Intelligence, DAO, Human-Robot Interaction, Oracles, Robonomics, Society 5.0, Tactile Internet, Trust Game.

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

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
6Genesis	6G Enabled Smart Society and Ecosystem
6GFP	6Genesis Flagship Program
AI	Artificial Intelligence
AGI	Artificial General Intelligence
ANN	Artificial Neural Network
AR	Augmented Reality
AMM	Automated Market Making
ABI	Application Binary Interface
API	Application Programming Interface
APT	Advanced Persistent Threat
ACC	Access Control Contract
ACK	Acknowledgment
AWS	Amazon Web Services
B5G	Beyond 5G
BS	Base Station
BIoT	Blockchain-based IoT
CoMP	Coordinated MultiPoint
CCSC	Crypto Currency Smart Card (CCSC)
CoC	Computation Oriented Communication
CPU	Central Processing Unit
CTS	Clear To Send
CoZ	Crowd-of-Oz
CV	Computer Vision
CI	Collective Intelligence
CPS	Cyber-Physical Systems
CPSS	Cyber-Physical-Social Systems
DVB	Digital Video Broadcasting
DEX	Decentralized Exchanges
DCF	Distributed Coordination Function
DIFS	DCF Interframe Space
DLT	Distributed Ledger Technology

DApps	Decentralized Applications
DAO	Decentralized Autonomous Organization
DSOC	Decentralized Self-Organizing Cooperative
DNS	Domain Name System
eMBB	enhanced Mobile Broadband
EPON	Ethernet Passive Optical Network
ETSI	European Telecommunications Standards Institute
ECDSA	Elliptic Curve Digital Signature Algorithm
EVM	Ethereum Virtual Machine
ESF	Edge Sample Forecast
EOA	Externally Owned Account
ERC	Ethereum Request for Comments
ESPN	ExtraSensory Perception Network
e-Deliveries	Registered Electronic Delivery Services
FiWi	Fiber-Wireless
GSM	Global System for Mobile Communications
GWAP	Games With A Purpose
H2H	Human-to-Human
H2M	Human-to-Machine
H2R	Human-to-Robot
HABA/MABA	Humans-Are-Better-At/Machines-Are-Better-At
HART	Human-Agent-Robot Teamwork
HetNets	Heterogenous Networks
HITL	Human-In-The-Loop
HO	Human Operator
HRI	Human-Robot Interaction
HSI	Human System Interface
HCI	Human-Computer Interfaces
HTML	HyperText Markup Language
HIT	Human Intelligence Task
IoT	Internet of Things
IoE	Internet of Everything
IP	Internet Protocol
IA	Intelligence Amplification
ITU	International Telecommunication Union
ICO	Initial Coin Offering
IPFS	Inter-Planetary File System
IFrame	Inline Frame
ICT	Information and Communications Technology
JC	Judge Contract
KPI	Key Performance Indicators
LTE-A	LTE-Advanced
LLL	Lisp Like Language
LPWA	Low-Power Wide-Area
LoRa	Long Range
LED	Light-Emitting Diode
MIMO	Multiple-Input Multiple-Output
mmWave	millimeter-Wave

NFT	Non-Fungible Token
M2M	Machine-to-Machine
mMTC	massive Machine Type Communications
MAP	Mesh Access Point
MEC	Multi-access Edge Computing
MP	Mesh Point
MPP	Mesh Portal Point
MR	Mobile Robot
MU	Mobile User
MTurk	Amazon Mechanical Turk
NOMA	Non-Orthogonal Multiple Access
NAT	Network Address Translation
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
PON	Passive Optical Networks
PHY	Physical Layer
PoW	Proof-of-Work
PoS	Proof-of-State
P2P	Peer-to-Peer
QR	Quick Response
RSS	Really Simple Syndication
RACS	Remote APDU Call Secure
RF	Radio Frequency
RAN	Radio Access Network
RTS	Request To Send
RFID	Radio Frequency Identification
RPC	Remote Procedure Call
SMS	Short Message Service
SIFS	Short Interframe Space
SSI	Self-Sovereign Identity
SLA	Service Level Agreement
SHA	Secure Hash Algorithm
sHRI	social Human-Robot Interaction
TOR	Teleoperator Robot
TLD	Top-Level Domain
TDM	Time Division Multiplexing
URLLC	Ultra-Reliable Low-Latency Communications
URL	Uniform Resource Locator
VPN	Virtual Private Network
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
WOR	WiFi Offloading Ratio
WOBANs	Wireless-Optical Broadband Access Networks
WoZ	Wizard-of-Oz
XR	Extended Reality

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Chapter 1

Introduction

1.1 Background and Motivation

1.1.1 Evolution of Mobile Networks and Internet

The general evolution of global mobile network standards was first to maximize coverage in the first and second generations and then to maximize capacity in the third and fourth generations. In addition to higher capacity, research on 5G mobile networks has focused on lower end-to-end latency, higher spectral efficiency and energy efficiency, and more connection nodes [1]. More specifically, the first generation (1G) mobile network was designed for voice services with a data rate of up to 2.4 kbit/s. It used analog signals to transmit information, and there was no universal wireless standard. Conversely, 2G was based on digital modulation technologies and offered data rates of up to 384 kbit/s, supporting not only voice services but also data services such as short message service (SMS). The dominant 2G standard was the global system for mobile (GSM) communication. The third-generation (3G) mobile network provided a data rate of at least 2 Mbit/s and enabled advanced services, including web browsing, TV streaming, and video services. For achieving global roaming, 3GPP was established to define technical specifications and mobile standards. 4G mobile networks were introduced in the late 2000s. 4G is an all Internet Protocol (IP) based network, which is capable of providing high-speed data rates of up to 1 Gbit/s in the downlink and 500 Mbit/s in the uplink in support of advanced applications like digital video broadcasting (DVB), high-definition TV content, and video chat. LTE-Advanced (LTE-A) has been the dominant 4G standard, which integrates techniques such as coordinated multipoint (CoMP) transmission and reception, multiple-input multiple-output (MIMO), and orthogonal frequency division multiplexing (OFDM) [2]. The main goal of 5G has been to use not only the microwave band but also the millimeter-wave (mmWave) band for the first time in order to significantly increase data rates up to 10 Gbit/s [3]. Another feature of 5G is a more efficient use of the spectrum, as measured by increasing the number of bits per Hertz [4]. ITU's International Mobile Telecommunications 2020 (IMT 2020) standard proposed the following three major 5G usage scenarios: (*i*) enhanced mobile broadband (eMBB), (*ii*) ultra-reliable and low latency communications (URLLC), and (*iii*) massive machine-type communications (mMTC) [5].

One of the most interesting 5G low-latency applications is the emerging *Tactile Internet* that envisages realizing *haptic communications* and thereby enabling users to not only see and hear but also touch and manipulate remote physical and/or virtual objects through the Internet [6] [7]. The Tactile Internet, which is driven by recent advancements in computerization, automation, and robotization, is expected to significantly augment human-machine interaction, thereby converting today's content delivery networks into skillset/labour delivery networks [8], [9], [10]. The Tactile Internet holds promise to create new entrepreneurial opportunities and jobs, which are expected to have a profound socioeconomic impact on almost every segment of our everyday life with use cases ranging from augmented/virtual reality (AR/VR) and autonomous driving to healthcare and smart grid. Many of these industry verticals (e.g., AR/VR, tele-diagnosis, tele-surgery, and telepresence) require very low latency and ultra-high reliability for realizing ultra-responsive interactive applications such as bilateral teleoperation/telepresence. Note, however, that some use cases which do not necessarily require mobility all the time can be realized over fixed broadband networks. This suggests that future cellular networks need to be fully converged networks, allowing for a flexible selection of different fixed and mobile access technologies while sharing core network functionalities [11].

Interactive systems, including in particular AR/VR and teleoperation, demand an ultra-low round-trip latency of 1-10 ms together with high reliability. The high availability and security, ultra-fast and highly reliable response times and carrier-grade reliability of the Tactile Internet will add a new dimension to the interaction of humans with machines/robots. To gain a more profound understanding of the Tactile Internet, it may be helpful to compare it to the emerging Internet of Things (IoT) and 5G mobile networks. While the concept of IoT is far from novel and goes back

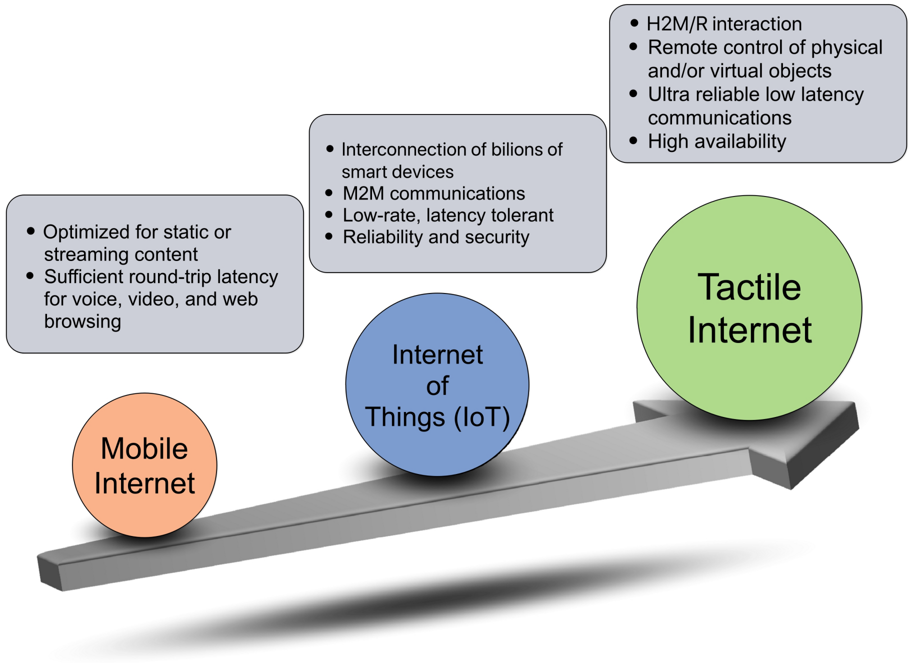


Figure 1.1: Revolutionary leap of the Tactile Internet in compliance with ITU-T Technology Watch Report.

to 1995, it is only recently that we are experiencing a rapidly increasing growth of interest in IoT from both industry and academia. Fig. 1.1 depicts the revolutionary leap of the Tactile Internet in compliance with the ITU-T[1] Technology Watch Report on the Tactile Internet [12]. While the ultra-fast response time and carrier-grade reliability of the Tactile Internet will add a new dimension to human-machine interaction, emerging 5G networks have to handle an unprecedented growth of mobile data traffic as well as an enormous volume of data from smart sensors and actuators, the empowering elements of the IoT.

The difference between the Tactile Internet and IoT may be best expressed in terms of underlying communications paradigms and enabling end devices. The Tactile Internet involves the inherent human-in-the-loop (HITL) nature of human-to-machine interaction, whereas the IoT is centered around autonomous machine-to-machine (M2M) communications without any interaction with humans. The Tactile Internet relies on human-to-machine/robot (H2M/R) interaction and thus allows for a human-centric design approach towards creating novel immersive experiences, expanding humans' capabilities through the Internet. Furthermore, the Tactile Internet may be viewed as an extension of immersive VR from a virtual to a physical environment. It allows for the

[1]International Telecommunication Union - Telecommunication Standardization Sector (ITU-T)

tactile steering and control of not only virtual but also real objects, e.g., teleoperated robots. 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 artificial intelligence (AI) capabilities.

Recently, in [13], we introduced the *Internet of No Things* as an important stepping stone toward ushering in the 6G post-smartphone era, in which smartphones may not be needed anymore. 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 type of computing or storage devices. It envisions Internet services to appear from the surrounding environment when needed and disappear when no needed. The transition from the current gadgets-based Internet to the Internet of No Things is divided into three phases: (*i*) bearables (e.g., smartphone), (*ii*) wearables (e.g., Google and Levi's smart jacket), and then finally (*iii*) nearables. Nearables denote nearby 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.

In [14], Joseph A. Paradiso outlined his pioneering work on extrasensory perception (ESP) in an IoT context at MIT Media Lab. The authors showed that 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 "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 [15]. This is now widely referred to as ubiquitous computing, though Mark Weiser called it *embodied virtuality* originally.

Fig. 1.2 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 influence. An interesting phenomenon for changing behavior in an online virtual environment is known as the "Proteus effect," where the

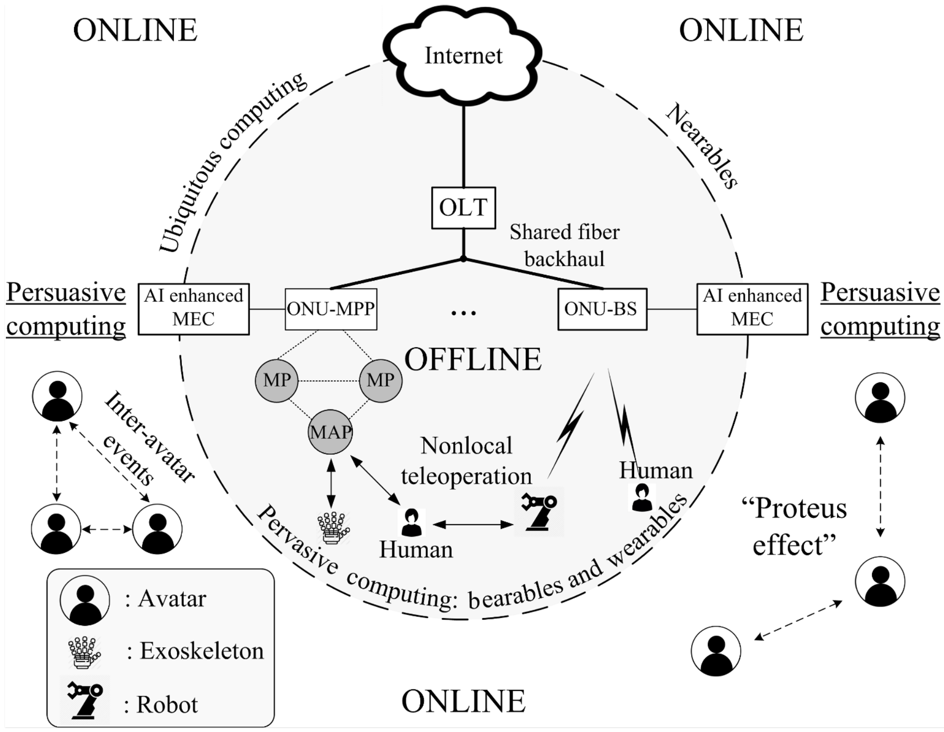


Figure 1.2: Extrasensory perception network (ESPN) architecture integrating the three evolutionary stages of mobile computing: (*i*) ubiquitous, (*ii*) pervasive, and (*iii*) persuasive computing.

behavior of individuals is shaped by the characteristics and traits of their virtual avatars, especially through interaction during inter-avatar events. The underlying physical network infrastructure, which is illustrated in Fig. 1.2, consists of a fiber 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 (Fig. 1.2). Further, in [16], the authors 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.

1.1.2 6G Vision

As 5G is entering the commercial deployment phase, research has started to focus on 6G mobile networks, which are anticipated to be deployed by 2030 [17] [18] [19]. Typically, next-generation systems do not emerge from the vacuum, but follow the industrial and technological trends from previous generations. Potential research directions of 6G consistent with these trends were provided in [20], including among others:

- *6G will continue to move to higher frequencies with wider system bandwidth*: Given that the spectrum at lower frequencies has almost been depleted, the current trend is to obtain wider bandwidth at higher frequencies in order to increase the data rate more than 10 times.
- *Massive MIMO will remain a key technology for 6G*: Massive MIMO has been the defining technology for 5G that has enabled the antenna number to increase from 2 to 64. Given that the performance gains have saturated in the areas of channel coder and modulator, the hope of increasing spectral efficiency for 6G will remain in the multiple antenna area.
- *6G will take the cloud service to the next level*: With the ever-higher data rates, short delays, and low transmission costs, many of the computational and storage functions have been moved from the smartphone to the cloud. As a result, most of the computational power of the smartphone can focus on presentation rendering, making VR, AR, or extended reality (XR) more impressive and affordable. Many AI services that are intrinsically cloud-based may prevail more easily and broadly. In addition to smartphones, less expensive functional terminals may once again flourish, providing growth opportunities in more application areas.
- *Grant-free transmissions could be more prominent in 6G*: In past cellular network generations, transmissions were primarily based on a grant-oriented design with strong centralized system control. More advanced grant-free protocols and approaches will be needed for 6G. It is possible that the non-orthogonal multiple access (NOMA) technology may have another opportunity to prevail due to its short delay performance even though it failed to take off during the 5G time period.
- *mMTC is more likely to take shape in the older generation before it can succeed in the next generation*: mMTC has been one of the major directions for the next-generation system design since the market growth of communications between people has saturated. High expectations have been put on 5G mMTC to deliver significant growth for the cellular industry. Until now, however, this expectation has been mismatched with the reality on the ground. Therefore, the current trend appears to indicate that mMTC would be more likely to prevail by utilizing older technology that operates in a lower band.

- *6G will transform a transmission network into a computing network*: One of the possible trademarks of 6G could be the harmonious operations of transmission, computing, AI, machine learning, and big data analytics such that 6G is expected to detect the users' transmission intent autonomously and automatically provide personalized services based on a user's intent and desire.

In September 2019, the world's first 6G white paper was published as an outcome of the first 6G wireless summit, which was held in Levi, Finland, earlier in March 2019 with almost 300 participants from 29 countries, including major infrastructure manufacturers, operators, regulators as well as academia [21]. Each year, the white paper will be updated following the annual 6G wireless summit. While 5G was primarily developed to address the anticipated capacity growth demand from consumers and to enable the increasing importance of the IoT, 6G will require a substantially more holistic approach, embracing a much wider community. Further, 6G will become more human-centered than 5G, which primarily focused on industry verticals. Putting people at the center of a future super-smart society lies also at the heart of the recently emerging concept of *Society 5.0* [22].

Many of the key performance indicators (KPIs) used for 5G are valid also for 6G. However, in beyond 5G (B5G) and 6G, KPIs in most of the technology domains once again point to an increase by a factor of 10-100, though a 1000 times price reduction from the customer's viewpoint may be also key to the success of 6G [23]. Note that cost reduction is particularly important for providing connectivity to rural and underprivileged areas, where the cost of backhaul deployment is the major limitation. According to [24], providing rural connectivity represents a key 6G challenge and opportunity given that around half of the world population lives in rural or underprivileged areas. Among other important KPIs, 6G is expected to be the first wireless standard exceeding a peak throughput of 1 Tbit/s per user.

Arguably more interestingly, 6G envisions that totally new services such as telepresence, as a surrogate for actual travel, will be made possible by combinations of graphical representations (e.g., avatars), wearable displays, mobile robots and drones, specialized processors, and next-generation wireless networks. Similarly, smartphones are likely to be replaced by pervasive XR experiences through lightweight glasses, whereby feedback will be provided to other senses via earphones and haptic interfaces. Furthermore, 6G needs a network with embedded trust given that the digital and physical worlds will be deeply entangled by 2030. Toward this end, blockchain also known as distributed ledger technology (DLT) may play a major role in 6G networks due to its capability to establish and maintain trust in a distributed fashion without requiring any central authority.

1.1.3 Blockchain and Distributed Ledger Technologies

The radical potential of blockchain technology has long spread outside the world of crypto into the hand of the general public. We've all heard through one way or another that it is most likely the most revolutionary technology that is presently available in any known market and that includes the real world as well as the digital space. Blockchain technology is principally behind the emergence of Bitcoin [25] and many other cryptocurrencies that are too numerous to mention [26]. A blockchain is essentially a distributed database of records (or public ledger) of all transactions or digital events that have been executed and shared among participating parties [27]. Each transaction in the public ledger is verified by consensus between the majority of the participants in the system. Once entered, information can never be erased. The blockchain contains a certain and verifiable record of every single transaction ever made. At the point when the block reaches a certain size, it is timestamped and linked to the previous block through a cryptographic hash, thereby forming a chain of timestamped blocks (hence the name blockchain), as depicted in Fig. 1.3.

Blockchain technology is being successfully applied in both financial and non-financial applications. It has the potential to reduce the role of one of the most important economic and regulatory actors in our society, the middleman [28] [29]. Blockchain technology was initially linked to the decentralized cryptocurrency Bitcoin, as it is the main and first application of the network (known as Blockchain 1.0 [30]). However, there exist many other use cases and several hundred different applications besides Bitcoin that use blockchain technology as a platform such as Ethereum.

Ethereum is a type of open software platform that runs on blockchain technology. At its heart lies the so-called Ethereum Virtual Machine (EVM), which is capable of executing code of arbitrary algorithmic complexity [31]. The Ethereum platform can be used not only as a cryptocurrency but also to allow developers to write smart contracts, program codes stored on a blockchain that are executed when predetermined conditions are met. Ethereum smart contracts allow end-users to interact with next-generation decentralized applications (DApps). As opposed to traditional centralized applications, where the backend code is running on centralized servers, DApps are apps whose server-client models are decentralized. DApps run on blockchain networks without central

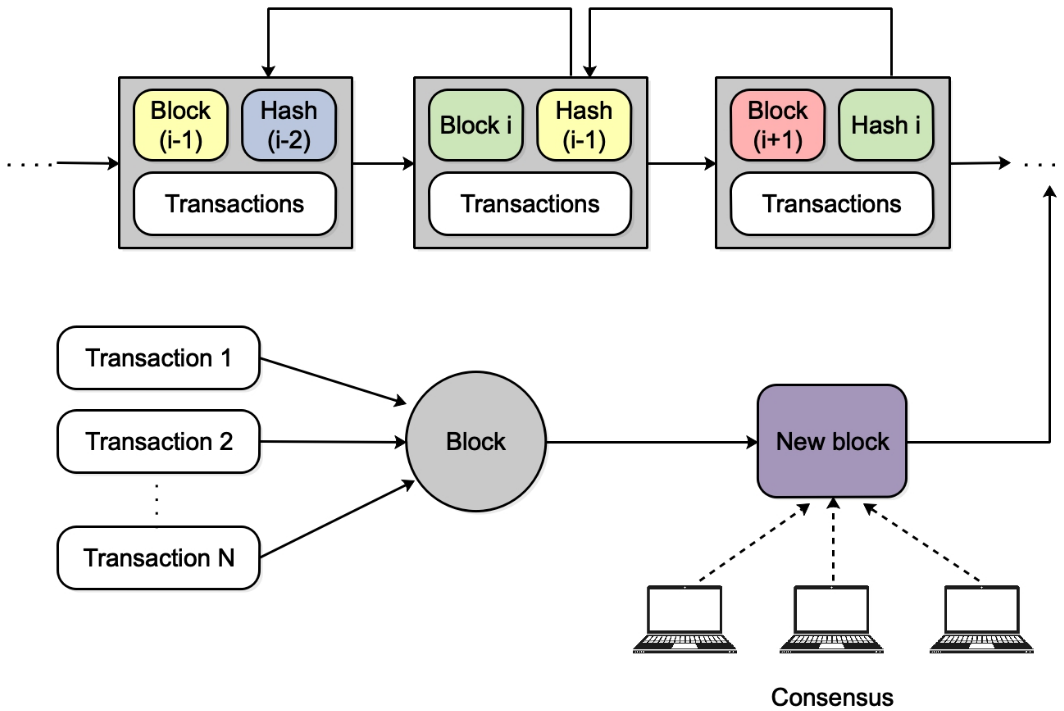


Figure 1.3: A graphical representation of blockchain transaction workflow.

authority and use decentralized storage protocols. DApps may be used in many other fields by making the process of creating applications much easier and more efficient. For instance, they can be used for realizing non-financial blockchain DApps (e.g., IoT device registration Dapp, blockchain-based digital identity application). The rise of Ethereum and smart contracts heralded Blockchain 2.0 [30].

As the hype of blockchain technology advanced, Blockchain 3.0 aims to popularize blockchain-based solutions expanding the traditional sectors (finance, goods transactions, and so on) to government, IoT, decentralized AI, supply chain management, smart energy, health, data management, and education [32] [33]. Therefore, the applications of blockchain have evolved to much wider scopes. However, these new applications introduce new features to the next generation platforms including key aspects such as platforms interconnection or more advanced smart contracts that provide higher levels of transparency while reducing bureaucracy with self-enforcing code. These new technologies, therefore, promise more decentralized and spontaneous coordination over the Internet between users who do not know or trust each other, often referred to as decentralized autonomous organizations (DAO). DAO exist as open-source, distributed software for executing smart contracts built within the Ethereum project. DAO is like a decentralized organization, except that autonomous software

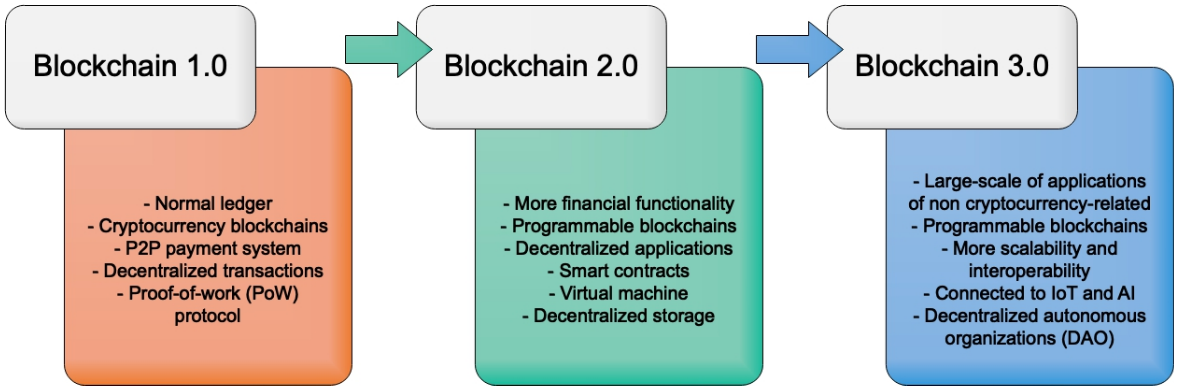


Figure 1.4: Evolution of blockchain technology.

agents (i.e., smart contracts) make the decisions, not humans. In a more decentralized setup, the governance rules automatically steer behavior with tokenized incentives and disincentives [34]. In such cases, programmable assets called tokens managed by a special smart contract act as governance rules to incentivize and steer a network of actors without centralized intermediaries [34]. Further, the tokens issued by the DAO enable their respective holders to vote on matters about the development of the organization and make decisions. As a result, the decision taking process is automated and a consensus is reached among the participants. For illustration, Fig. 1.4 depicts the evolution of blockchain technology from Blockchain 1.0 to 3.0.

The introduction of smart contracts to the blockchain has added the programmability to this disruptive technology and has changed the software ecosystem by removing third parties for administration of (non)business purposes. Although promising, smart contracts and blockchain do not have access to the information outside of their networks (i.e., off-chain data). The blockchain in fact is an enclosed system where interactions are limited to the data available on it. Hence, it is still an open practical problem referred to as the "oracle problem" that is defined as how real-world data can be transferred into/from the blockchain [35]. Toward this end, oracles (also known as data feeds) act as trusted third-party services that send and verify the external information and submit it to smart contracts to trigger state changes in the blockchain [36]. Oracles may not only relay information to the smart contracts but also send it to external resources. They are simply contracts on the blockchain for serving data requests by other contracts. Without oracles, smart contracts would have limited connectivity; hence, they are vital for the blockchain ecosystem due to broadening the scope of smart contracts operation.

1.2 Advanced Blockchain Technologies: Prior Art and Recent Progress

In this section, we review prior research work related to advanced blockchain technologies and, after classifying them into three separate yet interdependent categories, we discuss each one in greater detail. The main branches of our classification are DAO, blockchain oracles, and token engineering.

1.2.1 DAO

The last few years have seen the emergence of DAO in the field of blockchain as a new form for running organizations on the Internet. DAO is a novel socio-technical systems that enable a new way for online coordination and decision-making. DAO as a new form of online governance are collections of smart contracts deployed on a blockchain platform that intercede groups of members (humans or machines). In short, DAO may be defined as a group of members with common goals that join under a blockchain infrastructure that enforces a set of shared rules. Typically, the members of a DAO are registered, each with a unique address. They also have an amount of governance tokens linked to that address, which are usually required for participation, and may play a role in the DAO decision-making process. It is also common that DAO manage resources, e.g., cryptocurrencies, whereby DAO members may decide how to allocate them through a decision system.

The first remarkable DAO was *The DAO*, launched in April 2016 by a group of programmers. The DAO was a sort of hedge fund, in which contributors could directly vote for proposed projects. Investors would exchange Ether for tokens during an Initial Coin Offering (ICO). Then investors would vote for new projects with their votes or tokens. In June 2016, due to an error in The DAO code, an attacker robbed a large part of its funds [37]. Another example of DAO on decentralized finance (DeFi) is *MakerDAO*[2], which began in 2015. MakerDAO aims to bring financial stability and transparency to the world economy. This community governs the Maker Protocol, which defines the use of the *Dai token*, a stable cryptocurrency that avoids financial risk when Ethereum's cryptocurrency value fluctuates. A variety of DAO platforms have recently emerged to facilitate the deployment of DAO in the blockchain by significantly reducing the technological knowledge required and providing *DAO software as a service*. These DAO platforms enable users with sufficient knowledge on how blockchains work and how to create a DAO using a template that typically can

[2]MakerDAO white paper: `https://makerdao.com/en/whitepaper/`

be customized. The main platforms are Aragon[3], DAOstack[4], and Colony[5], as explained in more detail in the following:

- *Aragon:* Aragon is by far the largest DAO platform. Aragon provides a static template to make one's own DAO, but it also allows one to create a customized one. The template sets a special token, which is used by a small group of members to take decisions, like accepting new members. The other key feature that Aragon introduces are permissions, which serve as an access control system intended to safely connect apps and entities (users or other apps) together. Initially, the DAO creator has the permissions to manage it, but usually, the creator transfers those permissions to the voting app such that the DAO is managed through voting. This enables more democratic decentralized governance models.

- *DAOstack:* Unlike Aragon, the DAOstack platform does not offer many customizations. Among others, they currently provide a single decision-making system for all their DAOs. This voting system, called *holographic consensus* [38], aims to solve the problems of scaling a DAO. In holographic consensus, the quorum required to approve a proposal can be reduced from absolute majority to relative majority if some conditions are met. The most significant condition concerns the predictors or stakers, who are not necessarily members from any DAO. Those predictors can stake a special token called *GEN* to predict the result of a proposal. If stakers are right, they are rewarded, whereas if they fail, they lose their stake. Regarding the proposal, if the staked amount reaches a specific limit, then the quorum of that proposal will be reduced to a relative majority. As a result, stakers help DAO to highlight meaningful proposals and make profit if their service are useful. In practice, this behaviour mimics a prediction market [39].

- *Colony:* Colony has been the latest and recently released DAO platform that enables the creation of DAO, or "colonies", as they named them. Colony's DAO are shared by people with common goals and resources to accomplish them, though these DAOs can be split into domains or even sub-domains with more specific purposes[6]. Those purposes are translated into tasks that DAO members may accomplish to gain more influence. On the other hand, DAO members may have a reputation token and the only way to obtain more is by performing tasks,

[3]`https://aragon.org/`
[4]`https://alchemy.daostack.io/`
[5]`https://colony.io/`
[6]Colony Technical White Paper, `https://colony.io/whitepaper.pdf`

which can also be exchanged by non-reputational tokens like Ethereum's native cryptocurrency Ether. Unlike Aragon or DAOstack, which are vote-driven and use voting systems to allocate resources, Colony has a meritocratic system because the only way to increase the members' influence is working for the organization [40]. By avoiding to vote, all decisions are approved by default unless someone has an objection, in which case it is discussed and resolved via voting.

1.2.2 Blockchain Oracles

Blockchain oracles can be classified depending on a number of different qualities: (*i*) *source,* i.e., the origin of data, (*ii*) *direction of information,* i.e., inbound or outbound from the viewpoint of the blockchain, (*iii*) *the initiator of the data flow,* whether it is push- or pull-based communication, (*iv*) *trust,* i.e., centralized or decentralized, and (*v*) *design pattern.*

Oracle data sources can range from (*i*) *software oracles,* where data comes from online sources (e.g., online web servers or database), (*ii*) *hardware oracles,* where data comes from the physical world (e.g., IoT devices, robots), and (*iii*) *human oracles,* in which an individual with specialized knowledge/skills in a particular field can play the role of the oracle. They can research and verify the authenticity of information from various sources and translate that information to smart contracts. Since human oracles can verify their identity using cryptography, the possibility of a fraudster faking their identity and providing corrupted data is relatively very low.

Direction of information means the way information flows, i.e., from or to external resources with respect to the initiator of the data flow. Toward this end, there are four combinations of these options: (*i*) *pull-based inbound oracle,* when the on-chain component requests the off-chain state from an off-chain component, (*ii*) *pull-based outbound oracle,* when the off-chain component retrieves the on-chain state from an on-chain component, (*iii*) *push-based inbound oracle,* when the off-chain component sends the off-chain state to the on-chain component, (*iv*) *push-based outbound oracle,* when the on-chain component sends the off-chain state to an off-chain component.

Further, there is the concept of trust that can be centralized or decentralized. *Centralized oracles* are efficient but they can be risky because a single entity provides information, controls the oracles, and a failure makes the contracts less resilient to vulnerabilities and attacks. In contrast, *decentralized oracles* (i.e., consensus-based oracles) increase the reliability of the information provided to the smart contracts by querying multiple resources. It should be noted that an oracle is considered decentralized if it is permissionless such that users can join or leave, and every user has equal rights [41]. Finally, oracles design patterns are defined as (*i*) *request-response,* when the data space is huge and can be implemented as on-chain smart contracts and initiated on-chain or off-chain oracles for monitoring, retrieving, and returning data, (*ii*) *publish-subscribe,* when the data is expected to change, e.g., really simple syndication (RSS) feeds, and (*iii*) *immediate read,* when the data is required for an immediate decision.

There exist many commercial and open-source tools that implement inbound oracles. *Orisi*[7] is a solution for a distributed set of inbound oracles for Bitcoin, which are executed by independent and trustworthy third parties. The majority of all oracles have to agree on the outcome from external data. To fulfill this purpose, money from senders and receivers is parked at a multiple-signature address, including all signatures as well as the signature address. Orisi is categorized as a pull-based inbound oracle. Oraclize, recently rebranded as *Provable Things*[8] is a popular service for inbound oracles that works with multiple smart contract enabled blockchain platforms. The service acts like a trusted intermediary between blockchains and a variety of independent data sources. Its Provable Engine executes a set of instructions to react as certain conditions are met, thus making it classifiable both as a push-based and a pull-based inbound oracle.

Reality Keys provides a combination of both automated and human-driven pull-based inbound oracles [42]. *Chainlink*[9] offers a general-purpose framework for building decentralized inbound oracles, providing decentralization on both oracle and data-source levels. A Chainlink node can have multiple external adapters for different data sources. *Witnet* provides a decentralized oracle network protocol based on Ethereum [43]. It also enables miners to earn tokens. An Ethereum bridge is implemented, providing Witnet nodes to run Ethereum nodes with the option to operate with Ether and make contract calls.

Blockchain inbound oracles have also been considered in a number of research works. Xu et al. introduce the concept of *validation oracles*, namely trusted third-party operators (either automatic or human) that act as inbound oracles [44]. The authors distinguish between internal ones,

[7] `https://orisi.org/`
[8] `https://provable.xyz/`
[9] `https://chain.link/`

periodically transmitting external verified data to the blockchain, and external ones, operating as trusted external validators of transactions based on information that is external to the blockchain. According to our scheme, we see that the former is push-based and the latter is pull-based. Among the pioneering research works in the field of oracles is *ASTRAEA* introduced by Adler et al. as a decentralized pull-based inbound oracle service [45]. The implementation provides a voting game, which decides the truth or inaccuracy of propositions. Players can be voters or certifiers. While certifiers play a role in cases with the requirement for high accuracy, voters are utilized for low-risk/low-reward roles. Zhang et al. present *Town Crier*, a push-based inbound oracle that acts like a data-feed system connecting a blockchain with a back-end that scrapes secure websites [46].

More interestingly, Heiss et al. provide a set of key requirements for trustworthy data on-chaining, explaining the challenges and the solutions for them [47]. They argue that in addition to safety and liveness as the characteristics of a distributed systems, truthfulness is necessary as it prevents execution of blockchain state transition from untruthful data provisioning. Based on these properties. Challenges are defined for each of them as: *availability*, *correctness*, and *incentive compatibility*. Incentive compatibility consists of two key characteristics: (*i*) attributability referred to as mapping data to the source provider, and with respect to the behavior, the data source can be rewarded or penalized, and (*ii*) accountability defined as depositing stake before providing data, and upon the truthful data provisioning, it is paid back. Correctness consists of authenticity and integrity such that the former deals with approving the data source and the latter shows the data should become untampered during the transition, respectively. Finally, liveness refers to availability and accessibility such that the former implies that the availability of the system should be as good as of its least available component i.e., the outage should be kept minimum. The latter means that data must be accessible at any time.

1.2.3 Token Engineering

Tokens have emerged with the introduction of *Web3* [34]. While Web1 allowed everyone to share ideas and Web2 allowed communities to form and discuss those ideas, Web3 enables those communities to leverage financial capital and go from discussions to tangible action. At their core, tokens are entries in distributed ledgers that are assigned to blockchain accounts and for which transactions require authorization, thereby authenticity and preventing modification and tampering without consent. Tokens are designed in a customised way by using a token template that can be extended or instantiated. Tokens can be understood as an asset that resides on the blockchain, which can be stored or managed using Ethereum addresses and special smart contracts. There are various types of tokens that can be built on Ethereum, usually used in DApps and followed an existing standard. The most popular tokens standard are described below:

- *ERC-20 Standard*[10]*:* ERC-20 tokens can be defined as a group of identical tokens (i.e., fungible tokens), all with the same properties. They follow the ERC-20 standard which includes a common set of rules for creating and managing fungible tokens. The use of ERC-20 tokens enables the creation of small economies that have liquid markets for different use cases. ERC-20 tokens can be traded on multiple types of platforms such as regular exchanges, decentralized exchanges (DEX), witch is a peer-to-peer (P2P) marketplace that connects cryptocurrency buyers and sellers, or with an automated liquidity pool which enables seamless token swaps using automated market making (AMM) algorithms to determine the price of ERC-20 tokens.
- *ERC-721 Standard*[11]*:* ERC-721 tokens are non-fungible tokens (NFT). This implies that each token has a unique set of properties and values associated with it. The ERC-721 standard is an interface that each smart contract that creates ERC-721 tokens has to implement. There are multiple functions that enable interactions with NFTs such as finding the owner address of an ERC-721 token or approving the transfer of an ERC-721 token. ERC-721 tokens have found applicability in many domains of the Ethereum space, the most relevant being gaming, arts, collectibles items, utilities, and VR real estate[12]. ERC-721 tokens can also change ownership and be traded for other tokens or Ether. However, the way this is done is different. Since all ERC-721 tokens have unique properties, AMM algorithms are not feasible to be implemented.
- *ERC-1155 Standard*[13]*:* ERC-1155 is a new token proposal standard aimed at creating both fungible and non-fugible tokens in the same contract. This could be particularly useful for games that want to create more complex in-game economies.

[10] https://eips.ethereum.org/EIPS/eip-20
[11] https://eips.ethereum.org/EIPS/eip-721
[12] https://www.cryptovoxels.com/parcels/2
[13] https://eips.ethereum.org/EIPS/eip-1155

1.3 Objectives

The objectives of this thesis are as follows:

- The Tactile Internet is considered one of the most interesting low-latency applications for creating novel immersive experiences. Further, the Tactile Internet enables haptic feedback by delivering physical experiences remotely. The first objective of the thesis is to investigate the specific challenges of the Tactile Internet stemming from the fact that it is also known as the *Internet of Skills,* where humans transfer knowledge, expertise, and skills to humans/robots without the restriction of physical boundaries. In such a Tactile Internet scenario, the key challenge addressed in this thesis centers around coordinating groups of humans and getting them to behave according to pre-specified rules and goals and in a trusted way when a human and/or robot fails during task execution.

- For realizing its successful deployment in a Tactile Internet scenario, it is crucial to identify the basic concepts, features, structure, and taxonomy of the Tactile Internet. Subsequently, some of the typical Tactile Internet applications and network infrastructure requirements need to be identified. Most notably, the proposed low-latency FiWi enhanced LTE-A HetNets based on advanced multi-access edge computing with embedded AI capabilities was shown to meet those requirements. One of the main challenges and objectives of this thesis is to understand the concept of the *human-agent-robot teamwork* (HART) design approach towards achieving advanced human-machine coordination by means of a superior process for fluidly orchestrating human and machine coactivity.

- The fundamental concepts and potential of Ethereum blockchain technologies for society and industry have emerged recently. Motivated by the fact that most research on Ethereum has been focusing on the IoT, the objective of the thesis is to provide an up-to-date survey on how Ethereum can be used for realizing the emerging blockchain IoT (B-IoT). In addition, the thesis aims to explore the salient features that set Ethereum aside from other blockchains, including its symbiosis with other key technologies such as AI and robots as well as decentralized edge computing solutions. An important objective of the thesis is to go beyond IoT and provide insights into leveraging the concept of the DAO to help provide trust and decentralization of the Tactile Internet. Further, one of the main objectives of the thesis is to enhance the human operator/robot's capabilities of skills transfer via nudging the crowd of human experts by means of rewards through smart contracts in an Internet of skills scenario. The deployment of the DAO and smart contracts in the emerging Tactile Internet has not been addressed prior in the existing literature.

- Behavioral economics is a hot topic and is regularly featured in the top academic journals in economics, psychology, and science. Behavioral economics extends economic principles by allowing that our decisions to be affected by social and psychological influences apart from a rational calculation of benefits and costs. As a part of behavioral economics, behavioral game theory literature deals with situations where individual self-interested behavior leads to inefficient outcomes for the other players. There has been some effort to theoretically study techniques to induce trust, cooperative behavior, and efficiency in such situations. The goal of this thesis is to develop and examine the effects of a proposed blockchain smart contracts-based mechanism designed to improve social efficiency and normalized reciprocity in one of these situations: the trust game, the standard economics and behavioral laboratory experiment for measuring trust. In the trust game, one player (the trustor) has the choice of investing or not investing in a project, which is administered by the other player (the trustee). The investment is successful, if the amount invested multiplies in value. However, the trustee controls the procedure of investment: he may keep the total amount for himself or split it with the trustor. Another objective of the thesis is to extend the classical two-player trust game to a networked N-players trust game benefiting from social influence and peer pressure to improve both trust and trustworthiness using advanced blockchain technologies, most notably, an on-chaining blockchain oracle.

- Trust-based interactions with robots will be increasingly common in the future in the marketplace, workplace, on the road, and in every home. However, a looming concern is that people may not trust robots as they do humans. While trust in fellow humans has been studied extensively, little is known about how people extend trust to robots. Motivated by the 6G vision of the convergence of driving technological trends such as blockchain technologies and connected robotics, another objectives of the thesis is to explore the emerging field of *robonomics*, which studies the socio-technical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society. Specifically, the thesis studies the design of proper persuasive robotics strategies to change human behavior by leveraging social robots and embodied communications as a social influence mechanism. Further, the thesis aims to realize a blockchain-enabled implementation to compare trust-based investments and emotions of two identical economic games: human-human trust game and human-robot trust game where the robot impacts the human decision.

- The Industrial Revolution reduced the agricultural population from more than 90 percent to less than 5 percent. Similarly, the IT revolution reduced the manufacturing population from more than 70 percent to approximately 15 percent. The Intelligence Revolution of the 6G era will have also an impact in reducing the entire services population. Upon the question of where will people go and what will they do then, recent research gives the following answer: Gaming. Not leisure, but scientific gaming in cyberspace. Artificial societies (e.g., DAO), computational experiments, and parallel execution—the so-called ACP approach—may form the scientific foundation while cyber-physical social system (CPSS) platforms may be the enabling infrastructure for the emergence of intelligent industries. Everything will have its parallel avatar or digital twin in cyberspace such that we can conduct numerous scientific games before any major decision or operation. Motivated by those trends, the goal of the thesis is to explore the concept of Society 5.0, the next evolutionary step of Industry 4.0/5.0. Society 5.0 nicely aligns with 6G's anticipated shift from industry verticals to more human-centeredness. More interestingly, the objective of the thesis is to shed light on the emerging Internet of No Things as a CPSS layer of our proposed DAO-based Society 5.0 framework. Further, the thesis aims to study the tokenization process in blockchains to create a digital twin that replaces real values (e.g., assets, rights) with blockchain tokens that reflect these values.

- Collective intelligence will play an important role in the vision of future 6G mobile networks. In contrast to previous generations, 6G will be transformative and will revolutionize the wireless evolution from connected things to connected intelligence. The final objective of the thesis is to explore the concept of stigmergy, a biological self-organization mechanism widely found in social insect societies for facilitating indirect communication, collective intelligence, and internal coordination among offline agents via traces (feedback loops) created in a blockchain-based online environment. Specifically, the thesis examines the design of a proper incentive mechanism in the form of purpose-driven tokens to help facilitate collaboration by incentivizing an autonomous group of people to individually contribute to a collective goal.

1.4 Research Methodology

The research methodology applied in this thesis includes network architecture, mechanism design, smart contract, persuasive robotics strategies, and testbed experiments, as summarized in Fig. 1.5 and briefly described in the following.

- *Network architecture:* Novel blockchain-based skills transfer techniques are proposed to the FiWi-based network architecture of the emerging immersive low-latency Tactile Internet with AI-enhanced MEC. In particular, the applied techniques include smart contracts, which allow for successfully accomplishing tasks via shared skills among failing robots/humans and skilled humans. Further, an on-chaining blockchain oracle for a networked N-player trust game is developed to enable cooperative good behavior to help propagate trust and trustworthiness among a cluster of players.
- *Mechanism design:* To address the above mentioned objectives, several mechanisms are included in the thesis ranging from nudge contract, experimenter smart contract, blockchain mechanism deposit, loyalty reward program, reward-punishment mechanism, an on-chaining oracle, token contracts, and persuasive robotics strategies scripts, as well as introducing novel teleoperation techniques such as Crowd of Oz (CoZ).
- *Smart contract:* Different kinds of smart contracts are designed to apply reinforcement and punishment contingencies to help humans manage their own behavior. The specific characteristics of the developed contracts are identified by studying several behavioral techniques ranging from (*i*) nudging, in which we influence behavior without punishment for skills transfer in the context of the Tactile Internet, (*ii*) positive reward/penalty function without giving direct economical incentives, e.g., loyalty reward/penalty points, (*iii*) restrict the number of choices available to a player by self-control strategy, e.g., the deposit mechanism used in the experimenter contract, (*iv*) internality strategy in which we use a long-term benefit or cost to an individual that she or he does not consider when making the decision to consume a good or service, e.g., earning 1 Ether for each accumulated 10 loyalty reward points, and (*v*)

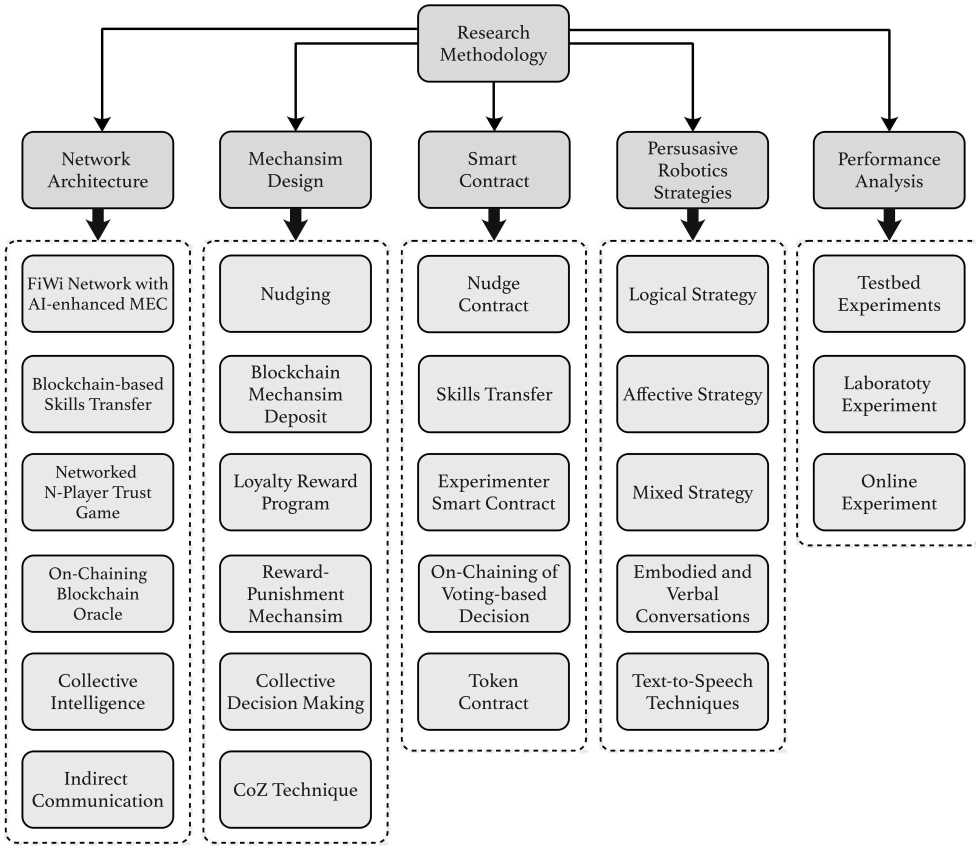


Figure 1.5: Research methodology.

aggregating collective intelligence and collective decision-making by means of decentralized voting mechanism, e.g., on-chaining of voting-based decision. In addition, token contracts have been adopted to help achieve a common goal as well as regulating access rights.

- *Persuasive robotics strategies:* Different persuasive robotics strategies are used in our research for the emerging field of robonomics. These strategies include logical, affective, and mixed strategies. Specifically, we developed teleoperation techniques to improve the abilities of the widely used social robot Pepper for both embodied and verbal communications. The strategies contain a set of reward and punishment mechanisms, as well as economical, technical advice, and encouragement enabled by Pepper via text-to-speech techniques.

- *Testbed experiments:* To find relevant and reliable data, a laboratory experiment is adopted in our research for measuring trust and trustworthiness of our three developed blockchain-enabled experiments: classical trust game, N-player trust game, and human-robot trust game. Further, an online experiment enabled by Amazon Mechanical Turk (MTurk) is used for our research as well. MTurk has recently become popular among experimental and social scientists as a source of survey and experimental data. Further, MTurk participants are slightly more representative of the world population than are standard Internet samples and are significantly more diverse than typical laboratory experiment samples. The compensation of anonymous MTurk workers in our experiment does not affect data quality. Also, the data obtained are more reliable as those obtained via traditional methods. An experimental testbed for the collective intelligence of a blockchain-enabled Society 5.0 was developed to validate the accuracy of the proposed scenario via real-world measurements using both laboratory and online experiments.

1.5 Contributions of the Thesis

This thesis is a compilation of four publications (3 journal articles and one book chapter), which are published or submitted for publication in high-calibre IEEE journals as well as a renowned book publisher (i.e., CRC Press). The key contributions of the thesis are briefly discussed in the following.

1.5.1 From Blockchain Internet of Things (B-IoT) Towards Decentralizing the Tactile Internet

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

[BC1] A. Beniiche, A. Ebrahimzadeh, and M. Maier. From Blockchain Internet of Things (B-IoT) Towards Decentralizing the Tactile Internet. *CRC Press*: Blockchain-enabled Fog and Edge Computing: Concepts, Architectures and Applications, Editors: Muhammad Maaz Rehan, Mubashir Husain Rehmani, pp. 3-30, July 2020.

This part of the thesis focuses on integrating blockchain with the emerging Tactile Internet as one of the most interesting human-machine interaction applications and the next leap in the evolution of today's Internet of Things (IoT). After explaining the commonalities and specific differences between Ethereum and Bitcoin blockchains, we first provided an up-to-date survey on how

Ethereum can be used for realizing the emerging blockchain IoT (B-IoT). Next, we showed that the Tactile Internet integrates human users, artificial intelligence (AI) software agents, and robots into teams. The resultant human-agent-robot team (HART) in turn enables clusters of local co-production and collaboration, which leverage human intelligence to support robots and AI agents. We then elaborated on how specific Ethereum blockchain technologies may be leveraged to realize future techno-social systems, notably the Tactile Internet. We showed that a central role plays the decentralized autonomous organization (DAO), which executes smart contracts on the Ethereum blockchain and requires the involvement of human participants to perform certain tasks that autonomous AI-based software agents and robots themselves cannot do (e.g., voting, collective decision making, and skills transfer). In the attempt of keeping the DAO as autonomous as possible, we used the teleoperated robot as an autonomous agent (automation at the center), while letting the human operator be a decision-maker supported by a set of nearby skilled human operators (humans at the edge) who transfer knowledge when the human/robot is in need, resulting in a new hybrid form of human-robot collaboration [48].

1.5.2 The Way of The DAO: Toward Decentralizing the Tactile Internet

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

[J1] A. Beniiche, A. Ebrahimzadeh, and M. Maier. The Way of The DAO: Toward Decentralizing the Tactile Internet. *IEEE Network*, vol. 35, no. 4, pp. 190-197, July/Aug. 2021.

This work proposes the use of blockchain technologies and specifically the aforementioned concept of DAO in order to decentralize the Tactile Internet and enhance the performance and execution times of mobile applications. To achieve this objective, different methodologies were applied harnessing the partially or fully decentralized end-user equipment and edge computing server solutions, as well as crowdsourcing of human expertise to perform tasks that teleoperated robots struggle to complete reliably. Also, the concept of blockchain nudge contract was introduced to improve the task completion capabilities of unskilled decentralized members of the DAO. The simulation results provided illustrate that higher decentralization can lead to up to 90% improvement in task completion performance for an optimal offloading probability. Also, we demonstrated that crowdsourcing of human intelligence can severely improve task completion performance, especially in cases where robots are failing to complete physical tasks. Thus, to promote skilled user intervention and successfully complete tasks, the concept of nudge contract was adopted for skills transfer. To the best of our knowledge, this work was one of the first ones that study the combination of two emerging technologies, namely the Tactile Internet and blockchain technologies [74].

1.5.3 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:

[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.

The analysis of trust and reciprocity in behavioral economics starts from the insight that people do not generally like to see unequal outcomes. People do not like to be treated unfairly, and they do not like to see others being treated unfairly either. If we feel that we are being treated unfairly then we are less likely to trust and reciprocate. The interplay between trust and reciprocity is a key element in many of the cooperative and collaborative activities that we undertake every day, from collaborative teamwork (e.g., HART, DAO, and the aforementioned process of skills transfer between humans and robots/humans in the context of the Tactile Internet) to the altruism we show in donating or charity. In this work, we investigated methods to improve trust and reciprocity between agents. Toward this end, we focused on the widely studied trust game of behavioral economics in a blockchain context. Further, we presented a networked version of the trust game, involving a third party called observers, whose primary goal was to discourage selfish behavior. Blockchain smart contracts and oracles were employed in the context of both classical and networked trust games. We demonstrated that the way in which our economic decisions are determined and reinforced can be realized by a range of factors —apart from money— including deposit mechanism as a precommitment and self-control of agents and the presence of social influences such as peer pressure by observers and, more interestingly, persuasive social robots in the emerging field of robonomics. To the best of our knowledge, this work was the first to implement blockchain techniques in behavioral and economic game experiments such as the trust game [79].

1.5.4 Society 5.0: Internet as if People Mattered

The outcome of this research was submitted to the following journal article and the main contributions of this work are summarized below:

[J3] A. Beniiche, S. Rostami, and M. Maier. Society 5.0: Internet as if People Mattered. *IEEE Wireless Communications Magazine*, under review.

In this work, we focused on the wireless evolution of connected things to collective intelligence (CI), which plays a central role in the 6G vision of rendering future mobile networks more human-centered than 5G. Towards this end, we adopted the unifying concept of stigmergy, a common mechanism used to produce cognition in the human brain as well as natural societies (e.g., social insects), to advance CI in future self-organizing techno-social systems known as cyber-physical-social systems (CPSS) such as the Tactile Internet and the future Internet of No Things. We showed that CPSS is instrumental in realizing the human-centered *Society 5.0* vision. Society 5.0 envisions human beings to increasingly interact with social robots and embodied AI in their daily lives. Specifically, in this work, we proposed a techno-social environment using advanced blockchain technologies for CPSS members, which extends human capabilities and enables activities toward human co-becoming by facilitating indirect communication via tokenized digital twins that steer the collective behavior toward higher levels of CI in a stigmergy enhanced Society 5.0 and future token economy based Web3. Further, we experimentally demonstrated how the collective human intelligence of a blockchain-enabled DAO can be enhanced via purpose-driven tokens. Such purpose-driven tokens helped facilitate collaboration by incentivizing an autonomous group of people to individually contribute to a collective goal [97].

1.6 List of Publications

Publications included in this thesis

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

Journals

[J1] A. Beniiche, A. Ebrahimzadeh, and M. Maier. The Way of The DAO: Toward Decentralizing the Tactile Internet. *IEEE Network*, vol. 35, no. 4, pp. 190-197, July/Aug. 2021.

[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] A. Beniiche, S. Rostami, and M. Maier. Society 5.0: Internet as if People Mattered. *IEEE Wireless Communications Magazine*, under review.

Book Chapter

[BC1] A. Beniiche, A. Ebrahimzadeh, and M. Maier. From Blockchain Internet of Things (B-IoT) Towards Decentralizing the Tactile Internet. *CRC Press*: Blockchain-enabled Fog and Edge Computing: Concepts, Architectures and Applications, Editors: Muhammad Maaz Rehan, Mubashir Husain Rehmani, pp. 3-30, July 2020.

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.

[J4] 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.

[J5] 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.

1.7 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.

Chapter 2 investigates Ethereum with respect to its capability to develop new models of distributed ownership such as the Tactile Internet. Recent progress on Ethereum and open challenges are discussed in detail. In this chapter, we also discuss similarities and differences between Bitcoin and Ethereum blockchains. The comparison determines that Ethereum is a better choice as a blockchain platform. We also argue that Ethereum is better than other blockchains because of a number of salient features including DAO and its cooperative working with AI and robots and also that it is highly compatible with decentralized edge computing solutions. In our studies, we show that DAO gives birth to a new hybrid form of collaboration, in which intelligence and automation are at the center and humans operate at the edges. Finally, we conclude the chapter by outlining open research challenges and future work.

Chapter 3 elaborates on the potential of the DAO to help decentralize the Tactile Internet and aligns its decentralization with AI-enhanced multi-access edge computing (MEC). Our presented results demonstrate that higher degrees of decentralization lower the completion times of computational jobs. In addition, we extend the existent BIoT framework's judge contract, which controls IoT devices' behavior and punishes them by blocking network access, to a broader Tactile Internet context. The developed nudge contract aims at completing interrupted physical tasks by learning from a remote skilled human member of the DAO while minimizing the learning loss. Our nudge contract modifies human behavior by means of a suitable reward mechanism (instead of punishment) in order to foster trusted skill transfers.

Chapter 4 investigates the widely studied trust game of behavioral economics in a blockchain context, paying close attention to the importance of developing efficient cooperation and coordination techniques. 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 and demonstrate experimentally that a social efficiency of up to 100% can be achieved by using deposits to enhance both trust and trustworthiness. We then present an on-chaining blockchain oracle architecture for a networked N -player trust game that involves a third type of human agent called observers, who track the players' investment and reciprocity. The presence of third-party reward and penalty decisions helps raise the average normalized reciprocity above 80%, even without requiring any deposit. Further, we focus on the emerging field of robonomics, which studies the socio-technical impact of blockchain technologies on social human-robot interaction and behavioral economics for the social integration of robots into human society. Finally, we experimentally demonstrate that mixed logical-affective persuasive strategies for social robots improve the trustees' trustworthiness and reciprocity significantly.

Chapter 5 explores future 6G mobile networks and their anticipated shift to become more human-centered, thereby enabling the so-called *Society 5.0* vision. Further, we build on our recent work on robonomics in the 6G era. As mentioned above, robonomics investigates social human-robot interaction and its socio-technical impact as well as blockchain technologies and cryptocurrencies, not only coins but—more interestingly—also tokens. Specifically, we study the tokenization process of creating *tokenized digital twins* of assets and access rights in the physical and digital world, paying close attention to its central role in the future Web3 and its underlying token economy, the successor of today's information and platform economies. After introducing our CPSS based bottom-up multilayer token engineering framework for Society 5.0, we experimentally demonstrate how the collective human intelligence of a blockchain-enabled DAO can be enhanced via purpose-driven tokens.

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

Chapter 2

From Blockchain Internet of Things (B-IoT) Towards Decentralizing the Tactile Internet

This chapter contains material extracted from the following publication:

[48] A. Beniiche, A. Ebrahimzadeh, and M. Maier. From Blockchain Internet of Things (B-IoT) Towards Decentralizing the Tactile Internet. *CRC Press*: Blockchain-enabled Fog and Edge Computing: Concepts, Architectures and Applications, pp. 3-30, July 2020.

In the following, my key contributions in the aforementioned publication are explained in greater detail: (1) I largely contributed to writing the whole manuscript, including in particular surveying the state-of-the-art of blockchain technologies in Sections 2.2, identifying the challenges of integrating blockchain, IoT, and edge computing in Section 2.3, and exploring in Section 2.4 how Ethereum DAO may be leveraged to decentralize the Tactile Internet, (2) I partially contributed to the conception phase in Section 2.5, (3) I contributed to Sections 2.6 by discussing in details the symbiosis of blockchain, AI, and augmented intelligence and the importance of shifting the research focus from AI to intelligence amplification (IA), and (4) I identified open research challenges and future work in Section 2.7.

2.1 Introduction

The Internet has been constantly evolving from the mobile Internet to the emerging Internet of Things (IoT) and future Tactile Internet. Similarly, the capabilities of future 5G networks will extend far beyond those of previous generations of mobile communication. Beside 1000-fold gains in area capacity, 10 Gb/s peak data rates, and connections for at least 100 billion devices, an important aspect of the 5G vision is *decentralization*. While 2G-3G-4G cellular networks were built under the design premise of having complete control at the infrastructure side, 5G systems may drop this design assumption and evolve the cell-centric architecture into a more device-centric one. While there is a significant overlap of design objectives among 5G, IoT, and the Tactile Internet—most notably ultra-reliable and low-latency communication (URLLC)—each one of them exhibits unique characteristics in terms of underlying communications paradigms and enabling end-devices [8].

Today's Internet is ushering in a new era. While the first generation of digital revolution brought us the Internet of information, the second generation—powered by decentralized *blockchain* technology—is bringing us the Internet of value, a true peer-to-peer platform that has the potential to go far beyond digital currencies and record virtually everything of value to humankind in a distributed fashion without powerful intermediaries [29]. Some refer to decentralized blockchain technology as the "alchemy of the 21st century" since it may leverage end-user equipment for converting computing into digital gold. Arguably more importantly, though, according to Don and Alex Tapscott the blockchain technology enables trusted collaboration that can start to change the way wealth is distributed as people can share more fully in the wealth they create, rather than trying to solve the problem of growing social inequality through the redistribution of wealth only. As a result, decentralized blockchain technology helps create platforms for distributed capitalism and a more inclusive economy, which works best when it works for everyone as the foundation for prosperity. Furthermore, the authors of [49] pointed out the important role of blockchain and distributed ledger technology (DLT) applications as a next-generation of distributed sensing services for 6G driving applications whose need for connectivity will require a synergistic mix of URLLC and massive machine type communications (mMTC) to guarantee low-latency, reliable connectivity, and scalability. Furthermore, blockchains and smart contracts can improve the security of a wide range of businesses by ensuring that data cannot be damaged, stolen, or lost. In [50], the authors presented a comprehensive survey on the utilization of blockchain technologies to provide distributed security services. These services include entity authentication, confidentiality, privacy, provenance, and integrity assurances.

A blockchain technology of particular interest is *Ethereum*, which went live in July 2015. Ethereum made great strides in having its technology accepted as the blockchain standard, when Microsoft Azure started offering it as a service in November 2015.[1] Ethereum was founded by a Canadian called Vitalik Buterin after his request for creating a wider and more general scripting language for the development of *decentralized applications (DApps)* that are not limited to cryptocurrencies, a capability that Bitcoin lacked, was rejected by the Bitcoin community [31]. Ethereum enables new forms of economic organization and distributed models of companies, businesses, and ownership, e.g., self-organized holacracies and member-owned cooperatives. Or as Buterin puts it, while most technologies tend to automate workers on the periphery doing menial tasks, Ethereum automates away the center. For instance, instead of putting the taxi driver out of a job, Ethereum puts Uber out of a job and lets the taxi drivers work with the customer directly (before Uber's self-driving cars will eventually wipe out their jobs). Hence, Ethereum doesn't aim at eliminating jobs so much as it changes the definition of work. In fact, it gave rise to the first *decentralized autonomous organization (DAO)* built within the Ethereum project. The DAO is an open-source, distributed software that exists "simultaneously nowhere and everywhere," thereby creating a paradigm shift that offers new opportunities to democratize business and enable entrepreneurs of the future to design their own entirely virtual organizations customized to the optimal needs of their mission, vision, and strategy to change the world [51].

There exist excellent surveys on Bitcoin and other decentralized digital currencies, e.g., [27]. Likewise, the fundamental concepts and potential of blockchain technologies for society and industry in general have been described comprehensively in various existent tutorials, e.g., [28]. In this chapter, we focus on how blockchain technologies can be used in an IoT context by providing an up-to-date survey on recent progress and open challenges for realizing the emerging *blockchain IoT (B-IoT)*. Unlike the IoT without any human involvement in its underlying machine-to-machine (M2M) communications, the Tactile Internet is anticipated to keep the human in (rather than out of) the loop by providing real-time transmission of haptic information, i.e., touch and actuation, for the remote control of physical and/or virtual objects through the Internet. Towards this end, we elaborate on how Ethereum blockchain technologies, in particular the DAO, may be leveraged

[1] M. Gray, "Ethereum Blockchain as a Service now on Azure," `https://azure.microsoft.com`.

to realize future techno-social systems, notably the Tactile Internet, which at present is yet unclear in many ways how this would work exactly [28].

The remainder of this chapter is structured as follows. In Section 2.2, we first explain the commonalities of and specific differences between Ethereum and Bitcoin blockchains followed by a description of the DAO in technically greater detail. Section 2.3 defines the integration of blockchain and IoT (B-IoT), we discuss the motivation of such integration followed by a description of the challenges of integrating blockchain and edge computing. In Section 2.4, after briefly reviewing the key concepts of the emerging Tactile Internet, we introduce the so-called human-agent-robot teamwork (HART) design approach and our proposed low-latency FiWi enhanced LTE-A HetNets based on advanced multi-access edge computing (MEC) with embedded artificial intelligence (AI) capabilities. In Section 2.5, we elaborate on the potential role of Ethereum and in particular the DAO in helping decentralize the Tactile Internet. Section 2.6 discusses the symbiosis of blockchain, AI, and augmented intelligence in more detail. We identify open challenges and future work in Section 2.7. Finally, Section 2.8 concludes the chapter.

2.2 Blockchain Technologies

In this section, we give a brief overview of the basic concepts of blockchain technologies, paying a particular attention to the main commonalities and specific differences between Ethereum and Bitcoin. We then introduce the DAO, which represents a salient feature of Ethereum that cannot be found in Bitcoin.

2.2.1 Ethereum vs. Bitcoin Blockchains

Blockchain technologies have been undergoing several iterations as both public organizations and private corporations sought to take advantage of their potential. A typical blockchain network is essentially a distributed database (also known as ledger) comprising records of all transactions or digital events that have been executed by or shared among participating parties. Blockchains may be categorized into public (i.e., permissionless) and private (i.e., permissioned) networks. In the former category, anyone may join and participate in the blockchain. Conversely, a private blockchain applies certain access control mechanisms to determine who can join the network. A

Table 2.1: Public vs. Private Blockchains

	Public Blockchain	**Private Blockchain**
Network Type	Fully decentralized	Partially decentralized
Access	Permissionless read/write	Permissioned read/write
User Identity	Pseudo-anonymous	Known participants
Consensus Mechanism	Proof-of-work/Proof-of-state	Pre-approved participants
Consensus Determination	By all miners	By one organization
Immutability	Nearly impossible to tamper	Could be tampered
Purpose	Any decentralized applications	Business applications

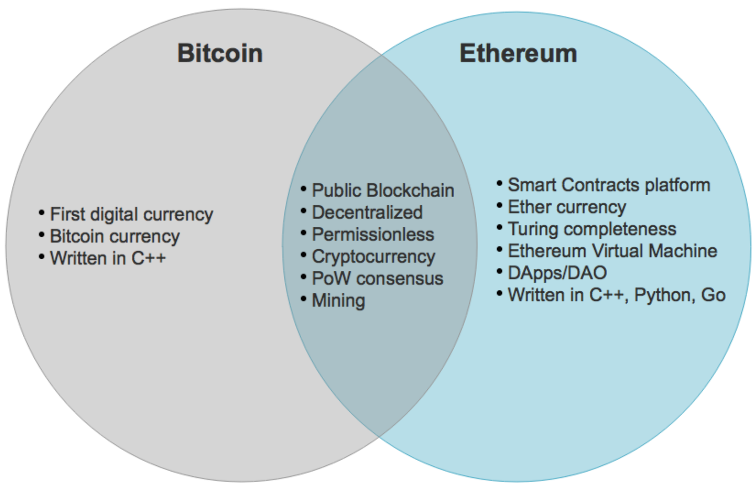


Figure 2.1: Bitcoin and Ethereum blockchains: Commonalities and differences.

public blockchain is immutable because none of the transactions can be tampered or changed. Also, it is pseudo-anonymous because the identity of those involved in a transaction is represented by an address key in the form of a random string. Table 2.1 highlights the major differences between public and private blockchains, as discussed in further detail below. Note that both Ethereum and Bitcoin are public blockchains.

Fig. 2.1 illustrates the main commonalities of and differences between Bitcoin and Ethereum blockchains. The Bitcoin blockchain is predominantly designed to facilitate Bitcoin transactions. It is the world's first fully functional digital currency that is truly decentralized, open source, and censorship resistant. Bitcoin makes use of a cryptographic *proof-of-work (PoW)* consensus mechanism based on the SHA-256 hash function and digital signatures. Achieving consensus provides extreme levels of fault tolerance, ensures zero downtime, and makes data stored on the blockchain forever unchangeable and censorship-resistant in that everyone can see the blockchain history, including any data or messages. There are two different types of actors, whose roles are defined as follows:

- **Regular nodes:** A regular node is a conventional actor, who just has a copy of the blockchain and uses the blockchain network to send or receive Bitcoins.
- **Miners:** A miner is an actor with a particular role, who builds the blockchain through the validation of transactions by creating blocks and submitting them to the blockchain network to be included as blocks. Miners serve as protectors of the network and can operate from anywhere in the world as long as they have sufficient knowledge about the mining process, the hardware and software required to do so, and an Internet connection.

In the Bitcoin blockchain, a block is mined about every 10 minutes and the block size is limited to 1 MByte. Note that the Bitcoin blockchain is restricted to a rate of 7 transactions per second, which renders it unsuitable for high-frequency trading. Other weaknesses of the Bitcoin blockchain include its script language, which offers only a limited number of small instructions and is non-Turing-complete. Furthermore, developing applications using the Bitcoin script language requires advanced skills in programming and cryptography.

Ethereum is currently the second most popular public blockchain after Bitcoin. It has been developed by the Ethereum Foundation, a Swiss nonprofit organization, with contributions from all over the world. Ethereum has its own cryptocurrency called *Ether*, which provides the primary form of liquidity allowing for exchange of value across the network. Ether also provides the mechanism for paying and earning transaction fees that arise from supporting and using the network. Like Bitcoin, Ether has been the subject of speculation witnessing wide fluctuations. Ethereum is well suited for developing DApps that need to be built quickly and interact efficiently and securely via the blockchain platform. Similar to Bitcoin, Ethereum uses a PoW consensus method for authenticating transactions and proving the achievement of a certain amount of work. The hashing algorithm used by the PoW mechanism is called Ethash. Different from Bitcoin, Ethereum developers expect to replace PoW with a so-called *proof-of-stake (PoS)* consensus[2]. PoS will require Ether miners to hold some amount of Ether, which will be forfeit if the miner attempts to attack the blockchain network. The Ethereum platform is often referred to as a Turing-complete *Ethereum virtual machine*

[2] Currently, Ethereum operates on a proof of work consensus model. Ethereum 2.0 proof-of-stake (PoS) is designed to be launched in three phases: The "Beacon Chain" phase was launched on 1 December 2020 and created the Beacon Chain, a PoS blockchain that will act as the central coordination and consensus hub of Ethereum 2.0. The second phase called "The Merge" will merge the Beacon Chain with the current Ethereum network, transitioning its consensus mechanism from proof-of-work to proof-of-stake. It is expected to be released in the first half of 2022. Then, the "Shard chains" phase will implement state execution in the shard chains with the current Ethereum 1.0 chain expected to become one of the shards of Ethereum 2.0. Shard chains will spread the network's load across 64 new chains. Also, it is expected to be released in 2022.

(EVM) built on top of the underlying blockchain. Turing-completeness means that any system or programming language is able to compute anything computable provided it has enough resources. Note that the EVM requires a small amount of fees for executing transactions. These fees are called gas and the required amount of gas depends on the size of a given instruction. The longer the instruction, the more gas is required.

While the Bitcoin blockchain simply contains a list of transactions, Ethereum's basic unit is the *account*. The Ethereum blockchain tracks the state of every account, whereby all state transitions are transfers of value and information between accounts. The account concept is considered an essential component and data model of the Ethereum blockchain since it is vital for a user to interact with the Ethereum network via transactions. Accounts represent the identities of external agents (e.g., human or automated agents, mining nodes). Accounts use public key cryptography to sign each transaction such that the EVM can securely validate the identity of the sender of the transaction.

Beside C++, Ethereum supports several programming languages based on JavaScript and Python, e.g., Solidity, Serpent, Mutan, or LLL, whereby Solidity is the most popular language for writing so-called *smart contracts*. A smart contract is an agreement that runs exactly as programmed without any third-party interference. It uses its own arbitrary rules of ownership, transaction formats, and state-transition logic. Each method of a smart contract can be invoked via either a transaction or another method. Smart contracts enable the realization of DApps, which may look exactly the same as conventional applications with regard to application programming interface (API), though the centralized backend services are replaced with smart contracts running on the decentralized Ethereum network without relying on any central servers. Interesting examples of existent DApps include Augur (a decentralized prediction market), Weifund (an open platform for crowdfunding), Golem (supercomputing), and Ethlance (decentralized job market platform), among others. To provide an effective means of communications between DApps, Ethereum uses the *Whisper* peer-to-peer protocol, a fully decentralized middleware for secret messaging and digital cryptography. Whisper supports the creation of confidential communication routes without the need for a trusted third party. It builds on a peer sampling service that takes into account network limitations such as network address translation (NAT) and firewalls. In general, any centralized service may be converted into a DApp by using the Ethereum blockchain.

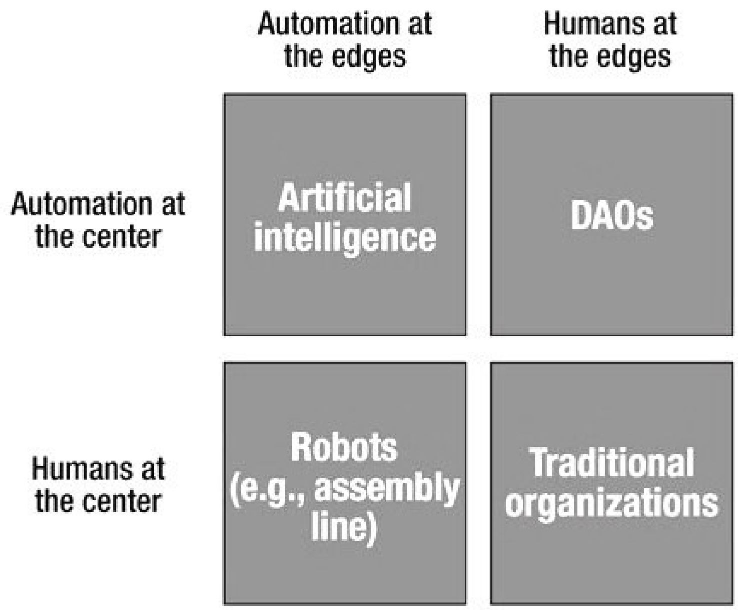


Figure 2.2: DAOs vs. artificial intelligence, traditional organizations, and robots (widely deployed in assembly lines, among others): Automation and humans involved at their edges and center (source: Ethereum Blog).

2.2.2 Decentralized Autonomous Organizations (DAOs)

The most remarkable thing about cryptocurrencies and blockchain might be how they enable people and organizations on a global level, all acting in their own interest, to create something of immense shared value. Many observers assert that this is a real alternative to current companies. The decentralization, crowd-based technologies of cryptocurrencies, distributed ledgers, distributed consensus and smart contracts provide the possibility to fundamentally change the way people organize their affairs and offer a new paradigm for enterprise design. Two recent efforts to substitute a crowd for a company are blockchain technology and DAOs. DAOs are decentralized organizations without a central authority or leader. They operate on a programming code that is encoded on the blockchain (e.g., Ethereum). Like the blockchain, the code of a DAO moves away from traditional organizations by removing the need for centralized control. Not even the original developers of the DAO have any extra authority since it runs independently without any human intervention. It may be funded by a group of individuals who cover its basic costs and give the funders voting rights rather than any kind of ownership or equity shares. This creates an autonomous and transparent system that will continue on the network for as long as it provides a useful service to its members.

Table 2.2: Comparison of Bitcoin and Ethereum blockchains

	Bitcoin	**Ethereum**
Currency	Bitcoin	Ether
Applications	Cryptocurrency	Cryptocurrency, Smart Contract, DApps/DAO
Written in	C++	C++, Go, Python
Consensus	Proof-of-work (based on SHA-256)	Proof-of-work (Ethash), Planning for Proof-of-stake
Turing Completeness	No	Yes
Anonymity Mechanisms	No	Yes (with Whisper protocol)
Censorship Resistance	No	Yes
Transaction Limit	7 transactions/sec	20 transactions/sec
State Concept	No	Data
Smart Contract Languages	No	Solidity, Serpent, Mutan, LLL
Smart Contract Execution	No	Ethereum Virtual Machine (EVM)
Block Time	10 min	15 seconds
Data Model	Transaction-based	Account-based
Client P2P Connections	No	Yes (with Whisper protocol)
Routing	No	Yes (Whisper protocol)

A successful example of deploying the DAO concept for automated smart contract operation is *Storj*, which is a decentralized, secure, private, and encrypted cloud storage platform that may be used as an alternative to centralized storage providers like Dropbox or Google Drive. A DAO may be funded by a group of individuals who cover its basic costs, giving the funders voting rights rather than any kind of ownership or equity shares. This creates an autonomous and transparent system that will continue on the network for as long as it provides a useful service for its customers. DAOs exist as open-source, distributed software that executes smart contracts and works according to specified governance rules and guidelines. Vitalik Buterin described on the Ethereum Blog the ideal of a DAO as follows: It is an entity that lives on the Internet and exists autonomously, but also heavily relies on hiring individuals to perform certain tasks that the automation itself cannot do. Unlike AI based agents that are completely autonomous, a DAO still requires heavy involvement from humans specifically interacting according to a protocol defined by the DAO in order to operate. For illustrating the destinction between a DAO and AI, Fig. 2.2 shows a quadrant chart that classifies DAOs, AI, traditional organizations as well as robots, which have been widely deployed in assembly lines among others, with regard to automation and humans involved at their edges and center. We will elaborate on how this particular feature of DAOs (i.e., automation at the center and humans at the edges) can be exploited for decentralizing the Tactile Internet below in Section 2.5. Towards this end, we also briefly note that according to Vitalik Buterin a DAO is non-profit, though one can make money in a DAO, not by providing investment into the DAO itself but by participating in its ecosystem, e.g., via *membership*.

For convenience, Table 2.2 summarizes the technical details of our comparison of Bitcoin and Ethereum blockchains.

2.3 Blockchain IoT and Edge Computing

In this section, after defining the integration of blockchain and IoT (B-IoT), we discuss the motivation of such integration followed by a description of the challenges of integrating blockchain and edge computing.

2.3.1 Blockchain IoT (B-IoT): Recent Progress and Related Work

Recall from Section 2.1 that the IoT is designed to enable communications among machines without relying on any human involvement. Thus, its underlying M2M communications is useful for enabling the automation of industrial and other machine-centric processes. The emerging B-IoT represents a powerful combination of two massive technologies—blockchain and M2M communications—that allows us to automate complex multi-step IoT processes, e.g., via smart contracts. With the ever-increasing variety of communication protocols between IoT devices, there is a need for transparent yet highly secure and reliable IoT device management systems. This section surveys the state of the art of the emerging B-IoT, describing recent progress and open challenges.

The majority of IoT devices are resource constrained, which restricts them to be part of the blockchain network. To cope with these limitations, the author of [52] proposed a decentralized access management system, where all entities are part of an Ethereum blockchain except for IoT devices as well as so-called *management hub* nodes that request permissions from the blockchain on behalf of the IoT devices belonging to different wireless sensor networks. In addition, entities called *managers* interact with the smart contract hosted at a specific *agent node* in the blockchain in order to define and/or modify the access control policies for the resources of their associated IoT devices. The proof-of-concept implementation evaluated the new system architecture components that are not part of the Ethereum network, i.e., management hub and IoT devices, and demonstrated the feasibility of the proposed access management architecture in terms of latency and scalability. Another interesting Ethereum case study can be found in [53], which reviews readily available Ethereum blockchain packages for realizing a smart home system according to its smart contract features for handling access control policy, data storage, and data flow management.

The architectural issues for realizing blockchain-driven IoT services were investigated in greater detail in [54]. In a preliminary study using a smart thing renting service as an example B-IoT service, the authors compared the following four different architectural styles based on Ethereum: (*i*) fully centralized (cloud without blockchain), (*ii*) pseudo distributed things (physically located in central cloud), (*iii*) distributed things (directly controlled by smart contract), and (*iv*) fully distributed. The preliminary results indicate that a fully distributed architecture, where a blockchain endpoint is deployed on the end-user device, is superior in terms of robustness and security.

The various perspectives for integrating secure elements in Ethereum transactions were discussed in [55]. A novel architecture for establishing trust in Ethereum transactions exchanged by smart things was presented. To prevent the risks that secret keys for signature are stolen or hacked, the author proposed to use javacard secure elements and a so-called *crypto currency smart card (CCSC)*. Two CCSC use cases were discussed. In the first one, the CCSC was integrated in a low-cost B-IoT device powered by an Arduino processor, in which sensor data are integrated in Ethereum transactions. The second use case involved the deployment of CCSC in remote APDU call secure (RACS) servers to enable remote and safe digital signatures by using the well-known elliptic curve digital signature algorithm (ECDSA).

Blockchain transactions require public-key encryption operations such as digital signatures. However, not all B-IoT devices can support this computationally intensive task. For this reason, in [56], the authors proposed a preliminary design of a *gateway-oriented* approach, where all blockchain related operations are offloaded to a gateway. The authors noted that their approach is compatible with the Ethereum client side architecture.

Due to the massive scale and distributed nature of IoT applications and services, blockchain technology can be exploited to provide a secure, tamper-proof B-IoT network. More specifically, the key properties of tamper-resistance and decentralized trust allow us to build a secure authentication and authorization service, which does not have a single point of failure. Towards this end, the authors of [57] made a preliminary attempt to develop a security model backed by blockchain that provide confidentiality, integrity, and availability of data transmitted and received by nodes in a B-IoT network. The proposed solution encompasses a *blockchain protocol layer* on top of the TCP/IP transport layer and a *blockchain application layer.* The first one comprises a distributed consensus algorithm for B-IoT nodes while the latter one defines the IoT security specific transactions and their semantics for the higher protocol layers. To evaluate the feasibility and performance of the proposed layered architecture, B-IoT nodes connected in a tree topology were simulated using 1 Gbps Ethernet or 54 Mbps WiFi links. The simulation results showed that the block arrival rate was not affected much by the increased latency and reduced bandwidth, when replacing wired Ethernet with wireless WiFi links, as the block difficulty adjustment adapts dynamically to the network conditions.

Among various low-power wide-area (LPWA) technologies, *long range (LoRa)* wireless radio frequency (RF) is considered one of the most promising enabling technologies for realizing massive IoT deployment. In [58], the authors presented a proof-of-concept demonstrator to enable low-power, resource-constrained LoRa IoT end-devices to access an Ethereum blockchain network via an intermediate gateway, which acts as a full blockchain node. More specifically, a battery-powered IoT end-device sends position data to the LoRa gateway, which in turn forwards it through the standard Go-lang-based Ethereum client *Geth* to the blockchain network using a smart contract. An event based communication mechanism between the LoRa gateway and a backend application server was implemented as proof-of-concept demonstrator.

One of the fundamental challenges of object identification in IoT stems from the traditional domain name system (DNS). Typically, DNS is managed in centralized modules and thus may cause large-scale failures due to unilateral advanced persistent threat (APT) attacks as well as zone file synchronization delays in larger systems. Clearly, a more robust and distributed name management system is needed that supports the smooth evolution of DNS and renders it more efficient for IoT and the future Internet in general. Towards this end, a decentralized blockchain-based domain name system called *DNSLedger* was introduced in [59]. To rebuild the hierarchical structure of DNS, DNSLedger contains two kinds of blockchain: (*i*) a single *root chain* that stores all the top-level domain information and (*ii*) multiple *top-level domain (TLD) chains*, each responsible for the information about its respective domain name. In DNSLedger, servers of domain names act as blockchain nodes, while each TLD chain may select one or more servers to join the root chain.

DNSLedger clients may execute common DNS functions such as domain name look-up, application, and modification.

Many of the aforementioned studies considered Ethereum as the blockchain of choice among other blockchain platforms given its maturity and its smart contract platform. It was shown that fully distributed Ethereum architectures are able to enhance both robustness and security. Furthermore, a gateway-oriented design approach was often applied to offload computationally intensive tasks from low-power, resource-constrained IoT end-devices onto an intermediate gateway and thus enable them to access the Ethereum blockchain network. Also, it was shown that the block arrival rate does not deteriorate much by the increased latency and reduced bandwidth of WiFi access links.

Despite the recent progress, the salient features that set Ethereum aside from other blockchains (see Section 2.2) remain to be explored in more depth, including their symbiosis with other emerging key technologies such as AI and robots as well as decentralized cloud computing solutions known as *edge computing*. A question of particular interest hereby is how decentralized blockchain mechanisms may be leveraged to let emerge *new hybrid forms of collaboration among individuals*, which haven't been entertained in the traditional market-oriented economy dominated by firms rather than individuals [28].

2.3.2 Blockchain Enabled Edge Computing

One of the critical challenges in cloud computing is the end-to-end responsiveness between the mobile device and an associated cloud. To address this challenge, multi-access edge computing (MEC) is proposed, which is a mobility-enhanced small-scale cloud data center that is located at the edge of the Internet (e.g., Radio Access Network (RAN)) and in close proximity to mobile subscribers. An MEC entity is a trusted, resource-rich computer or cluster of computers that is well-connected to the Internet and available for use by nearby mobile devices. According to the white paper published by ETSI, MEC is considered as a key emerging technology to be an important component of next-generation networks. In light of the aforementioned arguments, the integration of blockchain and edge computing into one unified entity becomes a natural trend. On one hand, by incorporating blockchain into the edge computing network, the system can provide reliable access and control of the network, computation, and storage over decentralized nodes. On the other hand, edge computing enables blockchain storage and mining computation from power-limited devices. Furthermore, off-chain storage and off-chain computation at the edges enable scalable storage and computation on the blockchain [60].

Several recent studies on blockchain and edge computing have been carried out. In [61], resource-constrained IoT devices were released from computation-intensive tasks by offloading blockchain consensus processes and data processing tasks onto more powerful edge computing resources. The proposed EdgeChain was built on the Ethereum platform and uses smart contracts to monitor and regulate the behavior of IoT devices based on how they act and use resources. Another blockchain-enabled computation offloading scheme for IoT with edge computing capabilities, called BeCome, was proposed in [62]. The authors of this study aimed at decreasing the task offloading time and energy consumption of edge computing devices, while achieving load balancing and data integrity.

The study in [63] proposed a blockchain-based trusted data management scheme called BlockTDM for edge computing to solve the data trust and security problems in an edge computing environment. Specifically, the authors proposed a flexible and configurable blockchain architecture that includes a mutual authentication protocol, flexible consensus, smart contract, block and transaction data management as well as blockchain node management and deployment. The BlockTDM scheme is able to support matrix-based multichannel data segment and isolation for sensitive or privacy data protection. Moreover, the authors designed user-defined sensitive data encryption before the transaction payload is stored in the blockchain system. They implemented a conditional access and decryption query of the protected blockchain data and transactions through an appropriate smart contract. Their analysis and evaluation show that the proposed BlockTDM scheme provides a general, flexible, and configurable blockchain-based paradigm for trusted data management with high credibility.

In summary, blockchain-enabled edge computing has become an important concept that leverages decentralized management and distributed services to meet the security, scalability, and performance requirements of next-generation of communications networks, as discussed in technically greater detail in Section 2.5.

2.4 The IEEE P1918.1 Tactile Internet

In this section, we give a brief overview of the basic concepts, features, structure, and taxonomy of the Tactile Internet. Subsequently, some of the typical Tactile Internet applications and network infrastructure requirements are presented in greater detail.

2.4.1 The Tactile Internet: Key Principles

The term Tactile Internet was first coined by Fettweis in 2014. In his seminal paper [6], the Tactile Internet was defined as a breakthrough enabling unprecedented mobile applications for tactile steering and control of and virtual objects by requiring a round-trip latency of 1-10 ms. Later in 2014, ITU-T published a Technology Watch Report on the Tactile Internet, which emphasized that scaling up research in the area of wired and wireless access networks will be essential, ushering in new ideas and concepts to boost access networks' redundancy and diversity to meet the stringent latency as well as carrier-grade reliability requirements of Tactile Internet applications [12]. The Tactile Internet provides a medium for remote physical interaction in real-time, which requires the exchange of closed-loop information between virtual and/or real objects (i.e., humans, machines, and processes). This mandatory end-to-end design approach is fully reflected in the key principles of the reference architecture within the emerging IEEE P1918.1 standards working group (formed in March 2016), which aims to define a framework for the Tactile Internet [64]. Among others, the key principles envision to (*i*) develop a generic Tactile Internet reference architecture, (*ii*) support local area as well as wide area connectivity through wireless (e.g., cellular, WiFi) or hybrid wireless/wired networking, and (*iii*) leverage computing resources from cloud variants at the edge of the network. The working group defines the Tactile Internet as a "network or network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in perceived real-time by humans or machines." Some of the key use cases considered in IEEE P1918.1 include teleoperation, haptic communications, immersive virtual reality, and automotive control.

To give it a more 5G-centric flavor, the Tactile Internet has been more recently also referred to as the 5G-enabled Tactile Internet [7, 65]. Recall from above that unlike the previous four cellular generations, future 5G networks will lead to an increasing integration of cellular and WiFi technologies and standards [66]. Furthermore, the importance of the so-called backhaul bottleneck

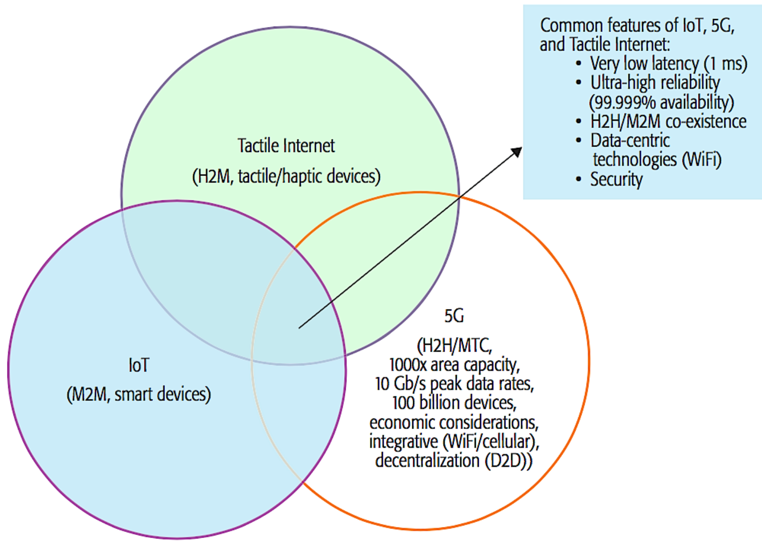


Figure 2.3: The three lenses of IoT, 5G, and the Tactile Internet: Commonalities and differences.

needs to be recognized as well, calling for an end-to-end design approach leveraging both wireless front-end and wired backhaul technologies. Or, as eloquently put by Andrews, the lead author of [66], "placing base stations all over the place is great for providing the mobile stations high-speed access, but does this not just pass the buck to the base stations, which must now somehow get this data to and from the wired core network?" [67].

Clearly, the Tactile Internet opens up a plethora of exciting research directions towards adding a new dimension to the human-to-machine interaction via the Internet. According to the aforementioned ITU-T Technology Watch Report, the Tactile Internet is supposed to be the next leap in the evolution of today's IoT, although there is a significant overlap among 5G, IoT, and the Tactile Internet. For illustration, Fig. 2.3 provides a view of the aforementioned commonalities and differences through the three lenses of IoT, 5G, and the Tactile Internet. The major differences may be best expressed in terms of underlying communications paradigms and enabling devices. IoT relies on M2M communications with a focus on smart devices (e.g., sensors and actuators). In co-existence with emerging MTC, 5G will maintain its traditional human-to-human (H2H) communications paradigm for conventional triple-play services (voice, video, data) with a growing focus on the integration with other wireless technologies (most notably WiFi) and decentralization. Conversely, the Tactile Internet will be centered around human-to-machine (H2M) communications leveraging tactile/haptic devices. More importantly, despite their differences, IoT, 5G, and the

Tactile Internet seem to converge toward a common set of important design goals:

- Very low latency on the order of 1 ms
- Ultra-high reliability with an almost guaranteed availability of 99.999 percent
- H2H/M2M coexistence
- Integration of data-centric technologies with a particular focus on WiFi
- Security

Importantly, the Tactile Internet involves the inherent human-in-the-loop (HITL) nature of human-to-machine interaction, as opposed to the emerging IoT without any human involvement in its underlying M2M communications. While M2M communications is useful for the automation of industrial and other machine-centric processes, the Tactile Internet will be centered around human-to-machine/robot (H2M/R) communications and will thus allow for a human-centric design approach towards creating novel immersive experiences and extending the capabilities of the human through the Internet, i.e., augmentation rather than automation of the human [68].

2.4.2 Human-Agent-Robot Teamwork (HART)

A promising approach toward achieving advanced human-machine coordination by means of a superior process for fluidly orchestrating human and machine coactivity may be found in the still young field of human-agent-robot teamwork (HART) research [69]. Unlike early automation research, HART goes beyond the singular focus on full autonomy (i.e., complete independence and self-sufficiency) and cooperative/collaborative autonomy among autonomous systems themselves, which aim at excluding humans as potential teammates for the design of human-out-of-the-loop solutions. In HART, the dynamic allocation of functions and tasks between humans and machines, which may vary over time or be unpredictable in different situations, plays a central role. In particular, with the rise of increasingly smarter machines, the historical humans-are-better-at/machines-are-better-at (HABA/MABA) approach to decide which tasks are best performed by people and which by machines rather than working in concert has become obsolete. To provide a better understanding of the potential and limitations of current smart machines, T. H. Davenport and J. Kirby classified in their latest book "Only Humans Need Apply: Winners and Losers in the Age of Smart Machines"[3]. the capabilities of intelligent machines along two dimensions, namely, their ability to act and their ability to learn. The ability to act involves four task levels, ranging from the most basic tasks (e.g., analyzing numbers) to performing digital tasks (done by agents) or even physical tasks (done by robots). On the other hand, the ability to learn escalates through four levels, spanning from human-support machines with no inherent intelligence to machines with context-awareness, learning, or even self-aware intelligence.

According to [69], among other HART research challenges, the development of capabilities that enable autonomous systems not merely to do things for people, but also to work together with people and other systems represents an important open issue in order to treat the human as a "member" of a team of intelligent actors rather than keep viewing him as a conventional "user." In the following, we introduce and extend the concept of fiber-wireless (FiWi) enhanced LTE-Aadvanced (LTE-A) heterogeneous networks (HetNets) in order to enable both local and non-local teleoperation by exploiting AI enhanced MEC capabilities to achieve both low round-trip latency and low jitter.

2.4.3 Low-Latency FiWi Enhanced LTE-A HetNets

FiWi access networks, also referred to as wireless-optical broadband access networks (WOBANs), combine the reliability, robustness, and high capacity of optical fiber networks and the flexibility, ubiquity, and cost savings of wireless networks [70]. To deliver peak data rates up to 200 Mb/s per user and realize the vision of complete fixed-mobile convergence, it is crucial to replace today's legacy wireline and microwave backhaul technologies with integrated FiWi broadband access networks.

In [71], we investigated the performance gains obtained from unifying coverage-centric 4G mobile networks and capacity-centric FiWi broadband access networks based on data-centric Ethernet technologies with resulting fiber backhaul sharing and WiFi offloading capabilities in response to the unprecedented growth of mobile data traffic. We evaluated the maximum aggregate throughput, offloading efficiency, and in particular the delay performance of FiWi enhanced LTE-A HetNets, including the beneficial impact of various localized fiber-lean backhaul redundancy and wireless

[3] T. H. Davenport and J. Kirby, "Only Humans Need Apply: Winners and Losers in the Age of Smart Machines," First edition, Harper Business, 2016.

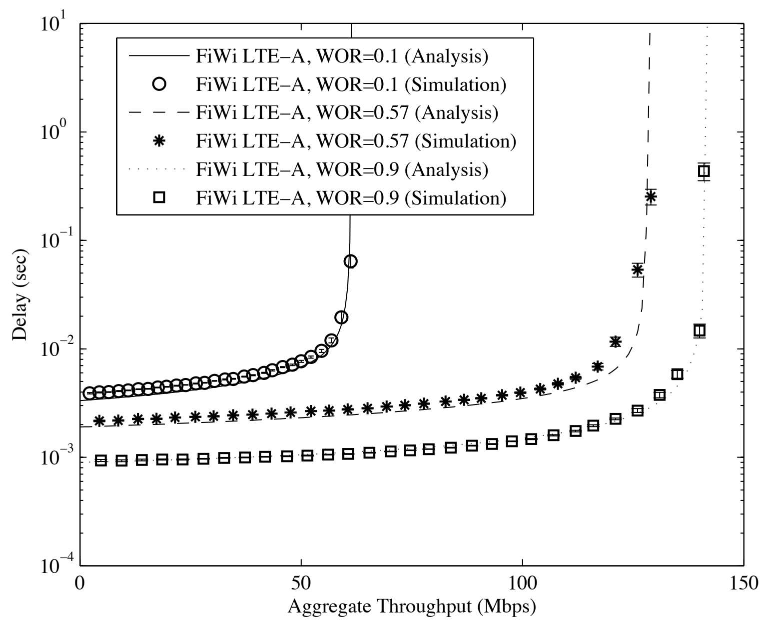


Figure 2.4: Average end-to-end delay vs. aggregate throughput for different WiFi offloading ratio (WOR).

protection techniques, by means of probabilistic analysis and verifying simulation. In our study, we paid close attention to fiber backhaul reliability issues stemming from fiber faults of an Ethernet passive optical network (EPON) and WiFi offloading limitations due to WiFi mesh node failures as well as temporal and spatial WiFi coverage constraints.

For illustration, Fig. 2.4 depicts the average end-to-end delay performance of FiWi enhanced LTE-A HetNets vs. aggregate throughput for different WiFi offloading ratio (WOR) values, whereby $0 \leq \text{WOR} \leq 1$ denotes the percentage of mobile user traffic offloaded onto WiFi. The presented analytical and verifying simulation results were obtained by assuming a realistic LTE-A and FiWi network configuration under uniform traffic loads and applying minimum (optical and wireless) hop routing. For further details the interested reader is referred to the work presented in [71]. For now, let us assume that the reliability of the EPON is ideal, i.e., no fiber backhaul faults occur. However, unlike EPON, the WiFi mesh network may suffer from wireless service outage with probability 10^{-6}. We observe from Fig. 2.4 that for increasing WOR the throughput-delay performance of FiWi enhanced LTE-A HetNets is improved significantly. More precisely, by changing WOR from 0.1 to 0.57 the maximum achievable aggregate throughput increases from about 61 Mbps to roughly 126 Mbps, i.e., the maximum achievable aggregate throughput has more than doubled. More importantly, further increasing WOR to 0.9 does not result in an additional significant increase of the maximum achievable aggregate throughput, but it is instrumental in decreasing the average end-to-end delay and keeping it at a very low level of 10^{-3} second (1 ms) for a wide range of traffic loads. Thus, this result shows that WiFi offloading the majority of data traffic from 4G mobile networks is a promising approach to obtain a very low latency on the order of 1 ms.

2.4.4 AI Enhanced MEC: Pushing AI to the Edge

Fig. 2.5 depicts the generic network architecture of FiWi enhanced LTE-A HetNets with AI enhanced MEC servers. The fiber backhaul consists of a time or wavelength division multiplexing (TDM/WDM) IEEE 802.3ah/av 1/10 Gb/s EPON with a typical fiber range of 20 km between the central optical line terminal (OLT) and remote optical network units (ONUs). The EPON may comprise multiple stages, each stage separated by a wavelength-broadcasting splitter/combiner or a wavelength multiplexer/demultiplexer. There are three different subsets of ONUs. An ONU may either serve fixed (wired) subscribers. Alternatively, it may connect to a cellular network base station (BS) or an IEEE 802.11n/ac/s WLAN mesh portal point (MPP), giving rise to a collocated ONU-BS or ONU-MPP, respectively. Depending on her trajectory, a mobile user (MU) may communicate through the cellular network and/or WLAN mesh front-end, which consists of ONU-MPPs, intermediate mesh points (MPs), and mesh access points (MAPs) [16].

Human operators (HOs) and teleoperator robots (TORs) are assumed to communicate only via WLAN, as opposed to MUs using their dual-mode 4G/WiFi smartphones. Teleoperation is done either locally or non-locally, depending on the proximity of the involved HO and TOR, as illustrated in Fig. 2.5. In local teleoperation, the HO and corresponding TOR are associated with the same MAP and exchange their command and feedback samples through this MAP without traversing the fiber backhaul. Conversely, if HO and TOR are associated with different MAPs, non-local teleoperation is generally done by communicating via the backhaul EPON and central OLT. Despite recent interest in exploiting machine learning for optical communications and networking, edge intelligence for enabling an immersive and transparent teleoperation experiences for human operators has not been explored yet. In [16], we applied machine learning at the edge of our considered communication network for realizing immersive and frictionless Tactile Internet experiences. To realize edge intelligence, selected ONU-BSs/MPPs are equipped with AI-enhanced MEC servers. These servers rely on the computational capabilities of cloudlets collocated at the optical-wireless interface (see

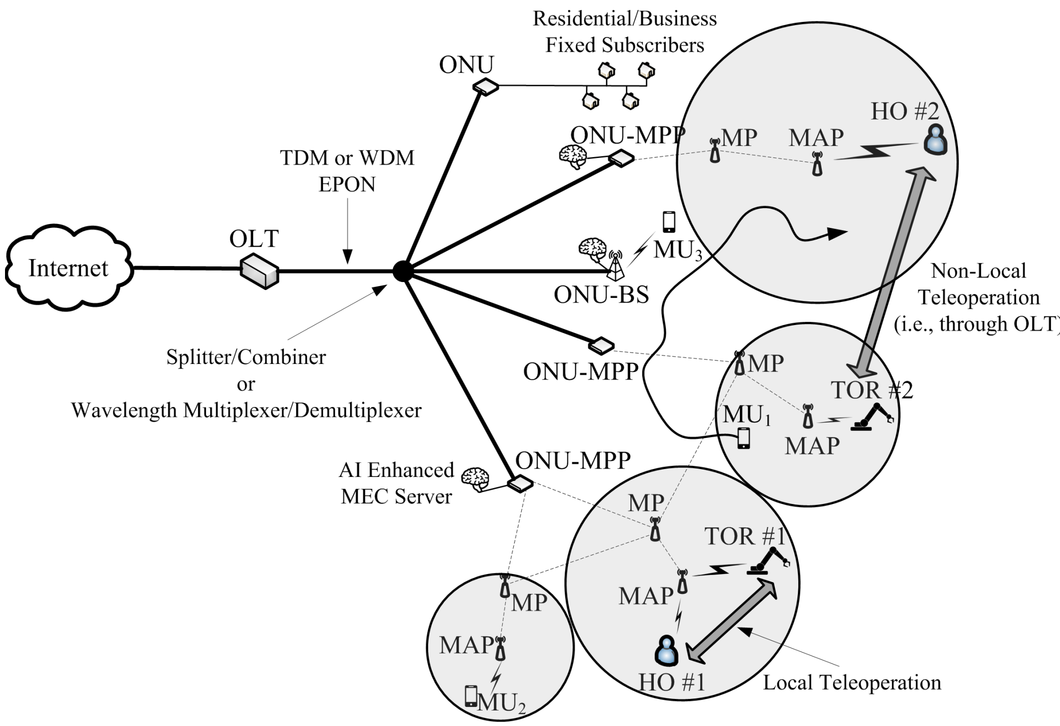


Figure 2.5: Architecture of FiWi based Tactile Internet with AI enhanced MEC for local and non-local teleoperation.

Fig. 2.5) to forecast delayed haptic samples in the feedback path. As a consequence, the HO is enabled to perceive the remote task environment in real-time at a 1-ms granularity, thus resulting in a tighter togetherness, improved safety control, and increased reliability of the teleoperation systems.

2.5 Decentralizing the Tactile Internet

Recall from Section 2.1 that the Tactile Internet will involve the inherent HITL nature of human-to-machine interaction, as opposed to the emerging IoT. Thus, it allows for a human-centric design approach towards extending the capabilities of the human through the Internet for the augmentation rather than automation of the human. Recently, in [68], we put forward the idea that the Tactile Internet may be the harbinger of human augmentation and human-machine symbiosis envisioned by contemporary and early-day Internet pioneers. More specifically, we elaborated on the role of AI enhanced agents may play in supporting humans in their task coordination between humans and machines. Toward achieving advanced human-machine coordination, we developed a distributed allocation algorithm of computational and physical tasks for fluidly orchestrating HART coactivities, e.g., the shared use of user- and/or network-owned robots. In our design approach, all HART members established through communication a collective self-awareness with the objective of minimizing the task completion time.

In the following, we search for synergies between the aforementioned HART members and the complementary strengths of the DAO, AI, and robots (see Fig. 2.2) to facilitate local human-machine coactivity clusters by decentralizing the Tactile Internet. Towards this end, it's important to better understand the merits and limits of AI. Recently, Stanford University launched its *One Hundred Year Study on Artificial Intelligence (AI100).* In the inaugural report "Artificial Intelligence and Life in 2030," the authors defined AI as a set of computational technologies that are inspired by the ways people use their nervous systems and bodies to sense, learn, reason, and take action. They also point out that AI will likely replace tasks rather than jobs in the near term and highlight the importance of *crowdsourcing* of human expertise to solve problems that computers alone cannot solve well.

2.5.1 Decentralized Edge Intelligence

First, let us explore the potential of leveraging mobile end-user equipment by partially or fully decentralizing MEC. We introduce the use of AI enhanced MEC servers at the optical-wireless interface of converged fiber-wireless mobile networks for computation offloading. Assuming the same default network parameter setting and simulation setup as in [68], we consider $1 \leq N_{Edge} \leq 4$ AI enhanced MEC servers, each associated with 8 end-users, whereof $1 \leq N_{PD} \leq 8$ partially decentralized end-users can flexibly control the amount of offloaded tasks by varying their computation offloading probability. The remaining $8 - N_{PD}$ are fully centralized end-users that rely on edge computing only (i.e., their computation offloading probability equals 1). Note that for $N_{Edge} = 4$, all end-users may offload their computation tasks onto an edge node. Conversely, for $N_{Edge} < 4$, one or more edge nodes are unavailable for computation offloading and their associated end-users fall back on their local computation resources (i.e., fully decentralized). Fig. 2.6 shows the average task completion time vs. computation offloading probability of the partially decentralized end-users for different N_{Edge} and N_{PD}. We observe from Fig. 2.6 that for a given N_{Edge}, increasing N_{PD} (i.e., higher level of decentralization) is effective in reducing the average task completion time. Specifically, for

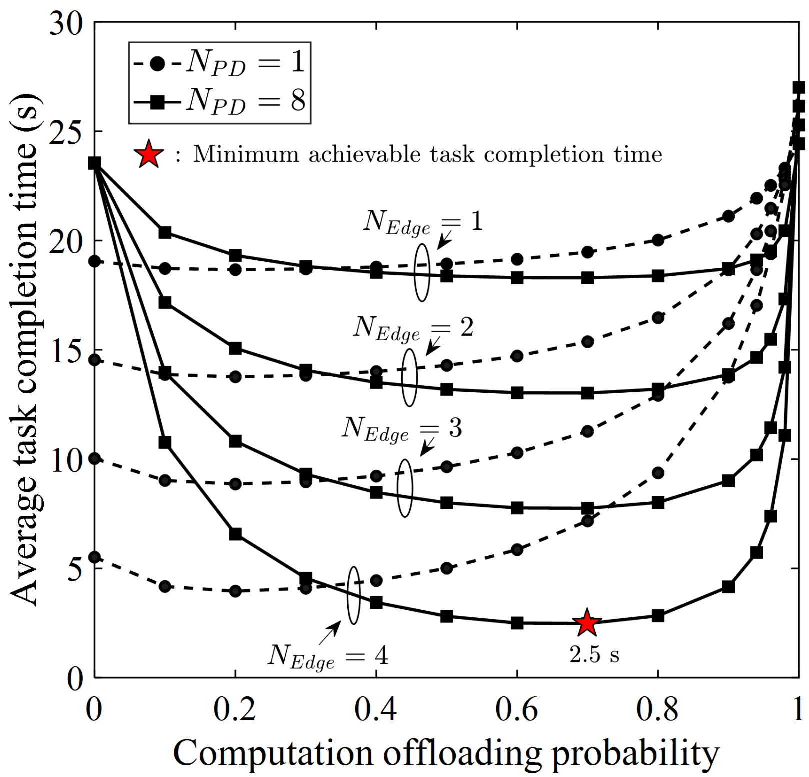


Figure 2.6: Average task completion time (in seconds) vs. computation offloading probability for different numbers of partially decentralized end-users (N_{PD}) and AI enhanced MEC servers (N_{Edge}).

$N_{Edge} = 4$, a high decentralization level ($N_{PD} = 8$) allows end-users to experience a reduction of the average task completion time of up to 89.5% by optimally adjusting their computation offloading probability to 0.7.

As interconnected computing power has spread around the world and useful platforms have been built on top of it, the *crowd* has become a demonstrably viable and valuable resource. According to [51], there are many ways for companies that are squarely at the core of modern capitalism to tap into the expertise of uncredentialed and conventionally inexperienced members of the technology-enabled crowd such as the DAO. In [68], we developed a self-aware allocation algorithm of physical tasks for HART-centric task coordination based on the shared use of user- and network-owned robots. Recall from Section 2.4 that by using our AI enhanced MEC servers as autonomous agents, we showed that delayed force feedback samples coming from TORs may be locally generated and delivered to HOs in close proximity. Note, however, that the performance of the sample forecasting based teleoperation system heavily relies on the accuracy of the forecast algorithm.

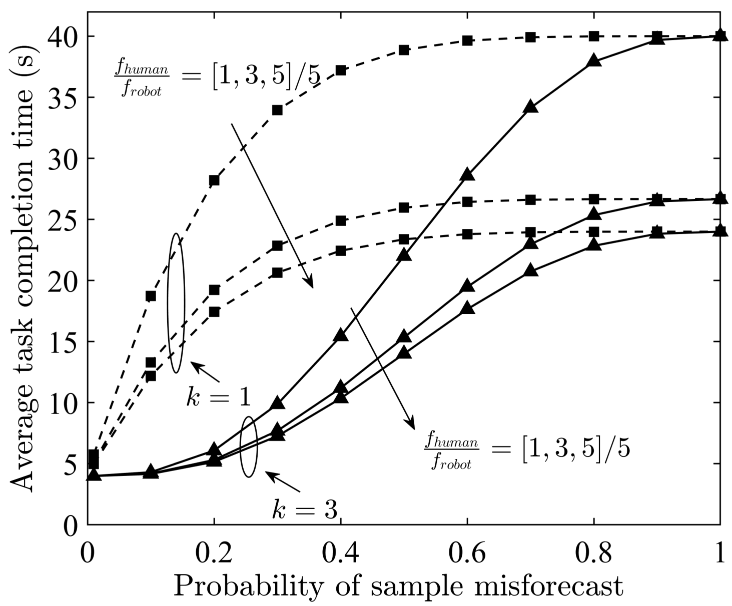


Figure 2.7: Average task completion time (in seconds) vs. probability of sample misforecast for different number of misforecasts (k) and ratio of human and robot operational capabilities $\left(\frac{f_{human}}{f_{robot}}\right)$.

2.5.2 Crowdsourcing: Expanding the HO Workforce

Towards realizing DAO in a decentralized Tactile Internet, Ethereum may be used to establish HO-TOR sessions for remote physical task execution, whereby smart contracts help establish/maintain trusted HART membership and allow each HART member to have global knowledge about all participating HOs, TORs, and MEC servers that act as autonomous agents following the widely used gateway-oriented approach (see Section 2.3). An HO remotely executes a given physical task until k out of the recent n haptic feedback samples are misforecast. At this point, (s)he immediately stops the teleoperation and informs the agent. The agent assigns the interrupted task to an available HO in vicinity, who then traverses to the task point and finalizes the physical task. For $n = 5$, Fig. 2.7 depicts the average task completion time vs. probability of sample misforecast for different k and $\frac{f_{human}}{f_{robot}}$, where f_{human} and f_{robot} denote the capability (in terms of number of operations per second) of a human and robot for performing physical tasks, respectively. We observe that the task completion time increases as the probability of sample misforecast grows from 0 to 0.25 for $k = 1$, whereas it remains almost unchanged for $k = 3$. Further, note that as humans become more capable (i.e., increasing $\frac{f_{human}}{f_{robot}}$), the resultant task completion time decreases until it hits a plateau, as traversing incurs additional delays.

2.6 Blockchain, AI, and Human Intelligence: The Path Forward

Today, artificial intelligence, machine learning, robots, and IoT are converging to create a new wave of change as they begin to take advantage of cryptocurrencies, initial coin offerings (ICOs), virtual assets, and tokenization of everything. The outcome of this convergence of innovations and human cause fears about job loss, robot overlords, and the future in general [72].

In [68], we touched on the importance of shifting the research focus from AI to intelligence amplification (IA) by using information technology to enhance human decisions. Note, however, that IA becomes difficult in dynamic task environments of increased uncertainty and real-word situations of great complexity. IA, also known as cognitive augmentation or machine augmented intelligence, will be instrumental in enhancing the creativity, understanding, efficiency, and intelligence of humans.

2.6.1 The Rise of the Decentralized Self-Organizing Cooperative

A very interesting example to catalyze human and machine intelligence toward a new form of self-organizing artificial general intelligence (AGI) across the Internet is the so-called *SingularityNET*.[4] One can think of SingularityNet as a *decentralized self-organizing cooperative (DSOC)*, a concept similar to the aforementioned DAO. DSOC is essentially a distributed computing architecture for making new kinds of smart contracts. Entities executing these smart contracts are referred to as agents, which can run in the cloud, on phones, robots, or other embedded devices. Services are offered to any customer via APIs enabled by smart contracts and may require a combination of actions by multiple agents using their collective intelligence. In general, there may be multiple agents that can fulfill a given task request in different ways and to different degrees. Each task request to the network requires a unique combination of agents, thus forming a so-called *offer network* of mutual dependency, where agents make offers to each other to exchange services via offer-request pairs. Whenever someone wants an agent to perform services, a smart contract is signed for this specific task. Towards this end, DSOC aims at leveraging contributions from the broadest possible variety of agents by means of superior discovery mechanisms for finding useful agents and *nudging* them to become contributors.

[4]SingularityNET Whitepaper, "SingularityNET: A decentralized, open market and inter-network for AIs," Nov. 2017. Online: `https://singularitynet.io`

2.6.2 Nudging Towards Human Augmentation

Extending on the DSOC concept, we advocate the use of the nudge theory for enhancing the human capabilities of unskilled crowd members of the DAO. According to Richard H. Thaler, the 2017 Nobel Laureate in Economics, the nudge theory claims that positive reinforcement and indirect suggestions can influence the behaviour of groups and individuals. A suitable nudging mechanism aims at completing interrupted local physical tasks by learning from a remote skilled DAO member, who is able to transfer her knowledge as data via a secure blockchain transaction embedded in a smart contract with an appropriate reward for each subtask. This smart contract will initially enhance the local human operator's capability, thereby allowing to successfully accomplish a given task via shared intelligence among failing robots and skilled humans.

2.7 Open Challenges and Future Work

The Internet has been constantly evolving from the mobile Internet to the emerging IoT and future Tactile Internet. Similarly, the capabilities of future 5G networks will extend far beyond those of previous generations of mobile communication. By boosting access networks' redundancy and diversity as envisioned in [12], FiWi enhanced 4G LTE-A HetNets with AI enhanced MEC hold great promise to meet the stringent latency and reliability requirements of immersive Tactile Internet applications. In [73], we recently outlined some research ideas that help tap into the full potential of the Tactile Internet. However, other concepts such as the above discussed spreading ownership, DAO, and HART membership will be instrumental in ushering in new ideas and concepts to facilitate local human-machine coactivity clusters by completely decentralizing edge computing via emerging Ethereum blockchain technologies in order to realize future techno-social systems such as the Tactile Internet, which by design still requires heavy involvement from humans at the network edge instead of automating them away. More work lies ahead to integrate Ethernet based FiWi enhanced mobile networks with Ethereum blockchain technologies. Although blockchain technology is promising technology to enhance today's IoT, there are still many research issues to be addressed before the integration of blockchain with IoT, especially in future mobile networks (i.e., 6G and beyond) that play a primordial role in constructing the underlying infrastructure for blockchains.

2.8 Conclusions

In this chapter, we showed that many of the emerging B-IoT studies use Ethereum as the blockchain of choice and apply a gateway-oriented design approach to offload computationally intensive tasks from resource-constrained end-devices onto an intermediate gateway, thus enabling them to access the Ethereum blockchain network. Building on our recent Tactile Internet work on orchestrating hybrid HART coactivities, we showed that higher levels of decentralized AI enhanced MEC are effective in reducing the average completion time of computational tasks. Further, for remote execution of physical tasks in a decentralized Tactile Internet, we explored how Ethereum's DAO and smart contracts may be used to establish trusted HART membership and how human crowdsourcing helps decrease physical task completion time in the event of unreliable forecasting of haptic feedback samples from teleoperated robots. We outlined future research avenues on technological convergence in order to successfully accomplish hybrid machine+human tasks by tapping into the shared intelligence of the crowd.

Chapter 3

The Way of the DAO: Towards Decentralizing the Tactile Internet

This chapter contains material extracted from the following publication:

[74] A. Beniiche, A. Ebrahimzadeh, and M. Maier. The Way of The DAO: Towards Decentralizing the Tactile Internet. *IEEE Network*, vol. 35, no. 4, pp. 190-197, July/Aug. 2021.

In the following, my key contributions in the aforementioned publication are explained in greater detail: (1) fully engaged in the brainstorming phase, the initial phase of formulating the ideas, and writing a raw draft, (2) major contributions in Section 3.3.1, including algorithmic work, extending the B-IoT framework from judge contract to nudge contract, (3) I partially contributed in the conception phase for the simulation results in Section 3.3.2, and (4) equally contributed in writing the manuscript.

3.1 Introduction

We have seen in Chapter 2 that there has been a growing interest in adapting blockchain to the specific needs of the IoT in order to develop a variety of B-IoT applications, ranging from smart cities and Industry 4.0 to financial transactions and farming, among others. Towards this end, the authors of [75] pointed out the important role of smart contracts, which are defined as pieces of self-sufficient decentralized code that are executed autonomously when certain conditions are met, whereby Ethereum was one of the first blockchains using smart contracts. The use of Ethereum allows users to write and run their own code on top of the network. By updating the code, users are able to modify the behavior of IoT devices for simplified maintenance and error correction. Beside well-known B-IoT problems such as hosting a blockchain on resource-constrained IoT devices, low transaction rates, and long block creation times, the authors of [75] identified several significant challenges beyond early B-IoT developments and deployments that will need further investigation. Apart from technological challenges, e.g., access control and security, the authors concluded that shaping the regulatory environment, e.g., *decentralized ownership*, is one of the biggest issues to unlock the potential of B-IoT for its broader use.

Recently in [76], gateways were used to act as B-IoT service agents for their respective cluster of local resource-constrained IoT devices by storing their blockchain accounts and using them to execute smart contracts on their behalf. The proposed smart contract based framework consists of multiple access control contracts (ACCs). Each ACC maintains a misbehavior list for each B-IoT resource, including details and time of the misbehavior as well as the penalty on its subject, e.g., blocking access requests for a certain period of time. Further, in addition to a register contract, the framework involves the so-called *judge contract (JC)*, which implements a certain misbehavior judging method. After receiving the misbehavior reports from the ACCs, the JC determines the penalty on the corresponding subjects and returns the decisions to the ACCs for execution.

Despite the recent progress, the salient features that set Ethereum aside from other blockchains remain to be explored in more depth, including their symbiosis with other emerging key technologies such as AI and robots apart from decentralized edge computing solutions. A question of particular interest hereby is how decentralized blockchain mechanisms may be leveraged to let emerge new hybrid forms of collaboration among individuals, which haven't been entertained in the traditional market-oriented economy dominated by firms rather than individuals [28]. Of particular interest will be Ethereum's concept of the DAO. In fact, in their latest book on how to harness our digital future [51], Andrew McAfee and Erik Brynjolfsson speak of "The Way of The DAO" that may substitute a technology-enabled crowd for traditional organizations such as companies.

While 5G networks have not been widely deployed yet, early studies have already started to look beyond 5G networks and speculate what the future 6G vision might be. Unlike 5G, 6G will not only explore more spectrum at high-frequency bands, but converge driving technological trends. The authors of [49] argue that there will be the following three driving applications behind 6G: (*i*) blockchain and distributed ledger technologies, (*ii*) connected robots and autonomous systems, and (*iii*) wireless brain-computer interaction (a subclass of human-machine interaction). In this chapter, we focus on the Tactile Internet, which is supposed to be next leap in the evolution of today's IoT. Note that the IoT with its underlying M2M communications is useful for enabling the automation of industrial and other machine-centric processes. It is designed to enable communications among machines without relying on any human involvement. Conversely, the Tactile Internet will add a new dimension to H2M interaction involving its inherent HITL nature, thus allowing for a human-centric design approach towards creating novel immersive experiences and extending the capabilities of the human through the Internet, i.e., augmentation rather than automation of the human [16]. This chapter aims at addressing the open research challenges outlined above.

In [16], we covered various important aspects of the Tactile Internet (i.e., haptic traffic characterization and edge intelligence), but outlined future work on blockchain only briefly. In this chapter, we build on our findings in [16] and make the following contributions: (*i*) investigate the potential of leveraging mobile end-user equipment for decentralization via blockchain, (*ii*) explore how crowdsourcing may be used to decrease the completion time of physical tasks, and (*iii*) extend the B-IoT framework from judge contract to nudge contract for enabling the nudging of human users in a broader Tactile Internet context.

The remainder of the chapter is structured as follows. Section 3.2 elaborates on the potential role of Ethereum and in particular the DAO in helping decentralize the Tactile Internet. In Section 3.3, we explore possibilities to extend the B-IoT framework of judge contract to nudge contract for enabling the *nudging* of human users in a broader Tactile Internet context. Finally, Section 3.4 concludes the chapter.

3.2 Decentralizing The Tactile Internet

3.2.1 FiWi Enhanced Mobile Networks: Spreading Ownership

In [16], we have shown that the 5G URLLC requirements can be achieved by enhancing coverage-centric 4G LTE-A HetNets with capacity-centric FiWi access networks based on low-cost, data-centric EPON and WLAN technologies in the backhaul and front-end, respectively. Fig. 3.1 illustrates the architecture of such FiWi enhanced mobile networks in greater detail. The common EPON fiber backhaul is shared by a number of ONUs, which may either connect to fixed subscribers or interface with a WLAN MPP or a cellular BS. Some of the resultant ONU-MPPs/ONU-BSs may be equipped with an AI enhanced MEC server (to be described in more detail shortly). On the end-user side, we consider the following three types of subscribers: conventional MUs as well as pairs of HO and TOR involved in teleoperation, which may be either local or non-local.

More interestingly to this chapter, note that in [16], we explored the idea of treating the human as a "member" of a team of intelligent machines rather than keep viewing him as a conventional "user." In addition, we elaborated on the role AI enhanced agents (e.g., MEC servers) may play in supporting humans in their task coordination between humans and machines. Toward achieving advanced human-machine coordination, we developed a distributed allocation algorithm of computational and physical tasks for fluidly orchestrating hybrid HART coactivities. More specifically, all HART members established through communication a collective self-awareness with the objective of minimizing the task completion time based on the shared use of robots that may be either user- or network-owned. We were particularly interested in the impact of *spreading ownership* of robots across people whose work they may replace. Our results showed that from a performance perspective (in terms of task completion time) no deterioration occurs if the ownership of robots is shifted entirely from network operators to mobile users, though spreading ownership across end-users makes a huge difference in who reaps the benefits from new technologies such as robots. This also applies to blockchain technologies, of course. Recall from Section 3.1 that decentralized ownership is one of the biggest issues to unlock the potential of B-IoT for its broader use.

Given that 6G will support new service types, e.g., computation oriented communications (CoC) [77], where new smart devices call for distributed computation, we search for synergies between the aforementioned HART membership and the complementary strengths of the DAO, AI,

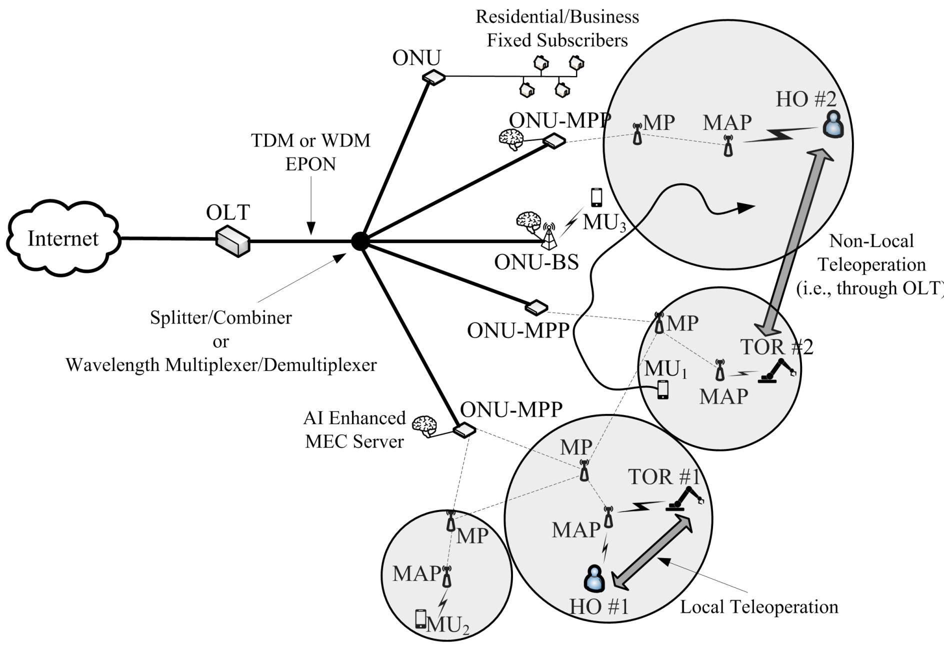


Figure 3.1: Architecture of FiWi enhanced mobile networks with AI enhanced MEC for immersive Tactile Internet applications.

and robots to facilitate local human-machine coactivity clusters by decentralizing the Tactile Internet. Towards this end, it's important to better understand the merits and limits of AI. Recently, Stanford University launched its *One Hundred Year Study on Artificial Intelligence (AI100).* In the inaugural report "Artificial Intelligence and Life in 2030," the authors defined AI as a set of computational technologies that are inspired by the ways people use their nervous systems and bodies to sense, learn, reason, and take action. They also point out that AI will likely replace tasks rather than jobs in the near term and highlight the importance of *crowdsourcing* of human expertise to solve problems that computers alone cannot solve well. As interconnected computing power has spread around the world and useful platforms have been built on top of it, the crowd has become a demonstrably viable and valuable resource. According to [51], there are many ways for companies that are squarely at the core of modern capitalism to tap into the expertise of uncredentialed and conventionally inexperienced members of the technology-enabled crowd such as the DAO.

3.2.2 AI Enhanced MEC

According to [77], 6G will go beyond mobile Internet and will be required to support ubiquitous AI services from the core to the end devices. In the following, we explore the potential of leveraging mobile end-user equipment by partially or fully decentralizing MEC. Recall from above that we introduced the use of AI enhanced MEC servers at the optical-wireless interface of FiWi enhanced mobile networks. In our considered scenario, we assume that the human-system interface (HSI) at the human operator side is equipped with the so-called AI-enabled edge sample forecasting module (ESF), which is responsible to provide the human operator with the predicted samples if the samples are lost or excessively delayed. This as a result helps the human operator have a transparent perception of the remote environment. In a B-IoT context, these MEC servers have been used as gateways that are required to act as B-IoT service agents to release resource-constrained IoT devices from computation-intensive tasks by offloading blockchain transactions onto more powerful edge computing resources, as discussed in Section 3.1. This design constraint can be relaxed in the Tactile Internet, where user equipment (e.g., state-of-the-art smartphones or the aforementioned user-owned robots) is computationally more resourceful than IoT devices and thus may be exploited for decentralization.

In our simulations, we set the FiWi network parameters as follows: Distributed Coordination Function Interframe Space (DIFS) = 34 μsec, Short Interframe Space (SIFS) = 16 μsec, Physical Layer (PHY) Header = 20 μsec, W_0 = 16 μsec, H = 6, ϵ = 9 μsec, Request To Send (RTS) = 20 bytes, Clear To Send (CTS) = 14 bytes, Acknowledgment (ACK) = 14 bytes, r_{WMN} = 300 Mbps, c_{PON} = 10 Gbps, PON fiber reach l_{PON} = 20 Km, average packet length $L = 1500$ bytes, $\varsigma_L^2 = 0$, ONU-AP radius = 10^2 m. We also consider $1 \leq N_{Edge} \leq 4$ AI enhanced MEC servers, each associated with 8 end-users, whereof $1 \leq N_{PD} \leq 8$ partially decentralized end-users can flexibly control the amount of offloaded tasks by varying their computation offloading probability. The remaining $8 - N_{PD}$ are fully centralized end-users that rely on edge computing only (i.e., their computation offloading probability equals 1). Note that for $N_{Edge} = 4$, all end-users may offload their computation tasks onto an edge node. Conversely, for $N_{Edge} < 4$, one or more edge nodes are unavailable for computation offloading and their associated end-users fall back on their local computation resources (i.e., fully decentralized). The computational capacity of MEC servers and partially decentralized end-users are set to 1.44 GHz and 185 MHz, respectively. For a more detailed description of the system model, parameter setting, and network configuration, the interested reader is referred to [16]. Fig. 3.2 shows the average task completion time vs. computation offloading probability of the partially decentralized end-users for different N_{Edge} and N_{PD}. We observe from Fig. 3.2 that for a given N_{Edge}, increasing N_{PD} (i.e., higher level of decentralization) is effective in

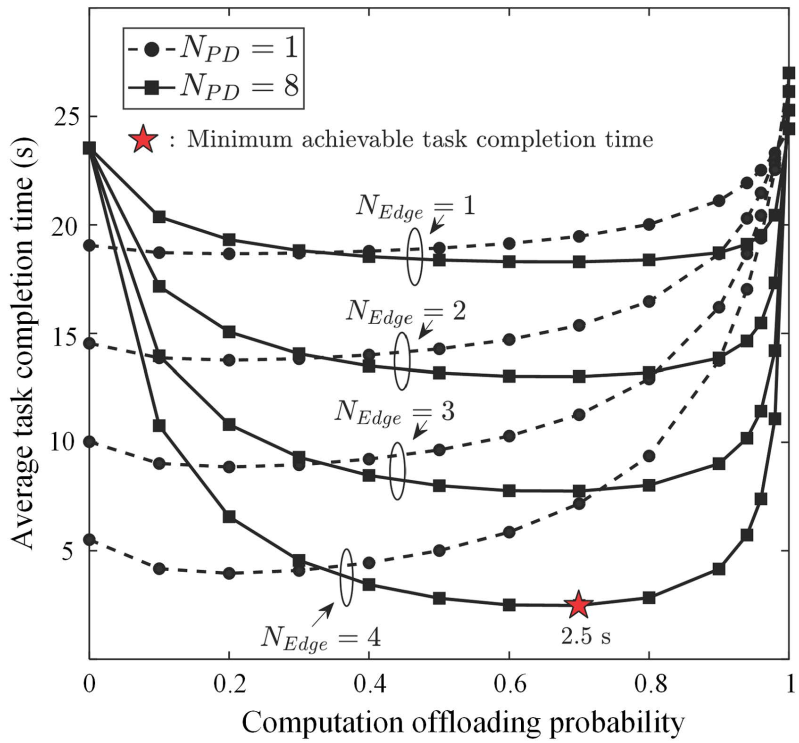


Figure 3.2: Average computational task completion time (in seconds) vs. computation offloading probability for different numbers of partially decentralized end-users (N_{PD}) and AI enhanced MEC servers (N_{Edge}).

reducing the average task completion time. Specifically, for $N_{Edge} = 4$, a high decentralization level ($N_{PD} = 8$) allows end-users to experience a reduction of the average task completion time of up to 89.5% by optimally adjusting their computation offloading probability to 0.7. As shown in Fig. 3.2, increasing N_{PD} results in not only a decrease of the average execution time, but also a decrease of the communication overhead/burden in the wireless fronthaul of our considered FiWi network, as a larger number of users shift the computation load from the MEC servers towards their local CPUs.

Note that in Fig. 3.2, the average task completion time is on the order of seconds, ranging from 2.5 to 25 seconds depending on the computation offloading probability. Hence, given Ethereum's transaction limit of 20 transactions/second, the notoriously low transaction rate of blockchain technologies doesn't pose a significant challenge to the execution of computational tasks and especially physical tasks carried out by robots in the context of the Tactile Internet, given that the mining process anticipated to be performed by a local CPU of a robot will be offloaded to a nearby MEC server to increase both task completion and transaction confirmation times.

3.2.3 Crowdsourcing

In [16], we developed a self-aware allocation algorithm of physical tasks for HART-centric task coordination based on the shared use of user- and network-owned robots. By using our AI enhanced MEC servers as autonomous agents, we showed that delayed force feedback samples coming from TORs may be locally generated and delivered to HOs in close proximity. More specifically, we developed an artificial neural network (ANN) based forecasting scheme of delayed (or lost) force feedback samples. By delivering the forecast samples to the HO rather than waiting for the delayed ones, we showed that AI enhanced MEC servers enable HOs to perceive the remote physical task environment in real-time at a 1-millisecond granularity and thus achieve tighter togetherness and improved safety control therein. Note, however, that the performance of the sample forecasting based teleoperation system heavily relies on the accuracy of the forecast algorithm.

In the following, we explore how crowdsourcing helps decrease the completion time of physical tasks in the event of unreliable forecasting of force feedback samples from TORs. Towards realizing DAO in a decentralized Tactile Internet, Ethereum may be used to establish HO-TOR sessions for remote physical task execution, whereby smart contracts help establish/maintain trusted HART membership and allow each HART member to have global knowledge about all participating HOs, TORs, and MEC servers that act as autonomous agents. We assume that an HO remotely executes a given physical task until X% of the most recently received haptic feedback samples are misforecast. At this point, the HO immediately stops the teleoperation and informs the agent. The agent assigns the interrupted task to a nearby human (e.g., an available HO) in vicinity of the TOR, who then traverses to the task point and finalizes the physical task. The probability of misforecast for a given ESF implementation can be quantified by calculating the long-run average of the ratio of the number of samples that are subject to misforecast to the number of those that are predicted correctly. Fig. 3.3 depicts the average task completion time vs. probability of sample misforecast for different traverse time $T_{traverse}$ of the nearby human and different ratio of human and robot operational capabilities $\frac{f_{human}}{f_{robot}}$, where f_{human} and f_{robot} denote the number of operations per second a human and robot is capable of performing, respectively. We can make several observations from Fig. 3.3. Obviously, it is beneficial to select humans with a shorter traverse time, who happen to be closer to the interrupted TOR. We also observe that the ratio $\frac{f_{human}}{f_{robot}}$ has a significant impact on the average task completion time. Clearly, for a ratio of smaller than 1 (i.e., 1/3), the human assistance is less useful since it takes him/her more time to complete the physical task. Conversely,

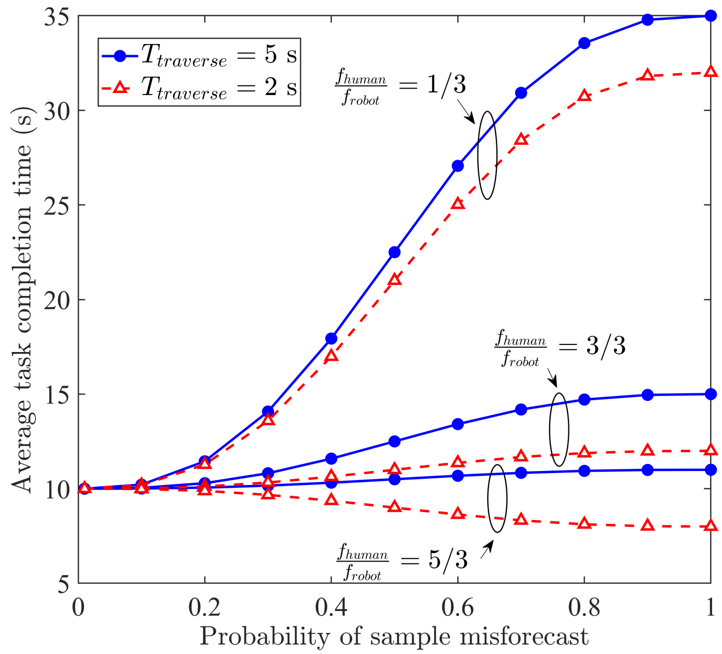


Figure 3.3: Average physical task completion time (in seconds) vs. probability of sample misforecast for different traverse time $T_{traverse} \in \{2, 5\}$ seconds of nearby human and different ratio of human and robot operational capabilities $\frac{f_{human}}{f_{robot}}$ (for X=80% fixed).

for a ratio of equal to 1 (i.e., 3/3) and especially larger than 1 (i.e., 5/3), crowdsourcing pays off by making use of the superior operational capabilities of the human. Whether humans or robots are better suited to perform a physical task certainly depends on its nature. However, for a given physical task, an interesting approach to benefit from the assistance of even uncredentialed and inexperienced crowd members of the DAO may be to enhance the capabilities of humans by means of *nudging*, as explained next.

3.3 Nudging: From Judge Contract to Nudge Contract

3.3.1 Cognitive Assistance: From AI to Intelligence Amplification (IA)

A widely studied approach to increase the usefulness of crowdsourcing has been edge computing, which may be used to guide humans step by step through the physical task execution process by providing them with *cognitive assistance*. Technically this could be easily realized by equipping humans with an augmented reality (AR) headset (e.g., HoloLens 2 with WiFi connectivity) that receives work-order information in real-time from its nearest AI enhanced MEC server. In [16], we elaborated on the importance of shifting the research focus from AI to intelligence amplification (IA) by using information technology to enhance human decisions. Note, however, that IA becomes difficult in dynamic task environments of increased uncertainty and real-word situations of great complexity.

3.3.2 HITL Hybrid-Augmented Intelligence

Many problems that humans face tend to be of high uncertainty, complexity, and open-ended. To solve such problems, human interaction and participation must be introduced, giving rise to the concept of *HITL hybrid-augmented intelligence* for advanced human-machine collaboration. HITL hybrid-augmented intelligence is defined as an intelligent model that requires human interaction and allows for addressing problems and requirements that may not be easily trained or classified by machine learning. In general, machine learning is inferior to the human brain in understanding unstructured real-world environments and processing incomplete information and complex spatio-temporal correlation tasks. Hence, machines cannot carry out all the tasks in human society on their own. Instead, AI and human intelligence are better viewed as highly complementary.

The Internet provides an immense innovation space for HITL hybrid-augmented intelligence. Specifically, cloud robotics and AR are among the fastest growing commercial applications for enhancing the intelligence of an individual in multi-robot collaborative systems. One of the main research topics of HITL hybrid-augmented intelligence is the development of methods that allow machines to learn from not only massive training samples but also human knowledge in order to accomplish highly intelligent tasks via shared intelligence among different robots and humans.

3.3.3 Decentralized Self-Organizing Cooperative (DSOC)

A very interesting example to catalyze human and machine intelligence toward a new form of self-organizing artificial general intelligence (AGI) across the Internet is the so-called *SingularityNET* (`https://singularitynet.io`). One can think of SingularityNet as a *decentralized self-organizing cooperative (DSOC)*, a concept similar to DAO. DSOC is essentially a distributed computing architecture for making new kinds of smart contracts. Entities executing these smart contracts are referred to as agents, which can run in the cloud, on phones, robots, or other embedded devices. Services are offered to any customer via APIs enabled by smart contracts and may require a combination of actions by multiple agents using their collective intelligence. In general, there may be multiple agents that can fulfill a given task request in different ways and to different degrees. Each task request to the network requires a unique combination of agents, thus forming a so-called *offer network* of mutual dependency, where agents make offers to each other to exchange services via offer-request pairs. Whenever someone wants an agent to perform services, a smart contract is signed for this specific task. Towards this end, DSOC aims at leveraging contributions from the broadest possible variety of agents by means of superior discovery mechanisms for finding useful agents and *nudging* them to become contributors.

3.3.4 Nudge Contract: Nudging via Smart Contract

Extending on DSOC and the judge contract introduced in Section 3.1, we develop a *nudge contract* for enhancing the human capabilities of unskilled crowd members of the DAO. According to Richard H. Thaler, the 2017 Nobel Laureate in Economics, a nudge is defined as any aspect of a choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives. Deployed appropriately, nudges can *steer people*, as opposed to steer objects—real or virtual—as done in the conventional Tactile Internet, to make better choices and positively influence the behavior of crowds of all types.

3.3.5 Results

Our nudge contract aims at completing interrupted physical tasks by learning from a skilled DAO member with the objective of minimizing the learning loss, which denotes the difference between the achievable and optimum task execution times. Given the reward enabled by the nudge contract and associated with each skill transferred, a remote skilled DAO member submits a hash address of the learning instructions to an unskilled human/robot. The hash address is stored on the blockchain, whereby the corresponding data of the learning instructions may be stored on a remote decentralized storage server, e.g., Inter-Planetary File System (IPFS)[1]. An unskilled human/robot can retrieve

[1] `https://ipfs.io/`

Algorithm 1 Nudge Contract

Input: Set $U = \{h_1, h_2, ..., h_n\}$ of n DAO members, capability vector $\mathbf{C} = [c_1, c_2, ..., c_n]$, distance vector $\mathbf{D} = [d_1, d_2, ..., d_n]$, interrupted task $\mathbf{T}$, required number D of actions to execute the interrupted task, interrupted robot r_0, capability requirement c_0 of the interrupted task

Decompose the given interrupted task $\mathbf{T}$ into N_{sub} subtasks
for $i = 1$ to n **do**
    if $c_i \geq c_0$ **then**
        $S \leftarrow h_i$
    end if
end for
$h^* \leftarrow \arg\min_{d_i} \{S\}$
Create a secure blockchain transaction between h^* and interrupted robot r_0
Send the learning instructions from h^* to r_0 through the established transaction
Use the multi-arm bandit selection strategy in [78] to help the robot learn the given set of subtasks
if all N_{sub} subtasks are learned successfully **then**
    learning process is successfully accomplished
    r_0 can execute the interrupted task $\mathbf{T}$ with the capability of h^*
else
    Learning process is failed
    DAO member h^* traverses to the interruption point to execute the task $\mathbf{T}$
end if
Reward the skilled DAO member h^* via blockchain smart contract

the learning instructions using the corresponding hash address. The ability to learn a given subtask[2] is characterized by the subtask learning probability. The learning process is accomplished if each subtask is learned successfully from a skilled DAO member, who in turn is rewarded via a smart contract (see Algorithm 1 for details). Fig. 3.4 shows the performance of our nudge contract for 50 DAO crowd members, whose ratio $\frac{f_{human}}{f_{robot}}$ is randomly chosen from $\{1/3, 3/3, 5/3\}$. We observe that for a given subtask learning probability, decreasing the number N_{sub} of subtasks helps reduce the learning loss, thus indicating the importance of a proper task decomposition method. More specifically, over-decomposition of the given task will result in performance deterioration unless a suitable learning mechanism is adopted to increase the subtask learning probability.

[2] We assume that the incoming physical tasks are decomposable, meaning that they can be broken into a number of subtasks. An example of such tasks can be the part assemblage in an industry automation scenario.

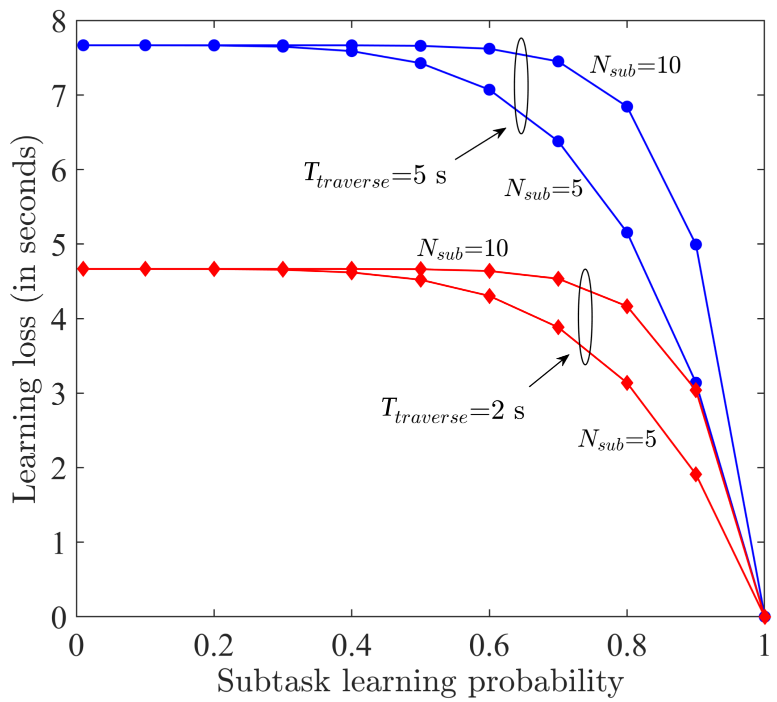


Figure 3.4: Learning loss (in seconds) vs. subtask learning probability for different number N_{sub} of subtasks and traverse time $t_{traverse}$.

3.4 Conclusions

In this chapter, we explored how Ethereum blockchain technologies, in particular the DAO, may be leveraged to decentralize the Tactile Internet, which enables unprecedented mobile applications for remotely steering real or virtual objects/processes in perceived real-time and represents a promising example of future techno-social systems. We showed that a higher level of decentralization of AI enhanced MEC reduces the average computational task completion time of up to 89.5% by setting the computation offloading probability to 0.7. Further, we observed that crowdsourcing of human assistance is beneficial in decreasing the average completion time of physical tasks for medium to high feedback misforecasting probabilities, provided the human offers equal or even superior operational capabilities, i.e., $\frac{f_{human}}{f_{robot}} \geq 1$. Towards this end, our proposed nudge contract tries to successfully accomplish tasks via shared intelligence among failing robots and skilled humans. An interesting research avenue to be explored is to offload the computation tasks not just on the MEC servers but also on the underutilized neighbor end-users, a method commonly known as *mobile ad hoc cloud*.

Chapter 4

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

This chapter contains material extracted from the following publication:

[79] 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 largely contributed to writing the whole manuscript, (2) I identified the challenges of integrating blockchain and robots for 6G in Section 4.2, (3) I identified the open research challenge to study the trust game of behavioral economics in a blockchain context in Section 4.3.1, (4) I proposed and developed the experimenter smart contract in Section 4.3.2, (5) I proposed the idea of mechanism deposit for the trust game in Section 4.3.3, (6) I proposed the idea of the on-chaining oracle to leverage on human intelligence for the networked N-player trust game in Section 4.4, (7) I developed and implemented the nudge contract in Section 4.4, (8) I proposed the idea of exploring the field of robonomics and I developed the persuasive robotics strategies scripts in Section 4.5, (9) I conducted all the experimental works, and (10) I obtained and analyzed all the results.

4.1 Introduction

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 [52]. 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 [45].

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 [47], 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.

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 [80]. 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. 4.1 illustrates the sequential exchange between trustor and trustee. The

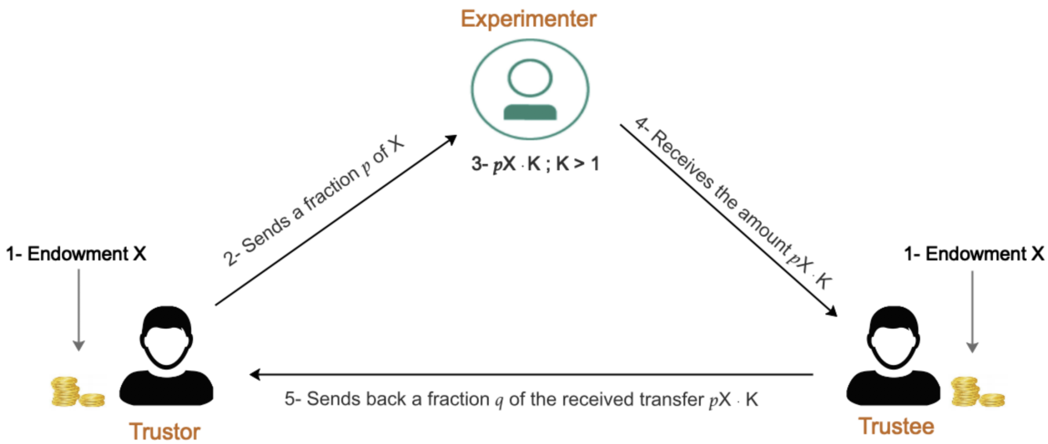


Figure 4.1: Classical trust game involving two human players (trustor and trustee) and one experimenter in the middle.

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 [83], 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 4.2, 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 4.3, 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 4.4 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 4.5, 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 4.6 concludes the chapter.

4.2 6G Vision: Blockchains and Robots

4.2.1 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 [49], 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 [81]. A combination of blockchain technologies and 6G communications network yield the following benefits:

- **Intelligent Resource Management:** According to [82], 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 [82]. 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 [82]. 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.

4.2.2 Blockchains and Robots

The authors of [49] 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 [81]. More specifically, in [82], 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.

4.3 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.

4.3.1 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 [84], 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 [84], 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 [84] was played in an unstructured environment, i.e., the population was not structured in any specific spatial topology or social network. In [85], 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 [84], where the existence of a single untrustworthy individual would eliminate trust completely and lead to zero global net wealth, the authors of [85] 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 [86], 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 [87]. 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)* [88]. 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.

4.3.2 Experimenter Smart Contract

First, we develop a smart contract that replaces the experimenter in the middle between trustor and trustee (see Fig. 4.1). 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.

4.3.3 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 [89]. 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.

4.3.4 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.

4.3.5 Results

Fig. 4.2 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. 4.2 also shows the interval between minimum and maximum measured score for each value of D.

We make the following interesting observations from Fig. 4.2. 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

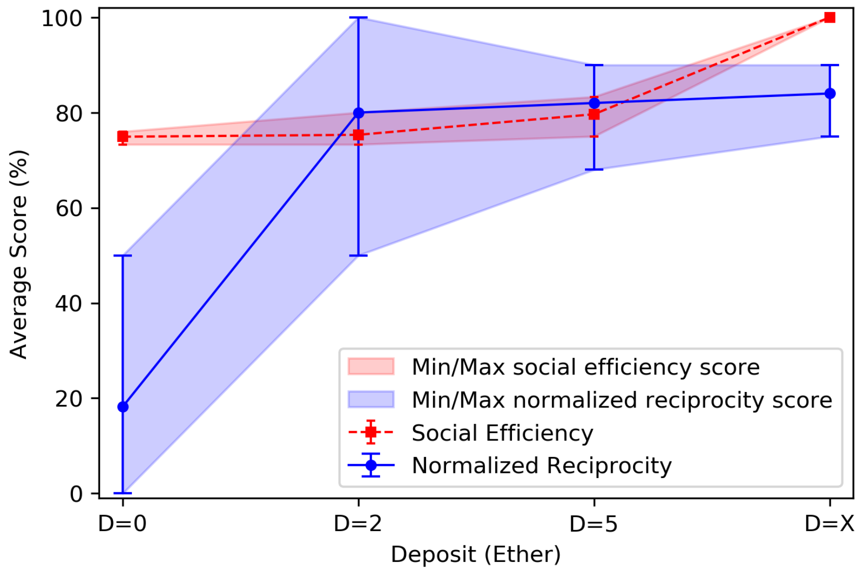


Figure 4.2: Average social efficiency and normalized reciprocity q/p vs. deposit $D = \{0, 2, 5, X\}$ Ether using experimenter smart contract with $K = 2$ and $X = 10$ (shown with minimum-to-maximum measured score intervals).

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. 4.2 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.

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

4.4.1 Architecture of Oracle

Fig. 4.3 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/`

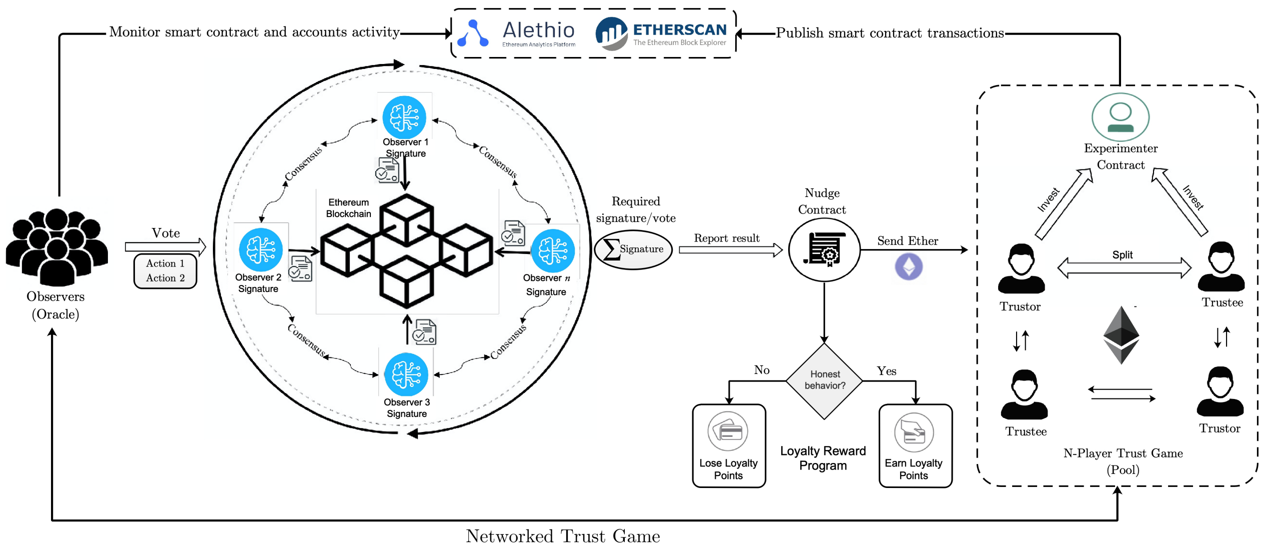


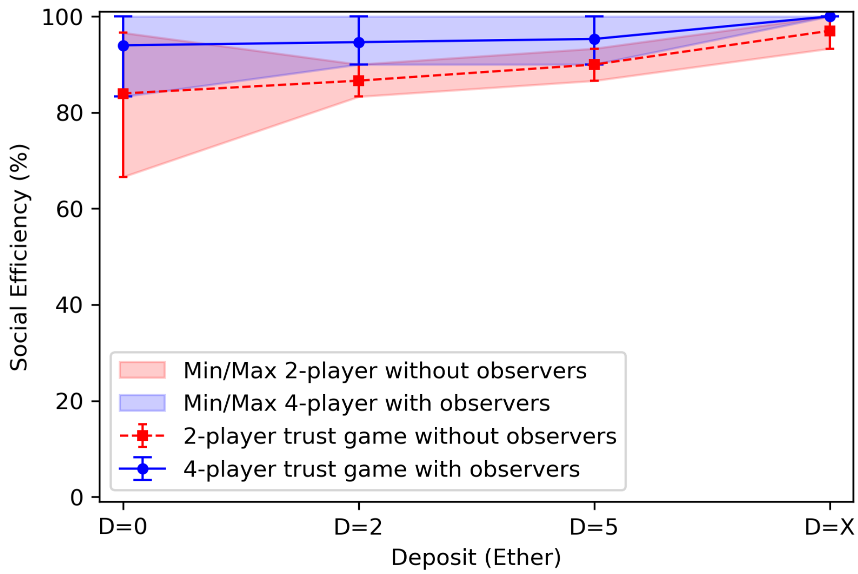
Figure 4.3: Architecture of on-chaining oracle for networked N-player trust game.

= 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., [90] [91].

4.4.2 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 4.4: 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.

4.4.3 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.

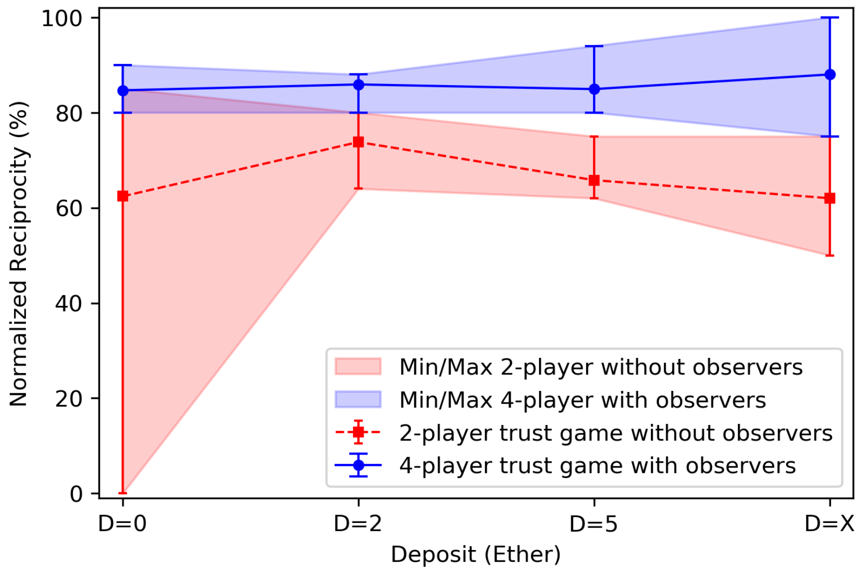


Figure 4.5: Average normalized reciprocity q/p vs. deposit $D = \{0, 2, 5, X\}$ Ether for 2-player trust game without observers and 4-player trust game with observers (shown with minimum-to-maximum measured score intervals).

Fig. 4.4 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. 4.5. However, while the presence of observers helps raise the average (and instantaneous) normalized reciprocity consistently above 80% (compared to below 80% in Fig. 4.2), there still remains room for further improvement, especially for $0 \leq D < X$.

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

4.5.1 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 [92].

Recently, in [93], 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 [94]. 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 [95], 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.

4.5.2 Persuasive Robotics Strategies

Similar to [96], 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 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[5]. 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[6], Flask[7], and CV2[8] tools. The Django server invokes a method on Pepper called "ALVideoDevice" to start recording

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

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 4.1: 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 4.1 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 4.1 enable the observers to control Pepper's text-to-speech and embodied communications using our developed CoZ platform.

4.5.3 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

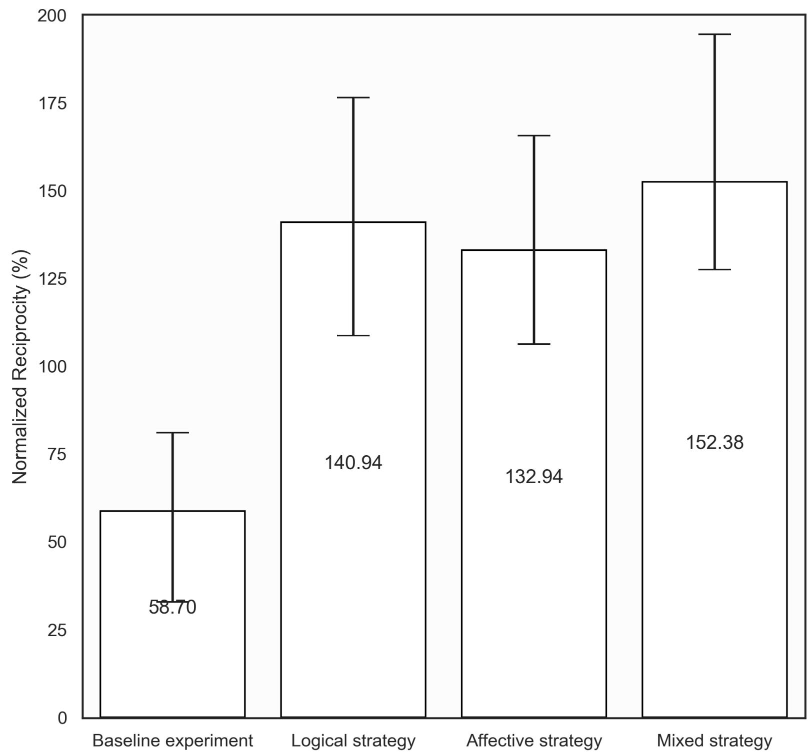


Figure 4.6: Average normalized reciprocity q/p without (baseline experiment) and with using logical, affective, and mixed logical-affective persuasive strategies for $D = 0$ (shown with minimum-to-maximum measured score intervals).

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., $D = 0$).

4.5.4 Results

Fig. 4.6 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%. 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.

4.6 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 5

Society 5.0: Internet as if People Mattered

This chapter contains material extracted from the following publication:

[97] A. Beniiche, S. Rostami, and M. Maier. Society 5.0: Internet as if People Mattered. *IEEE Wireless Communications Magazine*, under review.

In the following, my key contributions in the aforementioned publication are explained in greater detail: (1) I contributed to writing the whole manuscript, (2) I proposed the idea to explore Society 5.0, the next evolution of Industry 4.0, (3) I identified the challenges and the role of robonomics and tokenomics in Society 5.0 in Section 5.2, (4) I outlined the proposed path to a human-centered society and explained purpose-driven tokens and token engineering in technically greater detail, (5) I developed the cyber-physical-social systems (CPSS) based bottom-up multilayer token engineering DAO framework for Society 5.0 in Section 5.3, (6) I introduced the idea of stigmergic enhanced Society 5.0 and the concept of indirect communications, (7) I elaborated on how our proposed framework can be applied to advance human collective intelligence in the 6G era in Section 5.4, (8) I conducted the experimental works, and (9) I obtained and analyzed the results.

5.1 Introduction

Unlike previous generations, future 6G networks are anticipated to be transformative by revolutionizing the wireless evolution from "connected things" to "connected intelligence" [77]. In his critically acclaimed book "Social Physics," a term originally coined by Auguste Comte, the founder of modern sociology, MIT Media Lab professor Alex Pentland argues that social interactions (e.g., social learning and social pressure) are the primary forces driving the evolution of *collective intelligence (CI).* According to Pentland, CI emerges through shared learning of surrounding peers and harnessing the power of exposure to cause desirable behavior change and build communities. He concludes that humans have more in common with bees than we like to admit and that future techno-social systems should scale up ancient decision making processes we see in bees.

This conclusion is echoed by Max Borders through his concept of the *social singularity* that defines the point beyond which humanity will operate much like a hive mind, i.e., CI. Currently, two separate processes are racing forward in time: (*i*) the technological singularity: Machines are getting smarter (e.g., machine learning and AI), and (*ii*) the social singularity: Humans are getting smarter. In fact, he argues that these two separate processes are two aspects of the same underlying process waiting to be woven together towards creating new *human-centric* industries. More and more, we'll act like bees to get big things done, whereby humans act as neurons in a human hive mind with blockchain technology acting as connective tissue to create virtual pheromone trails, i.e., programmable incentives.

Ever since the beginning of industrialization, three industrial revolutions have been experienced with the development of steam engines (mid 18-19th century), electrification (1870 onward), and digitization (1970 onward), respectively. The current fourth industrial revolution has been enabled through the IoT in association with other emerging technologies, most notably cyber-physical systems (CPS). CPS help bridge the gap between manufacturing and information technologies and give birth to the smart factory. This technological evolution ushers in the *Industry 4.0* as a prime agenda of the High-Tech Strategy 2020 Action Plan taken by the government of Germany, the Industrial Internet from General Electric in the USA, and the Internet+ from China. A human-centered approach that puts humans in the loop of today's CPS is the *Society 5.0* initiative of the 5th Science and Technology Basic Plan taken by the government of Japan [98]. By functionally integrating human beings at the social, cognitive, and physical levels, CPS become so-called *cyber-physical-social*

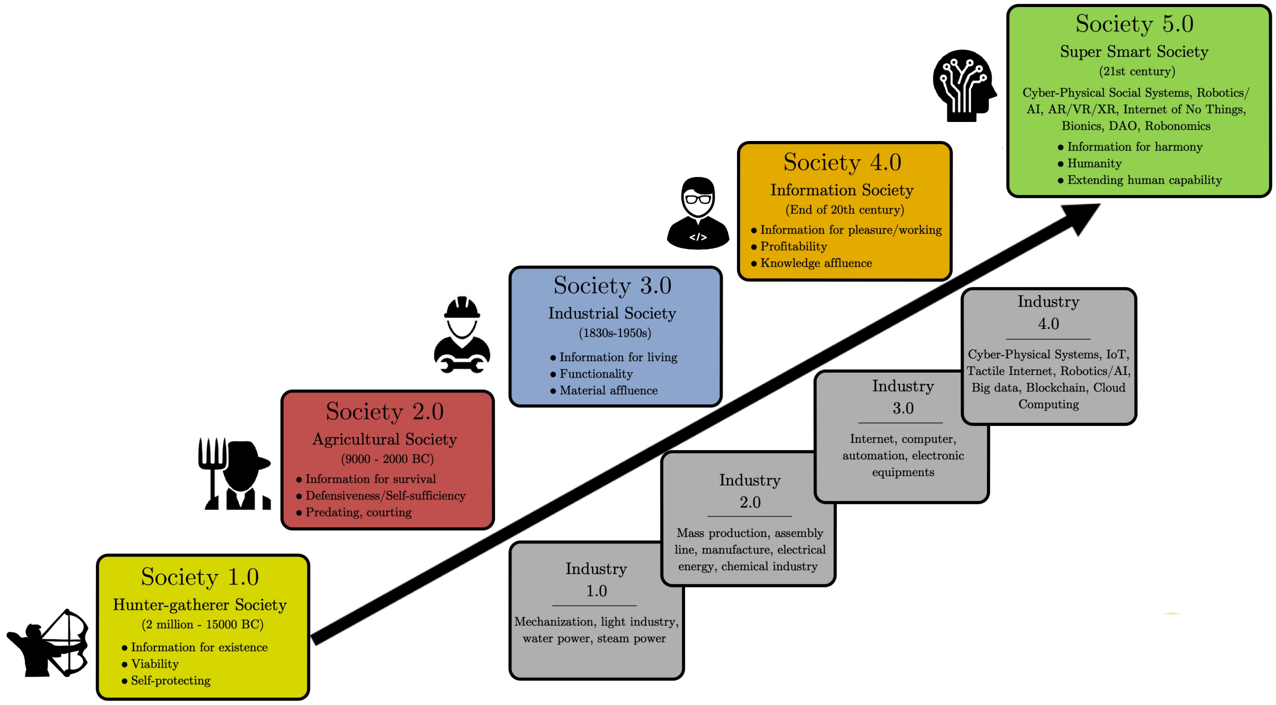


Figure 5.1: Co-evolution of society and industry toward Society 5.0 [100, 101, 102].

systems (CPSS) [99]. Members of CPSS may engage in a wide variety of cyber-physical-social behaviors. The human-centeredness of Society 5.0 was recently investigated in technically greater detail in [100]. The author of [100] describes the goal of Society 5.0 as the ability to create equal opportunities for all and to provide the environment that helps unleash the full potential of each individual. To do so, Society 5.0 will leverage on emerging Information and Communications Technology (ICT) to its fullest such that social barriers to each individual's self-realization are removed. For illustration, Fig. 5.1 depicts the transition from past to future societies and their co-evolution with industry [100, 101, 102].

Similar to Industry 4.0, Society 5.0 aims at seamlessly fusing the digital and physical worlds by using social robots, ambient intelligence, advanced human-computer interfaces (HCI), embodied AI, and various flavors of extended reality (XR), among others (see also Fig. 5.1). However, Society 5.0 tries to counterbalance the commercial emphasis of Industry 4.0. Towards this end, the overarching goal of Society 5.0 will be the creation of the world's first super smart society. Conversely, the focus of Industry 4.0 has been the creation of the smart factory that is fully automated and thus requires minimum human presence on-site. More interestingly, Society 5.0 also envisions a paradigm shift from conventional monetary to future nonmonetary economies based on technologies that can measure activities toward human co-becoming that have no monetary value (to be explained shortly in the context of *tokenomics*) [22].

It is interesting to note that the aforementioned Society 5.0 vision aligns surprisingly well with the far-reaching vision of future 6G networks. 6G is anticipated to be more human-centered than 5G, which primarily focused on industry verticals such as smart grids or smart cities, as outlined in the world's first 6G white paper of the 6GFP. In [103], we illustrated the potential of CPSS by presenting two prominent 5/6G examples of human-in-the-loop centric systems. The first one is the Tactile Internet, which is widely viewed as one of the most interesting 5G low-latency applications [16]. The second one is the future Internet of No Things, which serves as an important stepping stone toward ushering in the 6G post-smartphone era [13]. Arguably more important, we also elaborated on *robonomics*, an emerging field in the 6G era, and the role advanced blockchain technologies play in realizing the Society 5.0 vision.

In this chapter, we build on our recent work on robonomics in the 6G era. We aim at exploring advanced blockchain technologies that enable the next-generation Internet known as Web3, which leverages the concept of *tokenization* as a process for converting an item of value into digital tokens, thus giving rise to the aforementioned tokenomics. Tokenization digitally encapsulates assets as well as access rights and permissions to assets in the physical and digital world into units called tokens. We investigate the design of purpose-driven tokens to facilitate collaboration by incentivizing an autonomous group of people to individually contribute to Society 5.0. Towards this end, we first present our CPSS based bottom-up multilayer token engineering framework, putting a particular focus on the key role of its incentive mechanism layer in the important problem of token design. We then explore the concept of *indirect communication* to maintain social cohesion by the coupling of social and environmental organization via traces in a stigmergy enhanced Society 5.0, while steering its collective behavior towards the creation of tech-driven public goods.

The remainder of the chapter is structured as follows. Section 5.2 elaborates on the role of robonomics and tokenomics in Society 5.0. In Section 5.3, we outline our proposed path to a human-centered society and explain purpose-driven tokens and token engineering in technically greater detail. Further, we introduce our CPSS based bottom-up multilayer token engineering framework for a Society 5.0. In Section 5.4, we explain how our proposed framework can be applied to advance human collective intelligence in the 6G era. Section 5.5 describes its experimental implementation and highlights some illustrative results. Finally, Section 5.6 concludes the chapter.

5.2 Society 5.0: From Robonomics to Tokenomics

The authors of [94] provided insights into how blockchain and other decentralized technologies have an impact on the interaction of humans with robot agents and their social integration into human society. Towards this end, blockchain technologies can serve as a ledger, where robots and humans may access and record anything of value, such as ownership titles or financial transactions. Further, smart contracts help encode the self-enforceable and self-verifiable agreement logic between a robot and a human. Cryptocurrencies may be used to allow robots to hold financial obligations and enter into exchanges of value with a human, and vice versa.

The shift from conventional monetary economics to nonmonetary tokenomics and the central role tokens play in blockchain-based ecosystems were analyzed recently in [104]. Decentralized blockchain technologies have been applied in a non-monetary context by exploiting a process known as *tokenization* in different value-based scenarios. The tokenization of an existing asset refers to the process of creating a *tokenized digital twin* for any physical object or financial asset. The resultant tokens are tradeable units that encapsulate value digitally. They can be used as incentives to coordinate actors in a given regulated ecosystem in order to achieve a desired outcome. According to [104], tokens have a disruptive potential to expand the concept of value beyond the economic realm by using them for reputation purposes or voting rights. Through tokenization, different types of digitized value can be exploited in an ecosystem of incentives by sharing the rewards and benefits among its stakeholders.

Tokens can represent any existing digital or physical asset, as well as access rights to assets and permissions in the digital or physical world. A token is stored as an entry in the ledger and is mapped to a blockchain address, which represents the identity of the token holder. Originally, tokens were minted by using the underlying blockchain protocols. However, with the advent of Ethereum, tokens moved up the blockchain protocol stack and can now be created on the application layer, giving rise to so-called application tokens. With Ethereum, application tokens can be issued easily

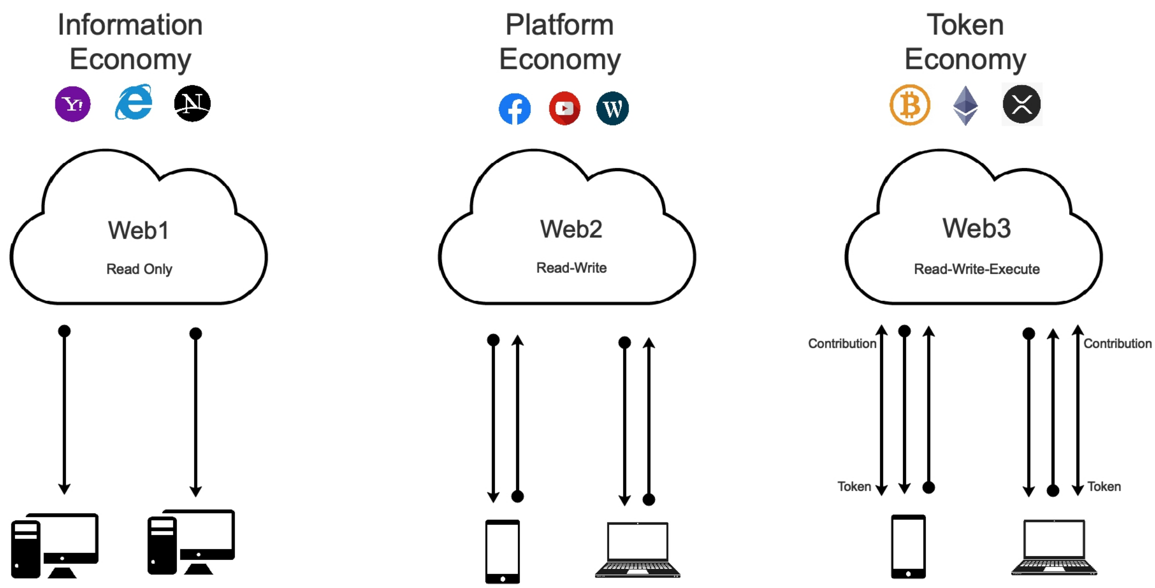


Figure 5.2: Evolution of Internet economy: From read-only Web1 information economy and read-write Web2 platform economy to read-write-execute Web3 token economy based on decentralized blockchain and self-executing smart contract technologies.

and cheaply following the Ethereum token standards (e.g., ERC-20) via a specific type of smart contract, known as token contract.

Tokens might be the killer application of blockchain networks and are recognized as one of the main driving forces behind the next-generation Internet referred to as the Web3 [34]. As shown in Fig. 5.2, while the Web1 (read-only web) and Web2 (read-and-write web) enabled the knowledge economy and today's platform economy, respectively, the Web3 will enable the *token economy* where anyone's contribution is compensated with a token. The token economy enables completely new use cases, business models, and types of assets and access rights in a digital way that were economically not feasible before, thus enabling completely new use cases and value creation models. Note that the term token economy is far from novel. In cognitive psychology, it has been widely studied as a medium of exchange, and arguably more importantly, as a positive reinforcement method for establishing desirable human behavior, which in itself may be viewed as one kind of value creation. Unlike coins, however, which have been typically used only as a payment medium, tokens may serve a wide range of different non-monetary purposes. Such purpose-driven tokens are instrumental in incentivizing an autonomous group of individuals to collaborate and contribute to a common goal. According to [34], the exploration of tokens, in particular different types and roles, is still in the very early stages.

The token economy plays a central role in realizing the emerging DAO, which has become a hot topic spawned by the rapid development of blockchain technology in recent years [105]. The DAO may be viewed as a social system composed of intelligent agents coevolving into human-machine integration based on real-world and artificial blockchain systems. In the DAO, all the operational rules are recorded on the blockchain in the form of smart contracts. Token economy incentives together with distributed consensus protocols are utilized to realize the self-operation, self-governance, and self-evolution of the DAO. In fact, according to the authors of [105], the use of tokens as incentives is the main motivator for the DAO, whereby the so-called *incentive mechanism* layer of their presented multi-layer DAO reference model will be key for the token design (to be discussed in more detail shortly).

5.3 The Path (DAO) to a Human-Centered Society

While a lot of tokens have been issued over the last few years, most of these issued tokens lack proper functionality and mechanism design. In this section, we aim at addressing these two shortcomings by discussing purpose-driven tokens and introducing the important problem of token engineering.

5.3.1 Purpose-Driven Tokens and Token Engineering

Recall from Section 5.2 that we are still in the very early stages of exploring different roles and types of tokens. For instance, so-called *purpose-driven tokens* incentivize individual behavior to contribute to a certain purpose or idea of a collective goal. This collective goal might be a public good or the reduction of negative externalities to a common good, e.g., reduction of CO_2 emissions. Purpose-driven tokens introduce a new form of public goods creation without requiring traditional intermediaries, e.g., governments. Blockchain networks such as Ethereum took the idea of collective value creation to the next level by providing a public infrastructure for creating an application token with only a few lines of smart contract code, whereby in principle any purpose can be incentivized. However, given that operational use cases are still limited, this new phenomenon of tech-driven public goods creation needs much more research and development [34].

Proof-of-work (PoW) is an essential mechanism for the maintenance of public goods [34]. Even though the collective production of public goods can result in positive externalities, it does not necessarily exclude other negative externalities, e.g., energy-intense mining process of blockchains. When designing purpose-driven tokens as a means to provide public goods, behavioral economics methods, e.g., the well-known nudging technique and behavioral game theory, provide important tools to steer individuals toward certain actions.

In the following, we focus on the important problem of *token engineering*, which is an emerging term defined as the theory, practice, and tools to analyze, design, and verify tokenized ecosystems [34]. It involves the design of a bottom-up token engineering framework along with the design of adequate mechanisms for addressing the issues of purpose-driven tokens. Note that mechanism design is a subfield of economics that deals with the question of how to incentivize everyone to contribute to a collective goal. It is also referred to as "reverse game theory" since it starts at the end of the game (i.e., its desirable output) and then goes backward when designing the (incentive) mechanism.

5.3.2 Token Engineering DAO Framework for Society 5.0

Recall from Section 5.2 that for the token design a multilayer DAO reference model was proposed in [105], though it was intentionally kept generic without any specific relation to Society 5.0. The bottom-up architecture of the DAO reference model comprises the following five layers: (*i*) basic technology, (*ii*) governance operation, (*iii*) incentive mechanism, (*iv*) organization form, and (*v*) manifestation. Due to space constraints, we refer the interested reader to [105] for further information on the generic DAO reference model and a more detailed description of each layer. In the following, we adapt the generic DAO reference model to the specific requirements of Society 5.0 and highlight the modifications made in our CPSS based bottom-up token engineering DAO framework.

Fig. 5.3 depicts our proposed multilayer token engineering DAO framework for Society 5.0 that builds on top of state-of-the-art CPSS. While the Internet of Things as prime CPS example has ushered in Industry 4.0, advanced CPSS such as the future Internet of No Things, briefly mentioned in Section 5.1, will be instrumental in ushering in Society 5.0. As explained in more detail in [13], the Internet of No Things creates a converged service platform for the fusion of digital and real worlds that offers all kinds of human-intended services without owning or carrying any type of computing or storage devices. It envisions Internet services to appear from the *surrounding environment* when needed and disappear when not needed. The transition from the current gadgets-based Internet

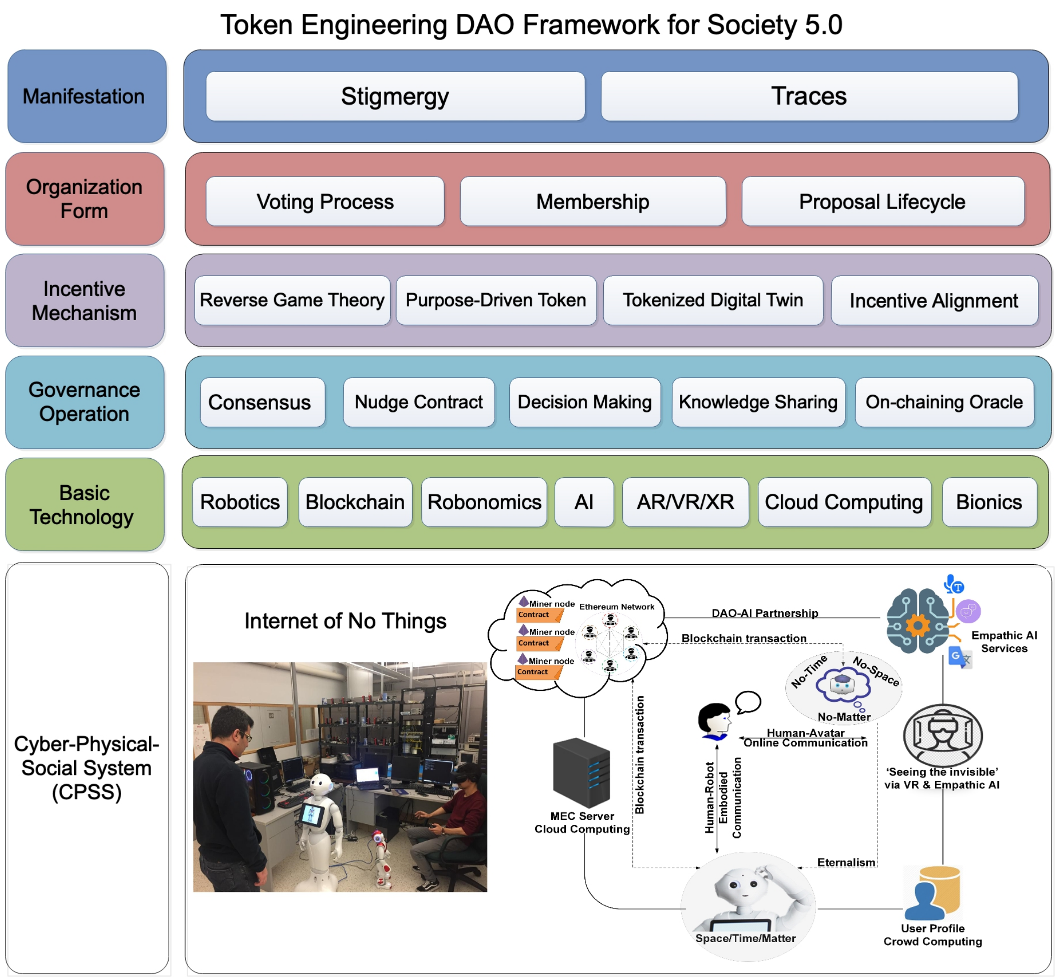


Figure 5.3: CPSS based bottom-up token engineering DAO framework for Society 5.0.

to the Internet of No Things is divided into three phases: (*i*) bearables (e.g., smartphone), (*ii*) wearables (e.g., Google and Levi's smart jacket), and then finally (*iii*) nearables. Nearables denote nearby 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. The basic technology layer at the bottom of Fig. 5.3 illustrates the key enabling technologies (e.g., blockchain) underlying the Internet of No Things. In addition, this layer contains future technologies, most notably bionics, that are anticipated to play an increasingly important role in a future super smart Society 5.0 (see also Fig. 5.1).

Above the basic technology layer, there exists the governance operation layer. Generally speaking, this layer encodes consensus via smart contracts (e.g., voting) and realizes the DAO's self-governance through on-chain and off-chain collaboration (on-chaining oracle). Further, this layer includes nudging mechanisms via smart contract (nudge contract), collective decision making, and knowledge sharing among its members. The incentive mechanism layer covers the aforementioned token related techniques and their proper alignment to facilitate token engineering. Next, the organization form layer includes the voting process and membership during the lifecycle of a proposed DAO project. Note that, in economics, public goods that come with regulated access rights (e.g., membership) are called *club goods*.

Finally, the manifestation layer allows members to take simple, locally independent actions that together lead to the emergence of complex adaptive system behavior of the DAO and Society 5.0 as a whole. Due to its striking similarity to decentralized blockchain technology, we explore the potential of the biological *stigmergy* mechanism widely found in social insect societies such as ants and bees, especially their inherent capability of self-organization and indirect coordination by means of olfactory *traces* that members create in the environment. Upon sensing these traces, other society members are stimulated to perform succeeding actions, thus reinforcing the traces in a self-sustaining autocatalytic way without requiring any central control entity, as explained below in Section 5.4.

5.3.3 The Human Use of Human Beings: Cybernetics and Society

A prominent example of moving a Web2-based social network to Web3 was Facebook's recent announcement in June 2019 to launch a new infrastructure to manage their own token coined *Libra* (later renamed Diem), including suitable price stability mechanisms for its exchange with fiat currencies. However, the design of tokenized currencies will not be sufficient for realizing the Society 5.0 vision. To see this, note that people, including former and founding executives, began publicly questioning the impact of social media on our lives and opened up about their regrets over helping create social media as we know it today.[1] For instance, during a public discussion at the Stanford Graduate School of Business, Chamath Palihapitiya, former vice president of user growth at Facebook, told the Stanford audience that the tools we have created are ripping apart the social fabric of how society works. It is eroding the core foundation of how people behave by and between each other. He concluded that he doesn't have a good solution. His solution is just that he doesn't

[1] https://gizmodo.com/former-facebook-exec-you-don-t-realize-it-but-you-are-1821181133

use these tools anymore, nor are his kids allowed to do so. Or, as Facebook's first president Sean Parker famously put it: "God only knows what it's doing to our children's brains."

Useful hints for more human-centered solutions may be found in the origins of cybernetics. In his seminal book "The Human Use of Human Beings: Cybernetics and Society," Norbert Wiener, the founder of cybernetics, argues that the danger of machines working on cybernetic principles, though helpless by themselves, is that such machines may be used by a human being or a block of human beings to increase their control over the rest of the human race. In order to avoid the manifold dangers of this, Wiener emphasizes the need for the anthropologist (see, e.g., [100]) and the philosopher. He postulates that scientists must know what man's nature is and what his built-in purposes are, arguing that the integrity of *internal communication* via feedback loops is essential to the welfare of society.

5.4 From Superorganism to Stigmergic Society & Collective Intelligence in the 6G Era

In this section, we explore how the aforementioned integrity of internal communication may be achieved in Society 5.0 by borrowing ideas from the biological superorganism with brain-like cognitive abilities observed in colonies of social insects. The concept of stigmergy (from the Greek words *stigma* "sign" and *ergon* "work"), originally introduced in 1959 by French zoologist Pierre-Paul Grassé, is a class of self-organization mechanisms that made it possible to provide an elegant explanation to his paradoxical observations that in a social insect colony individuals work as if they were alone while their collective activities appear to be coordinated. In stigmergy, traces are left by individuals in their environment that may feed back on them and thus incite their subsequent actions. The colony records its activity in the environment using various forms of storage and uses this record to organize and constrain collective behavior through a feedback loop, thereby giving rise to the concept of *indirect communication*. As a result, stigmergy maintains social cohesion by the coupling of environmental and social organization. Note that with respect to the evolution of social life, the route from solitary to social life might not be as complex as one may think. In fact, in the AI subfield of swarm intelligence, e.g., swarm robotics, stigmergy is widely recognized as one of the key concepts.

In the following, we illustrate how our CPSS based token engineering DAO framework in Fig. 5.3 can be applied to Society 5.0 and describe the involved bottom-up design steps of suitable purpose-driven tokens and mechanisms:

- **Step1: Specify Purpose**

  Recall from Section 5.3 that the design of any tokenized ecosystem starts with a desirable output, i.e., its purpose. As discussed in Section 5.1, the goal of Society 5.0 is to provide the techno-social environment for CPSS members that (*i*) extends human capabilities and (*ii*) measures activities toward human co-becoming super smart. Towards this end, we advance AI to CI among swarms of connected human beings and things, as widely anticipated in the 6G era.

- **Step 2: Select CPSS of Choice**

  We choose our recently proposed Internet of No Things as state-of-the-art CPSS, since its final transition phase involves nearables that help create intelligent environments for providing human-centered and user-intended services (see Section 5.3). In [13], we introduced an extrasensory perception network (ESPN), which integrates ubiquitous and persuasive computing in nearables (e.g., social robot, virtual avatar) to change the behavior of human users through social influence. In this chapter, we focus on blockchain and robonomics as the two basic technologies to expand *ESPN's online environment* and *offline agents*, respectively.

- **Step 3: Define PoW**

  Recall from Section 5.3 that PoW is an essential mechanism for the maintenance of tech-driven public goods. Specifically, we are interested in creating club goods, briefly mentioned in Section 5.3, whose regulated access rights avoid the well-known "tragedy of the commons." [106] To regulate access, we exploit the advanced blockchain technology of *on-chaining oracles*. On-chaining oracles are instrumental in bringing external off-chain information onto the blockchain in a trustworthy manner. The on-chained information may originate from human users. Hence, on-chaining oracles help tap into human intelligence [79]. As PoW, we define the oracles' contributions to the governance operation of the CPSS via decision making and knowledge sharing, which are both instrumental in achieving the specific purpose of CI.

- **Step 4: Design Tokens with Proper Incentive Alignment**

  Most tokens lack proper incentive mechanism design. Recall from Section 5.2 that the use

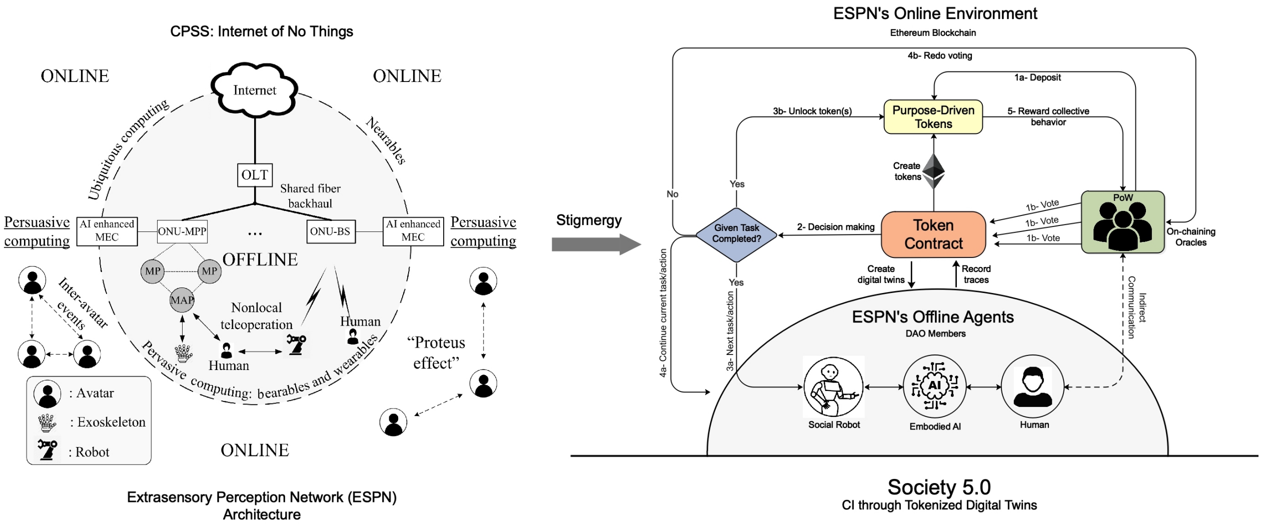


Figure 5.4: Stigmergy enhanced Society 5.0 using tokenized digital twins for advancing collective intelligence (CI) in CPSS.

of tokens as incentives lie at the heart of the DAO and their investigation has started only recently. Importantly, recall that the tokenization process creates *tokenized digital twins* to coordinate actors and regulate an ecosystem for the pursuit of a desired outcome by including *voting rights*. The creation of a tokenized digital twin is done via a *token contract* that incentivizes our defined PoW, involving the following two steps: (*i*) create digital twin that represents a given asset in the physical or digital world, and (*ii*) create one or more tokens that assign access rights/permissions of the given physical/digital asset to the blockchain address of the token holder.

- **Step 5: Facilitate Indirect Communication among DAO Members via Stigmergy & Traces**

  Finally, let the members participating in a given DAO project (*i*) record their purpose-driven token incentivized activities in ESPN's blockchain-enabled online environment and (*ii*) use these blockchain transactions (e.g., deposits) as *traces* to steer the collective behavior toward higher levels of CI in a stigmergy enhanced Society 5.0.

Fig. 5.4 illustrates the functionality of each of these five steps in more detail, including their operational interactions.

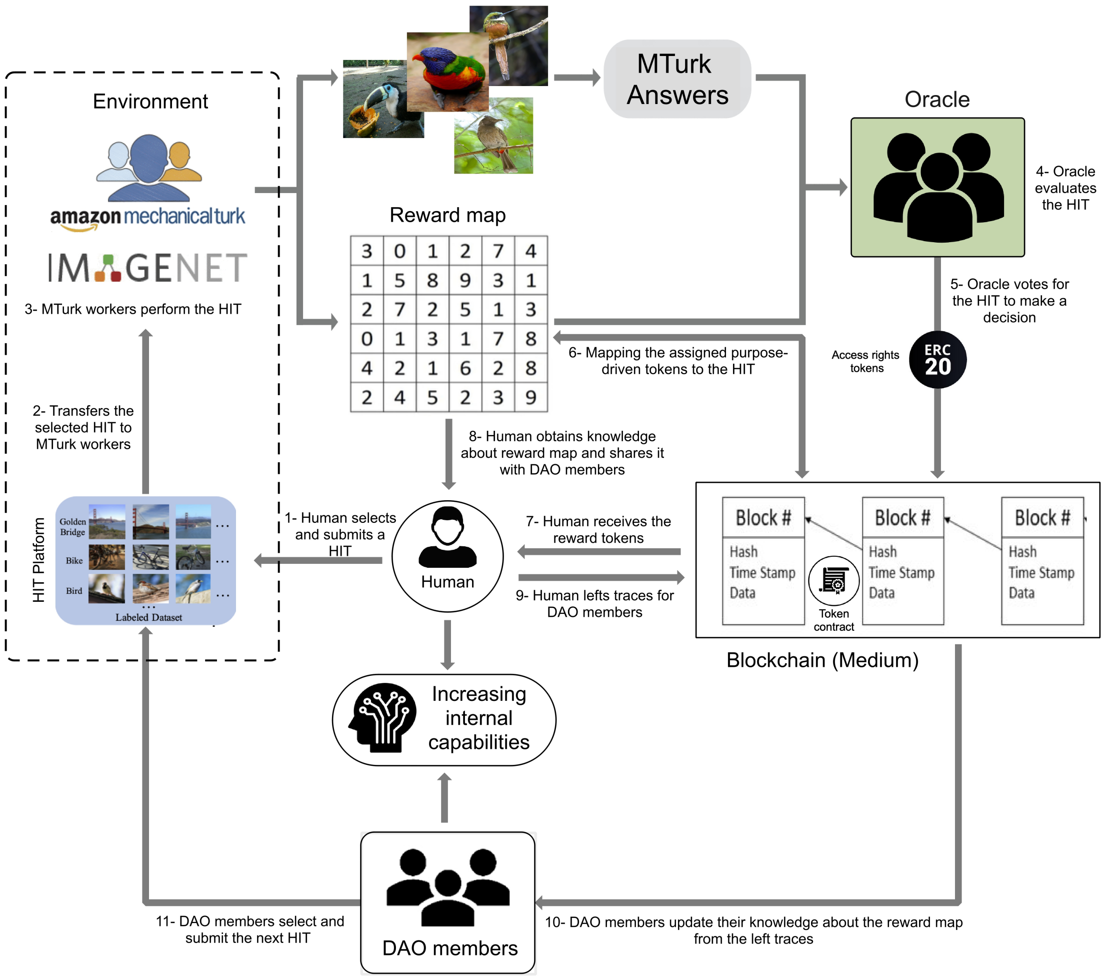


Figure 5.5: Discovery of hidden token reward map through individual or collective ImageNet tagging via Amazon MTurk and on-chaining oracle.

5.5 Implementation and Experimental Results

A general definition of human intelligence is the success rate of accomplishing tasks. In our implementation, human intelligence tasks (HIT) are realized by leveraging the image database ImageNet [2] widely used in deep learning research and tokenizing it. Specifically, humans are supposed to discover a hidden reward map consisting of purpose-driven tokens by means of image tagging, which is done by relying on the crowd intelligence of Amazon Mechanical Turk (MTurk) workers and the validation of their answers via a voting-based decision making blockchain oracle. We measure CI as the ratio of discovered/rewarded number and total number of purpose-driven tokens.

[2] https://www.image-net.org

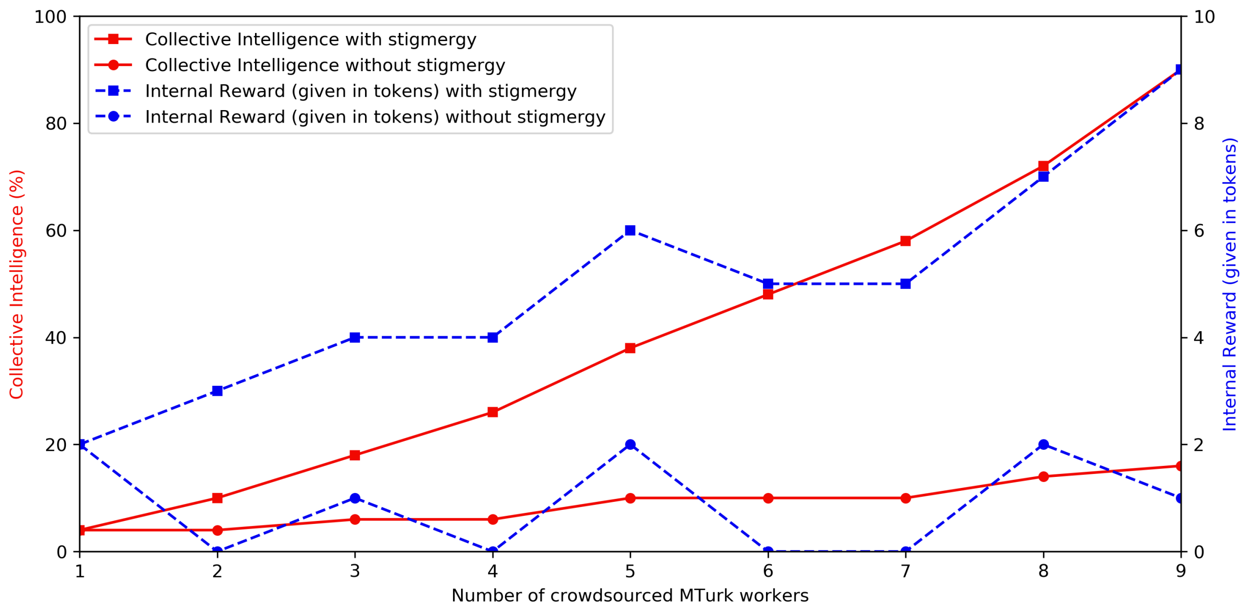


Figure 5.6: Collective intelligence (given in percent) and internal reward (given in tokens) with and without stigmergy vs. number of crowdsourced Amazon MTurk workers.

Fig. 5.5 depicts the set-up and experimental steps of our implementation in more detail. We developed a JavaScript based HIT platform to let a human select from 20 ImageNet images as well as add relevant image tagging information and deliver both to the properly configured MTurk and Amazon Web Services (AWS) accounts using an intermediate OOCSI server. The answers provided by MTurk workers to each submitted HIT were evaluated by an on-chaining oracle, which used ERC-20 compliant access right tokens to regulate the voting process and release the purpose-driven tokens assigned to each successfully tagged image. Finally, the human leaves the discovered/rewarded tokens as stigmergic traces on the blockchain to help participating DAO members update their knowledge about the reward map and continue its exploration.

Fig. 5.6 shows the beneficial impact of stigmergy on both collective intelligence and internal reward in terms of hidden tokens discovered in the reward map by a DAO with 8 members. For comparison, the figure also shows our experimental results without stigmergy, where the DAO members don't benefit from sharing knowledge about the unfolding reward map discovery process.

5.6 Conclusions

Society 5.0 nicely aligns with future 6G's anticipated shift from industry verticals to more human-centeredness. It leverages on CPSS that engage humans in cyber-physical-social behaviors and on technologies that enable a paradigm shift from conventional monetary to future non-monetary economies, such as our considered blockchain-based Web3 token economy and its important role in the recently emerging DAO. Given its similarity to decentralized blockchain technology, we adopted stigmergy—a biological self-organization mechanism widely found in social insect societies—for facilitating indirect communication and internal coordination among offline agents via traces (feedback loops) created in a blockchain based online environment. Our implemented CPSS based bottom-up token-engineering DAO framework for Society 5.0 was experimentally shown to increase both CI and rewarded purpose-driven tokens by means of stigmergic traces in a blockchain based online environment involving crowdsourced Amazon MTurk workers and validating on-chaining oracle.

Chapter 6

Conclusions

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

6.1 Summary

The blockchain revolution is about to flip the status quo of centralized systems in most industries in favor of more decentralized, transparent, open, secure, and efficient infrastructures. While most people view blockchain from a transactional perspective, there are still many salient aspects of a true blockchain that people have not paid particular attention to. These facets, however, are responsible for the nature of the technology as we know it and the reason why it's set to revolutionize the way people transact with others in the near and distant future. Blockchain is changing our society on a fundamental level. It is transforming what we can do online, how we do it, and who can participate. This thesis examined the design and investigation of the pillars of human-centered blockchain technologies for the 6G era.

The doctoral thesis is based on Ethereum blockchain as promising underlying human-centered technologies on which the 6G era is envisioned to rely. In particular, we studied different aspects of the emerging Tactile Internet and presented in-depth technical insights into realizing HITL-centric teleoperation Tactile Internet over FiWi enhanced networks, including the synergies between the HART membership and the complementary strengths of robots to facilitate local human-machine coactivity clusters by decentralizing the Tactile Internet using advanced blockchain technologies. Specifically, we studied the role of the Ethereum DAO and human crowdsourcing in helping decrease task completion time in the event of unreliable connectivity and/or network failures. Further, we investigated the role of behavioral economics games in studying trust and trustworthiness between agents. From the outcome of our investigation and experimentation, we showed that our considered trust game of behavioral economics can be enhanced using basic and advanced Ethereum blockchain techniques and using persuasive robots strategies borrowed from the field of robonomics. Finally, the thesis explored Society 5.0 as an important stepping stone toward realizing the vision of human-centered 6G mobile networks. Our focus was on exploring the role of the DAO, CPSS, and the future Web3 and its underlying token economy toward realizing collective intelligence in a stigmergic society. In the following, a more detailed summary of each chapter is presented.

In Chapter 2, we showed that many of the emerging B-IoT studies use Ethereum as the blockchain of choice and apply a gateway-oriented design approach to offload computationally intensive tasks from resource-constrained end-devices onto an intermediate gateway, thus enabling them to access the Ethereum blockchain network. Toward this end, we first explained the commonalities of and specific differences between Ethereum and Bitcoin blockchains followed by a description of the DAO in technically greater detail. We then discussed the motivation for the integration of blockchain and IoT (B-IoT) followed by a description of the challenges of integrating blockchain and edge computing. Building on our recent Tactile Internet work on orchestrating hybrid HART coactivities, we introduced our proposed low-latency FiWi enhanced LTE-A HetNets based on advanced MEC with embedded AI capabilities. We then showed that higher levels of decentralized AI-enhanced MEC are effective in reducing the average completion time of computational tasks. Further, for remote execution of physical tasks in a decentralized Tactile Internet, we explored how Ethereum's DAO and smart contracts may be used to establish trusted HART membership and how human crowdsourcing helps decrease physical task completion time in the event of unreliable forecasting of haptic feedback samples from teleoperated robots. We outlined future research avenues on technological convergence in order to successfully accomplish hybrid machine+human tasks by augmented and shared intelligence tapping into the theory of nudge, a recent novel development in behavioral economics concept popularized by Richard H. Thaler, the 2017 Nobel Laureate in Economics.

In Chapter 3, we explored how Ethereum blockchain technologies, in particular the aforementioned concept of the DAO, may be leveraged to decentralize the Tactile Internet, which enables unprecedented mobile applications for remotely steering real or virtual objects/processes in perceived real-time and represents a promising example of future techno-social systems. We showed that a higher level of decentralization of AI-enhanced MEC reduces the average computational task completion time of up to 89.5% by setting the computation offloading probability to 0.7. Further, we observed that crowdsourcing of human assistance is beneficial in decreasing the average completion time of physical tasks for medium to high feedback misforecasting probabilities, provided the human offers equal or even superior operational capabilities, i.e., $\frac{f_{human}}{f_{robot}} \geq 1$. Towards this end, we proposed a nudge contract as a technique to influence nearby human behavior without punishment for skills transfer in the context of the Tactile Internet. Specifically, the nudge contract aims to enable the skills transfer process as well as a reward by means of the Ethereum smart contract. We then showed that the considered nudge contract helps successfully accomplish tasks via shared intelligence among failing robots and skilled humans.

In Chapter 4, we covered some of the ways in which our decisions are affected by social influences and the behavior and attitude of other people. Towards this end, we investigated the widely studied trust game of behavioral economics in a blockchain context. Beside the design of a decentralized trust game without the need of the experimenter in the middle between players, we presented a simple but efficient blockchain-based mechanism of deposit as a pre-commitment between players. The term of pre-commitment was first introduced in 1978 by Thomas Schelling, the 2005 Nobel Laureate in Economics as part of a self-management system called *Egonomics*[1]. Later in 1979, the Norwegian philosopher, social, and political theorist Jon Elster developed the theory of pre-commitment, which he also calls self-binding in his work *Ulysses and the Sirens*[2]. Using this mechanism, we experimentally demonstrated that a social efficiency of up to 100% can be achieved to enhance both trust and trustworthiness between players (and thus investment and reciprocity). Further, we presented a voting-based on-chaining blockchain oracle architecture for a networked N-player trust game that involves a third type of player called observers, whose primary goal is to observe, track, and reward/punish players' behavior depending on their investment and reciprocity. The resultant peer pressure by the on-chaining oracle helps raise average normalized reciprocity above 80%. Finally, we experimentally demonstrated that players are more likely to give more

[1] T. C. Schelling, "Egonomics, or the Art of Self-Management," *The American Economic Review,* May 1978.

[2] Jon Elster, "Ulysses and the Sirens: Studies in Rationality and Irrationality," *Cambridge University Press,* 1979.

when their generosity is made public and encouraged by social robots, especially by leveraging the mixed logical-affective persuasive strategies for social robots of the emerging field of robonomics.

In Chapter 5, we explained that 6G will differ from 5G in several ways. 6G will not only explore more spectrum at high-frequency bands but also converge driving technological trends, including connected robotics and blockchain technologies. Importantly, we showed that 6G will become more human-centered than 5G, which primarily focused on industry verticals. Putting people at the center of a future super-smart society is the driving theme for the anticipated shift of research focus from Industry 4.0 to Society 5.0 based on CPSS, which integrate human beings at the social, cognitive, and physical levels and engage them in cyber-physical-social behaviors with diverse types of meta-human capabilities. Specifically, we focus on the paradigm shift from conventional monetary to future non-monetary economies, such as our considered blockchain-based Web3 token economy and its important role in the recently emerging DAO. Toward this end, we presented our CPSS based token engineering DAO framework for Society 5.0. Given its similarity to decentralized blockchain technology, we adopted stigmergy—a biological self-organization mechanism widely found in social insect societies—for facilitating indirect communication and internal coordination among offline agents via traces (feedback loops) created in a blockchain-based online environment. Most notably, we studied indirect communication mediated by tokenized digital twins to advance collective intelligence in a future Society 5.0 and a token economy-based Web3, where humans act like neurons in a hive mind with blockchain technology acting as connecting tissue to create programmable incentives known as tokens. Finally, we experimentally showed how to increase both CI and rewarded purpose-driven tokens by means of stigmergic traces in a blockchain-based online environment involving crowdsourced Amazon MTurk workers and validating on-chaining oracle.

6.2 Future Work

Throughout the thesis, we assumed that no agents could be untrusted, though the remote skillful agent is assumed to be always honest and failure-free. While the work produced by this line of research is useful with a trusted agent, we did not consider the general skill transfer scheme when the agent could misbehave. An interesting future research avenue is to build a robust decentralized Tactile Internet, in which we will design a set of smart contracts as a DAO to support recommender systems of trusted and skillful agents based on their past experience. The anticipated DAO, intended to run on a public blockchain (e.g., Ethereum), will offer the features of transparency, trust, and immutability. Agents (skills providers) are anticipated to register themselves in order to publish their skills or rate existing agents' skills based on their experience with them. The ratings are stored on the smart contract, thus on the blockchain. Next, human operators (skills seekers) can read from the recommender system smart contract to select the best skillful agents based on their rating. Agents can be skills seekers or providers. Further, we may use an escrow technique in the form of a smart contract, in which the skills seeker places the reward of skills in the form of Ether/ERC20 tokens. This provides proof-of-funds and allows for a much safer skills transfer and payment. Once confirmed, the selected skills provider can take ownership of controlling robots till the end of the teleoperation. Once the skills transfer process and the task are completed, the skills seeker successfully confirms the task and releases the escrow to the skills provider. Both recommender system and escrow smart contract allow to safely exchange Ether/ERC20 tokens and skills with one another. Currently, the trusted mediator is always a smart contract, but this solution will be also adapted in the future to use an oracle-based distributed human arbitrator pool in the case of a dispute between the two parties. The goal is to build a network of trusted collaborators around the Ethereum platform, grow the platform and ecosystem, and increase the probability of success for all components in a Tactile Internet teleoperation scenario.

Our focus on the DAO as a means of "automation at the center and human at the edge" opens an interesting future research direction for the Tactile Internet. This future research will be exploring the role of knowledge used by Google and its services to enhance their search engine's results with information gathered from a variety of sources. The knowledge is called *Google Knowledge Graph*[3]. The goal of our future research will be to build a blockchain-based framework for human intelligence at the edge of the Tactile Internet. Similar to proof-of-work consensus algorithm used in Bitcoin and Ethereum blockchain, we aim to design a proof-of-intelligence for collective aggregation and construction of useful knowledge that a failed robot needs to accomplish a disrupted task. The aggregation of human knowledge is anticipated to reduce task execution time while ensuring high efficiency and accuracy of the performed task. To do so, each human will act as a blockchain node in the process of knowledge construction and a consensus should be reached before selecting a leader whose role will be the transfer of the aggregated knowledge to the failing robot. The knowledge will be stored in the distributed database at the edge of the network (i.e., MEC). A token reward will be adopted in the proof-of-intelligence consensus to nudge and mobilize more participants in the

[3] `https://blog.google/products/search/about-knowledge-graph-and-knowledge-panels/`.

process of knowledge formation. We note that distributed knowledge aggregation and formation represents a form of collective intelligence.

While this research was focused on designing behavioral techniques via smart contracts, the next step will be the design of a decentralized online platform dedicated to the scientific communities. The goal of this platform will be to carry out experimental economics research. Unlike the widely used client-server *z-tree* tool, the anticipated platform will be based on decentralized blockchain technologies and use tokens instead of Ether or real money. More precisely, a stable token (e.g., Tether) will be used whose value is identical to fiat currency, e.g., USD or CAD. Further, we anticipate to extend our research to support more forms of behavioral games, e.g., public good games or extensive form games where oracles can be applied, e.g., simple Dutch auctions, double auctions, clock auctions. In addition, we aim to conduct research on blockchain-based behavioral, self-management, and self-awareness techniques such as the above mentioned egonomics toward increasing trust and trustworthiness between players in such games, thus opening up new research avenues for applying blockchain in behavioral economics games. Another interesting open research avenue will be to explore in-depth the emerging field of robonomics and studying the possibilities of allowing peer-to-peer financial transactions between humans and robots, which is up to now a challenging task.

Another interesting research avenue is to investigate the field of "human-based computation games" or "games with a purpose" (GWAP) which is a human-based computation technique of outsourcing steps within a computational process to humans in an entertaining way (e.g., gamification) [107]. The idea of GWAP, proposed by Luis von Ahn, is to design entertaining games that motivates people to solve a computational problem. Such games constitute a general mechanism for using brainpower to solve open problems. Our next step is to conduct more research on how to apply blockchain technologies in GWAP. We note that, unlike the aforementioned behavioral and economics games, GWAP do not rely on altruism or financial incentives. Instead, other blockchain mechanisms can be applied to keep players engaged in the game, e.g., token-based scores, player skill levels represented by tokens, as well as increasing player enjoyment by means of social robots.

Last but not least, an interesting future research avenue will be to extend our research on the role of blockchain token economy and DAO in realizing a collective intelligence with a biological mechanism (i.e., stigmergy). For a certain task, several available DAO members may to be continuously selected in a random manner to form a unit. A unit uses the power of collective intelligence of its members to take actions and solve tasks at different times. Similar to the pheromone left by ants in a certain area, traces represented by blockchain tokens earned with different values can be accumulated, which might create a positive feedback loop of the unit in the DAO (accumulated reward). In an ant colony, the pheromone is increased to become more attractive and serve as a history of the previous movements of ants. Similarly, the token may do the same and have a positive influence on this unit in the DAO. There is no need to discuss or vote for a unit to perform a task, if a unit is recognized as skillful and thereby will attract interest. The interest attracted will be from people actively involved in the unit and willing to put effort into carrying the task further, not votes from people with little interest or involvement. Given that the task execution is supported or rejected based on contributed effort (i.e., peer-production), not votes, input from people with more commitment to performing the task will have greater weight. This stigmergic mechanism will also put the unit's individual members in control over their own work in a self-organizing manner.

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Appendix A

Extended Synopsis in French

Conception et Investigation de Technologies Avancées de Blockchain Centrées sur l'Humain pour L'ère 6G

Introduction

La sixième génération (6G) de réseaux cellulaires sans fil devrait intégrer les derniers développements en matière d'infrastructure de réseau et les avancées technologiques émergentes. La 6G exploitera non seulement plus de spectre des bandes haute fréquence, mais convergera également vers les tendances technologiques, notamment la robotique connectée, l'intelligence artificielle (IA) et les technologies chaîne de blocs (Blockchain). Il existe également une forte idée que la nature des terminaux mobiles va changer, les robots mobiles intelligents étant censés jouer un rôle plus important. Il est important de noter que la 6G deviendra plus centrée sur l'humain que la 5G, qui se concentrait principalement sur les secteurs verticaux. Dans cette thèse, nous visons à explorer les technologies chaîne de blocs centrées sur l'humain pour l'ère 6G, tout en tirant parti des technologies émergentes. Nous explorons la symbiose de la chaîne de blocs avec d'autres technologies clés telles que l'Internet des objets (IdO), l'IA et les robots, tout en nous concentrant sur l'Internet tactile pour une interaction homme-machine avancée. Ensuite, nous étudions le domaine de la robonomie à l'ère de la 6G, qui intègre l'économie comportementale aux technologies de chaîne de blocs et à la robotique persuasive. Enfin, on décrit l'évolution de l'industrie 4.0 vers les systèmes cyber-physiques-sociaux centrés sur l'humain (CPSS). Nous présentons nos idées sur le changement anticipé de l'orientation de la recherche de l'industrie 4.0 basée sur l'IdO et Internet tactile vers les futurs systèmes technico-sociaux centrés sur l'humain et à quoi ressemblera ou pourrait ressembler la super intelligente société 5.0 du futur.

Objectifs

Le premier objectif de la thèse est d'étudier les défis spécifiques de l'Internet tactile, également connu sous le nom de Internet des compétences, où les humains transfèrent des connaissances, de l'expertise et des compétences aux autres humains/robots, à distance, sans restriction des limites physiques. Dans un tel scénario d'Internet tactile, le principal défi abordé dans cette thèse consiste à coordonner des groupes d'humains et à les amener à se comporter selon des règles et des objectifs prédéfinis et de manière fiable lorsqu'un humain et/ou un robot échoue pendant l'exécution d'une tâche. Pour réussir son déploiement dans un scénario d'Internet tactile, il est crucial d'identifier les concepts de base, les caractéristiques, la structure et la taxonomie de l'Internet tactile. Par la suite, certaines des applications typiques de l'Internet tactile et des exigences d'infrastructure de réseau doivent être identifiées. Plus particulièrement, il a été démontré que les réseaux hétérogènes (HetNets) fiber-sans fil (FiWi) à faible latence proposés, basés sur l'informatique de périphérie a accès multiples avec des capacités d'IA intégrées, répondaient à ces exigences. L'un des principaux défis et objectifs de cette thèse est de comprendre le concept de l'approche de *human-agent-robot teamwork* (HART) pour parvenir à une coordination homme-machine avancée au moyen d'un processus supérieur pour orchestrer de manière fluide les coactivités des machines. En outre, la thèse vise à explorer les principales caractéristiques qui distinguent Ethereum des autres chaîne de blocss, y compris sa symbiose avec d'autres technologies clés telles que l'IA et les robots, ainsi que les solutions d'informatique décentralisées. Un objectif important de la thèse est d'aller au-delà de l'IdO et de fournir des informations sur l'exploitation le concept Ethereum d'organisation autonome décentralisée (DAO) pour aider à fournir la confiance et la décentralisation de l'Internet tactile. En outre, l'un des principaux objectifs de la thèse est d'améliorer les capacités de transfert de compétences de l'opérateur humain/robot en incitant des experts humains au moyen de récompenses via des contrats intelligents dans un scénario d'Internet des compétences. Le déploiement d'une DAO et des contrats intelligents dans l'Internet tactile émergent n'a pas été abordé auparavant dans la littérature existante. Un autre objectif de cette thèse est de développer et d'examiner les effets d'un mécanisme proposé basé sur des contrats intelligents chaîne de blocs conçu pour améliorer l'efficacité sociale et la réciprocité normalisée dans le jeu de la confiance, un jeu d'économie standard largement utilisé en économie expérimentale et comportementale pour mesurer la confiance. Dans le jeu de la confiance, un joueur (trustor) a le choix d'investir ou de ne pas investir dans un projet, qui est administré par l'autre joueur (trustee). L'investissement est réussi si le montant investi se multiplie en valeur. Cependant, le trustee contrôle la procédure d'investissement : il peut garder le montant total pour lui-même ou le partager avec le trustor. Un autre objectif de la thèse est d'étendre le jeu de confiance classique à deux joueurs à un jeu de confiance en réseau de N joueurs bénéficiant de l'influence sociale et de la pression des pairs pour améliorer à la fois la confiance et la fiabilité en utilisant des technologies de chaîne de blocs avancées, notamment un oracle de chaîne de blocs. Motivé par la vision 6G de la convergence des tendances technologiques telles que les technologies chaîne de blocs et la robotique connectée, un autre objectif de la thèse est d'explorer le domaine de la *robonomie*, qui étudie l'impact socio-technique des technologies chaîne de blocs sur l'interaction homme-robot et l'économie comportementale pour l'intégration sociale des robots dans la société humaine. Plus précisément, la thèse étudie la conception de stratégies robotiques persuasives appropriées pour changer le comportement humain en tirant parti des robots sociaux et des communications incarnées comme mécanisme d'influence sociale. En outre, la thèse vise à réaliser une implémentation basée sur la chaîne de blocs pour comparer les investissements entre le jeu de confiance homme-homme et le jeu de confiance homme-robot où le robot a un impact sur la décision humaine. L'objectif final de la thèse est d'explorer le concept de stigmergie, un mécanisme d'auto-organisation biologique largement présent dans les sociétés sociales d'insectes, pour faciliter la communication indirecte, l'intelligence collective et la coordination interne entre les agents hors ligne via des traces (boucles de rétroaction) créées dans une chaîne de blocs. Plus précisément, la thèse examine la conception d'un mécanisme d'incitation approprié sous la forme de jetons à

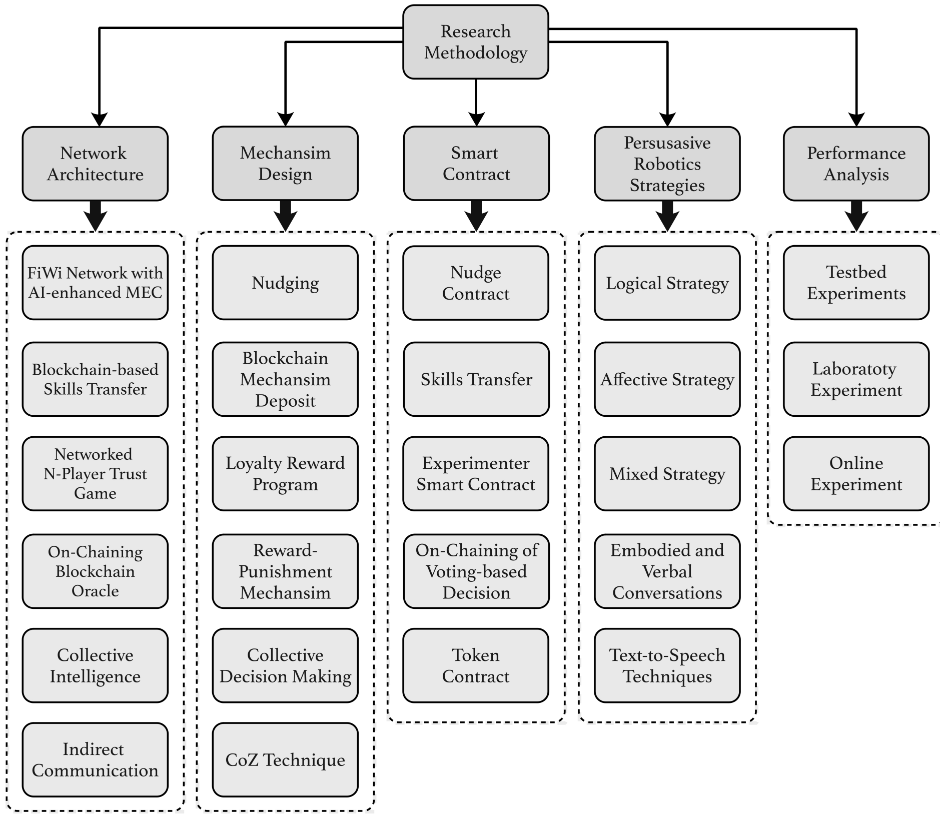

Figure R.1: La méthodologie de recherche.

finalité pour faciliter la collaboration en incitant un groupe autonome de personnes à contribuer individuellement à un objectif collectif.

Méthodologie

La méthodologie de recherche appliquée dans cette thèse comprend l'architecture de réseau, la conception de mécanismes, les contrats intelligent, les stratégies de robotique persuasive et les tests expérimentaux comme résumé dans la figure R.1. Dans cette thèse, de nouvelles techniques de transfert de compétences basées sur la chaîne de blocs sont proposées pour l'Internet tactile immersif à faible latence avec des serveurs l'informatique de périphérie à accès multiple (MEC) améliorés par l'IA. En particulier, les techniques appliquées incluent les contrats intelligents, qui permettent d'accomplir avec succès des tâches via des compétences partagées entre des robots/humains défaillants et des humains qualifiés. En outre, un oracle chaîne de blocs pour le jeu de confiance en réseau de N joueurs est développé pour permettre un bon comportement coopératif afin d'aider à propager la confiance et la fiabilité parmi un groupe de joueurs. En outre, de nouveaux mécanismes sont présentés tout au long de la thèse pour répondre aux objectifs mentionnés ci-dessus. Ces mécanismes comprennent un contrat incitatif, un contrat intelligent d'expérimentateur, un mécanisme de dépôt par chaîne de blocs, un programme de récompense de fidélité, un mécanisme de récompense-punition, un oracle en chaîne, des contrats de jeton et des scripts de stratégies robotiques persuasives, ainsi que l'introduction de nouvelles techniques de téléopération telles que Crowd of Oz (CoZ). En plus, différents types de contrats intelligents sont conçus pour appliquer des contingences de renforcement et de punition afin d'aider les humains à gérer leur propre comportement. Les caractéristiques spécifiques des contrats développés sont identifiées en étudiant plusieurs techniques comportementales allant du (*i*) mechanism incitatif, dans lequel nous influençons le comportement sans punition pour le transfert de compétences dans le contexte de l'Internet tactile, (*ii*) récompense/pénalité comme positive renforçateur sans donner d'incitations économiques directes, par exemple, récompense/pénalité de points de fidélité, (*iii*) restriction de nombre de choix disponibles pour un joueur par une stratégie d'autocontrôle, par exemple, le mécanisme de dépôt utilisé dans le contrat de l'expérimentateur, (*iv*) stratégie d'intériorité dans laquelle nous utilisons un avantage ou un coût à long terme pour un individu qu'il ne prend pas en compte lorsqu'il prend la décision de consommer un bien ou un service, par exemple, gagner 1 éther pour chaque 10 points de fidélité accumulés, et (*v*) agrégation de l'intelligence collective et la prise de décision collective au moyen d'un mécanisme de vote décentralisé, par exemple, l'enchaînement des décisions basées sur le vote. En outre, des contrats de jeton ont été adoptés pour aider à atteindre un objectif commun ainsi qu'à réglementer les droits d'accès. Finalement, différentes stratégies robotiques persuasives sont utilisées dans nos recherches pour le domaine émergent de la robonomie. Ces stratégies comprennent des stratégies logiques, affectives et mixtes. Plus précisément, nous avons développé des techniques de téléopération pour améliorer les capacités du robot social largement utilisé Pepper pour les communications verbales et corporelles. Les stratégies contiennent un ensemble de mécanismes de récompense et de punition, ainsi que des conseils économiques et techniques et des encouragements permis par Pepper via des techniques de text-parole vocale.

Contributions de la thèse

Cette thèse est une compilation de quatre publications (3 articles de revues et un chapitre de livre), qui sont publiées ou soumises pour publication dans des revues IEEE de haut calibre ainsi qu'un éditeur de livres renommé (c.-à-d. CRC Press). Les principales contributions de la thèse sont brièvement discutées ci-dessous.

De l'Internet des objets par chaîne de blocs (B-IdO) vers la décentralisation de l'Internet Tactile

Cette partie de la thèse se concentre sur l'intégration de la chaîne de blocs avec l'Internet tactile comme l'une des applications d'interaction homme-machine les plus intéressantes et le prochain bond dans l'évolution de l'IdO d'aujourd'hui. Après avoir expliqué les points communs et les différences spécifiques entre les chaîne de blocss Ethereum et Bitcoin, nous avons d'abord fourni une enquête à jour sur la façon dont Ethereum peut être utilisé pour réaliser l'IdO chaîne de blocs émergent (B-IdO). Ensuite, nous avons montré que l'Internet tactile intègre des utilisateurs humains, des agents logiciels IA et des robots dans des équipes. L'équipe HART qui en résulte permet à son tour des grappes de coproduction et de collaboration locales, qui tirent parti de l'intelligence humaine pour prendre en charge les robots et les agents d'IA. Nous avons ensuite expliqué comment les technologies spécifiques de la chaîne de blocs Ethereum peuvent être exploitées pour réaliser les futurs systèmes techno-sociaux, notamment l'Internet tactile. Nous avons montré qu'un rôle central joue l'organisation autonome décentralisée (DAO), qui exécute des contrats intelligents sur la chaîne de blocs Ethereum et nécessite l'implication de participants humains pour effectuer un certaines tâches que les agents logiciels autonomes basés sur l'IA et les robots eux-mêmes ne peuvent pas faire (par exemple, voter, prendre une décision collective et transmettre de compétences). Dans la tentative de garder DAO aussi autonome que possible, nous avons utilisé le robot téléopéré comme un agent autonome (automatisation au centre), tout en laissant l'opérateur humain être un décideur soutenu par un ensemble d'opérateurs humains qualifiés à proximité (humains en périphérie) qui transfèrent des connaissances lorsque l'humain/robot est dans le besoin, résultant en une nouvelle forme hybride de collaboration homme-robot.

Pour un déploiement réussi de la chaîne de blocs pour les applications Internet tactiles, il est crucial d'identifier les caractéristiques et caractéristiques principales de l'Internet tactile. Nous avons commencer par expliquer les concepts clés des exigences émergentes de l'Internet tactile, de la vision, de la structure et de l'infrastructure réseau. Deuxièmement, nous avons présenté la DAO, qui représente une caractéristique saillante d'Ethereum introuvable. Les DAO sont des organisations décentralisées sans autorité centrale ni responsable. Ils fonctionnent sur un code de programmation encodé sur la chaîne de blocs Ethereum. Comme la chaîne de blocs, le code d'une DAO s'éloigne des organisations traditionnelles en supprimant le besoin de contrôle centralisé. Même les développeurs originaux du DAO n'ont aucune autorité supplémentaire car elle fonctionne indépendamment sans aucune intervention humaine. Elle peut être financé par un groupe d'individus qui couvrent ses coûts de base et confèrent aux bailleurs de fonds des droits de vote plutôt que n'importe quel type de propriété ou d'actions. Cela crée un système autonome et transparent qui continuera sur le réseau aussi longtemps qu'il fournira un service utile à ses clients. Une DAO peut être financée par un groupe d'individus qui couvrent ses coûts de base, donnant aux bailleurs de fonds des droits de vote plutôt que n'importe quel type de propriété ou d'actions. Cela crée un système autonome et transparent qui continuera sur le réseau aussi longtemps qu'il fournira un service utile à ses clients. Les DAO existent en tant que logiciels distribués open source qui exécute des contrats intelligents et fonctionnent selon des règles et directives de gouvernance spécifiées. Vitalik Buterin, le fondateur d'Ethereum, a décrit sur le blog Ethereum que l'idéal d'une DAO comme suit: c'est une entité qui vit sur Internet et existe de manière autonome, mais qui repose également fortement sur l'embauche de personnes pour effectuer certaines tâches que l'automatisation elle-même ne peut pas faire. Contrairement aux agents basés sur l'IA qui sont complètement autonomes, une DAO nécessite toujours une forte implication de la part des humains interagissant spécifiquement selon un protocole bien défini pour fonctionner. Pour illustrer la différence entre une DAO et l'IA, la figure R.2 montre un graphique en quadrants qui classe les DAO, l'IA, les organisations traditionnelles ainsi que les robots, qui ont été largement déployés dans les chaînes de montage, entre autres, et elle montre le model des DAOs qui impliquent une automatisation au centre et des humains en périphérie.

Ensuite, nous décrivons un exemple très intéressant pour catalyser l'intelligence humaine et machine vers une nouvelle forme d'intelligence artificielle générale (AGI) auto-organisée sur Internet qu'on appelle la coopérative d'auto-organisation décentralisée (DSOC), un concept similaire au DAO susmentionné. DSOC est un ensemble de modèles de contrats intelligents que les agents d'IA peuvent utiliser pour demander que des travaux d'IA soient effectués, pour échanger des données et pour fournir les résultats des travaux d'IA. Ceux-ci incluent également les contrats à utiliser par des agents externes non-IA qui souhaitent obtenir des services d'IA de ces agents dans le réseau. N'importe qui peut créer un nœud (un agent d'IA) et le mettre en ligne, en l'exécutant sur un serveur, un ordinateur personnel ou un appareil intégré. Ce nœud serait entré dans le réseau, afin qu'il puisse demander et/ou accomplir des tâches d'IA en interaction avec d'autres nœuds, et s'engager dans des transactions économiques. À cette fin, nous visons à adopter le concept du DAO/DSOC pour

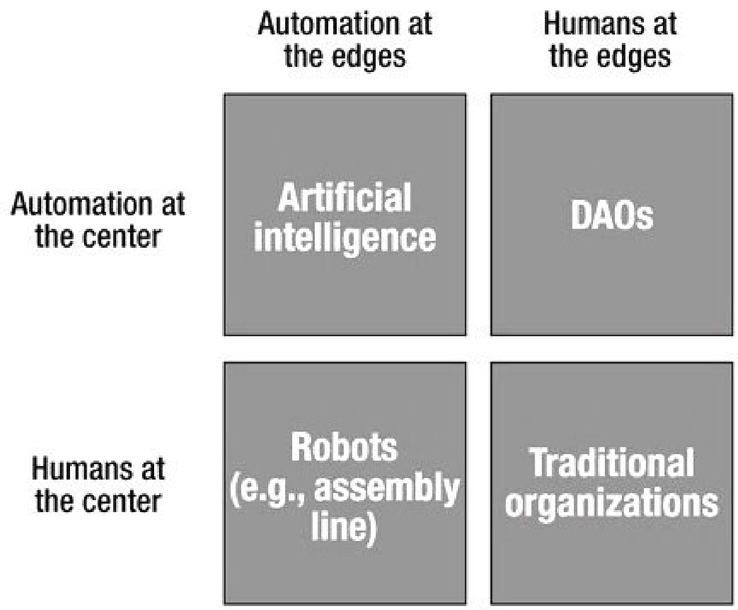

Figure R.2: DAOs vs intelligence artificielle, organisations traditionnelles et robots (largement déployés dans les chaînes de montage, entre autres) : L'automatisation et les humains sont impliqués en périphérie et au centre (source : Ethereum Blog).

permettre aux robots d'apprendre non seulement à partir d'échantillons d'entraînement massifs, mais également de connaissances humaines afin d'accomplir des tâches via une intelligence partagée entre différents robots et humains. Finalement, nous avons décrit un défi de recherche intéressant pour la collaboration homme-robot, soit le développement de techniques visant à transférer les compétences de l'homme au robot de manière fiable.

La voie de la DAO : Vers la décentralisation de l'Internet Tactile

Ce travail propose l'utilisation des technologies chaîne de blocs et plus précisément le concept de DAO précité afin de décentraliser l'Internet Tactile et d'améliorer les performances et les temps d'exécution des applications mobiles. Pour atteindre cet objectif, différentes méthodologies ont été appliquées en exploitant l'équipement de l'utilisateur final partiellement ou entièrement décentralisé et les solutions de serveur informatique de pointe, ainsi que le crowdsourcing d'expertise humaine pour effectuer des tâches que les robots téléopérés ont du mal à accomplir de manière fiable. En outre, le concept de contrat incitatif basé sur la chaîne de blocs a été introduit pour améliorer les capacités d'achèvement des tâches des membres décentralisés non qualifiés du DAO. Les résultats de simulation fournis montrent qu'une décentralisation plus poussée peut conduire à une amélioration jusqu'à 90% des performances d'achèvement des tâches pour une probabilité de déchargement optimale. En outre, nous avons démontré que le crowdsourcing de l'intelligence humaine peut considérablement améliorer les performances d'achèvement des tâches, en particulier dans les cas où les robots ne parviennent pas à accomplir les tâches physiques. Ainsi, pour favoriser l'intervention d'utilisateurs qualifiés et mener à bien les tâches, le concept de contrat incitatif a été adopté pour le transfert de compétences. À notre connaissance, ce travail a été l'un des premiers à étudier la

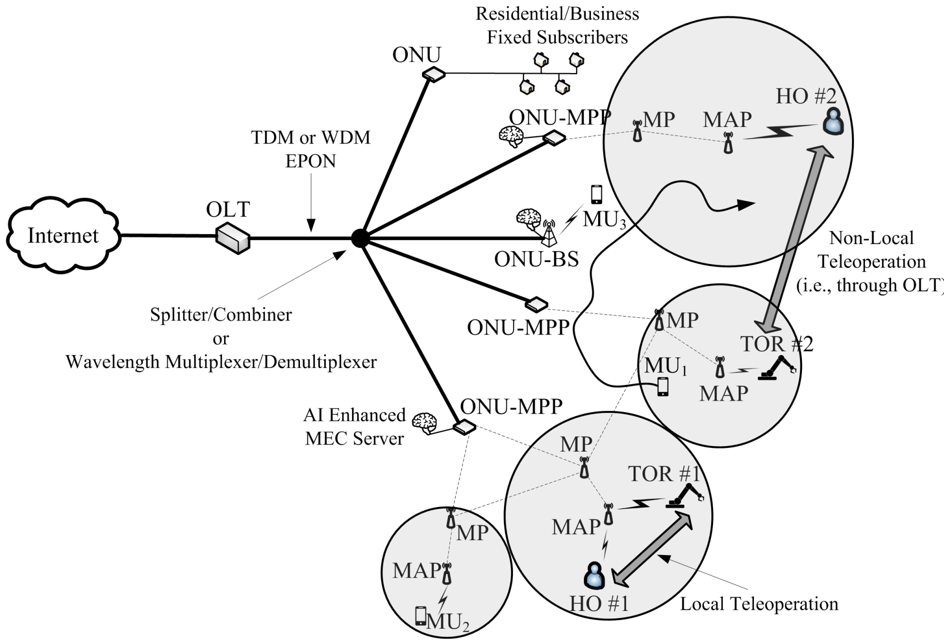

Figure R.3: Architecture des réseaux mobiles améliorés FiWi avec MEC équipé par l'IA pour des applications Internet tactiles immersives.

combinaison de deux technologies massives, à savoir l'Internet tactile et les technologies chaîne de blocs.

Nous avons montré que les exigences de communication 5G ultra-fiable à faible latence (URLLC) peuvent être satisfaites en améliorant les réseaux HetNet 4G LTE-A avec des réseaux d'accès FiWi centrés sur la capacité basés sur des technologies de réseaux optiques passifs (EPON) et réseau local sans fil (WLAN) à faible coût dans le réseau d'amenée et dans le réseau d'accès, respectivement. La figure R.3 illustre plus en détail l'architecture de ces réseaux mobiles améliorés FiWi. La liaison fibre EPON commune est partagée par un certain nombre d'unités de réseau optique (ONU), qui peuvent soit se connecter à des abonnés fixes, soit s'interfacer avec un point portail de maillage (MPP) sans fil ou une station de base (BS) cellulaire. Certains des ONU-MPP/ONU-BS résultants peuvent être équipés d'un serveur informatique de périphérie multi-accès (MEC) équipé par AI. Du côté de l'utilisateur final, nous considérons les trois types d'abonnés suivants : les utilisateurs mobile (UM) classiques ainsi que les couples de l'opérateur human (HO) et le robot téléopéré (TOR) impliqués dans la téléopération, qui peuvent être soit locaux soit non locaux.

Dans nos simulations, nous définissons les paramètres du réseau FiWi comme suit : espace intertrame de la fonction de coordination distribuée (DIFS) = 34 μsec, espace intertrame court (SIFS) = 16 μsec, en-tête de couche physique (PHY) = 20 μsec, W_0 = 16 μsec, H = 6, ϵ = 9 μsec, demande d'envoi (RTS) = 20 bytes, claire à envoyer (CTS) = 14 bytes, accusé de réception (ACK) = 14 bytes, r_{WMN} = 300 Mbps, c_{PON} = 10 Gbps, portée de la fibre PON l_{PON} = 20 Km, longueur moyenne des paquets L = 1500 bytes, $\varsigma_L^2 = 0$, ONU-AP rayon = 10^2 m. Nous considérons également les serveurs MEC améliorés par IA $1 \leq N_{Edge} \leq 4$, chacun associé à 8 utilisateurs finaux, dont $1 \leq N_{PD} \leq 8$ les utilisateurs finaux partiellement décentralisés peuvent contrôler de manière flexible la quantité de tâches tranferées en faisant varier leur probabilité de transfert de calcul. Les $8 - N_{PD}$ restants sont des utilisateurs entièrement centralisés qui dépendent uniquement de

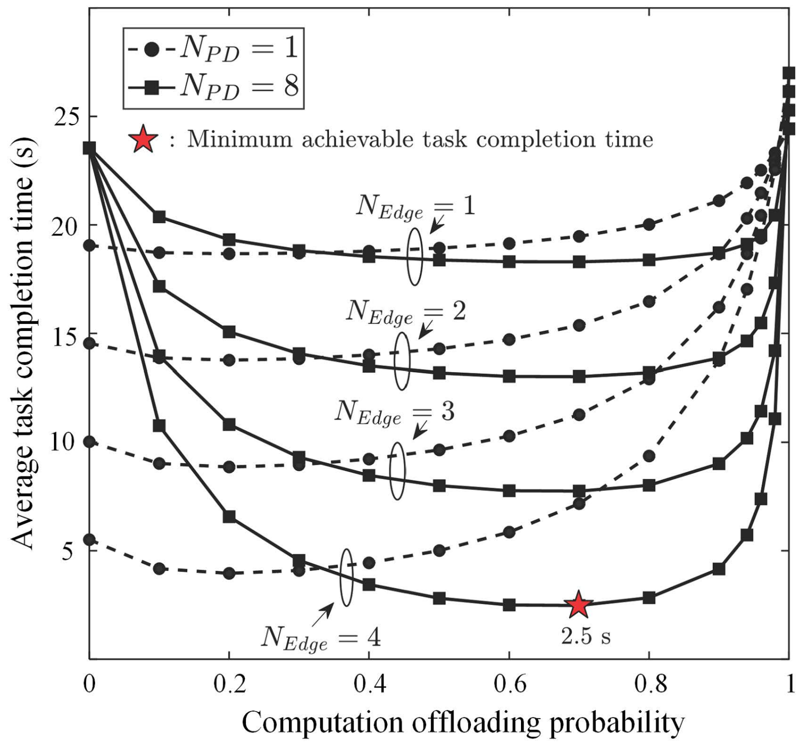

Figure R.4: Temps d'achèvement moyen des tâches de calcul (en secondes) par rapport à la probabilité de déchargement des calculs pour différents nombres d'utilisateurs finaux partiellement décentralisés (N_{PD}) et de serveurs MEC améliorés par l'IA (N_{Edge}).

l'informatique de périphérie (c'est-à-dire que leur probabilité de déchargement de calcul est égale à 1). Notez que pour $N_{Edge} = 4$, tous les utilisateurs finaux peuvent décharger leurs tâches de calcul sur un nœud de périphérie. Inversement, pour $N_{Edge} < 4$, un ou plusieurs nœuds de périphérie ne sont pas disponibles pour le déchargement des calculs et leurs utilisateurs finaux associés se rabattent sur leurs ressources de calcul locales (c'est-à-dire entièrement décentralisées). La capacité de calcul des serveurs MEC et des utilisateurs finaux partiellement décentralisés est respectivement fixée à 1,44 GHz et 185 MHz. La figure R.4 montre le temps d'achèvement moyen des tâches par rapport à la probabilité de déchargement des calculs des utilisateurs finaux partiellement décentralisés pour différents N_{Edge} et N_{PD}. Nous observons à partir de la figure R.4 que pour un N_{Edge} donné, l'augmentation de N_{PD} (c'est-à-dire un niveau de décentralisation plus élevé) est efficace pour réduire le temps moyen d'achèvement des tâches. Plus précisément, pour $N_{Edge} = 4$, un niveau de décentralisation élevé ($N_{PD} = 8$) permet aux utilisateurs finaux de bénéficier d'une réduction du temps moyen d'achèvement des tâches allant jusqu'à 89,5% en ajustant de manière optimale leur probabilité de transfert de calcul à 0,7. Comme le montre la figure R.4, l'augmentation de N_{PD} entraîne non seulement une diminution du temps d'exécution moyen, mais également une diminution de la surcharge/charge de communication de notre réseau FiWi, car un plus grand nombre d'utilisateurs déplacent la charge de calcul des serveurs MEC vers leurs processeurs locaux.

Ensuite, nous explorons comment l'externalisation aide à réduire le temps d'achèvement des tâches physiques en cas de l'impuissance des TOR. Pour réaliser DAO dans un Internet tactile décentralisé, Ethereum peut être utilisé pour établir des sessions HO-TOR pour l'exécution de tâches physiques à distance, grâce auxquelles les contrats intelligents aident à établir/maintenir une adhésion HART de confiance et permettent à chaque membre HART d'avoir une connaissance globale de tous les HO participants, TOR, et les serveurs MEC qui agissent comme des agents autonomes. Nous supposons qu'un HO exécute à distance une tâche physique donnée jusqu'à ce que X% des échantillons de retour haptique les plus récemment reçus soient mal prévus. A ce stade, le HO arrête immédiatement la téléopération et informe l'agent. L'agent attribue la tâche interrompue à un humain à proximité (par exemple, un HO disponible) à proximité du TOR, qui se rend ensuite au point de tâche et finalise la tâche physique. La probabilité d'erreur de prévision donnée peut être quantifiée en calculant la moyenne à long terme du rapport entre le nombre d'échantillons soumis à une erreur de prévision et le nombre de ceux qui sont correctement prédits. La figure R.5 représente le temps moyen d'achèvement de la tâche par rapport à la probabilité d'erreur de prévision de l'échantillon pour différents temps de parcours $T_{traverse}$ de l'humain à proximité et un rapport différent des capacités opérationnelles humaines et robotiques $\frac{f_{human}}{f_{robot}}$, où f_{human} et f_{robot} désignent le nombre d'opérations par seconde qu'un humain et un robot sont capables d'effectuer, respectivement. Nous pouvons faire plusieurs observations à partir de la figure R5. De toute évidence, il est avantageux de sélectionner des humains avec un temps de parcours plus court, qui se trouvent être plus proches du TOR interrompu. Nous observons également que le ratio $\frac{f_{humain}}{f_{robot}}$ a un impact significatif sur le temps moyen de réalisation des tâches. Clairement, pour un ratio inférieur à 1 (c'est-à-dire 1/3), l'assistance humaine est moins utile puisqu'elle lui prend plus de temps pour accomplir la tâche physique. A l'inverse, pour un ratio égal à 1 (c'est-à-dire 3/3) et surtout supérieur à 1 (c'est-à-dire 5/3), le crowdsourcing est payant en utilisant les capacités opérationnelles supérieures de l'humain. Que les humains ou les robots soient mieux adaptés pour effectuer une tâche physique dépend certainement de sa nature. Cependant, pour une tâche physique donnée, une approche intéressante pour bénéficier de l'externalisation pour améliorer les capacités des humains inexpérimentés du DAO au moyen de contract incitatif comme expliqué ci-après.

Notre contrat de nudge vise à effectuer des tâches physiques interrompues en apprenant d'un membre DAO qualifié dans le but de minimiser la perte d'apprentissage, ce qui dénote la différence entre les temps d'exécution des tâches réalisables et optimales. Compte tenu de la récompense permise par le contrat de nudge et associée à chaque compétence transférée, un membre DAO qualifié à distance soumet une adresse de hachage contient des instructions d'apprentissage à un humain/robot non qualifié. L'adresse de hachage est stockée sur la chaîne de blocs, les données correspondantes des instructions d'apprentissage pouvant être stockées sur un serveur de stockage décentralisé distant, par exemple, Inter-Planetary File System (IPFS). Un humain/robot non qualifié peut récupérer les instructions d'apprentissage en utilisant l'adresse de hachage correspondante. La capacité d'apprendre une sous-tâche donnée est caractérisé par la probabilité d'apprentissage de la sous-tâche. Le processus d'apprentissage est accompli si chaque sous-tâche est apprise avec succès d'un membre DAO qualifié, qui à son tour est récompensé via un contrat intelligent. La figure R.6 montre la performance de notre contrat de nudge pour 50 membres de DAO, dont le ratio $\frac{f_{human}}{f_{robot}}$ est choisi au hasard parmi $\{1/3, 3/3, 5/3\}$. Nous observons que pour une probabilité d'apprentissage de sous-tâche donnée, diminuer le nombre N_{sub} de sous-tâches permet de réduire la perte d'apprentissage, indiquant ainsi l'importance d'une méthode de décomposition de tâche appropriée. Plus précisément, une sur-décomposition de la tâche donnée entraînera une détérioration des performances à moins qu'un mécanisme d'apprentissage approprié ne soit adopté pour augmenter la probabilité d'apprentissage de la sous-tâche.

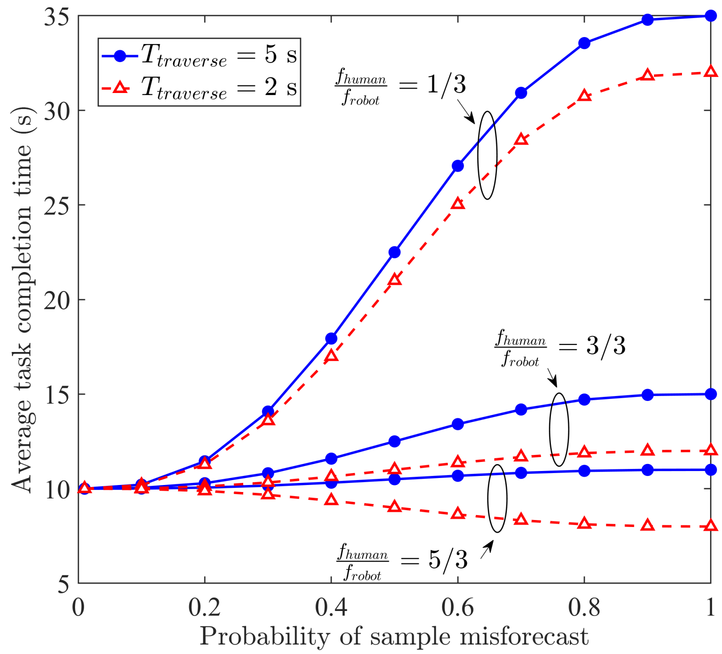

Figure R.5: Temps moyen d'achèvement de la tâche physique (en secondes) par rapport à la probabilité d'erreur de prévision de l'échantillon pour différents temps de parcours $T_{traverse} \in \{2, 5\}$ secondes de l'humain à proximité et avec les différents rapports des capacités opérationnelles humaines et robotiques $\frac{f_{humain}}{f_{robot}}$ (pour X=80% fixé).

La robonomie à l'ère de la 6G : jouer le jeu de la confiance avec des oracles en chaîne et des robots persuasifs

L'analyse de la confiance et de la réciprocité en économie comportementale part du constat que les gens n'aiment généralement pas voir des résultats inégaux. Les gens n'aiment pas être traités injustement et ils n'aiment pas non plus que les autres soient traités injustement. Si nous pensons que nous sommes traités injustement, nous sommes moins susceptibles de faire confiance et de rendre la pareille. L'interaction entre la confiance et la réciprocité est un élément clé dans de nombreuses activités coopératives et collaboratives que nous entreprenons chaque jour, du travail d'équipe collaboratif (par exemple, HART, DAO et le processus susmentionné de transfert de compétences entre les humains et les robots/humains dans le contexte de l'Internet tactile) à l'altruisme dont nous faisons preuve dans le don ou la charité. Dans ce travail, nous avons étudié des méthodes pour améliorer la confiance et la réciprocité entre les agents. À cette fin, nous nous sommes concentrés sur le jeu de confiance largement étudié dans l'économie comportementale, mais dans un contexte de chaîne de blocs. De plus, nous avons présenté une version en réseau du jeu de confiance, impliquant un tiers appelé observateurs, dont l'objectif principal était de décourager les comportements égoïstes. Les contrats intelligents et les oracles chaîne de blocs ont été utilisés dans le contexte de jeux de confiance classiques et en réseau. Nous avons démontré que la manière dont nos décisions économiques sont déterminées et renforcées peut être réalisée par une série de facteurs — en dehors de l'argent — y compris le mécanisme de dépôt en tant que pré-engagement et autocontrôle des agents et la présence d'influences sociales comme la pression des pairs par les observateurs et, plus intéressant encore, les robots sociaux persuasifs dans le domaine émergent de la robonomie. A notre

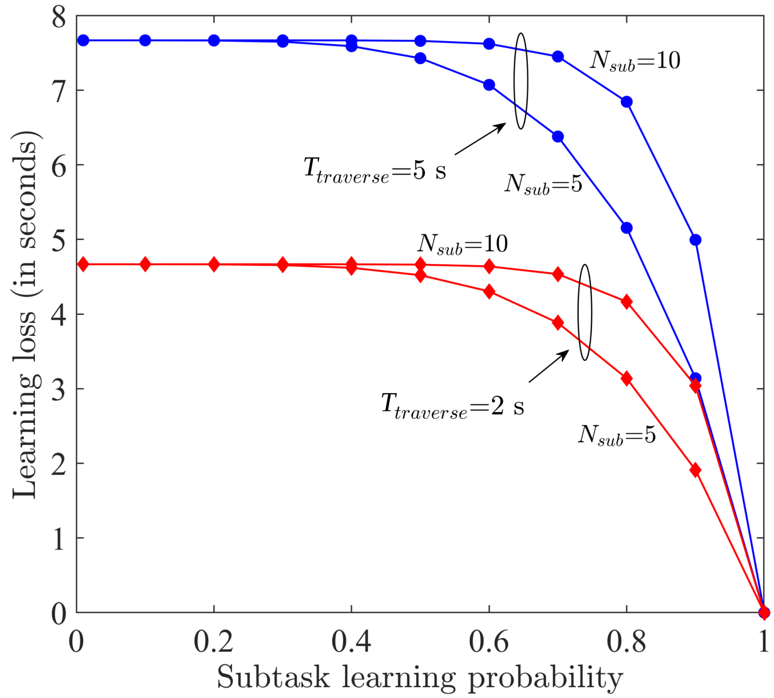

Figure R.6: Perte d'apprentissage (en secondes) par rapport à la probabilité d'apprentissage des sous-tâches pour un nombre différent de N_{sub} de sous-tâches et de temps de parcours $t_{traverse}$.

connaissance, ce travail a été le premier à mettre en œuvre des techniques de chaîne de blocs dans des jeux comportementaux et économiques tels que le jeu de confiance.

Une limitation majeure de la chaîne de blocs conventionnelle est son incapacité à interagir avec le monde extérieur puisque les contrats intelligents ne peuvent fonctionner que sur des données qui se trouvent sur la chaîne de blocs. Dans la chaîne de blocs émergente IdO (B-IdO), les capteurs sont généralement déployés pour amener les données de mesure des capteurs sur la chaîne de blocs. Les technologies avancées de chaîne de blocs permettent l'enchaînement d'informations hors chaîne externes à la chaîne de blocs provenant également d'utilisateurs réels, en dehors des capteurs et d'autres sources de données uniquement, tirant ainsi également parti de l'intelligence humaine. Pour surmonter cette limitation, les contrats intelligents peuvent utiliser ce qu'on appelle des oracles, qui sont des entités de chaîne de blocs de confiance dont la tâche principale est de collecter des informations hors chaîne et de les amener sur la chaîne de blocs en tant que données d'entrée fiables pour les contrats intelligents.

Le domaine émergent de la robonomie étudie l'impact sociotechnique des technologies chaîne de blocs sur l'interaction sociale homme-robot (sHRI) et l'économie comportementale, la théorie des jeux comportementaux et les crypto-monnaies (pièces et jetons) pour l'intégration sociale des robots dans la société humaine. Dans ce qui suit, nous nous concentrons sur le jeu de confiance classique, qui permet une étude plus systématique non seulement de la confiance et de la loyauté, mais aussi de la réciprocité entre les acteurs humains. Notons que le jeu de la confiance restera un instrument important pour l'étude du capital social et de sa relation avec la croissance économique pendant de nombreuses années à venir.

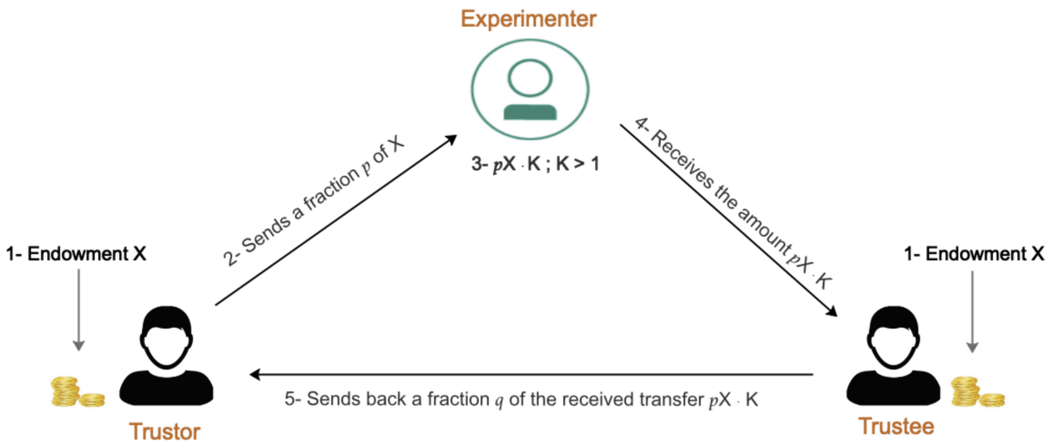

Figure R.7: Jeu de confiance classique impliquant deux joueurs humains (trustor et trustee) et un expérimentateur au milieu.

La figure R.7 illustre l'échange séquentiel entre le trustor et le trustee. Le trustor peut transférer une fraction $0 \leq p \leq 1$ de sa dotation au trustee. L'expérimentateur multiplie ensuite ce montant par un facteur $K > 1$, par exemple, 2 ou 3. Le trustee peut transférer une fraction $0 \leq q \leq 1$ du montant reçu directement au donneur de confiance sans passer par l'expérimentateur. Notons que le jeu de confiance capture tout échange économique générique entre deux acteurs. Nous avons développé une implémentation chaîne de blocs du jeu de confiance classique à l'aide d'Ethereum, dans laquelle l'expérimentateur placé entre l'administrateur et l'administrateur est remplacé par un contrat intelligent. De plus, nous avons ajouté un mécanisme de chaîne de blocs facultatif connu sous le nom de dépôt à notre contrat intelligent d'expérimentateur. Le dépôt est un mécanisme de chaîne de blocs de pré-engagement simple qui permet au trustee de soumettre un montant de $2 \leq D \leq X$ unités monétaires (Ether) en tant que dépôt au contrat intelligent de l'expérimentateur. Le dépôt n'est restitué au trustee que si une transaction avec $q > 0$ est complétée. Sinon, avec $q = 0$, le trustee perd le dépôt.

Nous avons étudié expérimentalement l'impact du dépôt sur les performances du jeu de confiance pour $K = 2$ et différentes valeurs de dépôt $D = 0, 2, 5, X$ Ether, où $D = 0$ dénote le jeu de confiance classique sans aucun dépôt. Au début de l'expérience, le trustor et le trustee ont reçu une dotation de $X = 10$ Ether. Nous avons exécuté l'expérience quatre fois, à chaque fois pour une valeur différente de D. Chacune des quatre expériences a duré cinq tours. A noter que pour l'expérience avec $D = 10$ Ether, le trustee a mis la totalité de sa dotation X dans le dépôt, donc $D = X$ Ether. Toutes les expériences ont été menées à travers Internet. Comme mesures d'intérêt, nous utilisons l'efficacité sociale et la réciprocité. L'efficacité sociale mesure la répartition optimale des ressources dans la société et est définie comme le rapport entre le gain total obtenu à la fois pour le trustor et le trustee et le gain maximal réalisable, qui est égal à $X(K + 1)$. Nous définissons la réciprocité normalisée comme le rapport q/p en tant que mesure de la réciprocité du trustee, q, en réponse à la générosité du trustor, p. Notez que la réciprocité normalisée est utile pour évaluer la répartition équitable des gains totaux de trustee au trustor, et vice versa, pour une efficacité sociale réalisable donnée.

La figure R.8 représente l'efficacité sociale moyenne et la réciprocité normalisée (tous deux donnés en pourcentage) par rapport au dépôt D (donné en Ether). Nous faisons les observations intéressantes suivantes à partir de la figure R.8. Premièrement, l'efficacité sociale augmente contin-

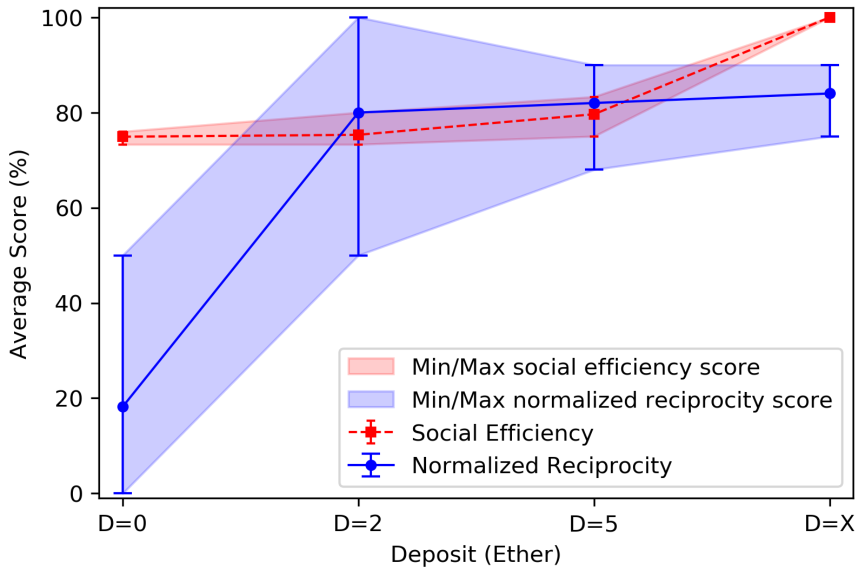

Figure R.8: Efficacité sociale moyenne et réciprocité normalisée q/p par rapport au dépôt $D = \{0, 2, 5, X\}$ Ether en utilisant un contrat intelligent d'expérimentateur avec $K = 2$ et $X = 10$ (montré avec des intervalles de score mesurés du minimum au maximum).

uellement pour un dépôt D croissant jusqu'à ce qu'elle atteigne le maximum de 100% pour $D = X$. Ainsi, la performance d'efficacité sociale du jeu de confiance classique peut être maximisée en appliquant correctement le mécanisme de dépôt de la chaîne de blocs avec $D = X$. Cela est dû au fait que le trustor envoie sa dotation complète (c'est-à-dire $p = 1$) après que le trustee a effectué son dépôt maximum. Ce faisant, un gain total maximum de 30 Ether est atteint, se traduisant par une efficacité sociale de 100%. Il vaut la peine de mentionner que cela a été le cas dans les cinq cycles de l'expérience. Deuxièmement, la réciprocité moyenne normalisée s'améliore significativement pour l'augmentation du dépôt D par rapport au jeu de confiance classique sans aucun dépôt ($D = 0$). Plus précisément, dans le jeu de confiance classique, la réciprocité normalisée moyenne est aussi faible que 18%. En revanche, pour un dépôt aussi faible que $D = 2$ Ether, la réciprocité moyenne normalisée s'élève à 80%. Il est intéressant de noter qu'une augmentation supplémentaire de D n'entraîne pas d'augmentations supplémentaires importantes, par exemple, la réciprocité normalisée moyenne est égale à 83% pour $D = X$. Par conséquent, le montant du dépôt ne modifie pas de manière significative la réciprocité normalisée avec q/p =80% pour $D > 0$. Enfin, la figure R.8 illustre que pour un dépôt D croissant, le comportement des deux joueurs devient plus cohérent, comme l'indiquent les intervalles décroissants des scores mesurés du minimum au maximum.

Ensuite, nous étendons le jeu de confiance classique à deux joueurs à un jeu de confiance en réseau à N joueurs, impliquant non seulement des joueurs humains mais aussi des oracles en chaîne. La figure R.9 illustre l'architecture de notre oracle en chaîne proposé pour le jeu de confiance en réseau à N-joueurs. L'architecture proposée comprend un ensemble de group. Chaque group contient trois types d'agents : (i) les trustors, (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 des critères de confiance et de fiabilité tels que l'investissement (p) et la réciprocité (q). Les observateurs fournissent leur intelligence humaine collective au contrat incitatif, un type spécifique de contrat intelligent utilisé pour donner du coude aux joueurs, afin de punir un group

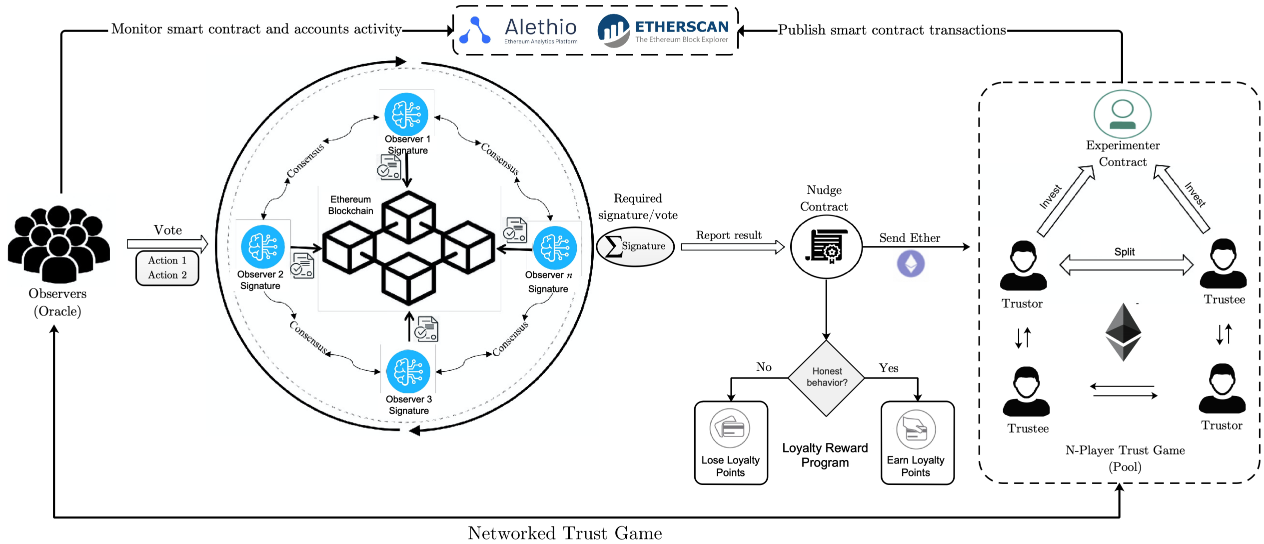

Figure R.9: Architecture d'oracle en chaîne pour le jeu de confiance en réseau de N-joueur.

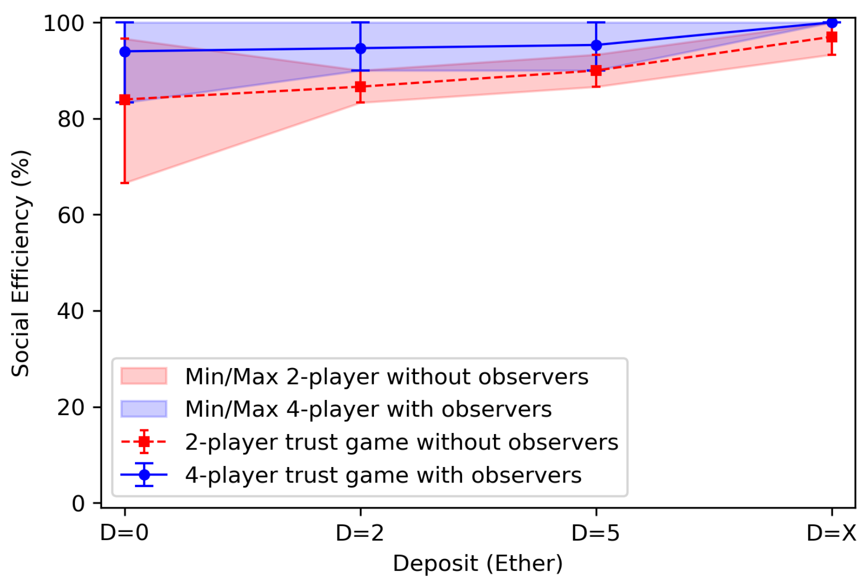

Figure R.10: Efficacité sociale moyenne par rapport au dépôt $D = \{0, 2, 5, X\}$ Ether pour un jeu de confiance à 2 joueurs sans observateurs et un jeu de confiance à 4 joueurs avec des observateurs (montré avec des intervalles de score mesurés du minimum au maximum).

ou un joueur individuel, qui démontre un comportement inapproprié, ou récompenser positivement un bon comportement.

La figure R.10 compare l'efficacité sociale moyenne du jeu de confiance à deux joueurs sans observateurs avec celle du jeu de confiance à quatre joueurs avec observateurs. La figure démontre clairement l'impact bénéfique de la présence d'observateurs sur l'efficacité sociale pour toutes les valeurs de D. A noter qu'avec les observateurs l'efficacité sociale instantanée atteint le maximum de 100% pour toutes les valeurs de D, par opposition au jeu de confiance à deux joueurs lorsque cela se produit nécessitant le dépôt complet de $D = X$ Ether. En ce qui concerne la réciprocité

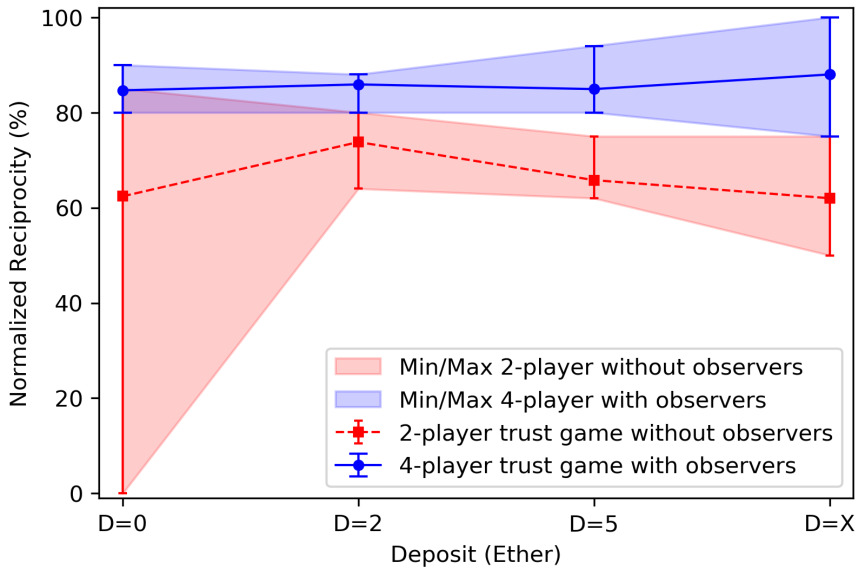

Figure R.11: Réciprocité normalisée moyenne q/p par rapport au dépôt $D = \{0, 2, 5, X\}$ Ether pour un jeu de confiance à 2 joueurs sans observateurs et un jeu de confiance à 4 joueurs avec observateurs (montré avec des intervalles de score mesurés du minimum au maximum).

normalisée réalisable avec et sans observateurs, les choses sont similaires, comme le montre la figure R.11. Cependant, bien que la présence d'observateurs contribue à élever la réciprocité normalisée moyenne (et instantanée) de manière constante au-dessus de 80% (par rapport à moins de 80% dans la figure R.8), il reste encore de la place pour de nouvelles améliorations, surtout pour $0 \leq D < X$.

En plus des oracles, les robots mobiles intelligents interagissant avec les utilisateurs humains apparaissent comme une solution prometteuse pour non seulement apporter une assistance physique et/ou émotionnelle, mais aussi pour inciter le comportement humain en bénéficiant de robots persuasifs. De nombreuses études ont montré que la présence physique de robots profite à une variété d'éléments d'interaction sociale tels que la persuasion, la sympathie et la fiabilité. Surtout, ces robots ressemblent moins à des outils qu'à des partenaires, dont le rôle de persuasion dans un environnement social est principalement centré sur l'humain.

Ensuite, nous avons exploré le domaine émergent de la robonomie à l'ère de la 6G. La robonomie étudie l'impact sociotechnique des technologies chaîne de blocs sur l'interaction sociale homme-robot (sHRI), l'économie comportementale, la théorie des jeux comportementaux et les crypto-monnaies (par exemple, Ether) pour l'intégration sociale des robots dans la société humaine. La robonomie implique une robotique persuasive, dans laquelle un agent robotique physique ou virtuel est utilisé comme exécuteur ou superviseur de la modification du comportement humain via des récompenses psychologiques en plus de récompenses tangibles.

Dans nos expériences, nous avons montré que les communications incorporées permises par des robots persuasifs contrôlés par des observateurs distants ont un impact social potentiellement plus important que les incitations monétaires telles que le dépôt. Plus précisément, nous avons développé une plate-forme Crowd-of-Oz (CoZ) pour permettre aux observateurs de contrôler à distance les gestes du robot social de Softbank Pepper placé devant le trustee et d'avoir un dialogue en temps réel via la technique de traduction de texte en parole. Notre interface CoZ affiche neuf boutons

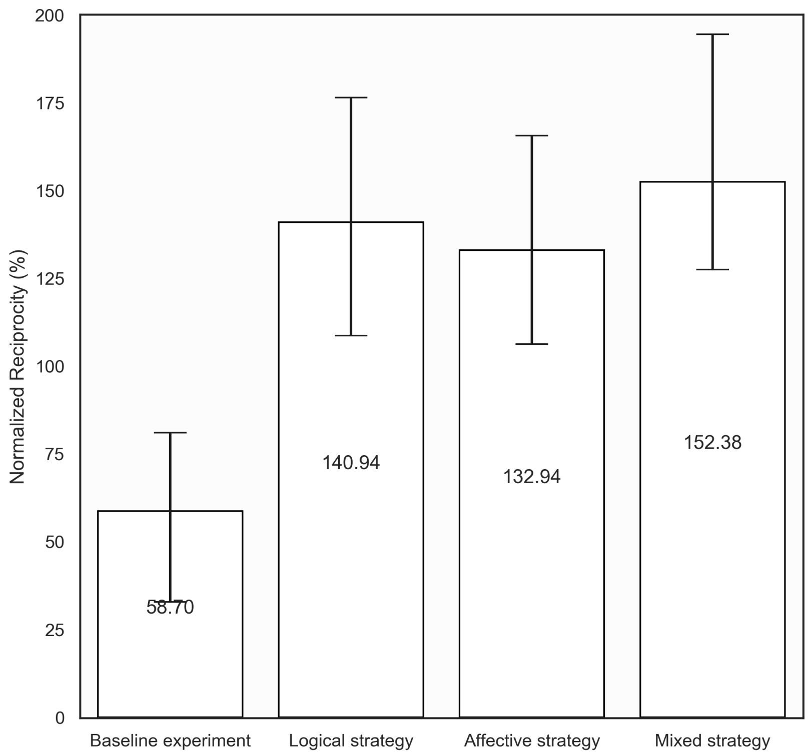

Figure R.12: Réciprocité normalisée moyenne q/p sans (expérience de base) et avec l'utilisation de stratégies de persuasion logiques, affectives et mixtes logique-affectives pour $D = 0$ (montré avec des intervalles de score mesurés minimum à maximum).

de repère social, sur lesquels les observateurs peuvent appuyer pour effectuer différents gestes de Pepper pendant la conversation et ainsi influencer le comportement de trustee. De plus, nous avons rédigé deux scripts, l'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 trustee. Chaque script contient des phrases prédéfinies stockées dans des menus déroulants dans l'interface CoZ, parmi lesquels les observateurs peuvent choisir afin de pousser le comportement de trustee vers la réciprocité via des messages texte-parole en temps réel. Nous avons ensuite mené des expériences à grande échelle impliquant 20 étudiants pour mesurer l'efficacité de notre plate-forme CoZ développée pour $D = 0$ (c'est-à-dire sans dépôt). À titre de comparaison, nous avons d'abord mené une expérience de base de jeu de confiance où les trustees n'interagissent pas avec Pepper, comme cela a été fait précédemment, suivie d'expériences exposant les trustees aux stratégies de persuasion logique, affective et mixte logique-affective de Pepper. La figure R.12 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 %.

Société 5.0 : Internet comme si les gens comptaient

Dans ce travail, nous nous sommes concentrés sur l'évolution des objets connectés sans fil vers l'intelligence collective (CI), qui joue un rôle central dans la vision 6G de rendre les futurs réseaux mobiles plus centrés sur l'humain que la 5G. À cette fin, nous avons adopté le concept unificateur de stigmergie, un mécanisme commun utilisé pour produire de la cognition dans le cerveau humain ainsi que dans les sociétés naturelles (par exemple, les insectes sociaux), pour faire progresser l'IC dans les futurs systèmes technico-sociaux auto-organisés connus sous le nom de systèmes cyber-physique-sociaux (CPSS) tels que l'Internet tactile et le futur Internet of No Things. Nous avons montré que le CPSS contribue à la réalisation de la vision centrée sur l'humain de la société 5.0. La société 5.0 envisage que les êtres humains interagissent de plus en plus avec les robots sociaux et l'IA incarnée dans leur vie quotidienne. Plus précisément, dans ce travail, nous avons proposé un environnement techno-social utilisant des technologies chaîne de blocs avancées pour les membres du CPSS, qui étend les capacités humaines et permet des activités vers le co-devenir humain en facilitant la communication indirecte via des jumeaux numériques tokenisés qui orientent le comportement collectif vers des niveaux plus élevés de CI dans une société améliorée par la stigmergie 5.0 et une future économie de jetons basée sur le Web3. De plus, nous avons démontré expérimentalement comment l'intelligence humaine collective d'une DAO peut être améliorée via des jetons axés sur l'objectif. De tels jetons à finalité ont contribué à faciliter la collaboration en incitant un groupe autonome de personnes à contribuer individuellement à un objectif collectif.

La quatrième révolution industrielle actuelle a été rendue possible grâce à l'IdO en association avec d'autres technologies émergentes, notamment les systèmes cyber-physiques (CPS). Les CPS aident à combler le fossé entre les technologies de fabrication et de l'information et à donner naissance à l'usine intelligente. Cette évolution technologique inaugure l'industrie 4.0 en tant que programme principal du plan d'action High-Tech Strategy 2020 pris par le gouvernement allemand, l'Internet industriel de General Electric aux états-Unis et l'Internet+ de la Chine. L'application de CPS dans les systèmes de production industrielle conduit à des systèmes de production cyber-physiques (CPPS), où les installations de production échangent des informations de manière autonome, agissent et se contrôlent indépendamment via des réseaux flexibles au moyen de communication de machine à machine (M2M). Les usines intelligentes sous l'industrie 4.0 présentent plusieurs avantages, tels qu'une gestion optimale des ressources, mais impliquent également une intervention humaine minimale dans la fabrication.

La philosophie derrière l'industrie 4.0 peut être considérée comme ce que l'on appelle la fabrication et la production sans éclairage, où les usines sont entièrement automatisées et ne nécessitent aucune présence humaine sur site. Par conséquent, ces usines peuvent fonctionner avec les lumières éteintes. Une philosophie complémentaire, plus centrée sur l'humain, qui met les humains dans la boucle de la CPS est la soi-disant initiative la société 5.0 du 5e Plan de base pour la science et la technologie pris par le gouvernement du Japon. Semblable à l'industrie 4.0, la société 5.0 fusionne l'espace physique et le cyberespace en tirant pleinement parti des technologies d'information et de communication (TIC) en appliquant non seulement des robots sociaux et une IA incarnée, mais également des technologies émergentes telles que l'intelligence ambiante et la réalité virtuelle/augmentée (V/AR). Cependant, la société 5.0 contrebalance l'accent commercial de l'industrie 4.0. Si le paradigme de l'industrie 4.0 est compris comme se concentrant sur la création de l'usine intelligente, la société 5.0 est orientée vers la création de la première société super-intelligente au monde.

L'objectif de la société 5.0 n'est rien de moins que la création d'opportunités égales pour tous et également de fournir l'environnement pour la réalisation du potentiel de chaque individu. À cette fin, la société 5.0 utilisera des technologies émergentes pour éliminer les obstacles physiques, administratifs et sociaux à la réalisation de soi de la personne. Lorsque les êtres humains sont fonctionnellement intégrés dans un CPS aux niveaux social, cognitif et physique, il devient un

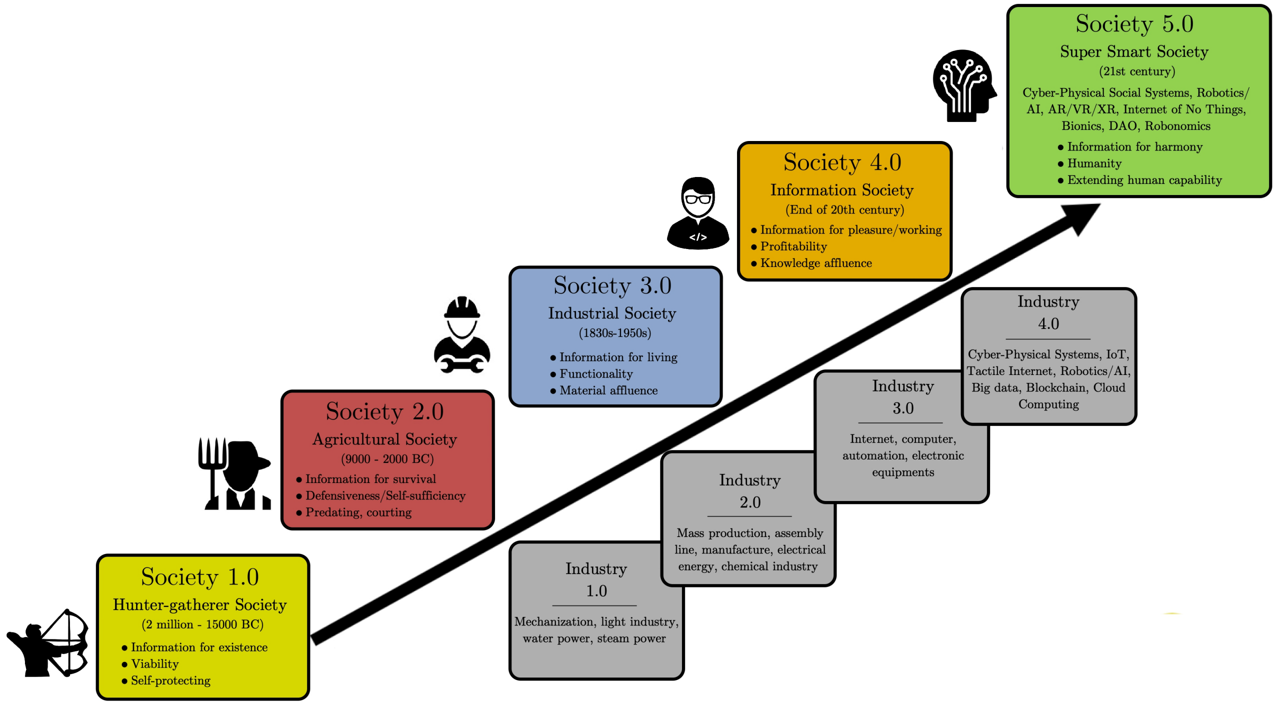

Figure R.13: Co-évolution de la société et de l'industrie vers la société 5.0 [100, 101, 102].

CPSS dont les membres peuvent s'engager dans des comportements cyber-physiques-sociaux qui permettent éventuellement à des êtres métahumains de types divers. de capacités surhumaines. L'inclusion dans la société 5.0 de diverses entités non humaines - notamment des robots sociaux et des agents d'IA - en tant que participants n'a rien de nouveau, mais plutôt quelque chose d'assez ancien, un retour à l'imprévisibilité, à la sauvagerie et aux rencontres continuelles avec l'autre qui caractérisaient les sociétés 1.0 et 2.0, grâce à la prévalence d'agences non humaines diverses résultant d'une forte dépendance à l'égard des animaux en tant qu'acteurs clés de la société et de la dimension religieuse et spirituelle des sociétés. A titre d'illustration, la figure R.13 montre les principales différences entre les différents types de société et leur co-évolution avec l'industrie de la société 1.0 à la société 5.0.

Ensuite, nous nous concentrons sur le problème important de l'ingénierie des jetons, qui est un terme émergent défini comme la théorie, la pratique et les outils pour analyser, concevoir et vérifier les écosystèmes à jetons. Cela implique la conception d'un cadre d'ingénierie de jetons ainsi que la conception de mécanismes adéquats pour résoudre les problèmes des jetons axés sur un objectif. Ces derniers incitent le comportement individuel à contribuer à un certain objectif ou à une idée d'un objectif collectif. Cet objectif collectif peut être un bien public ou la réduction des externalités négatives vers un bien commun, par exemple la réduction des émissions de CO_2. Les jetons à finalité introduisent une nouvelle forme de création de biens publics. Les réseaux de chaîne de blocs tels que Ethereum ont fait passer l'idée de création de valeur collective en fournissant une infrastructure publique pour la création d'un jeton d'application avec seulement quelques lignes de code de contrat intelligent, selon lequel, en principe, tout objectif peut être incité via des mécanismes de conception de jetons appropriés. Notez que la conception de mécanismes est un sous-domaine de l'économie qui traite de la question de savoir comment inciter tout le monde à contribuer à un objectif collectif.

Elle est également appelée théorie des jeux inversée car elle commence à la fin du jeu (c'est-à-dire sa sortie souhaitable) puis revient en arrière lors de la conception du mécanisme (d'incitation).

La figure R.14 illustre notre proposition de cadre DAO d'ingénierie de jetons multicouches pour Society 5.0 qui s'appuie sur des CPSS avancés tels que le futur Internet of No Things. Au-dessus de la couche technologique de base, il existe la couche d'opération de gouvernance. De manière générale, cette couche encode le consensus via des contrats intelligents (par exemple, le vote) et réalise l'auto-gouvernance du DAO grâce à la collaboration en chaîne et hors chaîne (oracle en chaîne). En outre, cette couche comprend des mécanismes de nudge via un contrat intelligent (contrat de nudge), une prise de décision collective et un partage des connaissances entre ses membres. La couche de mécanisme d'incitation couvre les techniques liées aux jetons susmentionnées et leur alignement approprié pour faciliter l'ingénierie des jetons. Ensuite, la couche de formulaire d'organisation comprend le processus de vote et l'adhésion pendant le cycle de vie d'un projet DAO proposé. Notez qu'en économie, les biens publics assortis de droits d'accès réglementés (par exemple, l'adhésion) sont appelés biens de club. Enfin, la couche de manifestation permet aux membres de prendre des actions simples et localement indépendantes qui, ensemble, conduisent à l'émergence d'un comportement de système adaptatif complexe du DAO et de la société 5.0 dans son ensemble. La figure R.15 illustre la transition de notre CPSS de choix vers une société améliorée par la stigmergie 5.0 en utilisant l'environnement en ligne basé sur les technologies avancées de chaîne de blocs Ethereum et impliquant différents types d'agents hors ligne (robot social, IA incarnée, humain). Ces agents hors ligne sont tous membres du DAO.

Une définition générale de l'intelligence humaine est le taux de réussite de l'accomplissement des tâches. Dans notre implémentation, les tâches d'intelligence humaine (HIT) sont réalisées en exploitant la base de données d'images ImageNet 2 largement utilisée dans la recherche en apprentissage profond et en la jotenisant. Plus précisément, les humains sont censés découvrir une carte de récompense cachée constituée de jetons ciblés au moyen d'un marquage d'image, qui se fait en s'appuyant sur l'intelligence et l'externalisation des travailleurs d'Amazon Mechanical Turk (MTurk) et la validation de leurs réponses via un oracle de chaîne de blocs de prise de décision basée sur le vote. Nous mesurons l'IC comme le rapport entre le nombre découvert/récompensé et le nombre total de jetons axés sur un objectif. Nous avons développé une plate-forme HIT basée sur JavaScript pour permettre à un humain de sélectionner parmi 20 images ImageNet ainsi que d'ajouter des informations de marquage d'image pertinentes et de fournir à la fois aux comptes MTurk et Amazon Web Services (AWS) correctement configurés à l'aide d'un intergiciel OOCSI. Les réponses fournies par les travailleurs de MTurk à chaque HIT soumis ont été évaluées par un oracle en chaîne, qui a utilisé des jetons de droit d'accès conformes à l'ERC-20 pour réguler le processus de vote et libérer les jetons à finalité attribués à chaque image étiquetée avec succès. Enfin, l'humain laisse les jetons découverts/récompensés sous forme de traces stigmergiques sur la chaîne de blocs pour aider les membres DAO participants à mettre à jour leurs connaissances sur la carte de récompense et à poursuivre son exploration.

La figure R.16 montre l'impact bénéfique de la stigmergie à la fois sur l'intelligence collective et la récompense interne en termes de jetons cachés découverts dans la carte de récompense par une DAO de 8 membres. À titre de comparaison, la figure montre également nos résultats expérimentaux sans stigmatisation, où les membres du DAO ne bénéficient pas du partage des connaissances sur le processus de découverte de la carte de récompense en cours.

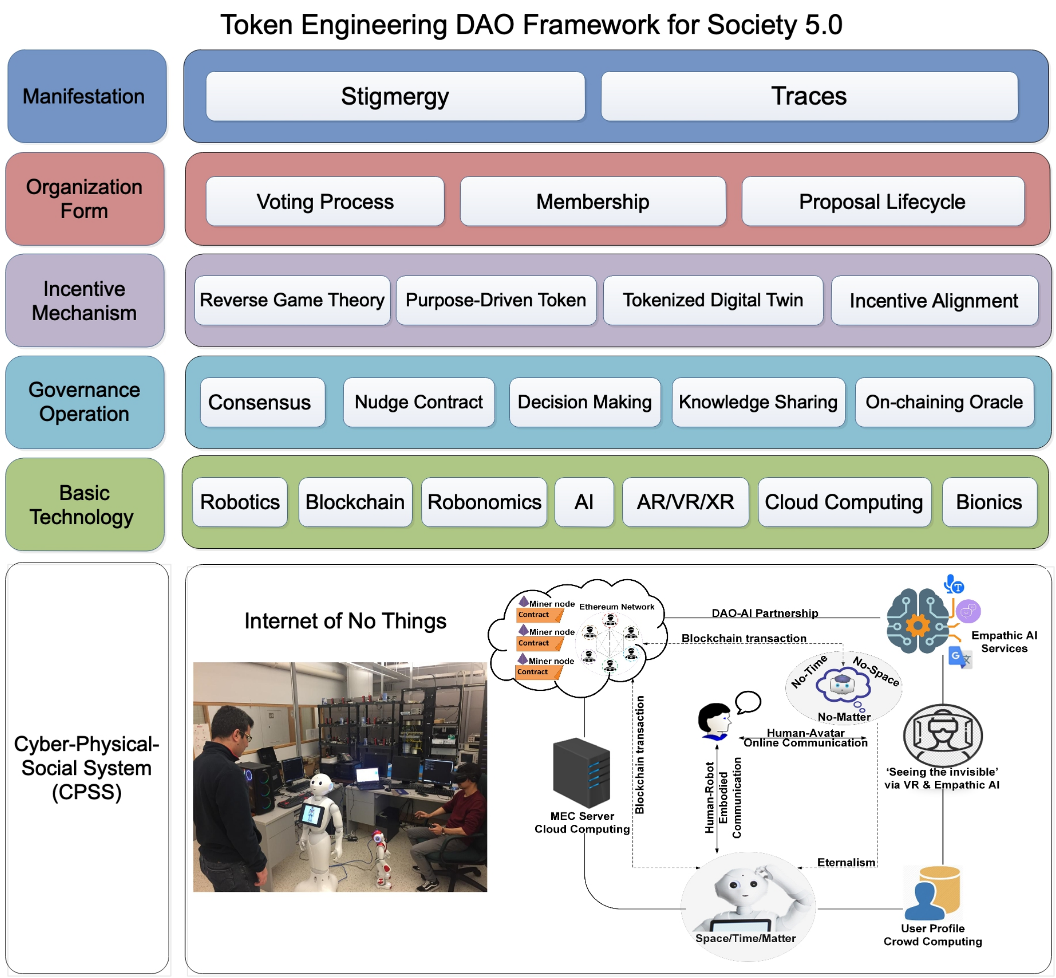

Figure R.14: Framework DAO d'ingénierie de jetons ascendant basé sur CPSS pour la Société 5.0.

Conclusion

La révolution de la chaîne de blocs est sur le point de renverser le statu quo des systèmes centralisés dans la plupart des industries en faveur d'infrastructures plus décentralisées, transparentes, ouvertes, sécurisées et efficaces. Alors que la plupart des gens considèrent la chaîne de blocs d'un point de vue transactionnel, il existe encore de nombreux aspects saillants d'une véritable chaîne de blocs auxquels les gens n'ont pas prêté une attention particulière. Ces facettes, cependant, sont responsables de la nature de la technologie telle que nous la connaissons et de la raison pour laquelle elle est sur le point de révolutionner la façon dont les gens traitent avec les autres dans un avenir proche et lointain. La chaîne de blocs transforme ce que nous pouvons faire en ligne, comment nous le faisons et qui peut participer.

Cette thèse de doctorat a examiné la conception et l'investigation des piliers des technologies chaîne de blocs centrées sur l'humain pour l'ère 6G. La thèse est basée sur la chaîne de blocs Ethereum en tant que technologie sous-jacente prometteuse centrées sur l'humain sur lesquelles l'ère 6G est censée s'appuyer. En particulier, nous avons montré au début que de nombreuses études émergentes sur le B-IdO utilisent Ethereum comme chaîne de blocs de choix et appliquent

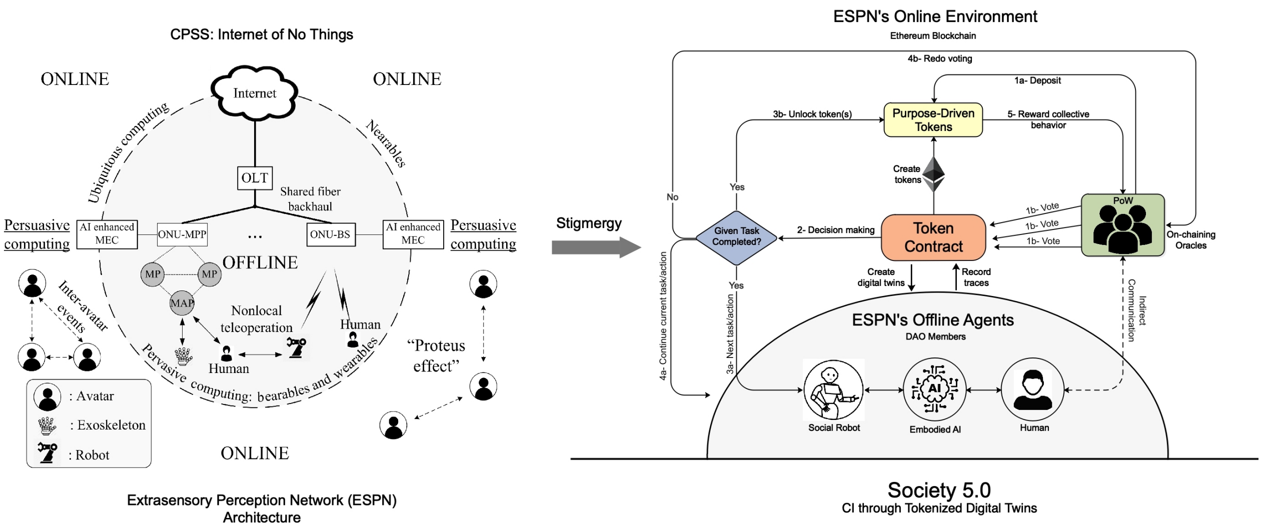

Figure R.15: Société 5.0 amélioré par la stigmergie en utilisant des jumeaux numériques jotenisés pour faire progresser l'intelligence collective (IC) dans le CPSS.

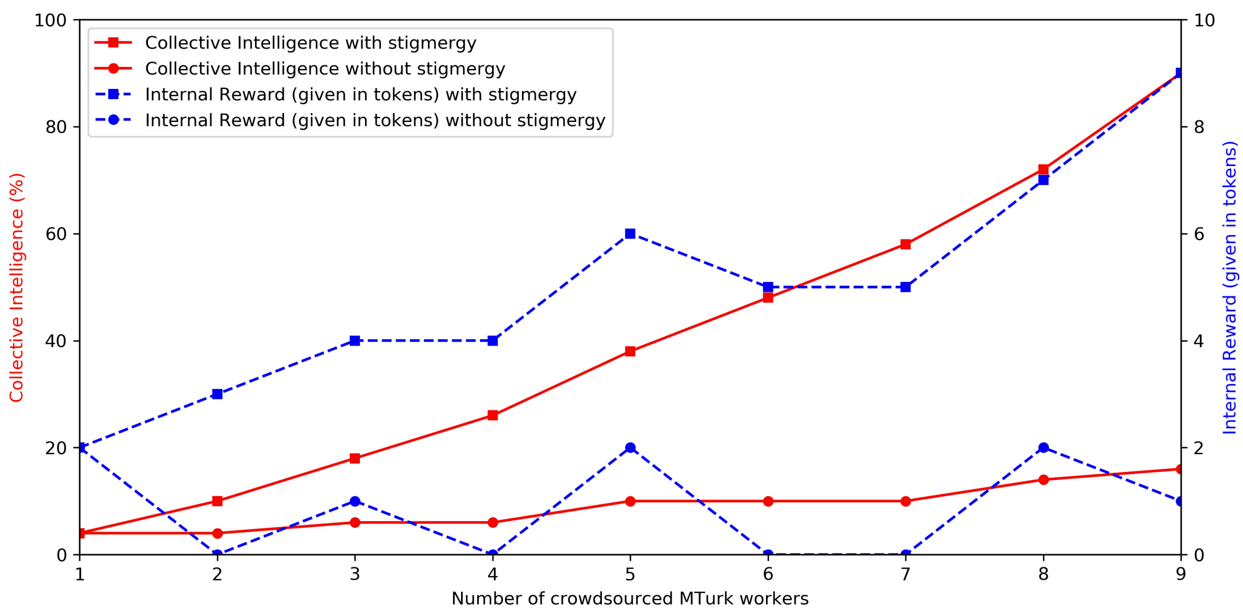

Figure R.16: Intelligence collective (donnée en pourcentage) et récompense interne (donnée en jetons) avec et sans stigmatisation par rapport au nombre de travailleurs Amazon MTurk externalisés.

une approche de conception orientée passerelle pour décharger les tâches de calcul intensives des périphériques finaux à ressources limitées sur un intermédiaire passerelle, leur permettant ainsi d'accéder au réseau chaîne de blocs Ethereum. À cette fin, nous avons d'abord expliqué les points communs et les différences spécifiques entre les chaîne de blocss Ethereum et Bitcoin, suivis d'une description technique plus détaillée du DAO. Nous avons ensuite discuté de la motivation pour l'intégration de la chaîne de blocs et de l'IdO (B-IdO) suivi d'une description des défis de l'intégration de la chaîne de blocs et l'informatique de périphérie. Sur la base de nos récents travaux sur l'Internet tactile et l'orchestration des coactivités HART hybrides, nous avons présenté notre proposition de réseaux HetNet LTE-A améliorés FiWi à faible latence basés sur MEC avancé avec des capacités d'IA intégrées. Nous avons ensuite montré que les serveurs MEC décentralisée améliorée par l'IA sont efficaces pour réduire le temps d'achèvement des tâches de calcul. En outre, pour l'exécution à distance de tâches physiques dans un Internet tactile décentralisé, nous avons exploré comment la DAO et les contrats intelligents d'Ethereum peuvent être utilisés pour établir une adhésion HART de confiance et comment le crowdsourcing humain aide à réduire le temps d'achèvement des tâches physiques en cas de prévision non fiable des échantillons de retour haptique à partir de robots téléopérés. Nous avons décrit les futures pistes de recherche sur la convergence technologique afin d'accomplir avec succès des tâches hybrides machine + humaine par une intelligence augmentée et partagée exploitant la théorie du nudge, un nouveau développement récent dans le concept d'économie comportementale popularisé par Richard H. Thaler, le lauréat du prix Nobel 2017 en économie. Ensuite, nous avons exploré comment les technologies chaîne de blocs d'Ethereum, en particulier le concept susmentionné de DAO, peuvent être exploitées pour décentraliser l'Internet tactile, qui permet des applications mobiles sans précédent pour piloter à distance des objets/processus réels ou virtuels en temps réel perçu et représente un exemple prometteur de futurs systèmes technico-sociaux. Nous avons montré qu'un niveau plus élevé de décentralisation du MEC amélioré par l'IA réduit le temps moyen d'achèvement des tâches de calcul jusqu'à 89,5% en définissant la probabilité de déchargement des calculs sur 0,7. De plus, nous avons observé que le crowdsourcing de l'assistance humaine est bénéfique pour réduire le temps d'achèvement moyen des tâches physiques pour des probabilités d'erreur de prévision de rétroaction moyennes à élevées, à condition que l'humain offre des capacités opérationnelles égales ou même supérieures, c'est-à-dire $\frac{f_{human}}{f_{robot}} \geq 1$. À cette fin, nous avons proposé un contrat de nudge comme technique pour influencer le comportement humain à proximité sans punition pour le transfert de compétences dans le contexte de l'Internet tactile. Plus précisément, le contrat nudge vise à permettre le processus de transfert de compétences ainsi qu'une récompense au moyen du contrat intelligent Ethereum. Nous avons ensuite montré que le contrat de nudge envisagé aide à accomplir avec succès des tâches via une intelligence partagée entre des robots défaillants et des humains qualifiés. En outre, nous avons couvert certaines des façons dont nos décisions sont affectées par les influences sociales et le comportement et l'attitude d'autres personnes. À cette fin, nous avons étudié le jeu de confiance largement utilisé dans l'économie comportementale dans un contexte de chaîne de blocs. Outre la conception d'un jeu de confiance décentralisé sans avoir besoin de l'expérimentateur au milieu entre les joueurs, nous avons présenté un mécanisme simple mais efficace de dépôt basé sur la chaîne de blocs comme un pré-engagement entre les joueurs. En utilisant ce mécanisme, nous avons démontré expérimentalement qu'une efficacité sociale allant jusqu'à 100% peut être atteinte pour améliorer à la fois la confiance et la loyauté entre les acteurs (et donc l'investissement et la réciprocité). De plus, nous avons présenté une architecture d'oracle chaîne de blocs basée sur le vote pour un jeu de confiance en réseau de N-joueur qui implique un troisième type de joueur appelé observateurs, dont l'objectif principal est d'observer, de suivre et de récompenser/punir le comportement des joueurs en fonction de leur investissement et de leur réciprocité. La pression des pairs par l'oracle en chaîne aide à augmenter la réciprocité normalisée moyenne au-dessus de 80%. Enfin, nous avons démontré expérimentalement que les joueurs sont plus susceptibles de donner plus lorsque leur générosité est rendue publique et encouragée par les robots sociaux, notamment en tirant parti des stratégies de persuasion mixtes logique-affective pour les robots sociaux du domaine émergent de la robonomie. Finalement, nous avons élaboré que la 6G différera de la 5G de plusieurs manières. La 6G explorera non seulement plus de spectre dans les bandes haute fréquence, mais convergera également vers les tendances technologiques motrices, y compris la robotique connectée et les technologies chaîne de blocs. Surtout, nous avons montré que la 6G deviendra plus centrée sur l'humain que la 5G, qui se concentrait principalement sur les secteurs verticaux. Placer les personnes au centre d'une future société super-intelligente est le thème moteur du changement d'orientation prévu de la recherche de l'industrie 4.0 à la société 5.0

basée sur le CPSS, qui intègre les êtres humains aux niveaux social, cognitif et physique. Plus précisément, nous nous concentrons sur le changement de paradigme des économies monétaires conventionnelles vers les futures économies non monétaires, telles que notre économie de jetons Web3 basée sur la chaîne de blocs et son rôle important dans la DAO. À cette fin, nous avons présenté notre cadre DAO d'ingénierie de jetons basé sur CPSS pour la société 5.0. Compte tenu de sa similitude avec la technologie chaîne de blocs décentralisée, nous avons adopté la stigmergie — un mécanisme d'auto-organisation biologique largement répandu dans les sociétés sociales d'insectes — pour faciliter la communication indirecte et la coordination interne entre les agents hors ligne via des traces (boucles de rétroaction) créées dans un environnement en ligne basé sur la chaîne de blocs. Plus particulièrement, nous avons étudié la communication indirecte médiée par des jumeaux numériques jotenisés pour faire progresser l'intelligence collective dans une future société 5.0 et un Web3 basé sur l'économie symbolique. Enfin, nous avons montré expérimentalement comment augmenter à la fois l'intelligence collective et les jetons récompensés au moyen de traces stigmergiques dans un environnement en ligne basé sur la chaîne de blocs impliquant des travailleurs Amazon MTurk externalisés et un oracle en chaîne.