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RESEARCH ARTICLE

Blockchain-Empowered Service Management for the Decentralized Metaverse of Things

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ABSTRACT The future of networking will be driven by the current emerging trends of combining the physical and virtual realities in cyberspace. Considering the ambient pandemic challenges, the role of virtual and augmented reality will definitely grow over time by transforming into the paradigm of the Metaverse of Things, where each person, thing or other entity will simultaneously exist within multiple synchronized realities. In this paper, we propose a novel framework for future metaverse applications composed of multiple synchronized data flows from multiple operators through multiple wearable devices and with different quality requirements. A new service quality model is proposed based on a customizable utility function for each individual data flow. The proposed approach is based on dynamic fine-grained data flow allocation and service selection using non-fungible tokens, which can be traded over the blockchain among users and operators in a decentralized mobile network environment.

INDEX TERMS Blockchain, metaverse, the IoT, NFT, 5G/6G.

I. INTRODUCTION

Evolution of the Internet of Things (IoT), artificial intelligence (AI), virtual and augmented reality (VR/AR) and 5G technologies is currently gaining increasing interest from different industrial verticals.

The IoT has completely changed the landscape of modern information and communication systems by enabling a bridge between the real and the digital world. This is achieved by providing the communication interface to low-cost devices, which interact with the physical objects or environment. Thus, the IoT creates a highly automated environment driven by the application of various AI algorithms with collaborative and smart-interconnected sensors and actuators.

One of the most appealing trends currently is the development of a metaverse. A metaverse is the evolution of AR/VR technologies toward interconnected virtual worlds [1]. Metaverses are developed based on the most advanced means of visualization, sensing and wireless communications. In addition, metaverse leverages the latest achievements of AI and blockchain technologies to achieve a truly immersive user experience with synchronized realities [2], [3]. Currently, metaverses are limited mostly to virtual worlds, where users can be engaged only through the VR headset and purchase

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virtual items as unique non-fungible tokens (NFTs). However, in the foreseeable future, a VR-based metaverse is expected to converge with AR glasses, wearable devices and existing IoT infrastructure to synchronize virtual and physical realities.

Therefore, considering the future combination of metaverse and IoT, we can expect that soon AR/VR glasses, earphones, watches and haptic sensors will be able to operate as a decentralized "smartphone" for the metaverse, which will enable immersive user engagement in a rich set of applications by all available human senses and personal metadata.

We call this concept a Metaverse of Things (MoT), which is composed of real people or things and their corresponding digital twins, which are synchronized across virtual and physical realities.

To achieve a real-time interactive high-resolution rendering of 3D worlds and objects, a huge data volume must be transmitted in real-time. Thus, MoT will impose more stringent requirements on the underlying 5G/6G mobile network infrastructure [4]. In addition, it is also clear that conventional service models, which were initially designed for smartphones and current mobile network operators (MNOs), will not be effective for the new types of user equipment (UEs). Hence, the most important challenge will be to transmit large amounts of data through the mobile network infrastructure and ensure that the *end user will be able to transmit or receive these data simultaneously over multiple parallel data flows through all of the UEs and with different QoS (Quality of Service) parameters*. For example, wearable devices can provide low-throughput sensory data to transmit the precise movements and gestures of the user, while AR/VR devices will receive the corresponding high-throughput 3D video stream rendered according to the corresponding user movements. Such functionality will provide a completely new user experience for various industries, such as remote surgeries, holographic telepresence, machinery maintenance, autonomous driving, etc. [5].

In this paper, we address the aforementioned problem by developing a multi-flow synchronized service provision for future MoT applications. The key idea is to slice the application in cyberspace, splitting the whole data flow into separate subflows. All subflows are independent and can be transmitted by different MNOs to various UEs and with a variety of QoS requirements while being orchestrated at the application layer. To ensure precise synchronization of the data flows and strict end-to-end QoS guarantees, we use unique NFTs for each application and each separate data flow, which are managed by smart contracts among UEs and MNOs based on the underlying blockchain infrastructure.

To the best of our knowledge, there are currently no research works that address the problem of decentralized quality of experience (QoE) management for applications composed of multiple data flows, which are transmitted by different MNOs and to various UEs. In addition, there are no works that consider the decentralized resource allocation in mobile networks by using NFTs as the tradable representation of network resources in the blockchain.

Thus, the main contributions of this article are as follows:

1) We propose a novel multi-flow synchronized service provisioning based on NFTs and blockchain for metaverse and IoT applications.
2) We propose a new service management model for decentralized multi-flow applications that allows us to derive the unique QoS metric for each individual data flow.
3) We propose a new method of dynamic multi-flow service selection for the decentralized multioperator network environment.

The remainder of this paper is organized as follows. Section II provides an overview of the key enablers of the MoT. Section III describes the system model and the proposed approach in detail. Section IV covers the simulation results and the discussion. Section V concludes the paper.

II. KEY ENABLERS FOR THE METAVERSE OF THINGS

In this section, we review the key technological trends, which are essential blocks for the MoT concept, such as IoT, digital twins, blockchain, AI, 6G, AR/VR, etc.

A. SERVICE MANAGEMENT IN 5G AND BEYOND MOBILE NETWORKS

To meet the stringent criteria posed on the reliability and latency of IoT applications in a fast-evolving environment, 5G networks represent the key technological aspect to be addressed jointly with various application use cases, including enhanced mobile broadband (eMBB), massive machine type communication (mMTC), ultra-reliable communication and low latency communication (URLLC). These 5G-oriented services will greatly enhance the efficiency and flexibility of intelligent systems by replacing the traditional cable setups and simplifying the digital transformation process [11].

The preliminary results delivered in [11] investigate the impact of different radio configurations at the physical and media-access control layers, which provides an important conclusion that the dedicated reserved bandwidth for the eMBB and URLLC use cases in industrial applications can strongly impact the effectiveness of the services in terms of the throughput and latency. Next, the authors in [12] proposed simultaneous support of eMBB and URRLC services via an explicit prioritization method, which allows perfect isolation and stable performance characteristics for URLLC-based industrial applications even in a dynamically changing environment, while eMBB traffic with slightly weaker requirements would experience dynamic transitions in terms of application performance.

Finally, some concluding remarks regarding the eMBB and URLLC performance in the isolated scenarios of 5G IIoT applications were comprehensively described in [13]. Applications of IIoT allowed real-time monitoring by

TABLE 1. Overview of the of existing service management solutions for 5G, Metaverse and IoT applications.

Reference	MoT components				
	IoT-IoS	5G-6G SLA	Metaverse	Blockchain	NFT
[6]–[10]	•				
[11]–[21]		•			
[4], [6], [8], [10], [13], [22]	•	•			
[1]–[3], [23], [24]			•	•	
[5], [25]	•		•	•	
[4], [6], [8], [10], [13], [22]	•	•			
[26]–[34]				•	
[35], [36]		•		•	
[37]–[41]	•	•		•	
[7], [30], [31], [33], [42]	•			•	
[43]–[45]					•
[46], [47]			•		•
Proposed framework	•	•	•	•	•

automated advanced control technologies in the manufacturing process [22]. For example, industrial services covered within the concept of Industry 5.0 already use some form of telemetry or remote support to enhance the key performance indicators (KPIs) [4], [14].

Currently, most of the services rely on the cloud and edge computing infrastructure to orchestrate service instances in cost-effective way. Such an approach enables the automation and softwarization of the service provisioning process. For example, in [15], authors propose an automation solution for vertical services provisioning and hierarchical Service Level Agreement (SLA) management. Authors consider three different scaling levels for applications, services and resources, respectively. Proposed solution is proven to be effective for both mission-critical and entertainment services. The partially decentralized approach for 5G service management is proposed in [16], where authors have developed a software-defined network with logically centralized but physically distributed controller to improve the QoS in 5G network.

Another way to differentiate QoS/QoE parameters in mobile networks is the network slicing. In [17] authors propose a hierarchical RAN slicing framework, which takes into account network level slicing, gNB level slicing and packet scheduling slicing. Proposed approach provides a fine-grained adjustment of network resources to achieve more effective service management.

There are many other solutions for SLA and QoS management in 5G mobile networks, which are summarized in Table 1. It should be noted, however, that these solutions assume homogeneous QoS per each application, and thus, no multi-flow service provision was considered in the works presented above.

B. INTERNET OF SKILLS IN A METAVERSE

With recent advancements related to 5G network deployments, the Internet of Skills (IoS) has received increasing attention as a solution for the delivery of physical skills across the globe over the internet.

Most notably, the IoS concept takes advantage of the fruitful fusion of recent advancements in the wireless communication industry represented by the 5G-enabled tactile internet, AI and robotics, creating new business opportunities for verticals in industries, such as healthcare and industrial remote engineering [6], [7]. The tactile internet can support most MoT applications by providing an ultra-reliable network with extremely low service latency [8]. Low latency is vital for applications, such as self-driving vehicles, AI-assisted smart medical devices, and manufacturing robots, where milliseconds can literally prevent disasters. These stringent requirements can be satisfied by deploying local 5G/6G networks with edge computing capabilities located therein [9]. To unleash the full potential of the Internet of Skills concept in the MoT environment, we need to extend the traditional concept of the tactile internet with haptic communications providing immersive user engagement by enriching the sensory experience in many critical aspects of industries [10]. Thus, the underlying idea of the IoS is naturally aligned with our proposed MoT concept.

It is clear that synchronization between physical and virtual worlds will heavily rely on the use of AI-based data processing algorithms to render the corresponding views and generate control commands in both directions. Therefore, security and robustness to external attack will be one of the important challenges for the MoT in the future [25].

A typical use case where the IoS can be applied with the MoT is a remote driving scenario, where an unmanned car is controlled over multiple parallel data flows, and including high-quality video streaming from and on-board cameras to VR headset, ultra-low latency data flows for the various sensory telemetry and ultra-low latency data flows for remote control by a steering wheel and pedals. Similar applications can be found in other areas, such as remote surgery, machinery maintenance, and entertainment.

C. BLOCKCHAIN-EMPOWERED METAVERSE OF THINGS

To synchronize the physical and virtual reality, the MoT system should be decentralized by its nature. Therefore, blockchain technology is considered one of the key enablers of the proposed concept. Blockchain can be an effective solution for decentralized and secure content sharing in MoT by leveraging the distributed ledger validated by the inner consensus algorithm.

Initially, blockchain was perceived as the mechanism for storing financial data and as the intermediary for various financial transactions. However, now we witness the trend of shifting it toward other domains, including the IoT environment, such as for healthcare services with support of Internet of Skills [26], automated manufacturing processes [27], secure data aggregation [28], mixed reality content sharing [29], COVID pandemic monitoring [30], etc.

Apart from the aforementioned scenarios, blockchain is particularly interesting for the decentralized SLA management in 5G/6G mobile network, which is needed for the MoT applications. The key requirement of the MoT is the flexible SLA policies, with dynamic pricing, continuous monitoring and control of the obligations without the third-party. Such framework has been proposed in [37], where authors proposed a framework to monitor SLA terms in an automatic and decentralized manner using smart contracts and blockchain technologies. Similar approaches that leverage blockchain and smart contracts for service management have been proposed in works [35], [38], [39], [40], [41].

It should be noted that the decentralized consensus mechanism of blockchain has high potential to ensure a secure interoperability of many sensors and actuators in the IoT system [31]. Nevertheless, there is still a challenge of finding the optimal trade-off between security, throughput and energy demand of the consensus algorithm. Considering that most IoT devices are constrained by power and computing capabilities, this problem is of paramount importance [32], [33]. Considering the huge traffic expectations and latency constraints in the MoT network [34], the abovementioned blockchain limitations will be the key implementation concerns, which are discussed in the following sub-subsection.

D. BLOCKCHAIN CONSENSUS ALGORITHMS

Blockchain is a peer-to-peer system where all nodes communicate directly without a centralized entity. The consensus algorithm is the key procedure of any blockchain network because it defines the way distributed nodes validate each transaction in a secure manner [48]. A transaction itself is the record that indicates the corresponding changes in the distributed ledger, which must be verified by several nodes. All nodes (or more than 51%) in the blockchain must update the new state of the distributed ledger, which ensures the security and immutability of each transaction [49].

Among all available consensus algorithms, choosing the optimal algorithm is not a trivial task. The consensus algorithm specifies how data are spreading among all blockchain nodes, how decisions are made by each node, and how the new block of verified transactions is added to the blockchain [50]. For brevity, in this paper, we will not cover all available consensus algorithms, considering that there are already some surveys that describe them in more detail [51], [52], [53], [54]. Instead, in the next subsection, we briefly compare the most widely adopted consensus algorithms and their suitability for MoT, such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Byzantine Fault Tolerance (BFT) and their corresponding modifications [52].

1. PoW is the first and most famous consensus algorithm. It is implemented in the Bitcoin blockchain. The main idea of PoW is the complex cryptographic puzzle (hash), which takes considerable time and energy to solve. This procedure is called mining. The nodes with the most computing power are more likely to win the contest for mining the next block [55]. In addition, each block contains a hash function of the previous block, which makes all blocks linked in the chain [56]. These features prevent any attack on the system if the number of blockchain nodes is large enough because no one is able to accommodate enough computing power within a short time frame to replace the part of the chain with faked transactions [57]. Apart from Bitcoin, the largest PoW blockchains are Ethereum 1.0, Litecoin, Monero, etc. Although PoW is the most decentralized and secure consensus algorithm, it has corresponding drawbacks, such as low throughput and high energy consumption. Therefore, it is not suitable for the proposed multi-flow service provisioning in a decentralized MoT system.

2. PoS has emerged as an energy-efficient consensus algorithm that replaced the mining process (i.e., complex cryptographic computing) by the validation process. Thus, instead of competing by computational performance, validators (nodes) compete with each other by their financial stakes locked in the system. This type of approach does not require complex computations because the contest will be won by the "richest" validator. At first glance, it may be seen as a risky option because extremely wealthy users can afford to accommodate 51% of the total stake in the network to centralize the entire blockchain and alter transactions for their own benefit. However, practically, this type of attack would be a huge risk of losing all the staked funds. In addition, PoS uses a random selection of validators among all eligible nodes who stake a minimal amount of money. This adds an additional security mechanism, which requires potential attackers to not only stake 51% of the total stake but also distribute it among more than half of the nodes eligible for validation. Therefore, such an attack is possible only for very small blockchains and is very unlikely for large and widely used PoS blockchains, such as Ethereum 2.0, Polkadot, and Cosmos [49]. Moreover, PoS provides much higher transaction throughput, much lower latency and unlimited scalability through a sharding mechanism, which make it a good candidate for MoT applications.

3. Delegated Proof-of-Stake has emerged as a faster version of the PoS, where the number of validators is decreased to the small group of delegates, which are elected by the majority of nodes [58]. This approach increases the transaction throughput and decreases the latency of the blockchain by reducing the minimal number of required validators to very few nodes. This, however, causes a less decentralized system, which makes the whole network less secure. The most widely used DPoS blockchains are EOS, TRON and Cardano.

4. Proof-of-Stake and Authority (PoSA) consensus represents a DPoS model, where validators are selected by the central authority. Such model has obvious drawbacks, because it makes the whole blockchain centralized. However, this feature allows to achieve a high throughput and scalability of the system. The first and the most used PoSA implementation is Binance Smart Chain, which generates a new block every 3 seconds [59].

5. Practical Byzantine Fault Tolerance (pBFT) is another popular consensus algorithm. In pBFT, nodes are sequentially ordered as primary and secondary nodes, which makes it similar to DPoS. However, in contrast to DPoS, in pBFT, secondary nodes should confirm the transaction and send the response to the primary nodes. If at least 2/3 of the secondary nodes confirm the transaction, the primary node confirms it as well. Consensus is then achieved if at least 2/3 of the primary nodes confirm the transaction. Thus, a practical Byzantine fault-tolerant blockchain can work properly up to one-third of malicious nodes in the network [60], [61]. Thus, with a larger number of nodes, the pBFT blockchain becomes more secure. Moreover, the most popular implementations of pBFT are the Hyperledger Fabric [62] and XRP Ledger [63]. While the former has gained a lot of attention for industrial IoT applications [64], the latter has been mostly considered the fastest solution for implementation of CBDC (Central Bank Digital Currency) [65].

The numerical comparison of above-mentioned consensus algorithms in terms of throughput, latency and security aspects is provided in Table 2.

E. BLOCKCHAIN AND NFT-BASED RESOURCE TOKENIZATION USING NFTs

Apart from security benefits and the decentralized trust among multiple agents, blockchain provides a convenient tool for resource management in heterogeneous communication systems. The recent solution is provided by ERC-721 Non-Fungible Token Standard. The key feature that distinguishes NFTs from traditional cryptocurrencies is its uniqueness to ensure that one NFT is not equal to other NFTs. This type of feature allows us to represent unique assets of the real world in the digital blockchain world and facilitate their transition over the internet. Such a feature allows the development of an infinite number of use cases for NFTs based on the different smart contracts [46].

Currently, there are already many activities in the blockchain industry that leverage NFTs as the key part in the overall development of the metaverse solutions. In addition, presently, NFTs are already adopted mostly by the gaming and entertainment industry, where they are used to replicate different virtual assets in games and metaverses [46], [47]. Nevertheless, in the context of Industry 5.0, blockchain and AI, NFTs can have a great impact considering the opportunity to digitize any real or virtual things in a secure and trustful manner [43], [44], [45].

Therefore, we consider NFT as the core component of the proposed framework for service management in MoT.

F. PREREQUISITES FOR THE MoT AND LIMITATION OF THE EXISTING SOLUTIONS

Despite of numerous related research works, currently there is not any complete solution for MoT. In Table 1, we summarize the existing research background in the context of MoT, and it's particular components such as IoT/IoS, 5G/6G, metaverse and blockchain. It is clearly seen that combination of the above-mentioned components enables the future development of MoT, as emphasized in the Table 1.

Therefore, a general framework is needed to combine all existing technologies under a common umbrella of decentralized multi-flow service management to provide a new secure and trustful networking ecosystem for the envisioned concept of the MoT.

The difference between IoT (IIoT) and the MoT is that the former is synchronizing any physical thing with its digital twin, while the latter is actually synchronizing realities in the physical and virtual world. The definition of "thing" within the new concept is more flexible because it can now refer to physically connected instances in the real world and to absolutely unique virtual things that are not present in the real world. From the industrial perspective, it also allows us to synchronize a physical infrastructure of robots, production lines, sensors and actuators with the corresponding virtual copy of the same environment by using a unique NFT for each entity.

Unlike the IoT, which can rely on any and even bad internet connectivity in some cases, the MoT will rely on the precise synchronization of multiple independent data flows to provide a comprehensive replication of real world context and surroundings in virtual reality. Thus, data from accelerometers, hyroscopes and haptic sensors need to be transmitted simultaneously with the data from smartphones, AR/VR headsets and cameras to transfer and visualize the relative movement of people, machines or vehicles in the virtual 3D space. We call this process a "multi-flow service provision," which is described later in the paper.

III. BLOCKCHAIN-EMPOWERED SERVICE MANAGEMENT FOR DECENTRALIZED METAVERSE AND IoT APPLICATIONS

In this section, we describe the proposed blockchain-based framework for the envisioned concept of the MoT, which aims to synchronize physical and virtual realities via the underlying network infrastructure by using the novel analytical definition of service quality evaluation and management for multi-flow decentralized applications.

A. SYSTEM MODEL

The conventional concept of network slicing, defined in 3GPP TS 29.531 [18], assumes that a separate virtual network infrastructure with dedicated QoS requirements is provided for each type of service, such as mMTC, URLLC and eMBB. Here, we extend this vision to metaverse slicing, which assumes a synchronized transmission of data flows

TABLE 2. Performance and functionality comparison of different blockchain infrastructures.

Consensus algorithm	Blockchain	Throughput, tps	Latency, s	Smart contracts	NFT
PoW	Bitcoin	5	600	No	No
	Ethereum 1.0	30	14	Yes	Yes
PoS	Ethereum 2.0	100k*	12	Yes	Yes
	Polkadot	100k*	6	Yes	Yes
	Cosmos	10k	1	Yes	Yes
DPoS	Cardano	1k	20	Yes	Yes
	EOS	4k	0.5	Yes	No
PoSA	BSC	300	3	Yes	Yes
pBFT	Hyperledger	20k	2	Yes	Yes
	XRP Ledger	1.5k	3.5	Yes	Yes

* with full sharding of Ethereum 2.0 or all parachains deployed in Polkadot

with different QoS parameters via multiple communication links of multiple MNOs and through multiple UEs to provide immersive engagement of users in a specific use case. An important assumption is that by the definition of UE, we assume conventional smartphones and, more likely, any other device, such as AR-glasses, smart-watch, earbuds, cameras, sensors, actuators, which are either wearable or are parts of the environment such as home, office or car. Correspondingly, we use the term "end user" to describe a person rather than a device. A typical application is considered to be assembled in a cyber-physical space based on partial information from each UE. As an example, we can imagine AR navigation, which not only relies on the GPS coordinates but also on the real-time data from the accelerometer to determine the spatial orientation.

Blockchain is distributed ledger technology, where data are effectively stored in a structure table, which is updated and verified by all nodes of the network. To maintain consistency with such a structure, we describe the proposed model as a matrix of the data flows $\underline{\mathbf{F}} \in \mathbb{R}^{I \times J}$:

$$\underline{\mathbf{F}} = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1J} \\ f_{21} & f_{22} & \cdots & f_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ f_{I1} & f_{I2} & \cdots & f_{IJ} \end{bmatrix} \in \mathbb{R}^{I \times J}. \tag{1}$$

In (1), each element of the matrix represents a data flow of the i-th UE with the QoS type j at the instantaneous moment of time. Naturally, there is a very low probability that all data flows will exist simultaneously, and the matrix is more likely to be sparse with many zero elements. To reflect a time dynamic in the model, we extend (1) with an additional time index as follows:

$$\underline{\mathbf{F}} = \begin{bmatrix} f_{ij1} & f_{ij2} & \cdots & f_{ijT} \end{bmatrix} \in \mathbb{R}^{I \times J \times T}. \tag{2}$$

In (2), each element represents an instantaneous state of the matrix (1) within the discrete time frame t. By physical meaning, the time index is infinite, but we limit it to the last time frame, for which we can schedule a data flow. Correspondingly, the smallest element in the tensor represented by (2) indicates the number of bits, which must be transmitted within the dedicated time interval to the corresponding i-th UE with the QoS slice j as follows:

$$f_{i,j,t} = \underline{\mathbf{F}}(i, j, t). \tag{3}$$

Thus, the total data rate at the discrete time interval t can be described as a function of (3) as follows:

$$R_t = \frac{\sum_i \sum_j f_{i,j,t}}{\tau}, \tag{4}$$

where τ is the time frame between two discrete intervals t and $t+1$. By representing (2) with values of (4), we can obtain a vector of target total data rates for the dedicated scheduling period as follows:

$$\underline{\mathbf{R}} = \begin{bmatrix} R_1 & R_2 & \cdots & R_T \end{bmatrix} \in \mathbb{R}^{T}. \tag{5}$$

Thus, the problem of scheduling in the proposed system model can be described by matching the vector in (5) with the vector of available bandwidth resources for the equivalent set of discrete time intervals $t \in (0, T)$ as follows:

$$\underline{\mathbf{W}} = \begin{bmatrix} W_1 & W_2 & \cdots & W_T \end{bmatrix} \in \mathbb{R}^{T}. \tag{6}$$

In general, to match data rate (5) and bandwidth (6), we need to derive the values of spectral efficiency, which depend on the channel characteristics between the base station and UE. However, considering the frequent fluctuations of the channel conditions due to the expected mobility of UEs and the decentralized service provision by multiple operators via different communication networks, we can redefine (6) as a vector of available data capacity per time interval as follows:

$$\underline{\mathbf{C}} = \begin{bmatrix} C_1 & C_2 & \cdots & C_T \end{bmatrix} \in \mathbb{R}^{T}. \tag{7}$$

If the available data capacity in a vector (7) is $C_i > \tau R_i$, scheduling can be performed without any need for adjustment. However, in the opposite situation when $C_i < \tau R_i$, we need to apply advanced scheduling based on different QoE metrics.

Hence, it is important to define a model for the service quality evaluation for each data flow, considering the individual features of each application.

The typical scheduling procedure in 3GPP-based mobile networks is performed in a dynamic manner according to the instantaneous channel conditions, user priority and service type. Nevertheless, within the proposed framework,

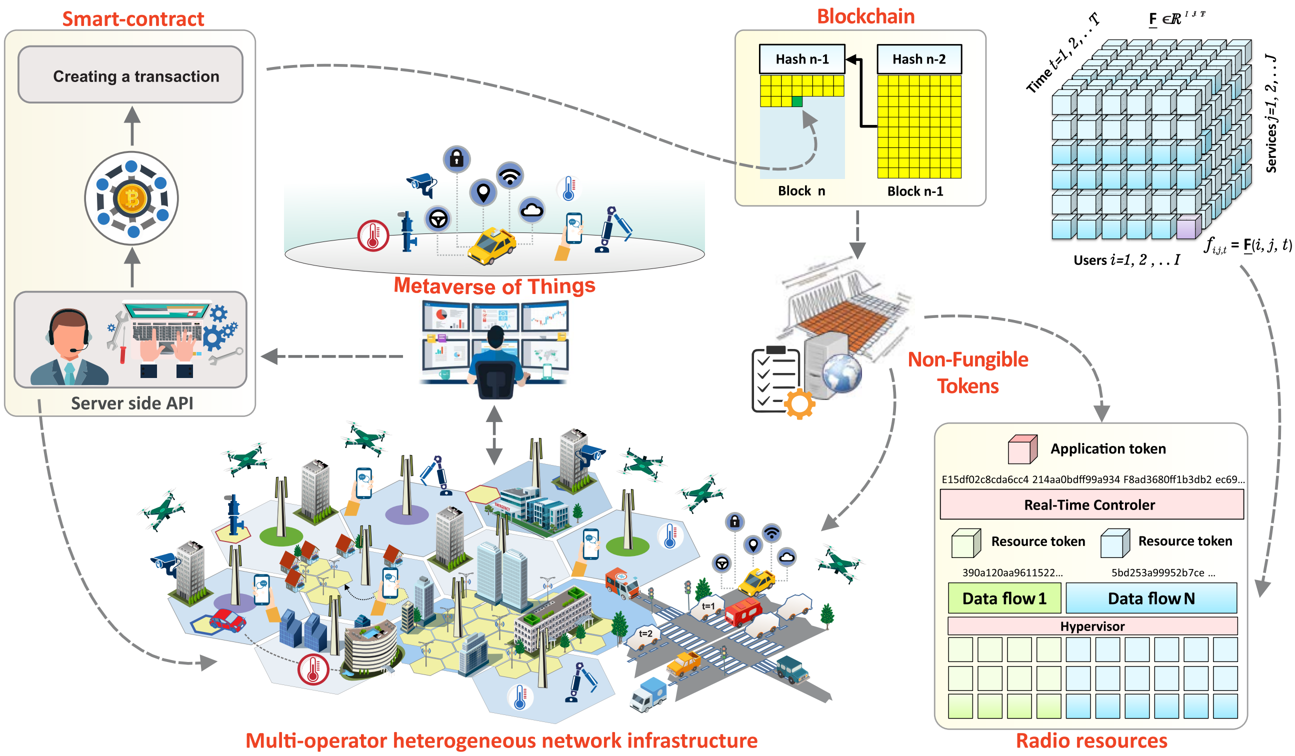

FIGURE 1. The generalized service management model of the blockchain-empowered Metaverse of things.

we propose a more comprehensive evaluation of the individual context of each application in the physical and virtual world while ensuring synchronized data delivery, high reliability and ubiquitous availability regardless of the serving MNO [19], [20], [21]. In addition, considering the unique feature of each device and data flow, the conventional definition of the service quality is no longer applicable because very often the typical future IoT application in the metaverse is composed of multiple synchronized data flows. In addition, economic constraints need to be considered because the trade-off between service price and service quality may have a substantial impact on the overall efficiency of the application.

B. BLOCKCHAIN-BASED SERVICE PROVISIONING FOR MULTI-FLOW IoT APPLICATIONS

We propose a decentralized model, where each UE has a unique identifier in the blockchain, which can be recognized by all registered MNOs. This type of solution allows the dynamic handling of service-level agreements (SLAs) based on the smart contracts and transactions of NFTs. An NFT is a token that can represent a unique asset and can be traded among different entities over the native blockchain infrastructure. Thus, blockchain can replace traditional billing systems and provide an open market for IoT services where UEs can choose among multiple offers from MNOs with different prices and SLAs [36]. Moreover, this type of approach allows the development of particular use cases based on multiple synchronized data flows from different UEs. The generalized system model of the proposed MoT concept is presented in Fig. 1.

Currently, there is an open question regarding the underlying blockchain infrastructure for the proposed MoT concept. As we discussed in section II, there are several blockchains that can be used for MoT, and each blockchain has its own pros and cons. Most of them are actively developing so that the current "status quo" in terms of performance can be easily changed anytime. Nevertheless, the essential requirements for MoTs are the support of smart contracts and NFTs with reasonable throughput and latency. Therefore, among the blockchains in Table 2, we can outline Ethereum 2.0, Polkadot and Cosmos as more decentralized and expensive, and BSC, Hyperledger and XRP Ledger as cheaper but more centralized MoT solutions.

As mentioned above, the key feature of the proposed framework is in the decentralized spatial representation of the data flows and their association with UEs, services and MNOs. In particular, a decentralized model allows UE to choose multiple MNOs for different services simultaneously and change them in quasi-real-time through blockchain smart contracts. Thus, an overall data flow in this scenario can be represented as follows:

$$\underline{\mathbf{F}} = \begin{bmatrix} f_{ij11} & f_{ij12} & \cdots & f_{ij1K} \\ f_{ij21} & f_{ij22} & \cdots & f_{ij2K} \\ \vdots & \vdots & \ddots & \vdots \\ f_{ijT1} & f_{ijT2} & \cdots & f_{ijTK} \end{bmatrix} \in \mathbb{R}^{I \times J \times T \times K}, \quad (8)$$

where the smallest data flow can be represented by a connection of the $i-th$ UE with the $j-th$ service to the $k-th$ MNO at the time interval t as follows:

$$f_{i,j,t,k} = \underline{\mathbf{F}}(i, j, t, k). \tag{9}$$

Note that matrix $\underline{\mathbf{F}}$ represents the same total data flow in both (2) and (8), and the following condition should be satisfied as follows:

$$\sum_i \sum_j \sum_t f_{i,j,t} = \sum_i \sum_j \sum_t \sum_k f_{i,j,t,k}. \tag{10}$$

Equations (8)-(10) represent how the total data flow splits among multiple MNOs and provide a flexible model for decentralized SLA management over blockchain infrastructure. Technically, blockchain allows us to trace all records about spectrum allocation and usage. In addition, the application of NFTs enables a forward market for the variety of services in Industry 5.0 and other areas. This means that each end user is able to schedule his or her own service usage in advance by purchasing the applications corresponding NFT token. A smart contract in this case can automatically split the target application into multiple data flows with different service requirements and purchase the NFT resource tokens for each data flow from any MNO. Despite the overall complexity of such multi-flow service provision, we expect that over time, a clear statistical pattern of network behavior will be found, and UEs will mostly select the same services from the same MNOs at the specific time intervals and coverage areas.

The proposed platform leveraging the analytical concept presented above consists of blockchain infrastructure and smart contract management services (Fig. 2). Smart contract management services have an application programming interface (API) frontend to interact with users and operators. Although we assume that the interaction between the UE and MNO will be automated without human intervention, we still leave an option for end users to influence this process by manually scheduling forward market service requests. Considering the rapid research in the blockchain area, we avoid any recommendation about target blockchain infrastructure. Currently, there are many available blockchains, and the Ethereum network was chosen for smart contract implementation to prove the proposed concept because it is the most commonly used and well-documented infrastructure.

C. SERVICE MANAGEMENT FOR DECENTRALIZED MULTI-FLOW APPLICATIONS

Within the context of multi-flow applications, such as metaverse, IIoT, autonomous driving, AR experience, etc., it is extremely difficult to explicitly calculate quality of experience (QoE) values based on common network KPIs. To resolve this problem, we propose using a utility function that provides weighted multicriteria optimization in terms of price and different service quality parameters [66] as

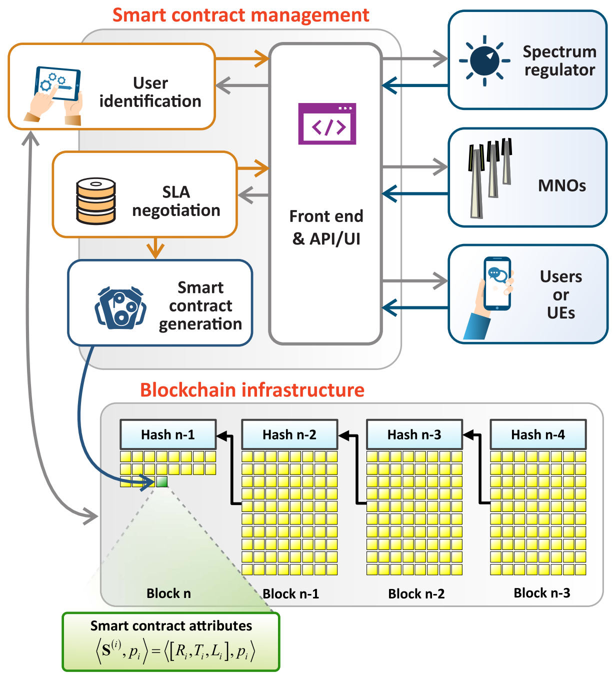

FIGURE 2. Proposed structure of the blockchain-based framework for decentralized service management in 6G.

follows:

$$u(q, p) = [\mu (q - q_{\min}) + (1 - \mu)(p_{\max} - p)], \tag{11}$$

where q is an integral QoE value of the data flow, p is the service price for the data flow normalized by time and determined by the algorithm presented in [67], q_{min} is the lowest QoE value acceptable by the user, and p_{max} is the highest service price that the user is willing to pay. An additional parameter $\mu \in (0, 1)$ is used to determine the preference of the end user in terms of the trade-off between the service price and the service quality.

The utility function (11) is unique for each individual UE i and service type j, and thus, can be presented in a similar way to (1) as follows:

$$\underline{\mathbf{U}} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1J} \\ u_{21} & u_{22} & \cdots & u_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ u_{I1} & u_{I2} & \cdots & u_{IJ} \end{bmatrix} \in \mathbb{R}^{I \times J}. \tag{12}$$

An integral quality parameter q can be represented as a weighted sum of all other parameters as follows:

$$q = R \cdot \beta^{(R)} + T \cdot \beta^{(T)} + L \cdot \beta^{(L)} \text{ and } \beta^{(R)} + \beta^{(T)} + \beta^{(L)} = 1, \tag{13}$$

where R, T, L are the throughput, latency and packet loss, respectively, as defined by the 5G quality identifier in 3GPP TS 23.501 [68]. By amending the corresponding values of $\beta^{(R)}, \beta^{(T)}, \beta^{(L)}$, in equation (13) each UE can define which parameters are more important and adapt the balance between them to customize its own service quality. As a result, a matrix of QoE requirements (12) is defined in real-time in a decentralized manner considering the context of each individual end user, UE and service data flow.

D. METHOD OF DYNAMIC MULTI-FLOW SERVICE SELECTION BY UEs

The main difference of the multi-flow service selection from the end user perspective is that there are many services, which are provided by superimposing the multiple separated data flows, which interact with the end user through multiple devices, such as sensors, cameras, AR headsets, robotic equipment, etc. To ensure the best possible immersive user experience, it is important that all these data flows are synchronized properly so that all functions will supplement each other in the correct way. This becomes especially challenging when we attempt to synchronize data flows with different requirements, such as tactile data, video data, and data from ambient sensors. To resolve this problem, we propose using NFTs to represent a multi-flow application as a single entity in the blockchain, which can be traded between users and MNOs.

Initially, a user can request an application as a whole through our framework, which is then translated into a set of smaller data flows with different service requirements, operators and UEs (smartphones, sensors, wearables, etc.).

Then, each UE is able to negotiate its service agreement with any MNO in advance through the contract management service in the proposed framework (Fig. 2). Smart-contract bids offered by MNOs to UEs contain the absolute values of partial quality parameters and the corresponding service price as follows:

$$\left\langle \mathbf{S}^{(i)}, p_i \right\rangle = \langle [R_i, T_i, L_i], p_i \rangle, \tag{14}$$

where i is an index of UE. Thus, UEs evaluate their integral utility functions as follows:

$$\underline{\mathbf{U}} = \begin{bmatrix} u_{ij11} & u_{ij12} & \cdots & u_{ij1K} \\ u_{ij21} & u_{ij22} & \cdots & u_{ij2K} \\ \vdots & \vdots & \ddots & \vdots \\ u_{ijT1} & u_{ijT2} & \cdots & u_{ijTK} \end{bmatrix} \in \mathbb{R}^{I \times J \times T \times K}. \tag{15}$$

Then, each UE selects the smart contract (14) with the highest utility function (15) among all available bids for each type of service j at each discrete time interval t:

$$f^{(k)} = \max_{\forall i,j,t} \underline{\mathbf{U}}(i, j, k, t). \tag{16}$$

Once a smart contract with utility (16) is executed, each selected MNO establishes the dedicated QoS flow for the corresponding UE with target parameters. Meanwhile, each UE receives a corresponding NFT associated with dedicated network resources, and the corresponding amount of cryptocurrency is held by a smart contract until successful confirmation of service provision. In the case of fair behavior, all money will be transferred to the wallet of the corresponding MNO.

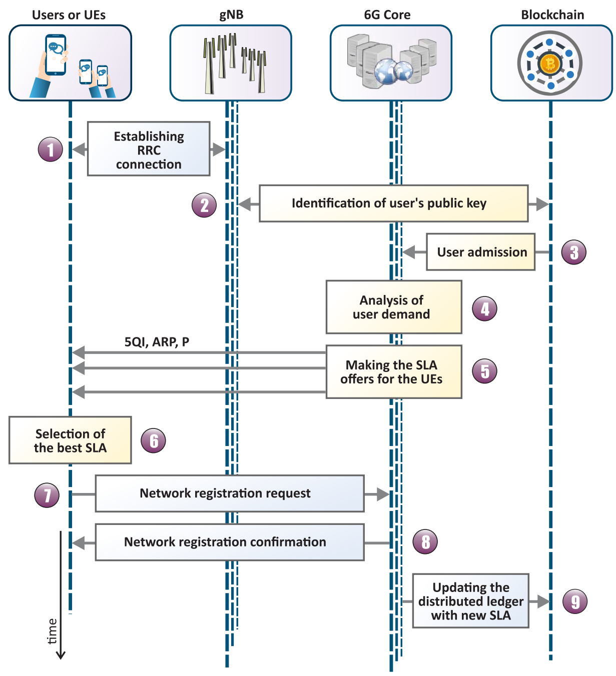

FIGURE 3. The generalized protocol diagram of the dynamic service selection between MNOs and UEs.

The high-level protocol diagram of the dynamic service selection between MNOs and end users is displayed in Fig. 3.

IV. NUMERICAL RESULTS

This section illustrates the performance characteristics of the proposed multi-flow service model for the case study of MoT networks consisting of a large number of UEs with different service requirements. The main setting of the radio resource allocation of the physical frame using carrier aggregation is as follows. We consider channel bandwidth $W = 5MHz$ consisting of 25 resource blocks allocated in two sub-GHz frequency carriers (3.6 GHz and 3.62 GHz). The total number of RBs is thus 50 RBs for each dedicated time slot (1 ms). The UEs follow the Manhattan mobility model with a velocity of $1m/s$ in the grid road topology. The dedicated KPIs are collected based on the Monte Carlo simulation approach, averaging $N = 1000$ of the simulation trials.

In the current simulations, we omit the numerical evaluation of the blockchain performance for the following reasons. First, there is no technical possibility to deploy and test a blockchain, with the meaningful number of nodes. Consequently, any implementation will be limited to either few nodes or to fully virtual blockchain simulation on a single machine. As result, all numerical values of the throughput and latency in a simulated blockchain will not be representative. Nevertheless, as mentioned in section III.B, there are already existing blockchains, which can satisfy the requirements of MoT, which makes the whole our concept feasible. Therefore, in the current paper, we provide the pure simulation results to assess the trade-off between possible scenarios of

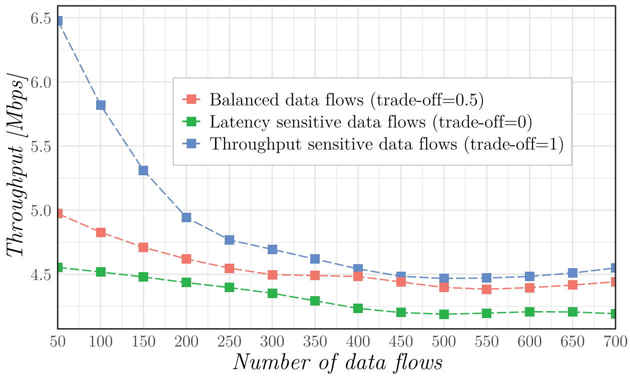

FIGURE 4. Average throughput of the different multi-flow data streams, which show the boundary cases (i.e., throughput- and latency-sensitive UEs) and the use case with equally balanced data flow.

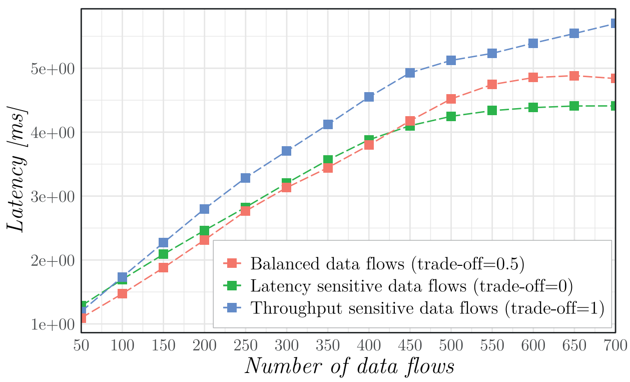

FIGURE 5. Average latency of the different multi-flow data streams, which show the boundary cases (i.e., throughput- and latency-sensitive UEs) and the use case with equally balanced data flow.

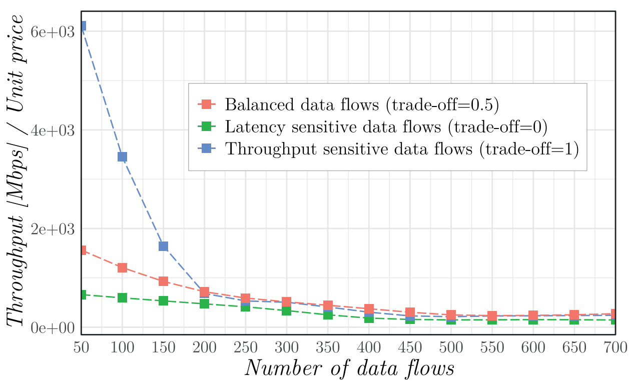

FIGURE 6. Average throughput of UEs per unit service price.

MoT applications by comparing the 3 borderline types of data flows: latency sensitive ($\beta^{(R)} = 0$, $\beta^{(T)} = 1$, $\beta^{(L)} = 0$), throughput sensitive ($\beta^{(R)} = 1$, $\beta^{(T)} = 0$, $\beta^{(L)} = 0$), and balanced ($\beta^{(R)} = 0.5$, $\beta^{(T)} = 0.5$, $\beta^{(L)} = 0$). It should be noted that to simplify the description, we neglect the packet loss because it has less of an impact on the system compared to the throughput and latency.

Comparing the results for throughput (Fig. 4) and latency (Fig. 5), we observe that they follow theoretical expectations

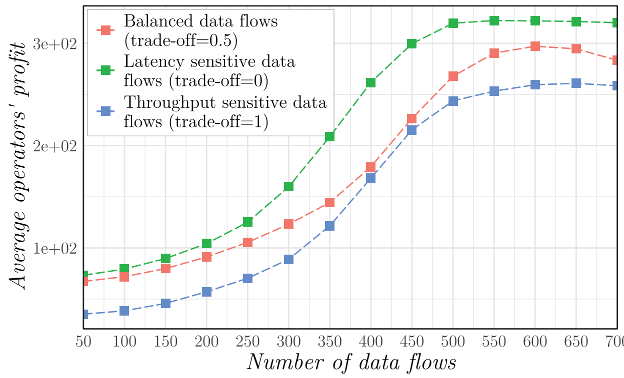

FIGURE 7. Operator's profit for boundary cases (i.e., throughput- and latency-sensitive UEs) and the use case with equally balanced data flow.

and behave exactly as needed in terms of balancing both metrics. For the latency-sensitive data flows, we do not observe high throughput because each data block is transmitted immediately in available resource blocks to reduce latency, while for the throughput-sensitive and latency-tolerant data flows, we tend to wait until a larger number of resource blocks will be available to ensure that large data blocks will have enough resources for transmission. Furthermore, balanced data flows are in the middle in both Fig. 4 and Fig. 5 because they must follow both requirements simultaneously. Nevertheless, we observe a clear relation between the number of data flows and all performance indicators. The difference in throughput between the 3 types of data flows is much higher when the number of data flows is low and diminishes with increasing data flow number (Fig. 4). This is clear because the total throughput is limited and divided between all data flows. Therefore, with a lower range of throughputs, we observe a lower difference between service types. In Fig. 5, we observe the opposite situation for latency because latency is increased for a higher number of data flows, and thus, we observe even more differences between the different service types.

Apart from the pure technical parameters, we also consider the economic aspects of the network because any decentralized system can be sustainable only in the case of a profitable business model. In Fig. 6, the normalized throughput per price unit is compared for different metrics, and we can observe the same relation between the service types as in Fig. 4, which is expected. However, when the number of data flows is larger, all service types converge to the same value of normalized throughput per price unit, which means that during a high load, throughput will depend more on the service price rather than on the type of service.

From the perspective of the MNOs in Fig. 7, we observe that their profit from the latency-sensitive data flows is consistently higher than that from the throughput-sensitive data flows. Balanced data flows are again averaged between borderline types. Naturally, the profit of operators rises with the growing number of users regardless of the service type, but for a very high number of data flows, it becomes more constant.

Since simulation results are provided for borderline cases, we can expect that the results for any other combination of $\beta^{(R)}, \beta^{(T)}, \beta^{(L)}$ will be within a range between throughput-sensitive and latency-sensitive data flows in terms of the metrics depicted in Fig. 4 - Fig. 7.

V. CONCLUSION AND FUTURE RESEARCH

In this paper, we have proposed a novel approach for managing service data flows considering the emerging trends of the metaverse, the Internet of Skills and Industry 5.0. We resolved the problem of synchronized data transmission and service provision through multiple devices to ensure immersive engagement of end users through all available means of sensing and visualization. In particular, we propose a blockchain-empowered framework for decentralized service management based on the multiple data flows of different service types and different MNOs. We represent multiflow applications by NFTs in the blockchain that enable them to be traded as assets among MNOs and end users. In addition, NFTs are also created for any network resource, which allows automation of the SLAs between UEs and MNOs by using smart contracts. Simulation results show that the proposed approach allows us to precisely adjust the QoE parameters for each IoT application in a decentralized manner to ensure the best trade-off between network performance indicators.

We assume that the proposed MoT trend requires a rethinking of the existing user interfaces from conventional all-in-one smartphone model to the customized wearable ecosystem of devices, empowered by the multiflow service provisioning. The synergic fusion of the advanced 5G/6G environment, edge computing AI, AR and wearable sensors will drive the post-smartphone era by replacing the powerful energy intensive processors to energy efficient small processors supplemented by edge computing. Such fusion will open many new interdisciplinary research directions such as multi-sensing, low-power wireless communications, embedded systems, AR rendering and visualization, edge computing, 6G technologies, robotics, digital twins, blockhain and AI solutions. In our future research, we will provide a more detailed study on the decentralized Metaverse of Things implementation for different application scenarios based on 6G, blockchain, NFTs, AR and AI solutions, as well as techno-economic aspects and future bussiness models.

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