Blockchain and AI-Enabled Framework for Dynamic Spectrum Management in Multi-Operator 6G Networks

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Abstract. 5G mobile networks have adopted a smart architectural design, which is flexible for various deployment scenarios and service requirements. Such transformations have enabled different business models for mobile network operators in both nationwide and local scales. 6G will feature even more flexible mobile network deployment driven by spectrum and infrastructure sharing among the operators. In this chapter, we propose a new multi-layer framework for 6G mobile network with decoupled operators and infrastructure planes. The proposed framework provides a flexibility of network configuration for multiple operators in condition of open spectrum and infrastructure market by using a multi-dimensional matrix representation of the data flows. In particular, the proposed model supports the dynamic switching of the operator and multi-operator service provision for the end users. As a case study, we have developed an AI-based workflow for the dynamic spectrum allocation among multiple mobile network operators. The key advantage of the proposed workflow is that it can be adjusted to the different combinations of the data flows and thus can be suitable for the spectrum allocation among multiple operators. The intelligent capabilities of the proposed workflow are provided by the deep recurrent neural network based on the long short-term memory architecture. The developed model has been trained over the custom dataset with realistic user mobility in urban area. Simulations results show that the proposed intelligent model provides a stable service quality for end users regardless of the serving operators and outperforms the static and semi-intelligent models.

Keywords: 6G, blockchain, artificial intelligence, decentralized mobile networks, multi-operator spectrum management.

1 Introduction

With the extensive proliferation of 5G technologies we are currently on a verge of the 5th industrial revolution driven by personalized and intelligent digital ecosystems. 5G has brought together a bunch of advanced technologies and enabled an instant connectivity among them with a high throughput and reliability. Nevertheless, a further evolution to the 6G technologies is inevitable in order to facilitate a sustainable interaction among various domains and industrial verticals and provide a personalized user experience. Whereas 5G has mainly been focused on the three main pillars of quality assurance, namely eMBB (Enhanced Mobile Broadband), mMTC (Massive Machine Type Communications) and URLLC (Ultra-Reliable Low Latency Communications), in 6G we can expect much more fine-grained differentiation of the service quality [1]. In particular, 6G should take into account a ubiquitous comprehension of the user context within physical, virtual and augmented reality, while providing the instant data delivery, high service reliability and availability regardless of the serving operator [2]. Considering the challenges, which have been brought by the COVID-19 pandemic, the further development of the mobile communications is focused towards consistent improvement of the remote work and education, including the holographic telepresence, the mixed reality and the Internet-of-Skills. It is now more apparent that modern smartphones in the foreseeable future will be replaced by a set of wearable devices such as integrated display glasses, headsets, tactile and biosensors, etc. Thus, the definition of service in 6G will transform from the modern device-oriented service provision to the future user-oriented service provision, so that multiple independent data streams through different hardware means will be combined in a synchronized manner to recreate an immersive experience of the end user [3]. Such transformations are now becoming feasible due to the growing capabilities of the visualization technologies, precise sensors and specialized processing units, which open new possibilities of interaction with human senses. Another example of multi-flow service provision can be found in the area of autonomous vehicles. According to Intel's prediction, the typical self-driving car of the future will generate approximately 4 terabytes of data per hour, coming from different cameras, sensors and controllers. The main challenge here is in the difference in the data purpose. While some critical data need to be transmitted instantly with low latency, there are also useful background data, which can be collected and transmitted over longer timeframes. Therefore, a typical V2x (Vehicle-to-Everything) service in 6G era will consist of the multiple orchestrated and synchronized data flows, with different requirements for latency, throughput and packet loss [4].

However, the conventional model of the mobile networks market has been only reasonable at the very beginning of mobile networks development to ensure nationwide coverage when 2G mobile networks started to be massively deployed around the world. As a result, we observed the very inefficient duplicated infrastructure deployment by operators, because all of them have to compete and no one is willing to give up a particular coverage area [5]. Nowadays, with the rapid technological development and the continuous increasing of the traffic demand operators are forced to densify their infrastructure in order to satisfy the ever growing number of the end users.

However, as mentioned above, in 6G we expect more diverse service requirements based on the cyber-physical experience of the end users. With multiple data-flows and different quality requirements, operators will need to develop and maintain even more redundant network infrastructure unless we find a new way to solve the challenge [6].

Considering the abovementioned challenges, in this chapter we propose a novel concept for the development of the future AI (Artificial Intelligence) and blockchain-enabled 6G networks. The key idea is in the economic decoupling of the network operators and network infrastructure, so that all operators will share the network infrastructure and will be able to contribute to the network development. This can democratize the mobile communications market by elimination of the current limitations and regulations for operators. In addition, we provide a case study for the decentralized spectrum management by multiple mobile network operators (MNOs) using a new AI-based workflow. The main contributions of this chapter are the following:

1. The multi-plane framework for the spectrum and infrastructure sharing among multiple MNOs is proposed by leveraging the AI and the distributed ledger technology.
2. Intelligent decentralized spectrum management workflow among multiple MNOs is proposed based on the deep recurrent neural networks and the blockchain technology.

2 Blockchain and AI-Empowered 6G Framework

Proposed framework consists of a user plane, an infrastructure plane, an operators' plane, a blockchain plane and an AI plane, as depicted in Fig.1.

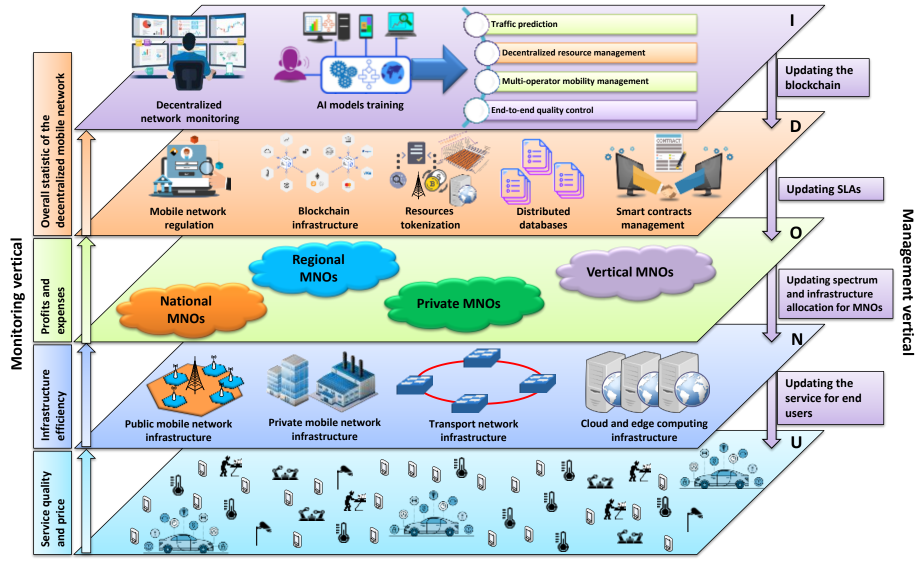

Fig. 1. The multi-plane architecture for the intelligent decentralized 6G mobile network.

All planes are responsible for their particular parameters and functions, which are coordinated to ensure the intelligent network management in a decentralized manner. Thus, the network infrastructure can be adjusted to any intent of the MNOs and the end users in order to meet the future cyber-physical applications in 6G mobile networks.

The *user plane (U)* contains users and their corresponding data flows with different service requirements. Since user experience in 6G will be mostly cyber-physical and will depend on multiple data flows, we propose a generalized model of the user plane as a two-dimensional matrix $\underline{\mathbf{F}} \in \mathbb{R}^{I \times J}$, where each row represents a vector of the data flows of a particular end user, while each column represents a vector that indicates the users of the particular type of service:

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

The smallest element of the matrix (1) represents the data flow of the user i with the service type j :

$$f_{i,j} = \underline{\mathbf{F}}(i,j). \tag{2}$$

Considering the fact that all users will not use all possible types of service, the matrix (1) will be sparse, because some elements $f_{i,j}$ may be equal to zeros. Note that, a row in a matrix (1) represents a person, not a device, so that all data flows that belongs to one user may not necessarily be transmitted through one device. Thus, the instantaneous total data flow of the user plane within the particular coverage area of the 6G mobile networks can be calculated as following:

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

By using the proposed granulation of the data flows, we can provide any combination of them by using the trivial operations of linear algebra. Therefore, such model is fully in line with the Cisco's definition of the intent-based networking that aims to configure the network upon the preferences of the end users.

The infrastructure plane (I) provides connectivity for the end users through any available wireless and wired access technology, such as macro and small cells, Wi-Fi access points, device-to-device communications, mMTC and V2x communications, Starlink, LEO (Low Earth Orbits) satellites (Starlink, etc.) and fixed optical broadband [7-9]. The data flows matrix (1) in the infrastructure plane is transformed to the three-dimensional form $\underline{\mathbf{F}} \in \mathbb{R}^{I \times J \times L}$:

$$\underline{\mathbf{F}} = \begin{bmatrix} f_{ij1} & f_{ij2} & \cdots & f_{ijL} \end{bmatrix} \in \mathbb{R}^{I \times J \times L}, \tag{4}$$

where the smallest element of the matrix (4) represents the data flow of the user i with the service type j through the infrastructure element l :

$$f_{i,j,l} = \underline{\mathbf{F}}(i,j,l). \tag{5}$$

Notwithstanding that by index l we can represent any type of the network infrastructure, for simplicity further in this work we will refer only to the cellular base stations like macro and small cells. The matrix (4) is sparser than the matrix (1), because all individual data flows in (1) are distributed among different base stations in (4). Hence, the instantaneous total data flow in the infrastructure plane is represented as following:

$$F(t) = \sum_i \sum_j \sum_l f_{i,j,l}(t) = \sum_i \sum_j f_{i,j}(t). \quad (6)$$

By the formalization of the infrastructure plane, we define a complete space of combinations of users, service types and base stations in a decentralized mobile network environment.

However, the last element of the puzzle is missing in the equation (4). Since there is not a service without a service provider, we define the *operators plane (O)*, which is aimed to distribute the data flows among multiple MNOs and link the corresponding SLAs (Service Level Agreements). For brevity, we omit the economic aspects of SLA between user and operator, and define the following assumptions based on the findings of our previous research [10-12]:

- user is able to change MNO in a real-time based on his own tradeoff between service quality and service price;
- user is able to get a service from multiple MNOs simultaneously;
- MNO may not necessarily be able to provide all available types of service;
- MNO is able to transmit multiple data flows through different devices of the end user.

Thus, the main idea is to enable the spectrum and infrastructure sharing by the MNOs within the single decentralized mobile network. Such idea, can be formalized by transformation of the matrix (4) to the four-dimensional matrix $\underline{\mathbf{F}} \in \mathbb{R}^{I \times J \times K \times L}$:

$$\underline{\mathbf{F}} = \begin{bmatrix} f_{ij11} & f_{ij12} & \cdots & f_{ij1L} \\ f_{ij21} & f_{ij22} & \cdots & f_{ij2L} \\ \vdots & \vdots & \ddots & \vdots \\ f_{ijK1} & f_{ijK2} & \cdots & f_{ijKL} \end{bmatrix} \in \mathbb{R}^{I \times J \times K \times L}, \quad (7)$$

where the smallest element of the matrix (7) represents the data flow of the user i with the service type j provided by the operator k through the base station l:

$$f_{i,j,k,l} = \underline{\mathbf{F}}(i,j,k,l). \quad (8)$$

Since the matrix (7) is a transformation of the matrix (5), it is also sparse and the instantaneous total data flow can be calculated as following:

$$F(t) = \sum_i \sum_j \sum_k \sum_l f_{i,j,k,l}(t) = \sum_i \sum_j \sum_l f_{i,j,l}(t) = \sum_i \sum_j f_{i,j}(t). \quad (9)$$

In order to provide the framework for the infrastructure sharing by MNOs we introduce an additional connectivity matrix $\underline{\mathbf{O}} \in \mathbb{R}^{K \times L}$, where each element can be either 0 or 1:

$$o_{k,l} = \begin{cases} 1, if \text{ base station } l \text{ is used by MNO } k \\ 0, \quad \text{otherwise} \end{cases} . \tag{10}$$

Considering the dynamic of the 6G mobile network in decentralized deployment and infrastructure sharing conditions, the matrix $\underline{\mathbf{O}} \in \mathbb{R}^{K \times L}$ is frequently modified in time. Therefore, in order to represent the network traffic served by MNO k in a discrete time interval t, we include an instantaneous matrix state $\underline{\mathbf{O}}(t)$ as following:

$$F_k(t) = \sum_i \sum_j \sum_l \left(f_{i,j,k,l}(t) \cdot o_{k,l}(t) \right) . \tag{11}$$

For simplicity, let's define that each base station can be used only by one MNO in a discrete time interval t, so that number of ones in a matrix $\underline{\mathbf{O}}$ will be always constant according to the following definition:

$$\sum_k \sum_l o_{k,l}(t) = L . \tag{12}$$

Thus, the equation (11) can be simplified to the following form:

$$F_k(t) = \sum_i \sum_j \sum_l f_{i,j,k,l}(t) . \tag{13}$$

Hence, in an *operators' plane* we provide the flexible decentralized data flows management considering the infrastructure sharing by the MNOs and adaptive MNO selection by the end users.

In order to manage the decentralized mobile network environment there is a need for a trustable and secure mechanism, which can ensure that spectrum and infrastructure sharing by MNOs will be fair and all parties will be satisfied. Therefore, we introduce the *blockchain plane (B)*, which provides a distributed ledger infrastructure on top of the conventional mobile network infrastructure. Distributed ledger (blockchain) is a decentralized system with peer-to-peer model, where there is not any single authority [14]. Blockchain is organized as an infinitely growing list of records, which are modified by transactions. Any transaction is validated and the copies of the modified ledger are shared among all nodes in the network. In order to keep the process secure, multiple transactions are assembled into a block, which is then hashed by using advanced cryptographic algorithms. The chain-like structure of the distributed ledger is achieved by linking the subsequent blocks in a way that hash value of previous block is included into next block as shown in Fig.2. This feature ensures that any past transaction cannot be modified, because it will cause the wrong hash values of the entire subsequent chain, which will be rejected by other nodes. The process of block validation is called mining and is conducted by a consensus mechanism among all nodes in the blockchain network [15].

In this chapter, we omit detailed explanation of the different consensus mechanisms and cryptographic algorithms, which are used in various types of blockchain, because they are quite widely studied in the literature [14,15]. Our main interest within the intelligent 6G framework is in the decentralized applications (dApp) based on the blockchain. Unlike traditional applications, which are based on centralized servers and single authority, dApp utilizes the blockchain to provide the trust between all involved parties through consensus mechanism.

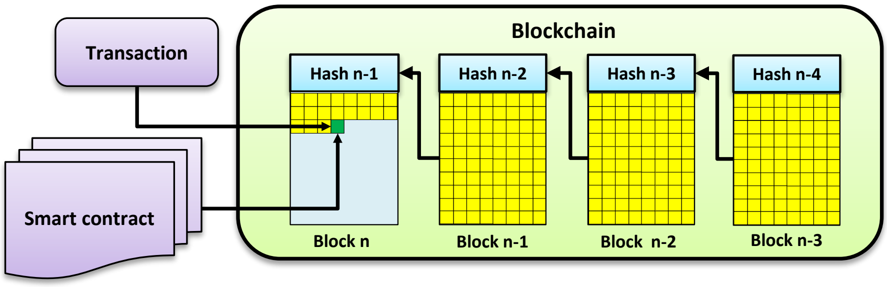

Fig. 2. An example of the blockchain operation.

Since blockchain is tamper-resistant, MNOs and regulator can use dApp as a useful tool for infrastructure and spectrum management [16,17]. The proposed structure of dApp for the intelligent 6G framework is shown in Fig. 3. We propose to use a combination of the traditional cloud-based applications, which are linked to Ethereum blockchain in order to enable spectrum and infrastructure sharing among MNOs by using smart contracts. Smart contract is a piece of code, which can be explicitly programmed to conduct several subsequent transactions in blockchain, which reflect certain financial agreements between multiple parties. For example, the MNO A can set the price of the base station rent in the smart contract, while MNO B can set a price, which he is willing to pay for the base station rent. Once conditions of both MNOs are met, the corresponding transactions will be automatically executed and MNO B will be indicated as an owner of the corresponding base station in the blockchain. Once the renting period will over, the smart contract will automatically execute the reverse transaction to return the ownership to the MNO A. Similar procedure can be applied for the spectrum sharing, as well as any other property, which can be shared among MNOs. Other role of proposed dApp is to manage SLAs between users and MNOs in a trustful and secure manner.

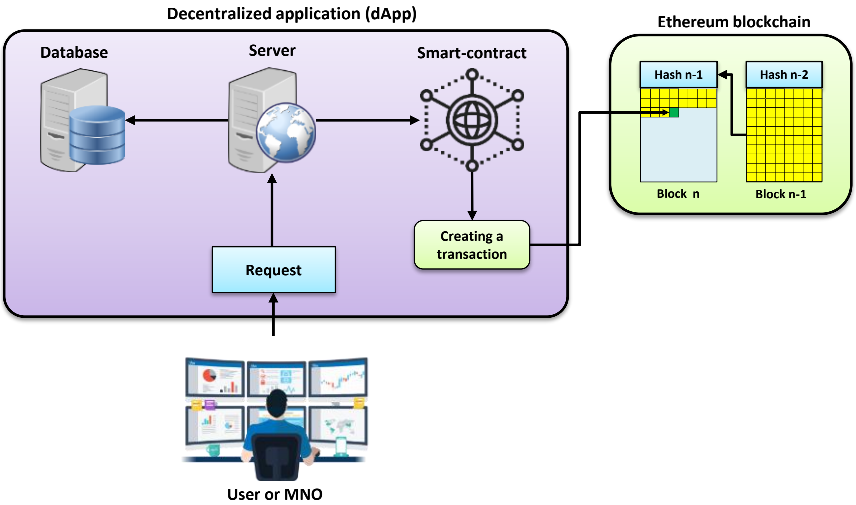

Fig. 3. The proposed structure of dApp for the decentralized 6G framework.

In order to bring the AI capabilities for the proposed decentralized 6G mobile network, we introduce the *AI plane (I)* to close a loop of network management in the proposed framework. The key parts of the AI plane are the data management and machine learning algorithms. The particular challenge of AI application in decentralized mobile networks is that we have the exogenous dynamic of the system, caused be the adaptive MNO switching by end user, spectrum and infrastructure sharing, etc. Hence, the conventional way of collecting and processing data by MNOs is not effective, because the external conditions are changing faster than the AI can be trained.

Thus, we introduce the model of intelligent decentralized network management (Fig. 4), which has the following features:

1. Joint network monitoring and data sharing by all MNOs.
2. Trained AI models can be either personal, which are used by MNOs to improve their services to end users, or public, which are shared among MNOs to increase the efficiency of the network resources utilization.
3. User database should be shared by all MNOs in order to maintain the proper service quality across all MNOs and network infrastructure.

The proposed system consists of the main core, which is responsible for the management of the AI models and interaction with shared network infrastructure and monitoring system by standardized protocols such as HTTP (HyperText Transfer Protocol), CoAP (Constrained Application Protocol) and MQTT (Message Queue Telemetry Transport). The system is integrated with the blockchain infrastructure in order to provide the secure solution for the data sharing among operators and joint decentralized network management through the dApp and the distributed ledger [18,19]. Thus, the intelligent coordination of all planes allows to provide the target flexibility of network configuration for any given intent of the MNOs and users. Thus, we provide the new framework for the 6G development that integrates the means of artificial intelligence and the blockchain technology to leverage the advantages of both centralized and decentralized business models in the mobile network, while eliminating their corresponding drawbacks and constraints. Such a solution allows to disrupt the mobile network market by enabling a trustable spectrum and infrastructure sharing among operators, underpinned by economic and legislative mechanisms [10-13].

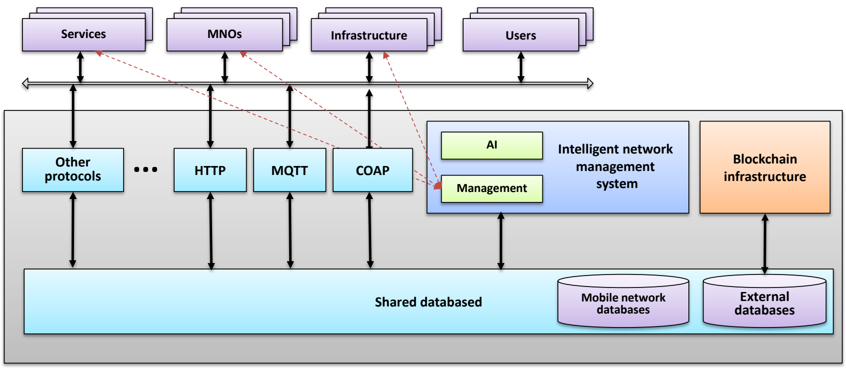

Fig. 4. The proposed functional model for the blockchain and AI-enabled decentralized 6G network management.

To further enhance the efficiency of spectrum sharing among MNOs considering their time-varying demands, in the next section we propose the intelligent spectrum management workflow based on the recurrent neural networks, which allows to predict a traffic demand of the particular network service and allocate enough spectrum in advance.

3 Deep Learning-Based Intelligent Multi-Operator Spectrum Management in 6G

The typical workflow of the intelligent spectrum and infrastructure management usually defines a set of target criteria, which are used as metrics of the network efficiency. Once, these metrics are defined, we need to find all factors, which have an impact on those parameters. Such factors can be classified into two groups: exogenous and endogenous. Exogenous factors cannot be controlled by MNOs, such as user mobility, service preferences, etc. Endogenous factors can be controlled by the MNOs, such as spectrum allocation and other configurable network parameters. Considering the impact of both groups of factors, we propose the following workflow of the intelligent network management as shown in Fig. 5.

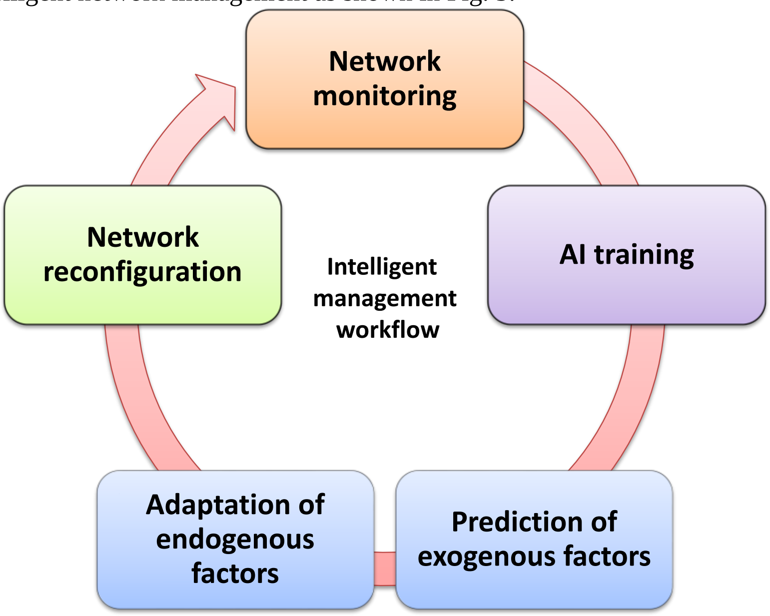

Fig. 5. The proposed workflow for the intelligent spectrum management among multiple MNOs in 6G.

Initially, we have a monitoring of the network parameters, which has two important functions in our workflow. First, monitoring provides datasets for training of the deep learning models. Second, monitoring is needed to evaluate the network performance and to make a decision on the efficiency of the trained models, and determine when additional training is required. The deep learning models used in this chapter are trained explicitly for the traffic prediction of the particular base stations, i.e. for prediction of the exogenous factors caused by the behavior of the end users. Then, obtained prediction is analyzed and used to make the corresponding adjustment of the endogenous factors, i.e. spectrum allocation for each base station and MNO. Finally, the corresponding reconfigurations are made by MNOs, which can include spectrum and infrastructure sharing agreements among them. After that, the loop returns to the monitoring state to evaluate the key performance metrics of the network.

Let's consider the traffic prediction of the decentralized mobile network in details. Typically, the mobility of end users depends on many factors such as job, family, car, public transportation and many others. Therefore, each user has unique attributes and patterns, because all of them have typical favorite places and some specific service types. The important aspect here is that such patterns are self-similar and has clear periodical characteristics, such as job schedule, etc. Therefore, such periodical patterns can be easily projected to a large group of people, because a group will be a superposition of individual user patterns, so that periodic structure will be maintained.

The unique feature of the proposed intelligent workflow is in its suitability for the decentralized 6G network with multiple MNOs and many different types of service. For simplicity of the representation we consider the total traffic prediction of each base station, taking into account the part of each MNO.

Considering the resource management on the cell level, individual features of each user are not important, and the equation (8) can be simplified to the following form:

$$f_{k,l}(t) = \sum_i \sum_j f_{i,j,k,l}(t). \tag{14}$$

Thus, equation (14) generalizes the data flow of the MNO k through the base station l regardless of users and service slices. Correspondingly, the entire data flow of the particular base station l can be calculated as:

$$f_l(t) = \sum_k f_{k,l}(t) \equiv \sum_i \sum_j \sum_k f_{i,j,k,l}(t). \tag{15}$$

Equations (14) and (15) generalize the traffic prediction and spectrum allocation for each base station. In Fig. 6, we show the different types of data flows granularity, which is supported by the proposed intelligent workflow for the 6G mobile network.

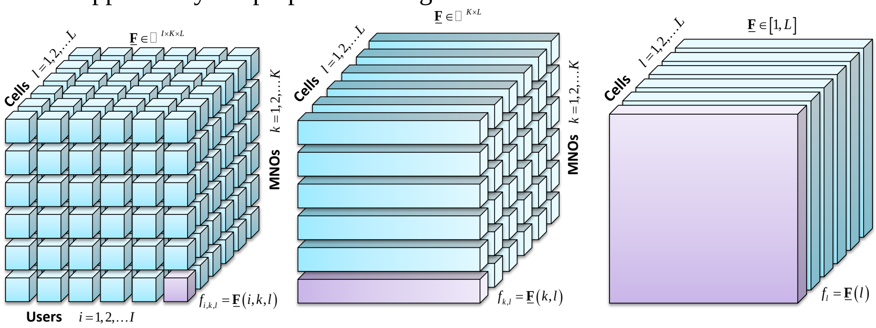

Fig. 6. The spatial representation of the data flows of multiple MNOs in a decentralized 6G mobile network.

As shown in Fig. 6, depends on the needs, we can either predict the individual traffic of each user with differentiation by MNO, the total traffic of each cell with differentiation by MNO or the total traffic of the each cell combined of all MNOs. As a model we use the recurrent neural network based on LSTM (Long-Short Term Memory) architecture. The model has 3 layers consisting of 256 LSTM cells, ReLU (Rectified Linea Unit) activation function and the Dropout block. The model has been chosen according to the requirements for long and short-term traffic prediction and has been validated in our previous research works [10, 20]. In the next section, we will present the simulation results and analysis for different combinations of the data flows.

4 Simulation Results and Performance Analysis of the AI-based Spectrum Management Workflow

The LSTM model has been trained by the custom dataset, generated in [12] for the realistic urban environment (Kosice, Slovakia) considering typical pattern of end users and real positions of base stations. The dataset consists of the 100 small cells, and 3 MNOs. Simulation results of total traffic prediction for four random cells are shown in Fig. 7.

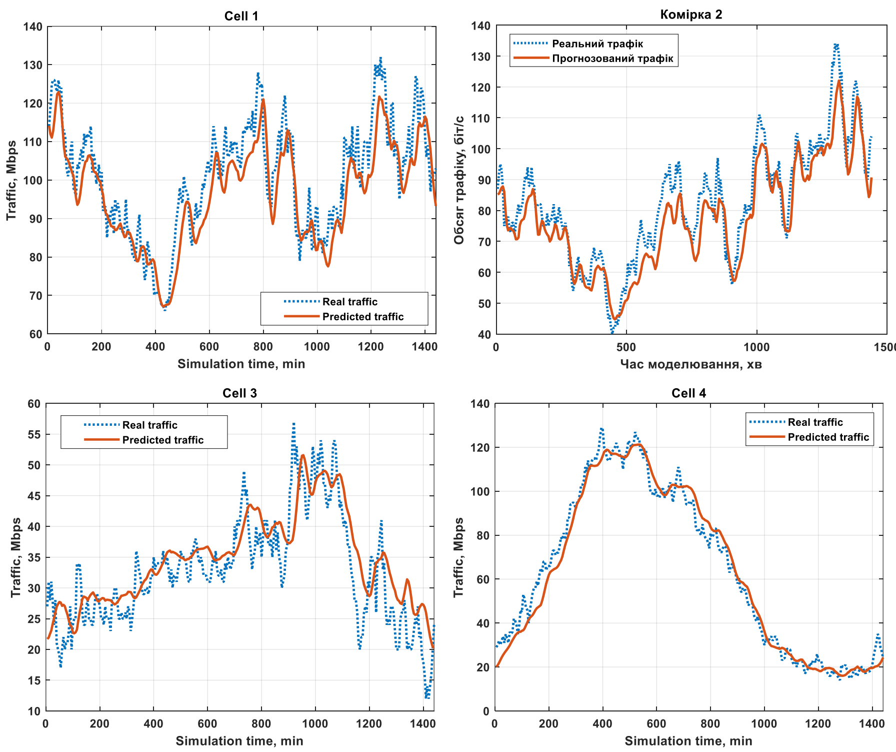

Fig. 7. Simulation results of the AI-based traffic prediction for the four arbitrary cells.

The spectrum management is formalized as following. Let's define a matrix of radio resources $\underline{\mathbf{W}} \in \mathbb{R}^{K \times L}$, which contains elementary fragments:

$$w_{k,l}(t) = \underline{\mathbf{W}}(k,l)_t, \tag{16}$$

where $w_{k,l}(t)$ – is a radio resource allocated for the MNO *k*, at the base station *l*. Thus, the total radio resource is equal to:

$$W = \sum_k \sum_l w_{k,l}(t),\ \forall t. \tag{17}$$

As a baseline let's consider a static method of uniform resource allocation among cells and MNOs. In such a case, for each MNO the bandwidth is defined independently from cells as following:

$$w_{k,l}(t) = \frac{W}{K \cdot L},\ \forall t,\ k \in (1, K), l \in (1, L)\ . \tag{18}$$

A more advanced method, proposed in [20] uses AI traffic prediction for each cell and static bandwidth allocation among the slices within one cell. This method requires initial traffic prediction for each cell $f_l'(t)$, and then the corresponding allocation of available radio resources for each MNO:

$$w_{k,l}(t) = \frac{f_l'(t) \cdot W}{K \sum_{b=1}^{L} f_b'(t)},\ \forall t,\ k \in (1, K), l \in (1, L)\ . \tag{19}$$

Unlike abovementioned methods, we propose a novel method that uses more fine-grained traffic predictions for each MNO independently. In such a case, initially we predict the traffic for each MNO within the single cell $f_{k,l}'(t)$. Thus, the equation for radio resource allocation will be modified as following:

$$w_{k,l}(t) = \frac{f_{k,l}'(t) \cdot W}{\sum_{a=1}^{K} \sum_{b=1}^{L} f_{a,b}'(t)} \approx \frac{f_{k,l}'(t) \cdot W}{\sum_{a=1}^{K} f_a'(t)} \approx \frac{f_{k,l}'(t) \cdot W}{\sum_{b=1}^{L} f_b'(t)},\ \forall t,\ k \in (1, K), l \in (1, L)\ . \tag{20}$$

Simulations are conducted for the different methods of resource allocation: static depicted by (18), semi-intelligent depicted by (19) and the proposed intelligent method depicted by (20). Simulation results for different cells and MNOs are shown in Figs. 8-9. Results are shown only for 4 cells, but they reflect the overall advantage of the proposed fine-grained spectrum management in terms of the stable user experience. Note that in order to properly estimate the effect of bandwidth allocation, all users have been assigned the same channel quality indicator and the round-robin scheduling has been applied. This constraint allows to eliminate all fluctuations of the throughput caused by variable channel conditions and to focus solely on bandwidth allocation for each MNO. The important aspect, which should be mentioned, is that the total available bandwidth for each MNO is equally allocated for all active users of the particular MNO. Therefore, for static and semi-intelligent resource allocation we observe the cases, when few users of one MNO can get very high throughput, while many users of the other MNO within the same cell or in the neighbor cell may experience significant service degradation. Considering that the percentage of users for each MNO within the cell is changing dynamically, the static and semi-intelligent bandwidth allocation experience severe fluctuations of the service quality depends on the number of users. Thus, comparing the results for all MNOs in different cells, we observe that by using the proposed intelligent spectrum allocation among different cells, the data rate fluctuations are mitigated and all users experiencing almost the same throughput, which is close to the optimal resource allocation for the chosen simulation scenario.

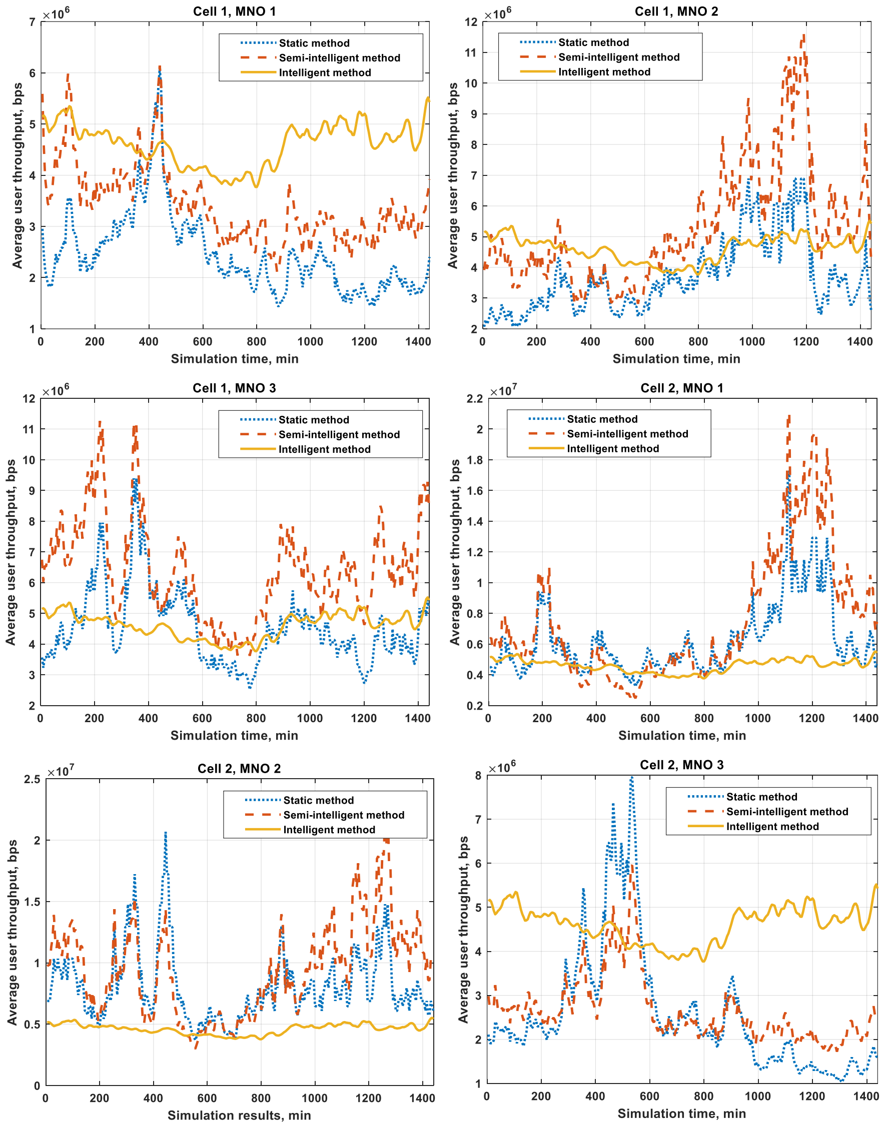

Fig. 8. Simulation results for the average user throughput of 3 MNOs for the cells 1-2.

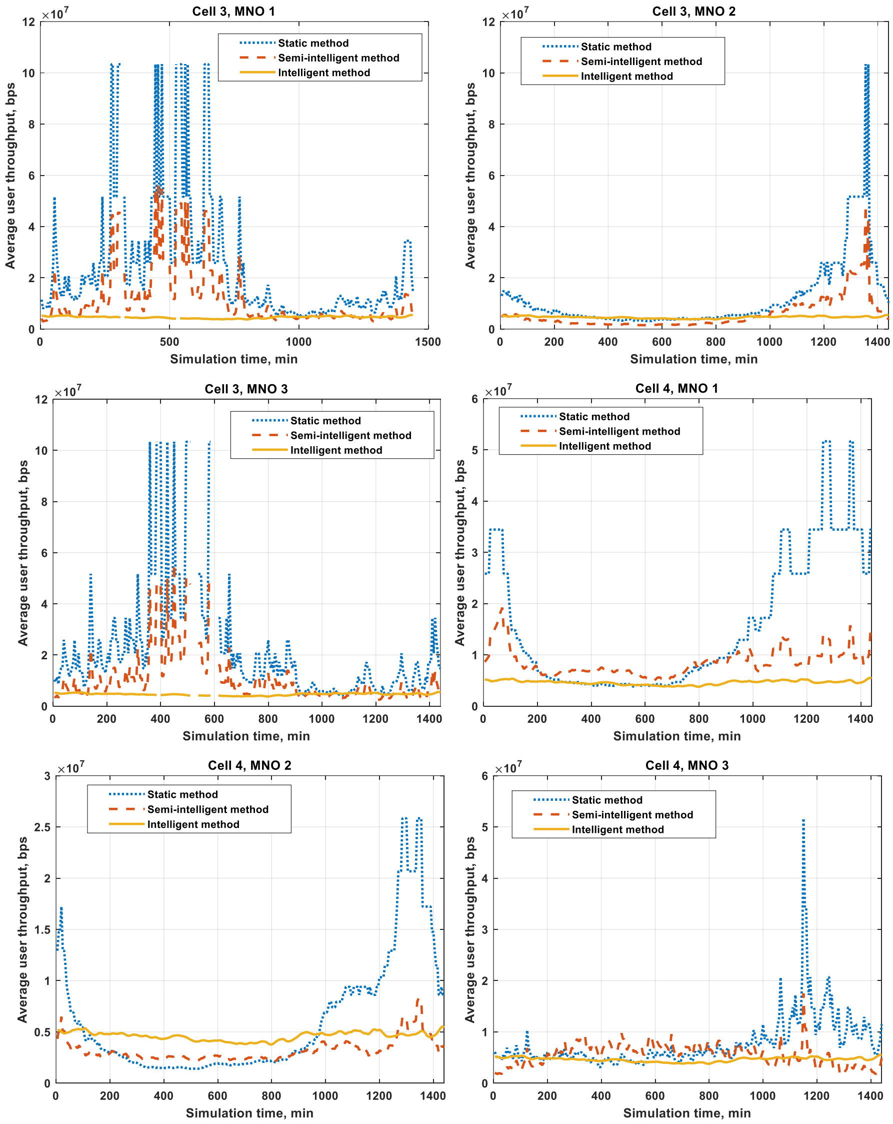

Fig. 9. Simulation results for the average user throughput of 3 MNOs for the cells 3-4.

Thus, the proposed intelligent spectrum management workflow allows MNOs in a decentralized 6G deployment to schedule their corresponding intents by using smart contracts, in order to pre-allocate the needed base stations and spectrum, considering the predicted user demand in each area and the expected number of serviced users. According to the previous findings in [10], such intelligent decentralized resource management allows MNOs to increase their profits by 19%, while maintaining the same service price for the end users.

5 Conclusion

In this chapter, we have proposed the novel concept of the decentralized 6G mobile network operation in condition of open spectrum and infrastructure market by using the combination of the AI and blockchain technologies. We have proposed a high-level architecture for the interactions between MNOs in terms of spectrum and infrastructure sharing. In addition, we have developed a new mathematical model for the data flows management in the decentralized 6G scenario. Furthermore, we have developed the AI-based workflow for network resource management, which achieves better network performance for multiple MNOs in the highly variable network conditions. Simulation results show that the proposed AI workflow provides fair bandwidth allocation for all users regardless of the serving MNO by learning the short and long term patterns of the traffic demand. In this chapter, we have omitted the detailed explanation of the economic aspects and underlying AI and distributed ledger solutions, which have been described in the previous research. In our future research, a particular attention will be given to the new cutting-edge AI and distributed ledger solutions, in order to estimate the performance of the multi-operator 6G network for various scenarios with open spectrum and infrastructure market.

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