Energy and Cost Efficient Resource Allocation for Blockchain-Enabled NFV

Shiva Kazemi Taskou, Mehdi Rasti, Member, IEEE, and Pedro H. J. Nardelli, Senior Member, IEEE

Abstract—Network function virtualization (NFV) is a promising technology to make 5G networks flexible and agile. NFV decreases operators’ OPEX and CAPEX by decoupling the physical hardware from the functions they perform. In NFV, users’ service request can be viewed as a service function chain (SFC) consisting of several virtual network functions (VNFs) which are connected through virtual links. Resource allocation in NFV is done through a centralized authority called NFV Orchestrator (NFVO). This centralized authority suffers from some drawbacks such as single point of failure and security. Blockchain (BC) technology is able to address these problems by decentralizing resource allocation. The drawbacks of NFVO in NFV architecture and the exceptional BC characteristics to address these problems motivate us to focus on NFV resource allocation to users’ SFCs without the need for an NFVO. To this end, we assume there are two types of users: users who send SFC requests (SFC requesting users) and users who perform mining process (miner users). For SFC requesting users, we formulate NFV resource allocation (NFV-RA) problem as a multi-objective problem to minimize the energy consumption and utilized resource cost, simultaneously. To address this problem, we propose an Approximation-based Resource Allocation algorithm (ARA) using Majorization-Minimization approximation method to convexify NFV-RA problem. Furthermore, due to the high complexity of ARA algorithm, we propose a low complexity Hungarian-based Resource Allocation (HuRA) algorithm using Hungarian algorithm for server allocation. Through the simulation results, we show that our proposed ARA and HuRA algorithms achieve near-optimal performance with lower computational complexity. Also, ARA algorithm outperforms the existing algorithms in terms of number of active servers, energy consumption, and average latency. Moreover, the mining process is the foundation of BC technology. In wireless networks, mining is performed by resource-limited mobile users. Since the mining process requires high computational complexity, miner users cannot perform it alone. So, in this paper, we assume that miner users can perform mining process with participating of other users. For mining process, the problem of minimizing the energy consumption and cost of users’ processing resources is formulated as a linear programming problem that can be optimally solved in polynomial time.

Index Terms—network function virtualization, blockchain, virtual network function, consensus mechanism, mining

1 INTRODUCTION

With the ever-increasing users’ traffic and demands on new services in 5G networks, flexibility, scalability, and agility are inevitable. To meet these requirements, Network Function Virtualization (NFV) has attracted great attention from both industry and academia [1]. The main idea of NFV defined by the European Telecom Standards Institute (ETSI) is decoupling the physical infrastructures from the functions running on them [2]. With NFV, network functions that are traditionally run on dedicated hardware which results in high CAPEX and OPEX are typically implemented as Virtual Network Functions (VNFs) on commodity devices in data centers [3].

In NFV, the users’ service requests called Service Function Chains (SFCs) consist of several different VNFs interconnected by virtual links in a given order. To serve SFCs, VNFs should be implemented on commodity devices and the processing resources should be allocated to them, and the communication between them must be provided by physical links bandwidth allocation such that the users’ requirements are satisfied [4]. One of the main challenges of NFV is the allocation of processing resources (known as VNF placement) and physical links bandwidth allocation to communicate between VNFs (known as routing) to execute SFCs [5].

According to the NFV architecture provided by ETSI, NFV Orchestrator (NFVO) is responsible for the creation and life cycle management of SFCs, management of VNFs, NFV infrastructure, and SFCs [6]. Furthermore, NFVO collects the service requests and performs a resource allocation algorithm to allocate processing resources and physical links bandwidth to the SFCs [3], [6]. This architecture relying on NFVO suffers from several drawbacks: (1) vulnerability to failure and the outage due to centralized management of NFV infrastructure [6], (2) the high probability and impact of the attack due to the shared NFV infrastructure between the tenants, and (3) the need for trust-based resource allocation and management in an NFV environment that is inherently trust-less [7]. Recently, blockchain technology has been regarded as a promising decentralized technology to address these pitfalls.

Blockchain (BC) is a decentralized ledger in which trusted data is stored in an untrusted environment in transaction format. In BC, all users and nodes of the network can communicate over a point-to-point network without the need of a centralized trusted entity [8]. In the second generation of BC networks known as Ethereum, smart contract-based BC was proposed [9]. Smart contracts are computer

S. Kazemi Taskou and M. Rasti are with Department of Computer Engineering, AmirKabir University of Technology, Tehran, Iran. (e-mail: {shiva.kt, rasti}@aut.ac.ir). M. Rasti is also a visiting assistant professor in Lappeenranta-Lahti University of Technology, Lappeenranta, Finland. Pedro H. J. Nardelli is with Lappeenranta-Lahti University of Technology, Lappeenranta, Finland. (e-mail: Pedro.Nardelli@lut.fi)
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programs that facilitate contracts between two or more parties. The smart contracts store all the rules agreed by the parties. These smart contracts are stored in the BC after verifying by all parties. The immutability of smart contracts after storing on the BC provides security for parties [9]. In smart contract-based BC, only transactions that satisfy all the conditions of stored smart contracts are validated [9].

Verification of smart contracts and validation of transactions and their ordering in blocks are done based on a consensus mechanism. In the consensus mechanism, nodes and parties agree on the BC status, which results in a single BC throughout the whole BC network verifying by all nodes, although this BC is stored in distributed nodes [10]. Some generations of BC networks such as Bitcoin [1] use an incentive-based consensus named mining process in their protocol to reach agreement in an untrusted environment and among a large number of distributed nodes [10]. Through the mining process, the nodes that perform the mining named miners insert a number of validated transactions into a new block, which is uniquely identified by its hash and time-stamp. In Bitcoin, miners employ the Proof-of-Work (PoW) algorithm for mining. In PoW, miners try to find a random value called nonce for achieving the block’s hash using their computation power. This nonce which should be less than a target value is set to avoid any conflicts and provide trust between nodes. The miner who finds the nonce faster than other miners wins the mining process and receives rewards from the BC network [12]. After generating the new block, the winning miner broadcasts it to all other nodes for verification of the block. The other nodes apply the transactions of this block and add its hash into the next block header. Each new block has the previous block’s hash in its header and a chain of continuous blocks forms the BC [13]. The main characteristics of BC include decentralization, transparency, immutability, availability, and security [12] make it suitable for applying to NFV.

On the other hand, energy consumption in data centers has many environmental, economic, and performance impacts. In addition, recent studies claim that the energy consumption of data centers worldwide in 2012 was 270 TWh [14]. Therefore, reducing the energy consumption of data centers is a very important challenge [14]. Furthermore, NFV has been proposed to reduce operators’ costs, so reducing operators’ consumed resource costs is an important challenge [15].

The drawbacks of the NFV architecture and the exceptional BC characteristics to address these problems as well as the importance of minimizing the energy consumption and costs motivate us to focus on resource allocation to users’ requested SFCs without the need for an NFVO, based on BC technology. To this end, we define the NFV Resource Allocation (NFV-RA) problem with the aim of minimizing the energy consumption and cost of utilized data center resources satisfying users’ maximum end-to-end tolerable delay. Furthermore, to implement NFVO in a distributed manner, we propose a BC framework for NFV resource allocation named NFVChain. To do so, we assume there exist two types of users in our considered system model: (1) users who request SFCs (SFC requesting users) and (2) users who perform the mining process (miner users). For SFC requesting users, we define the NFV-RA problem as explained above. Moreover, since miner users are unable to perform the mining because of their limited processing capacity, we assume each miner user performs the mining process with the help of a group of users. The miner should pay for consuming other users’ processing capacity. So, in this paper, for miner users, the problem of offloading the mining task to a group of users is defined to minimize the energy consumption in the mining process and minimize the cost of other users’ processing capacity. It is worth mentioning that we call this problem as Mining Offloading (MO) problem.

1.1 Related Works

In this section, we first discuss the related works from two aspects, namely resource allocation in NFV relied on ETSI proposed architecture followed by a discussion on the integration of BC technology with 5G networks.

1.1.1 Resource Allocation in NFV Relied on ETSI Proposed Architecture

The NFV-RA problem (i.e., VNF placement and routing) has been extensively investigated in literature [5], [16]–[28]. The problem of minimizing the end-to-end delay is considered in [16]–[18]. In [16], the end-to-end delay is defined as the waiting delay in the server processing queue, while in [17] and [18], the end-to-end delay is defined as the transmission delay over physical links. The problem of minimizing the transmission delay in [17] is defined as a mixed-integer linear programming (MILP) problem. To tackle the NP-hardness of this problem, a heuristic algorithm is proposed. The NFV-RA problem in [18] is defined as a multi-objective problem that aims to minimize the transmission delay and link bandwidth consumption and maximize servers’ load rate, simultaneously. Authors in [18] proposed a heuristic algorithm based on the breadth-first search method to solve this problem. The authors in [19]–[21] have proposed heuristic algorithms to minimize the number of utilized servers to reduce the cost of consumed computing resources of data centers. In [19] and [20], two active and inactive states for each server in the data center are assumed, and the aim of the NFV-RA problem is to minimize the number of active servers. In [20] and [21], the maximum end-to-end tolerable delay which is defined as the sum of processing delays on servers and transmission delays on links is guaranteed for each SFC request. The problem of minimizing the cost of utilized servers and physical links is investigated in [5], [22]–[24]. In [22], this problem is formulated as an ILP problem and an online algorithm has been proposed to address it. The NFV-RA problem in [5] is defined as a multi-objective problem with the aim of minimizing the cost of utilized servers and links and the cost of transmission delay over links. A heuristic algorithm is proposed to solve this problem in [5]. In [25]–[28], the servers and physical links are allocated to SFCs such that as many as possible SFC requests are admitted. Authors in [25] proposed an online heuristic algorithm to
maximize the number of admitted SFCs satisfying the end-to-end transmission delay requirement. In [25], the NFV-RA problem is formulated as a multi-objective problem to maximize the number of admitted SFCs and minimize the amount of utilized resources, simultaneously. The authors in [27] proposed a heuristic algorithm to address the NFV-RA problem which is defined as a multi-objective problem with the aim of minimizing the utilized links and maximizing servers’ utilization. The problem of minimizing the amount of required resources to accept all SFC requests is addressed in [28]. Furthermore, in [28], for each SFC request, the end-to-end delay which is defined as the sum of the transmission delay on the links is satisfied.

1.1.2 Integration of BC Technology With 5G Networks
The application of BC technology in 5G networks is investigated in several existing works [29]–[34]. In [29], BC technology is used to solve the problem of selfish behavior of relays in cooperative networks. In addition, traditionally, the trading between relays and users is modeled as an auction algorithm. It is worth noting that the auction algorithm is relied on third-party and suffers from drawbacks such as privacy, trust, and a single point of failure. To tackle these problems in [29], communication between users and relays is provided through smart contract-based blockchain. In the BC framework proposed in [29], users send their requests to relays by calling smart contract functions. Then, relays solve a power control optimization problem to calculate the best transmit power needed to send users requests. The relays then announce the cost that users have to pay for the transmission power by calling functions in the smart contract. Finally, users and relays exchange payment by calling smart contract functions. In [30], BC technology is implemented to enable communication between users and Mobile Edge Computing (MEC) servers which is traditionally established in a centralized manner. In [30], a BC-based framework is proposed in which users submit their requests to BC, other users and MEC servers decide about MEC server allocation to the users’ requests, performing a matching algorithm. Users’ requests and MEC servers’ responses are stored in BC history after the mining process. In [31], MEC servers announce their available resources by calling smart contract functions. Then, users decide to execute their tasks locally or offloading to the MEC servers by solving an optimization problem aiming at processing cost minimization. If they decide to offload, they request their required computation resources by calling functions in the smart contract. Based on the functions of this smart contract, users pay the costs to the MEC servers and the MEC servers lease their resources to the users. The authors in [32]–[33] propose BC-based approaches for virtual wireless networks. In virtual wireless networks, there is a broker that leases resources from the infrastructure provider (InP) and rents them to the mobile virtual network operators (MVNOs). This centralized broker suffers from a single point of failure and should be trusted. To overcome these problems, BC is a promising technology to implement a broker. In the proposed frameworks in [32]–[33], MVNOs send their resource requirements in a transaction and the InP announces the cost of their resources in response to this transaction. These transactions are added to the blocks and after mining stored in BC history. In [34], a permissioned BC is employed to reach a consensus to securely collect and synchronize information among multiple NFV management and orchestration (MANO) systems, where the required computation of the BC network is assumed to provided by MEC servers. Furthermore, the allocation of MEC servers’ computational resources to the BC network is done to minimize users’ cost and improve BC throughput.

To the best of our knowledge, there is no work in the literature that studies the NFV-RA problem considering BC technology. In addition, the problem of minimizing the energy consumption of servers and the cost of utilized resources for NFV-RA is addressed for the first time in this paper. To alleviate these drawbacks, in this paper, we focus on the blockchain-enabled NFV-RA. To do so, the problem of minimizing the servers’ energy consumption and minimizing the cost of utilized resources is formally stated as a multi-objective problem. Similar to [5], [16]–[28], the processing capacity of servers and the bandwidth of physical links are assumed to be limited. In addition, similar to [16]–[18], [21]–[22], [24], and [28], the end-to-end tolerable delay for each SFC request is guaranteed. Despite [7]–[18], [24], and [28] in which only the transmission delay over links is considered as the end-to-end delay, in this paper, not only the transmission delay on physical links but also the processing delay in servers are considered which is more practical. The authors in [5], [16]–[28] propose algorithms to allocate resources to the SFC requests through NFVO which is a centralized authority, in this paper, resource allocation to SFCs is performed through a smart contract-based BC as a decentralized approach in comparison with [5], [16]–[28]. Moreover, in contrast to [5], in which a permissioned BC is employed to reach consensus among multiple MANOs, we employ a more practical permissionless blockchain in which any node can act as a miner, and there is no need to trust in miners. Besides, in [5] the computing resources for performing the mining process are provided by MEC servers, while in this paper, we assume that the mining process is done by participating a group of users. Furthermore, the mining process to generate a new block is performed by resource-limited mobile devices that will not be able to perform the mining process alone due to the high computational complexity of the mining process. Hence, in our system model, the user who wants to perform the mining process (i.e., miner user) performs the mining process in collaboration with a group of other users. In this way, the miner user should pay to the other users for consuming their processing capacity. Therefore, for miner users, the problem of mining task offloading to a group of users is defined in order to minimize the miners’ energy consumption and the cost of other users’ processing capacity.

1.2 Our Contribution
Our main contributions are described as follows:

- In this paper, we exploit the advantages of BC technology to overcome the problems of NFV-RA through NFVO and propose a trusted, decentralized, and secure framework so-called NFVChain. In NFVChain, we consider two types of users, namely,
users who request SFCs (SFC requesting users) and users who perform the mining process as miner users. In fact, in NFVChain, the role of NFVO is distributed among miner users.

- In the system model, we consider two types of users, users who send SFC requests (SFC requesting users) and users who perform mining process (miner users).
  
  - For SFC requesting users, the NFV-RA problem aimed at minimizing the servers’ energy consumption and the cost of utilized processing resources and bandwidth of links is defined as a multi-objective problem satisfying the end-to-end tolerable delay for each SFC. This problem is a MILP problem, and due to its NP-hardness, we convert binary variables into continuous variables using a penalty function. Then we transform the problem into an LP problem using the Majorization-Minimization approximation method which can be solved by off-the-shelf optimization software packages. We call this algorithm as ARA (Approximation-based Resource Allocation). Additionally, to reduce the complexity of ARA algorithm, we propose a heuristic algorithm based on the Hungarian method named HuRA (Hungarian-based Resource Allocation).
  
  - For miner users, since they are unable to do the mininglonely because of their limited processing capacity, each miner performs the mining process with the help of a group of users. The miner user should pay for consuming other users’ processing capacity. A miner user who completes the mining process faster than other miners adds a new block to the BC and receives rewards. In this paper, for miner users, the problem of offloading the mining task to a group of users (i.e., MO problem) is defined to minimize the energy consumption in the mining process and minimize the cost of other users’ processing capacity. This problem is an LP problem and can be optimally solved by off-the-shelf optimization software packages in polynomial time.

- The simulation results demonstrate that our proposed ARA and HuRA algorithms to address the NFV-RA problem obtain near-optimal performance with very low complexity. Moreover, the performance of the optimal solution of the MO problem is shown via simulation results.

The remainder of this paper is organized as follows. In Section 2 we introduce the system model and notations. In Section 3 we formally state the NFV-RA problem. The MO problem for mining process and its solution are proposed in Section 4. The proposed algorithms to address the stated NFV-RA problem is presented in Section 5. Finally, the simulation results and conclusion are presented in Section 6 and Section 7 respectively.

2 System Model and Notations

Consider a BC-enabled NFV network which consists of two types of users: SFC requesting users and miner users. Therefore, there exists a set of $\mathcal{U} = \mathcal{U}_S \cup \mathcal{U}_M$ users, where $\mathcal{U}_S$ and $\mathcal{U}_M$ denote the set of SFC requesting users and miner users, respectively. In this section, we describe the notations for NFV, framework of BC-enabled NFV (NFVChain), and notations for blockchain network, respectively. The list of notations for NFV and blockchain network are represented, respectively, in Table 4 and Table 5 in Appendix A.

2.1 Network Function Virtualization Notations

The 5G core networks consist of two types of network functions (NFs) including control plane NFs and data plane NFs. The control plane NFs such as Access and Mobility Management Function (AMF), Session Management Function (SMF) and etc., handle control plane only and data plane NF i.e., User plane function (UPF) handles data plane only [35]. In 5G core networks, users for receiving their desired services should connect to the network. To do so, AMF, SMF, and UPF should be performed in order for establishing a tunnel between the users’ serving base stations and the UPF. These three NFs are required for all services, although other NFs may be implemented between these functions which their existence and order depend on the requested services [35].

In the NFV-based 5G core, each of the NFs is performed on commodity servers in the data center and communication between them is provided through physical links. Although in this paper, we consider 5G core virtualization, without loss of generality, this system model is applicable to virtualization of any kind of networks such as 5G radio access networks, LTE core and radio access networks, transport networks, and the Internet.

To implement an NFV-based 5G core, we assume there is a data center which is modeled as a directed graph $G = (\mathcal{V}, \mathcal{L})$, where $\mathcal{V}$ is the set of servers and $\mathcal{L}$ is the set of directed links. The server set $\mathcal{V}$ can be further categorized into three disjoint subsets, i.e., $\mathcal{V} = \{\mathcal{AC}, \mathcal{TR}, \mathcal{N}\}$ with $\mathcal{AC}$ as the access switches (source nodes), $\mathcal{TR}$ as the transport switches (destination nodes), and $\mathcal{N}$ as the processing servers. Each processing server $n \in \mathcal{N}$ has a maximum processing capacity, denoted by $C^{\text{max}}_n$ CPU cycles per second. Also, the maximum traffic which can be carried by link $l \in \mathcal{L}$ is limited to $B^{\text{max}}_l$ bits per second. It should be noticed that the access and transport switches do not have any computation capability and only forward traffic. Therefore, no limitation on processing capacity is considered for these switches.

We assume there is a set of SFC requesting users denoted by $\mathcal{U}_S$. Each SFC consists of a number of VNFs that run sequentially. Let $\mathcal{S}_i = \{1, 2, \cdots, J_i\}$ denote the SFC for user $i$, where $\mathcal{S}_i[1] = \text{AMF}$ and $\mathcal{S}_i[J_i] = \text{UPF}$. Furthermore, $\mathcal{S}_i[2], \mathcal{S}_i[3], \cdots, \mathcal{S}_i[J_i - 1]$ contain SMF and other VNFs whose existence and order depend on the provided service type by SFC $\mathcal{S}_i$. Additionally, by default each SFC $\mathcal{S}_i$ has a specific source node and destination node denoted by $\mathcal{S}_i[0]$ and $\mathcal{S}_i[J_i + 1]$, respectively. Specifically, the access switches and transport switches are considered as source and destination nodes, respectively i.e., $\mathcal{S}_i[0] \in \mathcal{AC}$ and $\mathcal{S}_i[J_i + 1] \in \mathcal{TR}$. 

To describe the embedding of the SFCs on data center, we define the binary variable \( x_{n,j}^{i} \) to indicate the embedding of \( j \)th VNF of user \( i \)'s SFC on server \( n \). If server \( n \) is chosen to perform \( j \)th VNF of user \( i \)'s SFC, \( x_{n,j}^{i} = 1 \), otherwise, \( x_{n,j}^{i} = 0 \). Also, \( y_{l}^{j+1} \) is a continuous variable that represents the bandwidth allocation of physical link \( l \) to virtual link between \( j \)th and \( j+1 \)th VNFs of user \( i \)'s SFC. Each link \( l \in \mathcal{L} \) is assumed to be bi-directional. We assume that the required CPU cycles for each VNF \( j \) of SFC \( S_i \) and the required bandwidth for links between \( j \)th and \( j+1 \)th VNFs of \( S_i \) are denoted by \( C_{i,j} \) and \( B_{l}^{\max} \), respectively. It should be noticed that different SFCs require different types of VNFs, that must be performed in order, and each of these VNFs requires processing resources, which is defined as the number of required CPU cycles per second. For example, a VNF to perform video encoding requires \( \lambda \) units of CPU processing capacity to encode a video stream with a required bandwidth for links between \( j \)th and \( j+1 \)th VNFs \( y_{l}^{j+1} \) are obtained by \( \sum_{n \in \mathcal{N}} \sum_{j \in \mathcal{S}_i} x_{n,j}^{i} C_{i,j}/C_{n}^{\max} + \sum_{l \in \mathcal{L}} \sum_{j \in \mathcal{S}_i \cup \{0\}} y_{l}^{j+1}/B_{l}^{\max} \). Accordingly, the end-to-end delay of SFC \( S_i \) is expressed as

\[
T_i = \sum_{n \in \mathcal{N}} \sum_{j \in \mathcal{S}_i} x_{n,j}^{i} C_{i,j}/C_{n}^{\max} + \sum_{l \in \mathcal{L}} \sum_{j \in \mathcal{S}_i \cup \{0\}} y_{l}^{j+1}/B_{l}^{\max}.
\] (1)

In this paper, to reduce the energy consumption in the data center, similar to [19–20], we consider two active and inactive modes for servers. To represent the mode of each server \( n \), we define the binary variable \( \beta_{n} \), if the server \( n \) is active, \( \beta_{n} = 1 \), otherwise, \( \beta_{n} = 0 \). If at least one VNF is assigned to the server \( n \), the server will be active, otherwise, the server will be inactive. In the inactive mode, the server is off and consumes no power [37]. While in the active mode, the server consumes the static power \( p_{n}^{s} \) to be active and power \( p_{n} \) to process every CPU cycle.

### 2.2 Framework of Blockchain-Enabled NFV (NFVChain)

To implement NFVChain, we design a smart contract which contains all agreed important rules between users and InP. Each smart contract has an address and smart contracts are created and published on the BC, (2) the InP advertises all available resources and unit price of its resources, (3) users submit their SFC requests, (4) the InP performs the resource allocation algorithms and sends the allocated resources and costs to the users, and (5) users pay to InP. The smart contract functions for NFV-RA is illustrated in Table 1. These functions are explained in more detail in what follows.

**InP-Information().** By calling this function, the InP advertises its wallet address (WA_{InP}), the unit price of its resources (cost), the available resources, and the information required by users including the power consumption of servers, the maximum processing capacity of servers, and maximum bandwidth of physical links (resources). Furthermore, it creates an empty set of SFCs (SFCs= []). InP then signs this transaction with its private key. Then it broadcasts the signed transaction to all users. By doing so, users are informed that InP wants to sell its resources.

**RA-Request().** Users authenticate the InP by checking its public key when they receive the transaction and confirm the available resources and the cost claimed by the InP (check(WA_{InP}, resources, cost)). If this information is correct, users will send their IDs, wallet addresses, quality of service (QoS) requirements, and SFC information in a transaction (ID_{SFC}, WA_{SFC}, requirement, information). Each user’s ID is added to the list of SFCs (add(SFCs, ID_{SFC})).

**ARA() & HuRA().** Upon receiving users’ transactions, the InP invokes the corresponding functions of one of the two proposed algorithms in Section 5 to address NFV-RA problem [14], i.e., ARA() or HuRA() algorithms. It then authenticates users by checking their public keys (verify(ID_{SFC}, WA_{SFC})). After successful authentication, InP executes ARA() or HuRA() algorithm (run(ARA algorithm) or run(HuRA algorithm)). The resource allocation results and the total cost of resources are sent to each user (send(ID_{SFC,RA results}) and send(ID_{SFC,cost})).

**Payment().** Each user confirms InP’s transaction by checking whether the QoS requirement is met (check(requirement satisfying)). Then it checks the total cost declared by the InP (check(cost)). If the resource allocation results and total cost are correctly stated by InP, the user pays the cost to the InP (send(WA_{InP}, cost)).

Briefly, in NFVChain, each SFC requesting user sends a transaction to InP, including its SFC information such as number and type of VNFs, required CPU cycles for each VNF, and required bandwidth between VNFs. Then, InP performs ARA or HuRa algorithms to allocate resources to SFC requesting users. The resource allocation results are sent to each user. These transactions are aggregated to one block by miners. Each miner who generates a block should perform the mining process. The winner miner’s block is added to BC. After adding the block to BC, all transactions such as transactions including resource allocation results are performed.

To add a block to BC, the transactions generated by InP and users should be verified by the miner users. To do so, the miner users check whether all transactions meet all the

| TABLE 1: smart resource allocation contract |
|---------------------------------------------|
| **InP-Information():** WA_{InP}, resources, cost, SFCs = [] |
| **RA-Request():** check(WA_{InP}, resources, cost), ID_{SFC}, WA_{SFC}, requirement, information, add(SFCs, ID_{SFC}) |
| **ARA():** verify(ID_{SFC}, WA_{SFC}), run(ARA algorithm), send(ID_{SFC,RA results}), send(ID_{SFC,cost}) |
| **HuRA():** verify(ID_{SFC}, WA_{SFC}), run(HuRA algorithm), send(ID_{SFC,RA results}), send(ID_{SFC,cost}) |
| **Payment():** check(requirement satisfying), check(cost), send(WA_{InP}, cost) |
conditions stated in the smart contract or not. If all conditions are met, the transaction is verified. To verify each transaction, miner users should check (1) the QoS requirement of users are satisfied, (2) the total cost announced by InP should be obtained according to the unit price of resources, (3) resource allocation algorithms are implemented correctly and their outputs are correct, and (4) the cost paid by the user should be the same as the cost declared by the InP. After transaction verification, miner users place a number of verified transactions in a new block and start the mining process. Once the block is mined, the new block is broadcast to all other miner users for verification, and the miner users add it to the BC after block verification. Each block contains a transaction in which the miner user has specified its preferred reward. Verification of the blocks is done in terms of (1) miner user’s requested reward not exceeding the specified value in the BC protocol, (2) all transactions of this task. In our system model, there is a set of users in system i.e., the energy consumption of user \( k \) is given by \( f_{i,k}D_{i,k}/R_{i,k} \), where \( R_{i,k} \) is the data rate between miner user \( i \) and user \( k \). Assuming a constant transmit power for all miner users, \( R_{i,k} \) is calculated by \( R_{i,k} = \log_2 \left( 1 + \frac{p_{i,k}h_{i,k}}{\sigma_k} \right) \), where \( p_{i,k} \) is the transmit power of miner user \( i \) to user \( k \), \( h_{i,k} \) is the path-gain from miner user \( i \) toward user \( k \), and \( \sigma_k \) is the noise power at user \( k \). Accordingly, the energy consumption for transmission from miner user \( i \) to user \( k \) is given by \( p_{i,k}f_{i,k}D_{i,k}/R_{i,k} \). The taking time of user \( k \) to process the corresponding portion of mining task \( i \) is given by \( T_{i,k}^{erce} = f_{i,k}D_{i,k}/F_{max} \) where \( F_{max} \) is the maximum CPU cycles per second of user \( k \)’s device for processing at each second. Accordingly, the total energy consumption during mining process is calculated by

\[
E_{mine}=\sum_{i \in U_M} \sum_{k \in K_i} \left[ p_{i,k} \left( f_{i,k}D_{i,k}/R_{i,k} \right) + \tilde{p}_k \left( f_{i,k}D_{i,k}/F_{max} \right) \right]. 
\]

3 Problem Formulation for NFV Resource Allocation

In this section, the optimization problem for allocating data center resources to SFC requesting users is stated. To do so, the multi-objective optimization problem is formally defined to minimize data center energy consumption and minimize the cost of utilized resources. In this problem, there are a number of constraints that must be satisfied. These constraints include constraints for VNF placement, routing, and the users’ QoS, which are respectively explained in what follows.

3.0.1 VNF Placement Constraints

For embedding the SFCs at data centers, only one server should be allocated to each VNF \( j \in S_i \). Therefore, in the resource allocation problem, we have

\[
C1: \sum_{n \in N} x_{i,j} = 1, \quad \forall i \in U_S, \quad \forall j \in S_i. 
\]

We assume that every VNF of each SFC should be mapped to a different server. So, we have

\[
C2: \sum_{j \in S_i} x_{i,j} \leq 1, \quad \forall i \in U_S, \quad \forall n \in N. 
\]

As aforementioned, each server at data center has limited processing capacity. The processing capacity limitation of servers which implement VNFs is represented by

\[
C3: \sum_{i \in U_S} \sum_{j \in S_i} x_{i,j} C_{i,j} \leq \beta_n C_{n}^{max}, \quad \forall n \in N. 
\]

The following constraint ensures that server \( n \) is active only when it hosts at least one VNF

\[
C4: x_{i,j} \leq \beta_n, \quad \forall n \in N, \quad \forall i \in U_S, \quad \forall j \in S_i. 
\]

3.0.2 Routing Constraints

Let \( C_{out}^n \) and \( C_{in}^n \) denote the outgoing links from server \( n \) and incoming links to server \( n \), respectively. The following constraint enforces flow conservation, i.e., the incoming traffic in servers that do not host VNFs should be equal to the outgoing ones. More precisely, this constraint ensures that the sum of the outgoing links bandwidth of server \( n \) that is running \( j \)th VNF of SFC \( S_i \) has to be the same as required bandwidth for transmitting traffic from \( j \)th to \( j+1 \)th VNF. Also, this constraint makes sure that sum of the incoming links bandwidth of server \( n \) that runs \( j+1 \)th VNF of SFC \( S_i \) has to be the same as required bandwidth for traffic transmission from \( j \)th to \( j+1 \)th VNF. So, the flow conservation constraint can be considered in the resource allocation problem as

\[
C5: \sum_{i \in E_{out}^n} y_{i,j+1} - \sum_{i \in E_{in}^n} y_{i,j+1} = B_i^{j,j+1}(x_{i,j}^{i,j+1}) - x_{i,j}^{i,j+1}, 
\]

\[
\forall i \in U_S, \quad \forall j \in S_i \cup \{0\}, \quad \forall n \in N. 
\]
It should be noted that constraint C5 ensures that sum of the outgoing links bandwidth of access switch (source node) to the server on which AMP is implemented has to be the same as required bandwidth between access switch and AMF. Likewise, the incoming links bandwidth to the transport switch (destination node) from UPF host server is the same as required bandwidth between UPF and transport switch.

The maximum bandwidth of links carry out the traffic is indicated by

$$\sum_{i \in U_S} \sum_{j \in S_i} y_{i,j}^{l+1} \leq B_{i}^{\max}, \forall l \in L,$$  

(8)

### 3.0.3 SFC Requesting Users’ QoS

The QoS requirement for user $i$’s SFC is defined as maximum end-to-end tolerable delay, $T_i^\text{th}$. Accordingly, we have

$$C7 : \sum_{n \in N} x_{i,n}^{j} \left(\frac{C_{i,j}^{\text{max}}}{C_{n}^{\text{max}}} \right) + \sum_{l \in L} \sum_{j \in S_i \cup \{0\}} \frac{y_{i,j}^{l+1}}{B_{i}^{\max}} \leq T_i^\text{th},$$  

(9)  

where $\forall i \in U_S$.

$C7$ means that the summation of processing delay on servers and transmission delay on physical links should not be larger than a maximum tolerable delay.

In NFV-RA, minimizing data center energy consumption and minimizing the cost of utilized data center resources are of interest. The energy consumed ($E$) in the data center is given by

$$E = \sum_{n \in N} \beta_{n} p_{n}^{i} + \sum_{n \in N} p_{n} \sum_{i \in U_S} \sum_{j \in S_i} \left(\frac{x_{i,n}^{j} C_{i,j}}{C_{n}^{\text{max}}} \right).$$  

(10)

The cost of resources for user $i$’s SFC is expressed as the unit price of each CPU cycle of server $n$ denoted by $\text{cost}_{i,n}$ and the unit price for transmitting each bit per second over physical link $l$ denoted by $\text{cost}_{i,l}$. So, the cost of resources used by all SFC requesting users is obtained by

$$\text{cost} = \sum_{n \in N} \sum_{i \in U_S} \sum_{j \in S_i} \left(\text{cost}_{i,n} x_{i,n}^{j} C_{i,j} \right) + \sum_{l \in L} \sum_{i \in U_S} \sum_{j \in S_i \cup \{0\}} \left(\text{cost}_{i,l} y_{i,j}^{l+1} \right).$$  

(11)

Accordingly, the objective function of NFV-RA problem is expressed as

$$\min_{\beta, X, Y} \sum_{n \in N} \beta_{n} p_{n}^{i} + \sum_{n \in N} p_{n} \sum_{i \in U_S} \sum_{j \in S_i} \left(\frac{x_{i,n}^{j} C_{i,j}}{C_{n}^{\text{max}}} \right),$$

$$\min_{\beta, X, Y} \left( \sum_{n \in N} \sum_{i \in U_S} \sum_{j \in S_i} \text{cost}_{i,n} x_{i,n}^{j} C_{i,j} \right) + \sum_{l \in L} \sum_{i \in U_S} \sum_{j \in S_i \cup \{0\}} \left(\text{cost}_{i,l} y_{i,j}^{l+1} \right).$$

(12)

The multi-objective function can be shown by a single objective function using the weighted sum method in which two objective functions are linearly combined. So, the objective function of NFV-RA problem in (12) is illustrated by a single-objective function as

$$F(\beta, X, Y) = \alpha \sum_{n \in N} \beta_{n} p_{n}^{i} + \sum_{n \in N} p_{n} \sum_{i \in U_S} \sum_{j \in S_i} \left(\frac{x_{i,n}^{j} C_{i,j}}{C_{n}^{\text{max}}} \right) + (1 - \alpha) \left[ \sum_{n \in N} \sum_{i \in U_S} \sum_{j \in S_i} (\text{cost}_{i,n} x_{i,n}^{j} C_{i,j}) \right] + \sum_{l \in L} \sum_{i \in U_S} \sum_{j \in S_i \cup \{0\}} \left(\text{cost}_{i,l} y_{i,j}^{l+1} \right),$$

(13)

where $0 \leq \alpha \leq 1$ is a given weighted factor which reflects the relative importance of energy consumption and utilized resources cost. $\beta$ is a vector of binary values which indicates the active and inactive modes of servers, $X$ and $Y$ are the server and link bandwidth allocation matrices. Therefore, the NFV-RA problem is formally stated as

$$\min_{\beta, X, Y} F(\beta, X, Y)$$

s.t.  

$C1, C2, C3, C4, C5, C6, C7,$

$C8 : \beta_{n} \in \{0, 1\}, \forall n \in N,$

$C9 : x_{i,n}^{j} \in \{0, 1\}, \forall n \in N, \forall i \in U_S, \forall j \in S_i,$

$C10 : y_{i,j}^{l+1} \geq 0, \forall l \in L, \forall i \in U_S, \forall j \in S_i \cup \{0\},$  

(14)

where $C8$ and $C9$ represents the binary nature of servers’ modes and server allocation variables, respectively. $C10$ implies that the allocated links bandwidth to users’ SFC should be a non-negative value. Problem (14) is an MILP problem and generally NP-hard. In Section 5, we propose two sub-optimal algorithms named ARA and HuRA to address problem (14).

### 4 Problem Formulation for Mining Process

To allocate NFV resources to SFC requesting users in a distributed manner employing BC technology, miner users should perform the mining process. The mining process consumes a significant amount of energy, so minimizing the energy consumption in the mining process is an important challenge. Besides, since in wireless networks, the resource-limited and battery-powered mobile devices act as miners, they cannot perform the mining process on their own, so in this paper, we assume that miner $i$ offloads the processing required for the mining process to a group of users and pays to them for their processing capacity consumption. Also, any miner who mines the block faster than the others receives a reward from BC network. Note that the communication between miners and participating users is provided through the device to device communication.

The reward that the winning miner receives is made up of two components: (1) a constant value ($R_{\text{const.}}$), (2) a variable value that depends on the number of transactions in the block ($N_{\text{Trans}} R_{\text{Trans}}$, where $N_{\text{Trans}}$ is the number of transactions in the mined block and $R_{\text{Trans}}$ is reward of each transaction) [41], [42].

The successfully of a mined block depends on two steps. In the first step, the winning miner must finish the mining process faster than the other miners. The probability of successfully at this step depends on the relative computing power of the miner. This probability is obtained from the
ratio of the miner user $i$’s demand to the total demand of all miner users as $D_i C_i / \sum_{j \in \mathcal{U}_M} D_j C_j$. In the second step, the winning block should be propagated faster than the other blocks in the network. A block may mine quickly, but because of its large size, it will be discarded due to the long propagation latency, which is called orphaning. The probability of a block being orphaned depends on the number of transactions in the block. It is also assumed that mined block production follows the Poisson distribution. Accordingly, the probability of a block being orphaned is given by $p_{\text{orphan}} = 1 - e^{-\lambda z N_{\text{trans}}}$, where $\lambda = \frac{1}{600}$ is the mean value of Poisson distribution and $z$ is a given network latency parameter. So the probability of winning a block is $1 - p_{\text{orphan}} = e^{-\lambda z N_{\text{trans}}}$. The corresponding reward to the miner $i$ is obtained by

$$Rw_i = \frac{D_i C_i}{\sum_{j \in \mathcal{U}_M} D_j C_j}(R_{\text{const}} + N_{\text{Trans}} R_{\text{Trans}}) e^{-\lambda z N_{\text{trans}}}.$$  

(15)

In this paper, we aim at minimizing the energy consumption of mining process and minimizing the cost minus reward of miners. Accordingly, the objective function of MO problem is

$$\min_{f} \sum_{i \in \mathcal{U}_M} \sum_{k \in \mathcal{K}_i} \left[ p_{i,k} \left( \frac{f_{i,k} D_i}{R_{i,k}} \right) + \tilde{p}_k \left( \frac{f_{i,k} D_i C_i}{F_{k}^{\text{max}}} \right) \right],$$

(16)

Similar to the objective function of NFV-RA, (16) can be illustrated as a single objective function

$$\min_{f} \gamma \left( \sum_{i \in \mathcal{U}_M} \sum_{k \in \mathcal{K}_i} \left[ p_{i,k} \left( \frac{f_{i,k} D_i}{R_{i,k}} \right) + \tilde{p}_k \left( \frac{f_{i,k} D_i C_i}{F_{k}^{\text{max}}} \right) \right] \right),$$

where $0 \leq \gamma \leq 1$ is a weighted factor which reflects the relative importance of energy consumption and offloading cost and $f$ is the offloading matrix. Hence, to implement NFVO in a distributed manner, the MO problem for mining process is formally stated as

$$\min_{f} \quad G(f)$$

(18a)

s.t.

$$\sum_{k \in \mathcal{K}_i} f_{i,k} D_i C_i \leq F_{k}^{\text{max}}, \quad \forall k \in \mathcal{K}_i, \quad \forall \mathcal{K}_i \subseteq \mathcal{U},$$

(18c)

$$\max_{k \in \mathcal{K}_i} \left( \frac{f_{i,k} D_i}{R_{i,k}} + \frac{f_{i,k} D_i C_i}{F_{k}^{\text{max}}} \right) \leq T_i^{\text{mine}}, \quad \forall i \in \mathcal{U}_M,$$

(18d)

$$f_{i,k} \geq 0, \quad \forall i \in \mathcal{U}_M, \quad \forall k \in \mathcal{K}_i, \quad \forall \mathcal{K}_i \subseteq \mathcal{U},$$

(18e)

3. Since in BC networks, at a rate of every 600 seconds, a new block is generated, the difficulty of generating a new block is dynamically adjusted so that it takes 600 seconds. Accordingly, the mining Poisson process has a fixed parameter for the whole miner users which equals to $\lambda = \frac{1}{600}$.  

where (18b) implies that the total portion of the mining task executed by all users collaborating to do mining task $i$ should be equal to 1, (18c) represents that the total CPU cycles of user $k$ which is allocated to miner users to do mining task should be less than the maximum processing capacity of user $k$’s device, (18d) shows that the delay for performing a mining process should be less than a maximum delay.

By solving the MO problem (18), each miner offloads its mining task onto a set of $\mathcal{K}_i$ users so that each participating user performs a portion of the mining task. Since the decision variables $f_{i,k} \geq 0, \forall i \in \mathcal{U}_M, \forall k \in \mathcal{K}_i$ in (18) is a continuous variable and the objective function and constraints of problem (18) are linear functions with respect to it, problem (18) is an LP problem. Therefore, the optimal solution of problem (18) can be easily obtained by off-the-shelf optimization software packages such as CVX toolbox.

5 OUR PROPOSED ARA AND HURA ALGORITHMS

To solve NFV-RA problem (14), we obtain optimal solution for a small-scale network using SCIP optimization toolbox. Furthermore, to deal with NP-hardness of the MILP problem (14), we relax the binary variables and add a penalty function to the objective function of problem (14) [45], [46]. This makes the objective function of problem (14) non-convex, so, we approximate it by Majorization-Minimization approximation method [45] and obtain a near-optimal solution. This proposed algorithm is called ARA which has high computational complexity and is suitable for benchmarking. Therefore, to reduce the computational complexity of ARA, we propose a heuristic algorithm based on Hungarian algorithm named HuRA.

5.1 Our Proposed ARA Algorithm

Because of binary nature of server allocation variables (i.e., $x_{n}^{i,j}$) and active or inactive modes of servers (i.e., $\beta_n$), NFV-RA problem (14) is NP-hard. So, to overcome this difficulty, similar to [45] and [46], we replace the binary variables constraint C8 and C9 in [14], respectively by following equivalent constraints

$$\text{C8.1} : \sum_{n \in \mathcal{N}} (\beta_n - \beta_n^2) \leq 0,$$

(19)

$$\text{C8.2} : 0 \leq \beta_n \leq 1, \quad \forall n \in \mathcal{N},$$

and

$$\text{C9.1} : \sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{S}_n} (x_{n}^{i,j} - x_{n}^{i,j}) \leq 0,$$

(20)

$$\text{C9.2} : 0 \leq x_{n}^{i,j} \leq 1, \forall n \in \mathcal{N}, \forall i \in \mathcal{U}_S, \forall j \in \mathcal{S}_i.$$  

By substituting the binary constraints C8 and C9 in [14] with constraints C8.1 and C8.2 in [19] and C9.1 and C9.2 in [20], problem (14) is transformed into a non-convex problem (due to the non-convexity of constraints C8.1 and C9.1). The following theorem is for handling constraints C8.1 and C9.1.

4. [Online available at] https://scip.zib.de/
Theorem 1. For sufficiently large values for \( \lambda_1 \gg 1 \) and \( \lambda_2 \gg 1 \), problem (14) is equivalent to the following problem.

\[
\begin{align*}
\min_{\beta, X, Y} & \quad F(\beta, X, Y) + \lambda_1 \sum_{n \in N} (\beta_n - \beta_{n_0}^2) + \\
& \quad \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} (x_{nij} - x_{nij}^*), \\
\text{s.t.} & \quad C1, C2, C3, C4, C5, C6, C7, C8.2, C9.2, C10,
\end{align*}
\]

where \( \lambda_1 \) and \( \lambda_2 \) act as penalty factors to penalize the objective function for any \( \beta_n \) and \( x_{nij} \) that is not equal to 0 or 1.

Proof. The proof is given in the Appendix B.

Let
\[
f(\beta, X, Y) = F(\beta, X, Y) + \lambda_1 \sum_{n \in N} \beta_n + \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} x_{nij}^2 \quad \text{and} \quad g(\beta, X) = \lambda_1 \sum_{n \in N} \beta_n^2 + \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} x_{nij}^2,
\]

the objective function of problem (21) can be written as difference of two convex functions \( f(\beta, X, Y) \) and \( g(\beta, X) \). So, problem (21) is a D.C programming problem. Majorization-Minimization approximation is a well-known method to convexify a D.C programming problem as a convex one. One approach for Majorization-Minimization approximation is the first-order Taylor approximation method. Thus, to convexify the objective function of (21), we approximate \( g(\beta, X) = \lambda_1 \sum_{n \in N} \beta_n^2 + \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} x_{nij}^2 \) by its first-order Taylor approximation as
\[
g(\beta, X) = g(\beta^t - 1, X^t - 1) + \nabla \beta g(\beta^t - 1, X^t)(\beta - \beta^t - 1) + \nabla X g(\beta^t - 1, X^t - 1)(X - X^t - 1),
\]

where \( \beta^t - 1 \) and \( X^t - 1 \) is the optimal solution of previous iteration. By doing so, problem (21) can be rewritten as

\[
\begin{align*}
\min_{\beta, X, Y} & \quad F(\beta, X, Y) + \lambda_1 \sum_{n \in N} \beta_n + \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} x_{nij} \quad - \lambda_1 \sum_{n \in N} [2\beta_n(\beta_n^t - 1) - (\beta_n^t - 1)^2] \\
& \quad - \lambda_2 \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} [2x_{nij}^t x_{nij}^t - (x_{nij}^t)^2], \\
\text{s.t.} & \quad C1, C2, C3, C4, C5, C6, C7, C8.2, C9.2, C10.
\end{align*}
\]

Proposition 1. The optimal solution of problem (22) at each iteration \( t \) provides a tight upper bound and local optimal for problem (14).

Proof. The proof is given in the Appendix C.

Algorithm 1: Our proposed ARA algorithm to solve NFV-RA problem (14)

1. Initialize maximum number of iterations \( t_{\text{max}} \), \( \lambda_1, \lambda_2 \gg 1 \), iteration index \( t = 1 \), and a feasible initial point \( \beta^0 \) and \( X^1 \).

2. Repeat

3. Solve convex optimization problem (22) by interior-point method \( [47] \) and obtain \( \beta^t, X^t \), \( Y^t \).

4. Set \( \beta^t = \beta^*, X^t = X^*, Y^t = Y^* \) and \( t \leftarrow t + 1 \).

5. Until convergence or \( t = t_{\text{max}} \).

5.2 Our Proposed HuRA algorithm

In problem (22), there are \( |U_S| \), \( |S_i| \), \( |N| \), \( |U| \), \( |L| \), decision variables and \( |U_S| \), \( |S_i| \), \( |N| \), \( |U| \), \( |L| \), linear constraints. So, the complexity of Algorithm 1 to solve problem (14) is \( O((|U_S| ||S_i|| |N| + |U_S| |S_i| |L| + |U|) + 2|N| + 2|L| + 2|U|) \) which is polynomial \([46]\). In what follows, to reduce the computational complexity of our proposed ARA algorithm, we propose a heuristic algorithm based on Hungarian algorithm to address problem (14) called as HuRA. To do so, we decompose NFV-RA problem (14) into two sub-problems, namely VNF placement and routing sub-problems. The VNF placement sub-problem is defined as

\[
\begin{align*}
\min_{\beta, X} & \quad \alpha \left[ \sum_{n \in N} \beta_n p_n^f + \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} x_{nij} C_{ij}/C_{ij}^\text{max} \right] \\
& \quad + (1 - \alpha) \left[ \sum_{n \in N} \sum_{i \in U_N} \sum_{j \in S_i} (\text{cost}_{i,n} x_{nij} C_{ij}) \right], \\
\text{s.t.} & \quad C1, C2, C3, C4, C7, C8, C9.
\end{align*}
\]

(23)

and the routing sub-problem is defined as follows.

\[
\begin{align*}
\min_{Y} & \quad (1 - \alpha) \left[ \sum_{l \in L} \sum_{i \in U_N} \sum_{j \in S_i, j \neq 0} (\text{cost}_{i,l} y_{ij}^t) \right], \\
\text{s.t.} & \quad C5, C6, C7, C10.
\end{align*}
\]

(24)

The VNF placement problem (23) is NP-hard due to the servers active or inactive modes and server allocation binary variables, so we propose a heuristic algorithm to solve it. Then, after placement the VNFs on the servers, the routing sub-problem which is an LP problem is optimally solved by the off-the-shelf optimization software packages.

Assuming having sufficient resources in data center to admit all SFCs, each VNF in each SFC must be implemented on one and only one server. To allocate servers to VNFs and server allocation binary variables, so we propose a heuristic algorithm to solve it. Then, after placement the VNFs on the servers, the routing sub-problem which is an LP problem is optimally solved by the off-the-shelf optimization software packages.
\[ A[j,n] \] represents the value of objective function if the server \( n \) is assigned to the \( j \)th VNF of SFC \( S_i \). If each server does not have the sufficient capacity for a VNF, we set the value of the corresponding element in matrix \( A \) to a big value that will not be selected by Hungarian algorithm. We give matrix \( A \) as an input to the Hungarian algorithm, the output of this algorithm is a matrix of 0 and 1 elements, indicating the assignment of the servers to the VNFs, so that the objective function of (23) is minimized. After VNF placement, we solve the routing sub-problem to connect the servers run VNFs. By solving the routing sub-problem, if a feasible routing finds, the algorithm terminates. Otherwise, the VNF placement must be redone. In this case, for each VNF, we calculate the processing delay for all the servers in the candidate set \( j \) and give the matrix as an input to the Hungarian algorithm. In this case, the output of the Hungarian algorithm will be a 0 and 1 matrix whose assignment is done in such a way that the processing delay for this SFC is minimized. Then the routing problem is resolved again.

After completion of VNF placement and routing for each SFC, we update the remaining capacity of the allocated servers as well as the bandwidth of allocated links. Also, we update the value of objective function. It is worth noting that the computational complexity of HuRA algorithm is \( O([U_S || \mathcal{N} || \mathcal{S}_i || \mathcal{N} || \mathcal{S}_i || \mathcal{L}] + |U_S||\mathcal{S}_i||\mathcal{N}||\mathcal{S}_i||\mathcal{L}|) \), since the computational complexity of Hungarian algorithm is \( O(N^3) \) [50] and Hungarian algorithm is implemented for each SFC, and the computational complexity to address LP problem (24) is \( O([U_S||\mathcal{S}_i||\mathcal{N}||\mathcal{S}_i||\mathcal{L}] + |U_S||\mathcal{S}_i||\mathcal{L}|) \). The pseudo-code of our proposed HuRA algorithm is illustrated in Algorithm 2 in Appendix D.

6 Simulation Results

In this section, we present the simulation results to evaluate the performance of our proposed ARA and HuRA algorithms to address NFV-RA problem [14]. To this end, we first compare the performance of the ARA and HuRA algorithms with the optimal solution to address problem (14). Then, we compare the ARA algorithm with the proposed algorithm in [20] in terms of the number of active servers, energy consumption, and average delay. Finally, we investigate the efficiency of the solution of MO problem [18] for the miner users. It is noteworthy that all of the curves introduced in the following are obtained by averaging from 100 independent snapshots.

6.1 Comparison of Our Proposed ARA and HuRA algorithms with Optimal Solution

To evaluate our proposed ARA and HuRA algorithms, we consider a directed graph in which servers are connected to each other with randomly established physical links. All simulation parameters are given in Table 2. In what follows, we compare the performance of our proposed ARA and HuRA algorithms with the optimal solution of NFV-RA problem [14].

![Fig. 1: Objective function of NFV-RA problem (14) vs. SFCs’ tolerant delay and number of servers](image1.png)

![Fig. 2: Objective function of NFV-RA problem (14) vs. SFCs’ number and servers processing capacity](image2.png)

\begin{table}[h]
\centering
\caption{Simulation parameters for NFV resource allocation}
\begin{tabular}{|l|c|}
\hline
Parameter & Value \\
\hline\hline
\( \alpha \) & 0.5 \\
\hline
required bandwidth between \( j \) and \( j+1 \)th VNF \( (B_{ij}^{j,j+1}) \) & random selection of \([100, 500]\) bit/s \\
\hline
required CPU cycles for VNF \( j \) & random selection of \([B_{ij}^{j,j+1}, 5B_{ij}^{j,j+1}]\) \\
\hline
unit price of each CPU cycle \( (\text{cost}_{i,n}) \) & random selection of \([0.1, 1]\) \\
\hline
unit price for transmitted each bit per second \( (\text{cost}_{i,j}) \) & random selection of \([0.1, 1]\) \\
\hline
server processing capacity \( (C_{i}^{\max}) \) & random selection of \([1, 10]\) Mcpu cycles/s \\
\hline
link bandwidth \( (B_{ij}^{\max}) \) & random selection of \([100, 500]\) Mbps \\
\hline
power consumption of server \( n \) \( (p_n) \) & random selection \([1, 5]\) W \\
\hline
static power of server \( n \) \( (p_{n0}) \) & random selection \([1, 10]\) W \\
\hline
VNFs number of each SFC \( (|S_i|) \) & random selection of \((3, 8)\) \\
\hline
\end{tabular}
\end{table}

\( |\mathcal{N}| \) is the number of servers. Because each VNF in each SFC has to be assigned to a different server, the number of servers is greater than the number of VNFs in each chain.

5.1 \( |\mathcal{S}_i| \) is the number of VNFs in SFC. We compare the performance of our proposed ARA and HuRA algorithms in comparison with the optimal solution of NFV-RA problem [14] versus SFCs’ maximum tolerable delay and the number of servers. For generating this figure, we set the number of SFCs to 5. From Fig. 1, it can be seen that the objective function of NFV-RA problem [14] decreases as the number of servers increases since there are more servers to choose for allocating to each VNF. Additionally, due to the processing capacity of the servers is randomly set, the probability of the existence of high-capacity servers increases, so we can run more VNFs on high-capacity servers. By doing so, the number of active servers is reduced which leads to a reduction in the objective function of NFV-RA problem [14] versus SFCs’ number and servers processing capacity.
resources lead to increased energy consumption and cost of
needed for providing service to them and more consumed
20\text{ms} \text{ tolerable delay to }

the number of servers to

versus the number of SFCs and processing capacity of servers

function of problem (14). On the other hand, when the SFCs’
maximum tolerable delay is reduced, the processing delay
and transmission delay can be reduced. Therefore, servers
with high processing capacity must be allocated to the VNFs
of these SFCs, even if they require lower processing capacity.
This means that due to the servers’ processing capacity
limitations, we cannot run VNFs of other SFCs that may
require higher processing on these servers, and we will
have to activate other servers. As a result, the number of
active servers increases which results in an increase in the
objective function of problem (14). Also, as can be seen in
Fig. 1 the ARA and HuRA algorithms achieve near-optimal
performance with lower computational complexity.

The performance of our proposed ARA and HuRA algo-
rithms in comparison with the optimal solution of problem
(14) versus the number of SFCs and processing capacity of
servers is shown in Fig. 2. For generating this figure, we set
the number of servers to 20 (\(|N| = 20\)), SFCs’ maximum tolerable delay to 20\text{ms} (\(T_i^{th} = 20\text{ms}\)), and the number of SFCs to 5 (\(|U_s| = 5\)). From Fig. 3, it can be observed that when the number of
VNFs of SFCs increases since more resources should be
allocated to them, the objective function of problem (14)
increases. Moreover, as physical link bandwidth increases,
more bandwidth of lower cost links can be allocated to
SFCs. Therefore, the cost of utilized physical link bandwidth
reduced which results in decreasing the objective function of
problem (14).

6.2 Comparison of Our Proposed ARA algorithm with
the Proposed Algorithm in [20]

In Figs. 4, 5, and 6 we compare the performance of ARA
algorithm with the HCA algorithm proposed in [20]. For a
fair comparison, to implement the ARA algorithm we omit
the constraint C2 (4) in problem (14).

Fig. 4 illustrates the number of active servers versus the
number of SFCs and processing capacity of the servers. As
can be seen from Fig. 4 with increasing the number of SFCs,
the number of active servers for providing services to these
SFCs is increased. Also, the number of active servers can be
reduced by increasing the processing capacity of the servers
due to the implementation of more VNFs on each server.
Moreover, Fig. 4 shows that the number of active servers
in the ARA algorithm is lower than the HCA algorithm
proposed in [20].

In Fig. 5 we compare the energy consumption of the
ARA algorithm with the HCA algorithm in [20]. As observed
from Fig. 5 with increasing the number of SFCs, energy consumption is increased. Also, energy consump-
tion is reduced when the processing capacity of servers
is increased. Furthermore, Fig. 5 illustrates that the ARA
algorithm outperforms the HCA algorithm proposed in [20] in terms of energy consumption.

Fig. 6 illustrates the average delay of SFCs versus the number of VNFs. From Fig. 6, it is observed that when the number of VNFs of each SFC is increased since more VNFs should be implemented to complete each SFC, the average delay is increased. Besides, increasing the bandwidth of physical links decreases the average delay because the transmission delay over links is reduced.

6.3 Performance of the Solution of MO Problem [18]

In this section, we simulate the optimal solution to address problem [18]. To do so, similar to [33], the path gain from each miner to users participating in mining process is modeled by $h_{i,k} = \nu d_{i,k}^{-\mu}$, where $d_{i,k}$ is the distance between miner $i$ and user $k$ which is randomly set, $\nu$ is a random value that is generated by the Rayleigh distribution, and $\mu = 3$ is the path loss exponent. The other simulation parameters are given in Table 3.

Table 3: Simulation parameters for mining process

| Parameter                          | Value   |
|-----------------------------------|---------|
| Number of users participating in mining process ($|K_i|)$ | 5       |
| Noise power ($\sigma_k$)          | $10^{-14}$ |
| Unit price of each CPU cycle ($\text{cost}_{i,k}$) | Random selection from [1, 10] |
| Users’ processing capacity ($\bar{e}_{\text{max}}$) | Random selection of [100, 500] cpucycle/s |
| Power consumption of user $k$ ($p_i$) | Random selection [0.1, 0.9] W |
| Transmit power of miner $i$ ($p_{i,k}$) | Random selection [1, 10] mW |
| Number of transactions in each block ($N_{\text{Trans}}$) | 5 |
| Constant reward ($R_{\text{const}}$) | 12.5 |
| Variable reward for each transaction ($R_{\text{Trans}}$) | 0.01 |
| Network latency parameter ($\gamma$) | 0.01 |

Fig. 7a shows the objective function of MO problem [18] with respect to the miner users’ maximum tolerable delay and the number of miner users. It can be seen, with decrease of the miner users’ maximum tolerable delay, since the mining process needs to be offloaded to more users and the increasing number of users participating in the mining increases the cost of the miner users paying them, the objective function of problem [18] increases. On the other hand, when the number of miner users increase, because all these miner users want to perform the mining process in order to receive rewards, both the energy consumption and the cost increase resulting in increasing the objective function of [18]. Also, in Fig. 7a the objective function of MO [18] versus the miner users’ demand and the processing capacity of the participating users is shown. From Fig. 7a it can be observed that by increasing the processing capacity of users participating in the mining process, because the miner users can offload the mining process to fewer number of users, the miner user’s energy consumption for sending the mining task to users is reduced. In addition, the miner user can offload most of the mining process to the less costly users. Therefore, by increasing the processing capacity of participating users in the mining process, the objective function of MO problem [18] is reduced. On the other hand, as miner users’ demand increases, since the miner users have to offload the mining process to more users, both energy consumption and payment costs increase, leading to an increase in the objective function of MO problem [18].

7 CONCLUSION

In this paper, we studied the NFV resource allocation. To do so, we formulated the NFV-RA problem aimed at minimizing the energy consumption and cost of utilized resources as a multi-objective problem. Due to the NP-hardness of this problem, we proposed two near-optimal algorithms named ARA and HuRA. For the ARA algorithm, we converted the binary variables into continuous ones by adding a penalty function to the objective function. Furthermore, to convexify NFV-RA problem, we employed Majorization-Minimization approximation method. By doing so, the transformed problem becomes a convex problem that can be solved by optimization software packages. In addition, to reduce the complexity of the ARA algorithm, we proposed the HuRA algorithm. For the HuRA algorithm, we decomposed the main NFV-RA problem into two sub-problems namely VNF placement and routing sub-problems. The VNF placement sub-problem is an ILP problem that can be optimally solved in polynomial time. The simulation results illustrated that our proposed ARA and HuRA algorithms achieve near-optimal performance with lower computational complexity.
the ARRA outperformed the existing algorithms in terms of the number of active servers, energy consumption, and average delay. On the other hand, resource allocation in NFV is done by NFVO as a centralized authority. The NFVO has drawbacks such as a single point of failure and security issues. Relying on the mining process, blockchain technology can address these pitfalls. In wireless networks, the mining process is performed by mobile users who have limited processing resources and cannot perform the mining process locally. Hence, we assume that miner users can perform the mining process with the participation of other users. The mining process has a lot of energy consumption. Additionally, miner users have to pay to other users for using their processing resources. Therefore, we formulated the problem of minimizing energy consumption and cost for miner users as an LP problem that can be optimally solved in polynomial time. As future work, one may consider queue latency on servers, which is more practical. In data centers, each server has a queue where users wait to receive processing resources. Considering this causes that the latency model will be different from that of our paper, we, our proposed algorithms should be accordingly revised to take the queuing latency into account. Furthermore, it can be assumed that users are with limited energy, and energy is harvested. To do so, an energy constraint is added to the constraints of the optimization problem, according to which the total energy consumption of users should not be larger than the total initial energy and harvested energy. By adding this constraint to the optimization problem, the solution proposed in this paper should be modified to ensure this constraint.

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Pedro H. J. Nardelli [M’07, SM’19] received the B.S. and M.Sc. degrees in electrical engineering from the State University of Campinas, Brazil, in 2006 and 2008, respectively. In 2013, he received his doctoral degree from University of Oulu, Finland, and State University of Campinas following a dual degree agreement. He is currently Associate Professor (tenure track) in IoT in Energy Systems at LUT University, Finland, and holds a position of Academy of Finland Research Fellow with a project called Building the Energy Internet as a large-scale IoT-based cyber-physical system that manages the energy inventory of distribution grids as discretized packets via machine-type communications (EnergyNet). He leads the Cyber-Physical Systems Group at LUT, and is Project Coordinator of the CHISTERA European consortium Framework for the Identification of Rare Events via Machine Learning and IoT Networks (FIREMAN) and of the project Swarming Technology for Reliable and Energy-aware Aerial Missions (STREAM) supported by Jane and Aatos Erkko Foundation. He is also Docent at University of Oulu in the topic of “communications strategies and information processing in energy systems”. His research focuses on wireless communications particularly applied in industrial automation and energy systems. He received a best paper award of IEEE PES Innovative Smart Grid Technologies Latin America 2019 in the track “Big Data and Internet of Things”. He is also IEEE Senior Member. More information: https://sites.google.com/view/nardelli