EdgeChain: Blockchain-based Multi-vendor Mobile Edge Application Placement

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Abstract—The state-of-the-art mobile edge applications are generating intense traffic and posing rigorous latency requirements to service providers. While resource sharing across multiple service providers can be a way to maximize the utilization of limited resources at the network edge, it requires a centralized repository maintained by all parties for service providers to share status. Moreover, service providers have to trust each other for resource allocation fairness, which is difficult because of potential conflicts of interest. We propose EdgeChain, a blockchainbased architecture to make mobile edge application placement decisions for multiple service providers. We first formulate a stochastic programming problem minimizing the placement cost for mobile edge application placement scenarios. Based on our model, we present a heuristic mobile edge application placement algorithm. As a decentralized public ledger, the blockchain then takes the logic of our algorithm as the smart contract. with the consideration of resources from all mobile edge hosts participating in the system. The algorithm is agreed by all parties and the results will only be accepted by majority of the mining nodes on the blockchain. When a placement decision is made, an edge host meeting the consumer's latency and budget requirements will be selected at the lowest cost. All placement transactions are stored on the blockchain and are traceable by every mobile edge service provider and application vendor who consumes resources at the mobile edge.

Index Terms—Mobile edge computing, blockchain, placement.

I. INTRODUCTION

The rapid advance of mobile edge computing (MEC) has been the last mile of enabling a shared, low-latency computational environment for multi-vendor mobile edge applications. MEC performs computing offloading, data storage, caching and processing, request distribution and service delivery from the mobile edge to end users [1]. Applications with low latency tolerance, such as augmented reality (AR), video streaming, and online gaming, can deploy their services on the edge hosts at a cost, to achieve lower latency and better user experience [2].

As the market gets mature, there will be multiple 5G service providers (SPs) provisioning MEC services to cover the same area: bigger wholesale players will invest in infrastructure to actually build mobile edge base stations, while there will also be mobile virtual network operators (MVNOs) renting resources from the former. These SPs can collaborate with each other in several ways for better utilization of the resources

at the edge: virtual SPs have to place mobile edge (ME) applications on one of the rented edge hosts, preferably with lower cost, regardless of SPs. On the other hand, MEC base stations from different SPs can share resources with each other to process bursting requests.

For encouraging SPs to enroll their eligible MEC base stations and hosts in resource sharing, it is common to give incentives to SPs for contributing their resources of the hosts for hosting edge applications. Following the changing demand of end users, certain types of edge applications need to be deployed on, migrated to, or removed from an edge host, in order to meet the service requirement. By deploying the edge applications at the right places, the edge application provider will save costs, while providing high-quality service with low latency to the end users. Meanwhile, the edge host will collect incentives for its resources effectively used.

Clearly, the edge computing framework needs a placement service to dynamically check the user needs and the available edge hosts, and determine the placement or removal of edge applications. In datacenters, virtual machine (VM) placement has been well investigated, mainly with the focus of more efficient resource utilization and lower operational expense (OPEX). However, the collaboration of multiple SPs and mobile edge applications vendors are posing new challenges for ME application placement from the following aspects:

- A placement model has to make transparent and consistent selections of the best host for each request for edge computing resources. Moreover, the model has to take into consideration that a mobile edge application may require multiple services chained together at the edge.
- A trusted party is required to determine the best place for application deployment. When an edge application is deployed on a mobile edge host, the application vendor needs to pay for the usage of the host. The placement algorithm has to avoid affiliation to either SP to ensure a neutral decision is made strictly according to the resource and the cost. It may create conflicts of interest to put any SP involved into the position of making placement decisions: placing mobile edge applications onto the SP's own hosts would bring revenue for renting their resources.
- The application placement service needs to be steadily available. Both the mobile edge hosting service providers

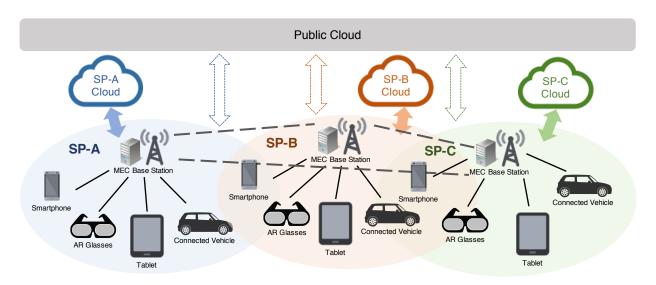


Fig. 1. A MEC scenario in a certain service area. There are 3 ME base stations from 3 different SPs: SP-A, SP-B, and SP-C. They serve there own users within the service area. For resource sharing and optimization purpose, the base stations are also connected to each other.

and the mobile edge application providers can constantly change. The placement service provider must remain in service regardless of the joining or quitting of vendors.

The challenges above urge a comprehensive solution uniting all SPs and their edge hosts without bias. In this paper, we present an architecture combined with its algorithm, namely EdgeChain, to create a decentralized placement service for mobile edge application that does not require trust to any party, i.e., trustless placement service. Compared with current placement solutions, EdgeChain has the following contributions:

- A cost model is presented as a stochastic programming problem, factoring in the pricing of edge hosts, latency, and service chaining.
- We develop a heuristic placement algorithm based on the proposed cost model with the consideration of efficiency for running by the blockchain.
- We introduce blockchain technologies to the MEC resource orchestration framework with two considerations:
 the first is to store the global resource availability, allocation, and consumption information that helps our algorithm make optimized decisions based on the global resource information. The second consideration is to have a decentralized public ledge for ensuring the neutrality of the placement decisions.
- The EdgeChain framework is presented to run our algorithm for making placement decisions. In our design, SPs and mobile edge application vendors participate in the maintenance of the blockchain. An EdgeChain client is embedded in the network function virtualization (NFV) framework to determine the placement based on the existing information on the blockchain. To our best knowledge, this is the first work that leverages blockchain to coordinate SPs for MEC application placement.
- Simulation results of our placement algorithm show its effectiveness in mobile edge host resource sharing among

SPs. We also implement the EdgeChain by leveraging VeChain [3], an enterprise-level blockchain-as-a-service framework derived from Ethereum [4].

We divide the contents into the following sections. The related work is illustrated in Section II. Section III formulates the problem. Section IV proposes the heuristic EdgeChain placement algorithm based on the problem formulation. Then the simulation results are shown in Section VI. Section VII concludes the paper.

II. RELATED WORK

The research directions in network service chaining (NSC) were discussed in [5]. For security considerations, the authors highlighted the difficulty of bringing short-lived network services to targeted users in a single subscriber network by using the current security schemes. The potential security problems in SFC were stated in RFC7498 [6], including service overlay security, trusted classification policy, and secure SFC encapsulation. We investigated a placement problem in MEC with the consideration of application availability in [7].

Xiong et al. proposed a pricing strategy for offloading the blockchain's resource-consuming proof-of-work tasks to edge computing nodes [8]. A two-stage Stackelberg game model was presented with both the edge computing service provider and the miners involved. A hierarchical distributed control system was built using Hyperledger Fabric blockchain [9]. The hosting locations of cloud and fog of blockchain were compared in [10] for IoT networks with the conclusion that fog nodes were better as network latency was the dominant factor.

Nakamoto introduced the concept of blockchain and implemented Bitcoin [11], a decentralized cryptocurrency that first resolved the double spending problem. Blockchains are based on Merkle trees [12] to efficiently allow multiple documents to be saved together in a block. As a decentralized public ledger,

TABLE I
PARTIES INVOLVED IN A MEC PLACEMENT SCENARIO

Party	Description
Users	Subscribers of applications and services over 5G networks with MEC enabled.
MECSPs	MEC service providers, who deliver MEC hosting services that can run <i>MEApps</i> at the network edge, close to end users. Examples include telecommunication companies like Rogers and Telus in Canada.
MEAVs	Mobile edge application vendors, who provide <i>MEApps</i> and services to end users. For instance, a company selling AR services.
MEApps	MEApps stand for mobile edge applications provided by MEAVs.
MEHosts	Servers that belong to different MECSPs to provide hosting service of <i>MEApps</i> .
HostLinks	Network links between hosts, regardless of which MECSP they belong to.
AppLinks	When <i>MEApps</i> are chained together, virtual links will be established for data transmissions traveling through the chain.

TABLE II
NOTATIONS USED IN PROBLEM FORMULATION

Notation	Description	
$s, \mathbb{V}_s, \mathbb{L}_s, v, l$	s is a service chain. \mathbb{V}_s is the set of all MEApps in	
	s. \mathbb{L}_s is the set of all AppLinks in s. A MEApp in s	
	is denoted by $v \in V_s$, and an AppLink between two	
	<i>MEApps</i> in s is denoted by $l \in \mathbb{L}_s$.	
$\mathbb{H}, \mathbb{E}, h, e, \mathbb{V}_h$	\mathbb{H} is the set of all <i>MEHosts</i> . \mathbb{E} is the set of all	
	HostLinks. A MEHost is denoted by $h \in \mathbb{H}$, and a	
	link between two <i>MEHosts</i> is denoted by $e \in \mathbb{E}$. \mathbb{V}_h	
	is the set of all $MEApps$ placed on h .	
u, m, c_s	u is an end user. m is a MECSP. c_s is the cost of	
	deploying s .	
$c_v, c_{vh_i,v'h_i}$	c_v is the cost of deploying v . $c_{vh_i,v'h_i}$ is the cost of	
	the AppLink between v on h_i and v' on h_j .	
n_s, P_m, h_m	n_s is the total number of users requesting s. P_m is a	
	random variable denoting the percentage of the users	
	of MECSP m . h_m is an edge host of m .	
γ_m, δ_m	γ_m is the unit price of serving m's own subscribers.	
	δ_m is the extra charge for m serving users of other	
~	MECSPs.	
C_v, M_v	CPU and memory requirement of the $MEApp\ v$.	
$B(e_{ij}), \zeta_{e_{ij}}$	$B(e_{ij})$ is the total bandwidth capacity of <i>HostLink</i> e_{ij} .	
D ()	$\zeta_{e_{ij}}$ is the unit price of the bandwidth of e_{ij} .	
$B_V(e_{ij})$	$B_V(e_{ij})$ is the total bandwidth used by MEApps	
D()	deployed on h_i and h_j .	
$B(v_{h_i}, v_{h_j})$	Bandwidth used between <i>MEHosts</i> h_i and h_j .	
C_h, M_h	CPU and memory capacity of the <i>MEHost h</i> .	
$t_{e_{ij}}, t_s, T_s$	$t_{e_{ij}}$ is the latency incurred on <i>HostLink</i> e_{ij} . t_s is the	
	latency of the service chain s. T_s is the max latency	
	allowed by s .	

blockchains can serve beyond cryptocurrencies. Ethereum [4] used blockchain to store smart contracts that support building virtually any decentralized application.

III. PROBLEM FORMULATION

We first list all parties involved in a MEC placement scenario in Table I. The problem is formulated from a MEAV's point of view: MEApps are direct consumers of the computing resources in the MEC environment, because a MEAV needs to pay MECSPs for hosting its applications in order to serve

their *users* and meet the latency requirement. Each *MEApp* is equivalent to a virtual machine (VM) deployed on a *MEHost*. *MEApps* provided by different *MEAV* can be combined as a service chain to provide comprehensive services. A service chain may span multiple *MEAVs*. In this case, revenues generated by the service chain can be distributed according to the usage of each *MEApp* on the service chain. For instance, a full-fledged AR service can load real-time navigation information from an online map application, while it can also load promotions of a shopping mall nearby from the mall's application. The navigation data is collected by the online map application, and the shopping mall application gets paid if the user "clicks" the links of the promotions.

The notations used in formulating the problem is shown in Table II. Define a chained service s as a forwarding graph [13] $G_s = (\mathbb{V}_s, \mathbb{L}_s)$, where \mathbb{V}_s is the set of all *MEApps* contributing to the service, and \mathbb{L}_s is the set of all *AppLinks* connecting applications together. A *MEApp* is denoted by $v \in \mathbb{V}_s$, and an *AppLink* between two *MEApps* is denoted by $l \in \mathbb{L}_s$.

The chained service is deployed on a graph of connected MEHosts $G_h = (\mathbb{H}, \mathbb{E})$, where \mathbb{H} is the set of all MEHosts owned by various MECSPs and \mathbb{E} is the set of all HostLinks. A MEHost is denoted by $h \in \mathbb{H}$, and a HostLinks between two MEHosts is denoted by $e \in \mathbb{E}$. The HostLinks can be either physical or virtual links with fixed capacities and latencies.

Suppose in a certain service area, there are n_s users from various *MECSPs* requesting the same chained service s from a *MEAV*. We use m to denote a *MECSP* and h_m for a *MEHost* that belongs to m. Define an assigning function x_{vh_m} , whose value is 1 if VM v is assigned to Host h_m , 0 otherwise.

$$x_{vh_m} \triangleq \begin{cases} 1, & v \text{ is deployed on } h_m; \\ 0, & \text{otherwise.} \end{cases}$$
 (1)

Define a binary indicator of an AppLink between two chained MEApps in s, denoted by $L(v_{h_i}, v_{h_j})$, such that

$$L(v, v') \triangleq \begin{cases} 1, & l \in \mathbb{L}_s \text{ exists between } v \text{ and } v'; \\ 0, & \text{otherwise.} \end{cases}$$
 (2)

Also, we use e_{ij} to represent the *HostLink* between h_i and h_j . The cost of deploying s is the sum of the cost of deploying each $MEApp\ v$ of the service and the cost of the traffic between each two adjacent MEApps in the service chain. It can be shown by

$$c_{s} = \sum_{h_{m} \in H} \sum_{v \in \mathbb{V}_{s}} c_{vh_{m}} x_{vh_{m}} + \sum_{h_{i}, h_{j} \in H} \sum_{v, v' \in \mathbb{V}_{s}} c_{vh_{i}, v'h_{j}} x_{vh_{i}} x_{v'h_{j}} L(v, v'),$$
(3)

where c_s represents the cost of deploying s and c_{vh_m} is for the cost of a MEApp v deployed on a MEHost h_m . We assume that the pricing scheme for the same MECSP is the same across all of its hosts. For a $MEHost\ h_m$, define its basic unit resource price, which is the unit price of serving its own subscribers, as γ_m . When h_m is serving users of other MECSPs, it charges a premium of δ_m for its unit resource, as the return for doing

courtesy for its partners. Therefore, the shared unit resource price of h_m can be represented by $(\gamma_m + \delta_m)$. Define C_{h_m} and M_{h_m} to be the capacity of vCPU and memory provided by h_m . Define C_v and M_v as the vCPU and memory consumed by v. Define P_m to be the random variable for percentage of the users using the service chain s via networks of the MECSP m. Depending on the numbers of active users for each MECSP, the total cost for the $mextine{MEAV}$ to place its $mextine{MEAPp}$ v onto a host of m is the cost incurred by users of other $mextine{MECSPs}$:

$$c_{vh_m} = n_s(C_v + M_v)P_m\gamma_m + n_s(C_v + M_v)(1 - P_m)(\gamma_m + \delta_m) = n_s(C_v + M_v)[P_m\gamma_m + (1 - P_m)(\gamma_m + \delta_m)] = n_s(C_v + M_v)[\gamma_m + (1 - P_m)\delta_m].$$
(4)

When a request from a *user* for a service chain arrives, the blockchain would know the *MECSP* from which the *user* subscribes. For the same placement decision, the value c_s can significantly differ over changing distribution of *users*. An example can be two *MECSPs* m_1 and m_2 , each with one host h_{m_1} and h_{m_2} . If all *users* are subscribers of m_1 and all *MEApps* are placed on *MEHosts* of m_1 , then the cost payable by the *MEAVs* would be lower than if all *users* were subscribers of m_2 .

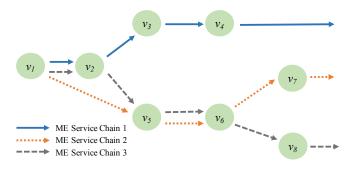


Fig. 2. An example of ME service chains. There are 3 ME service chains sharing the services provided by 8 MEApps.

A. HostLink Unit Price

When it comes to the cost modeling of a link between two MEHosts, link availability is an important part for the service consistency of the MEApps. If a heavily used HostLink is down, consequences can be catastrophic: even if all individual MEApps are running, the traffic would not be able to flow through between one or more pairs of MEApps and the service chain would not be functional. For each HostLink e_{ij} , there can be one or more AppLinks sharing its bandwidth. HostLink outages require migrating the MEApps if they cannot be fixed in time. Therefore, HostLink availability has significant influence on possible MEApp migrations and the potential costs incurred.

The link unit price of a *HostLink* e_{ij} , denoted by $\zeta_{e_{ij}}$, is then defined to describe how much to use the HostLink e_{ij} . The following two parameters will determine $\zeta_{e_{ij}}$.

The first parameter is $L(v_{h_i}, v_{h_j})$ as defined in Eqn. (2). The more AppLinks a HostLink carries, the more vital and expensive it becomes. The reason behind this ranking parameter is the potential consequence of migration: failure of a HostLink used by many VMs would lead to massive migration of all MEApps connected by that HostLink, which would be more disruptive to the service chain.

The other parameter $B_V(e_{ij})$ is the total bandwidth consumed by traffic between *MEApps* on the two hosts. It is selected because larger bandwidth usages would cause challenges at the time of migration: it can be hard to find another link with enough capacity.

$$B_V(e_{ij}) \triangleq \left[\sum_{v_{h_i}, v_{h_i}, h_i \neq h_j} B(v_{h_i}, v_{h_j}) \right]. \tag{5}$$

Combining the two parameters, we define the unit price $\zeta_{e_{ij}}$ of a *HostLink* e_{ij} , as the factor of the number of *AppLinks* between two hosts times the factor of traffic flowing through these links:

$$\zeta_{e_{ij}} = \frac{\left[\sum_{v_{h_i}, v_{h_j}, h_i \neq h_j} L(v_{h_i}, v_{h_j})\right]}{N_{e_{ij}}} \frac{B_V(e_{ij})}{B(e_{ij})}, \quad (6)$$

where $N_{e_{ij}}$ is the maximum number of virtual links possible on e_{ij} . Therefore, $\zeta_{e_{ij}} \in [0,1]$. The value of $\zeta_{e_{ij}}$ will rise to mark up a link's importance given it is either occupied by more pairs of VMs, or there is more traffic assigned to e_{ij} , or both. The cost of any two MEApps is then the sum of the cost serving users that belong to the MECSPs owning h_i and h_j and the cost serving other users timed by the price factor $\kappa_{e_{ij}}$:

$$c_{vh_{i},v'h_{j}} = n_{s}\zeta_{e_{ij}}(P_{m_{h_{i}}} + P_{m_{h_{j}}})\kappa_{m_{h_{i}}m_{h_{j}}} + n_{s}\zeta_{e_{ij}}(1 - P_{m_{h_{i}}} - P_{m_{h_{j}}})(\kappa_{m_{h_{i}}m_{h_{j}}} + \sigma_{m_{h_{i}}m_{h_{j}}})$$

$$= n_{s}\zeta_{e_{ij}}[(P_{m_{h_{i}}} + P_{m_{h_{j}}})\kappa_{m_{h_{i}}m_{h_{j}}} + (1 - P_{m_{h_{i}}} - P_{m_{h_{j}}})(\kappa_{m_{h_{i}}m_{h_{j}}} + \sigma_{m_{h_{i}}m_{h_{j}}})].$$
(7)

B. HostLink latency

Define the latency of the link e_{ij} to be $t_{e_{ij}}$. For a service chain s, the total latency t_s is then

$$t_s = \sum_{h_i, h_j \in \mathbb{H}} \sum_{v_{h_i}, v_{h_j} \in \mathbb{V}_s} L(v_{h_i}, v_{h_j}) x_{vh_i} x_{vh_j} t_{e_{ij}}.$$
 (8)

In the equation above, $t_{e_{ij}}$ is a constant depending on the particular e_{ij} . If $h_i = h_j$, then we consider the latency to be 0, since no actual HostLink is used for data transmission between the two MEApps. Define the maximum latency allowed for the service chain s is T_s . Then there must be $t_s \leq T_s$ to meet the latency requirement.

C. Stochastic Programming Formulation

The problem is formulated as a stochastic programming optimization. Define V_h as the set of all MEApps deployed on the $MEHost\ h$. The objective is to minimize the total cost of the service chain s to provide service with the lowest cost to the end user. As discussed in Section III, the optimization is to minimize the costs on MEHosts and HostLinks for all MEApps of s.

Minimize

$$c_{s} = \sum_{h_{m} \in \mathbb{H}} \sum_{v \in \mathbb{V}_{s}} c_{vh_{m}} x_{vh_{m}}$$

$$+ \sum_{h_{i}, h_{j} \in \mathbb{H}} \sum_{v, v' \in \mathbb{V}_{s}} c_{vh_{i}, v'h_{j}} x_{vh_{i}} x_{v'h_{j}} L(v, v')$$

$$= \sum_{h_{m} \in \mathbb{H}} \sum_{v \in \mathbb{V}_{s}} x_{vh_{m}} n_{s} (C_{v} + M_{v}) \left[\gamma_{m} + (1 - P_{m}) \delta_{m} \right]$$

$$+ \sum_{h_{i}, h_{j} \in \mathbb{H}} \sum_{v, v' \in \mathbb{V}_{s}} n_{s} \zeta_{e_{ij}} \left[(P_{m_{h_{i}}} + P_{m_{h_{j}}}) \kappa_{m_{h_{i}} m_{h_{j}}} + (1 - P_{m_{h_{i}}} - P_{m_{h_{j}}}) (\kappa_{m_{h_{i}} m_{h_{j}}} + \sigma_{m_{h_{i}} m_{h_{j}}}) \right] L(v, v'),$$

$$w.r.t. \quad x_{vh_{m}},$$

$$s.t. \quad B(e_{ij}) \geq \sum_{v_{h_{i}}, v_{h_{j}}, h_{i} \neq h_{j}} B(v_{h_{i}}, v_{h_{j}}),$$

$$(10)$$

$$C_h \ge \sum_{v \in \mathbb{V}_h} C_v,\tag{11}$$

$$M_h \ge \sum_{v \in \mathbb{V}_L} M_v,\tag{12}$$

$$\sum_{h_i, h_j \in \mathbb{H}} \sum_{v_{h_i}, v_{h_i} \in \mathbb{V}_s} L(v_{h_i}, v_{h_j}) x_{vh_i} x_{vh_j} t_{e_{ij}} \le T_s.$$
 (13)

Remarks

- Function (9) is the objective function. It minimizes the cost of all *MEApps* and *AppLinks* by using less hosts, while not exhausting them.
- Constraint (10) is the *HostLink* bandwidth capacity bounds between each two hosts. Traffic transmitted between any two hosts h_i and h_j must not exceed the corresponding bandwidth capacity $B(e_{ij})$.
- Constraints (11) and (12) are the CPU and memory capacity bounds for each MEHost. The CPU and memory used by MEApps coordinating with each other and by intra-host communications must not exceed C_h and M_h.
- Constraint (13) is the latency requirement of the service chain s to ensure that the total latency of s must not exceed the maximum latency allowed T_s.

IV. THE EDGECHAIN PLACEMENT ALGORITHM

The formulation presented in the previous section is a stochastic programming problem. Problems of this type been proved to be NP-hard [14]. It may not be computationally feasible when attempting to solve it in large scale. To apply our model to real-world scenarios, we design a heuristic algorithm

called EdgeChain to achieve suboptimal results by applying a hybrid strategy of best-fit and first-fit decreasing algorithm. The pseudo code of the algorithm is shown in Algorithm 1.

```
Algorithm 1: EdgeChain Placement Algorithm
```

```
Data: host_list: list of candidate MEHosts
```

Data: app: requested *MEApp* to be placed, including its max latency allowed, stored in latency

Data: max_latency: max latency allowed for the service chain

Result: The best *MEHost* in host_list to place app, or none if no valid host is found

```
1 begin
```

```
sort by percentage of users of the service chain
        descending
       if multiple MEHosts found then
3
          sort host list by the locations of app's last-hop
          if still multiple MEHosts found then
              sort by the latency of the HostLinks to the
               previous MEApps in the service chain
                ascending
          end
 8
       end
       for h \in \mathsf{host} list do
          latency ← all latencies added together if app
10
           placed on h
          if latency < max_latency then
11
              cpu left \leftarrow calculate remaining vCPU by C_h
12
               and C_v of each MEApp placed on h
              mem_left ← calculate remaining memory by
13
                M_h and M_v of each MEApp placed on h
              if cpu\_left \ge 0 and mem\_left \ge 0 then
14
                  return h
15
              end
16
          end
17
       end
18
       return none
19
20 end
```

A. Processing Order and selection of MEHosts

The EdgePlace algorithm runs on each mining node based on the Ethereum platform. The algorithm retrieves its input information from the blockchain, as all transactions and updates are recorded on the blockchain. The EdgePlace algorithm will select the *MEHosts* following the steps below.

1) Users: Sort all MEHosts by the percentage of users of the service chain. For each MEApp on the service chain, consider which MECSP has most users using it. Then MEHosts with the same MECSP will have higher ranks to deploy this MEApp. Since all MEHosts of the same MECSP have the same unit resource cost, the MEApp can be placed on any of the MEHosts that belongs to the best MECSP, to avoid the situation that too many MEApps are concentrated on one MEHost.

- 2) Last-hop MEApp: For MEHosts given higher priority in the previous step, sort by the locations of last-hop MEApps. MEHosts hosting the previous-hop MEApps will be considered first. This step is to reduce the traffic cost between different MECSPs.
- 3) Latency: For MEHosts given higher priority in the previous step, sort by the latency of the HostLinks to the previous MEApps in the service chain. MEHosts with lower latency will be considered first.

After the list of candidate *MEHosts* are sorted according to the steps above, the algorithm iterates the list and pick the first valid *MEHost* that has enough resources to place the *MEApp*, as well as meeting the latency requirement of the service chain.

V. EDGECHAIN DESIGN AND IMPLEMENTATION

In this section, we introduce the design and implementation of EdgeChain, a blockchain-based system that integrates with the existing MEC architecture for *MECSPs* and the scheduler of *MEAV*. There are mainly two reasons the blockchain is used in the system:

- The blockchain acts as a public ledger that stores all useful information and transactions made during the placement process. Exposure of the information would help the placement algorithm make optimized decisions considering the global resource demand and allocation. The blockchain enables such centralized resource information, in a decentralized implementation.
- As a public ledger applying proof-of-work verifications, the blockchain makes it nearly impossible to tamper the history stored in the blockchain. The EdgeChain algorithm will be downloaded by all mining nodes and they will execute the same algorithm with the same input. The placement result will only be accepted by the system if majority of the mining nodes reach agreement on the output. This will ensure the neutrality of the placement decisions.

The system takes requests to place *MEApps* from *MEAVs*, and the placement algorithm runs as the smart contract on the blockchain to select the best *MEHost* from all candidates. The NFV orchestrator of the related *MECSP* receives and enforces the placement decision, while posting the transaction onto the blockchain for recording. While this paper is written, the blockchain is implemented based on VeChain [3], an enterprise-level blockchain-as-a-service framework derived from Ethereum.

A. Data Entities

As Fig. 3 shows, there exist 6 types of data entities on the blockchain and they are related to each other to represent the status of *MEHosts* and placement decision of running *MEApps*. The descriptions of these data entities are illustrated below. Each data entity record has a unique Ethereum address for other to locate it on the blockchain. All types of data entities can be created, updated and deleted, while the blockchain will keep the audit trail of every change.

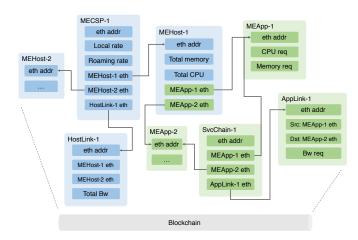


Fig. 3. Data entities and their relationship used by and stored in EdgeChain, including *MECSPs*, *MEHosts*, *HostLinks*, *SvcChains*, *MEApps*, and *AppLinks*.

- 1) MECSP: When a MECSP record is registered to EdgeChain, a record of this MECSP is added with the Ethereum addresses pointing to the records of all its eligible MEHosts and HostLinks. A MECSP record is updated whenever there is change to any MEHost or HostLink.
- 2) MEHost: A MEHost record registers under an existing MECSP to the blockchain. In a record, the vCPU and memory capabilities can be found, along with the Ethereum addresses pointing to the records of all MEApps placed onto it.
- 3) HostLink: Similar to MEHosts, a HostLink is under a registered MECSP, which contains the two MEHosts it connects, and the bandwidth of the HostLink.
- 4) SvcChain: A service chain is registered by a user to the blockchain to reflect the resource consumption of a chained service, including that from MEApps and the corresponding AppLinks. The service chain can have MEApps from multiple MEAVs.
- 5) MEApp: A MEAV will submit a record of a MEApp whenever it needs to spin up one. A record stores the vCPU, memory usage of the MEApp.
- 6) AppLink: AppLinks describe chained relationship between two MEApps. The source and destination MEApps are stored in an AppLink record, as well as network bandwidth requirement of this link.

B. EdgeChain Work Flow

A typical EdgeChain work flow can be demonstrated by Fig. 4, where there are three parties participating in the entire process: *MECSPs*, *MEAVs*, and mining nodes. We use circled numbers and alphabets to define the work flow in sequence.

- 1) A *user* requests a service chain from the blockchain. Such requests will be sent to the blockchain every time a user requests a service chain.
- (2) The request for the service chain is recorded. When the request is synced to the mining nodes, it will be broken into requests for *MEApps*. The mining nodes will run the logic to break down the service chain creation request. Then

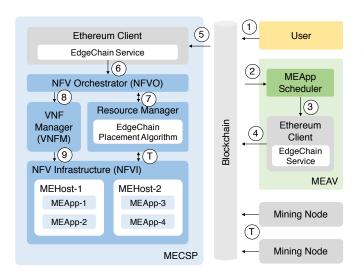


Fig. 4. Typical work flow of EdgeChain. *MECSPs*, *MEAVs*, and mining nodes participate in the process. Steps of the work flow are marked by circled numbers and alphabets with details documented in Section V-B.

the requests for *MEApps* are propagated to all corresponding *MEAVs*.

- (3) Based on its user demand, the *MEApp* Scheduler decides to create a new instance of MEApp and pass the request to the Ethereum client of the *MEAV*.
- (4) The Ethereum client running the EdgeChain service sends the request to the blockchain, creating records for the request of placing a new *MEApp*.
- (5) The request of creating a new *MEApp* arrives at a MECSP through its Ethereum client.
- 6 For every *MECSP*, the Ethereum client requests the NFV Orchestrator (NFVO) to call the EdgeChain placement algorithm downloaded to the resource manager for the decision of the placement. This will ensure that the placement algorithm be executed by different parties for verifying the results. The placement result returned by the next step will only be accepted if majority of the parties return the same placement result.
- 7 The NFVO calls the EdgeChain placement algorithm for the placement decision. Note that the decision can be a hash representing any *MEHost* within the entire MEC network. If the result points to a *MEHost* which does not belong to the current *MECSP*, then no actual placement will be done. Instead, only the result along with the algorithm's hash will be returned to the Ethereum client for verification.
- (8) If the result points to a *MEHost* of the current *MECSP*, then the NFVO will sends the request to place the *MEApp* to the VNF Manager (VNFM). Also, a transaction shown in Fig. 5 will be posted to the blockchain to record that placement actually occurs.
- 9 The VNFM sends the request to the NFV Infrastructure (NFVI) deploy the *MEAPP* onto the target *MEHost*.
- The mining nodes periodically perform the mining process to verify the blockchain, as well as earning Ethers for requesting placement services. Meanwhile, the resource

manager periodically synchronizes with the NFVI for the upto-date resource usage and availability, and then posts the updated information to the blockchain.

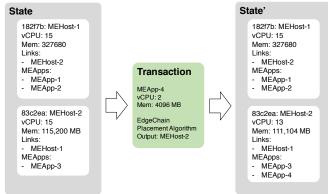


Fig. 5. A placement transaction in EdgeChain. A state transition happens upon a transaction. As this figure shows, *MEApp-4* is to be placed with the requirement of 2 vCPUs and 4096 MB of memory. The input of the EdgeChain placement algorithm is the current state of the two *MEHosts*. The result is to place *MEApp-4* onto *MEHost-2*. After the transaction is accepted, the resources taken by *MEApp-4* are deducted from the remaining resources of *MEHost-2*.

VI. NUMERICAL RESULTS

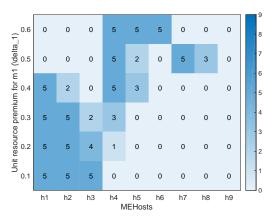
In this section, we illustrate the numerical results of the MEC placement cost changes based on varying mobile edge application user cases using CloudSim [15]. To clearly demonstrate the focused trends, the following assumptions are made to simplify the modeling of the problem without losing generality. We first discuss the placement results output by the EdgeChain algorithm for the same service chain on the same set of *MEHosts*.

- 1) The unit costs of the CPU and memory of all hosts for the same *MECSP* are the same.
- Costs of network bandwidth for all links follow the same unit price.
- One mobile edge application includes the same type of VMs with the same CPU, memory and network bandwidth requirements.
- 4) A request from the user will be processed by one VM, while the VM may communicate with other VMs to exchange information.

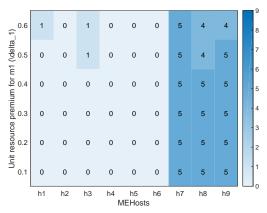
A. Parameters

With the assumptions above, we choose parameters for our placement model to evaluate the performance and the facts under different circumstances. First, we choose a MEC service scenario of 3 *MECSPs* m_1 , m_2 , and m_3 , each with 3 *MEHosts*, where h_1 , h_2 , h_3 belong to m_1 , h_4 , h_5 , h_6 belong to m_2 , and h_7 , h_8 , h_9 belong to m_3 .

Three identical requested service chain, each with 5 *MEApps* is to be placed. The *MEApps* of each service chain are denoted by v_1 , v_2 , v_3 , v_4 , and v_5 . The service chain starts from v_1 and ends at v_5 : $v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4 \rightarrow v_5$. We assume that all *MEApps* have the same CPU, memory and



(a)
$$P_{m_1} = 0.5$$
 and $P_{m_2} = P_{m_3} = 0.25$.



(b)
$$P_{m_1} = P_{m_2} = 0.25$$
 and $P_{m_3} = 0.5$.

Fig. 6. Placement results of 3 service chains consisting of 15 MEApps in all. The value of δ_{m_1} changes from 0.1 to 0.6. Figure (a) shows the placement decision when $P_{m_1}=0.5$ and $P_{m_2}=P_{m_3}=0.25$. In comparison, Figure (b) shows the placement decision when $P_{m_1}=P_{m_1}=0.25$ and $P_{m_3}=0.5$.

bandwidth requirements, which are shown in Table III, along with other parameters.

TABLE III
PARAMETERS FOR THE MEC SCENARIO

Parameter	Value	Parameter	Value
C_v	2 vCPUs	M_v	2048 MB
C_h	64 vCPUs	M_h	65536 MB
γ_{m_1}	1.0	δ_{m_1}	0.2
κ_{m_1}	1.0	σ_{m_1}	0.2
γ_{m_2}	0.8	δ_{m_2}	0.5
κ_{m_2}	0.8	σ_{m_2}	0.5
γ_{m_3}	1.2	δ_{m_3}	0.3
κ_{m_3}	1.2	σ_{m_3}	0.3
n_s	100 users	P_m	var
$B(e_{ij})$	10000 Mbps	B(v, v')	30 Mbps
$B(e_{ij}) \\ t_{e_{ij}}$	15 ms	T_s	50 ms

B. Placement trends with changing unit resource premium

The placement decision changes by the increase of δ_{m_1} under different user distributions are shown in Fig. 6, where

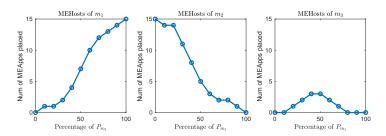


Fig. 7. Numbers of *MEApps* placed on the 3 *MEHost* with different percentages of *users* in the network. Users of m_1 increase from 0% to 100%, while those of m_2 decrease from 100% to 0%. There is no user for m_3 .

 δ_{m_1} , the unit resource premium payable to the *MECSP* for hosting *MEApps* for others, increases from 0.1 to 0.6. For comparison, in Fig. 6(a), most users are from m_1 . There is $P_{m_1}=0.5$ and $P_{m_2}=P_{m_3}=0.25$. Meanwhile, in Fig. 6(b), most users subscribe services from m_3 as $P_{m_1}=P_{m_1}=0.25$ and $P_{m_3}=0.5$.

From the results of the two scenarios, we learn that the *MEHosts* with lower combination of unit resource base price (γ_m) and unit resource premiums (δ_m) will be selected first. The *MEHosts* of the *MECSP* will have more weight upon consideration if there are more *users* from that *MECSP*.

C. Placement trends with changing user distribution

To further demonstrate the impact from the distribution of the *users*, we simulate various scenarios with different percentages of *users* for m_1 and m_2 , while there is no user for m_3 . Users of m_1 increase from 0% to 100%, while those of m_2 decrease from 100% to 0%.

The results have shown the trends of MEApps migrating to MEHosts owned by the MECSP that has more active users to avoid premiums charged by other MECSPs. However, resource sharing still takes place (m_3 hosting MEApps for m_1 and m_2) when needed for better latency results and service quality.

VII. CONCLUSIONS

In this paper, we have presented the architecture and the algorithms for mobile edge applications placement for multiple mobile edge computing service providers, leveraging the blockchain-based system called EdgeChain. Future work will be considering multiple service chains initiated by multiple users, to achieve lower overall costs for the entire system.

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