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Cost-Effective App Data Distribution in Edge Computing

Xiaoyu Xia, Feifei Chen, Qiang He*, *Member, IEEE*, John Grundy, *Senior Member, IEEE*, Mohamed Abdelrazek, and Hai Jin, *Fellow, IEEE*

Abstract—Edge computing, as an extension of cloud computing, distributes computing and storage resources from centralized cloud to distributed edge servers, to power a variety of applications demanding low latency, e.g., IoT services, virtual reality, real-time navigation, etc. From an app vendor's perspective, app data needs to be transferred from the cloud to specific edge servers in an area to serve the app users in the area. However, according to the pay-as-you-go business model, distributing a large amount of data from the cloud to edge servers can be expensive. The optimal data distribution strategy must minimize the cost incurred, which includes two major components, the cost of data transmission between the cloud to edge servers and the cost of data transmission between edge servers. In the meantime, the delay constraint must be fulfilled - the data distribution must not take too long. In this paper, we make the first attempt to formulate this Edge Data Distribution (EDD) problem as a constrained optimization problem from the app vendor's perspective and prove its \mathcal{NP} -hardness. We propose an optimal approach named EDD-IP to solve this problem exactly with the Integer Programming technique. Then, we propose an $O(k)$ -approximation algorithm named EDD-A for finding approximate solutions to large-scale EDD problems efficiently. EDD-IP and EDD-A are evaluated on a real-world dataset and the results demonstrate that they significantly outperform three representative approaches.

Index Terms—edge computing, optimization, data distribution, cost-effectiveness, edge server network.

1 INTRODUCTION

THE world has witnessed exponentially growing mobile data traffic in this decade promoted by a huge increase in mobile devices and Internet of Things (IoT) connected devices [1]. This explosion of mobile data traffic has led to a wealth of research aiming to relieve the enormous data transmission loads on networks. Conventional network paradigms facilitated by cloud computing, including content delivery networks, content-centric networks and information centric networks, cannot handle the increases in network latency and network congestion caused by the rapidly increasing mobile traffic. In recent years, edge computing has emerged as a new computing paradigm that push computing and storage resources to the edge of the cloud [2]. These edge servers, each powered by one or many physical machines, are deployed at base stations or access points that are geographically close to devices [3]. Vendors of mobile and IoT applications (referred to as *app vendors* together hereafter) can hire computing and storage resources on edge servers for hosting their apps to serve their own app users with low latency [4]. Offloading computation tasks

from app users' end-devices to nearby edge servers can ease the computation burden and energy consumption on those resource-limited end-devices [5], [6], [7], [8]. This is also a key technology of the 5G mobile network [9].

As edge servers become the entry points to the Internet for a larger number of mobile and IoT devices, a much larger proportion of the rapidly increasing mobile traffic data will be transmitted through those edge servers from the cloud. From an app vendor's perspective, caching app data on edge servers can considerably reduce the latency for their own users' data retrieval. In addition, it will largely reduce the volume of their app data transmitted between the cloud and its app users. This in turn will decrease the corresponding data transmission costs [10]. The new challenges raised by data caching in the edge computing environment have attracted many researchers' attention in recent years [11], [12], [13], [14], [15].

However, existing research efforts have focused on how to cache data across edge servers to achieve different optimization objectives, e.g., to minimize caching cost [14], to minimize retrieval latency [15], to guarantee the quality of transmissions [12], etc. The fact that data transmission from within the cloud to distributed edge servers may incur excessive costs is largely ignored. For example, Amazon Web Services charges up to US\$0.09 + US\$0.02 to transfer 1GB data out of its S3 data storage facilities to the internet¹. It is a significant component in the cost structure for app vendors to consider in the edge computing environment, similar to a large body of work on cloud computing [16], [17]. Unlike data transmission in cloud computing and wireless sensor networks [18], [19], [20], [21], app data distribution

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1. <https://aws.amazon.com/s3/pricing/>

in the edge computing environment consists of two major components: 1) data transmission from the cloud to edge servers; 2) and data transmission between edge servers. Both components must be considered in a systematic manner to formulate cost-effective data distribution strategies for app vendors. We refer to this problem as the edge data distribution (EDD) problem in this paper.

The scale of an EDD scenario can be very large and finding a solution is not trivial. To help app vendors formulate cost-effective EDD strategies that minimize the EDD cost while fulfilling the app vendor's EDD time constraint, this paper makes the first attempt to study the EDD problem from the app vendor's perspective. The key contributions of this paper are as follows:

- We formulate and model the EDD problem as a constrained optimization problem (COP) from the app vendor's perspective and prove that it is \mathcal{NP} -hard.
- We develop an optimal approach, namely EDD-IP, for finding optimal solutions to EDD problems with the Integer Programming technique.
- We develop an approximation approach named EDD-A for finding approximate solutions to large-scale EDD problems rapidly.
- We conduct extensive experiments on a widely-used real-world dataset to evaluate the proposed approaches against three representative approaches.

The rest of this paper is organized as follows. Section 2 motivates this research with an example. Section 3 formulates the EDD problem and proves its \mathcal{NP} -hardness. Section 4 presents and analyzes our optimal approach and approximation approach for solving the EDD problem. Section 5 evaluates the proposed approaches experimentally. Section 6 reviews the related work. Section 7 concludes this paper and points out the future work.

2 MOTIVATING EXAMPLE

Facebook Horizon² is a representative application that can significantly benefit from caching their data on edge servers. Facebook users wearing Oculus headsets can access VR videos and VR games on Facebook Horizon. Caching popular VR videos on edge servers will allow Facebook users covered by those edge servers to access the videos with minimum latency, which is critical because VR users are highly latency-sensitive. It will also reduce the data traffic between the Facebook Horizon server in the cloud and Facebook Horizon users. However, assuming a similar price for data transmission asked by Amazon, cost-ineffective data distribution strategies may cost Facebook Horizon significantly just to distribute VR videos to edge servers. As the number of Facebook Horizon users continues to grow, such extra expense will increase rapidly.

Fig. 1 presents an example EDD scenario with 10 edge servers in a specific geographic area. Those edge servers are connected via high-speed links to facilitate data transmissions between them [7], [22]. Let us assume that a Facebook Horizon VR video is to be cached on 7 of those edge

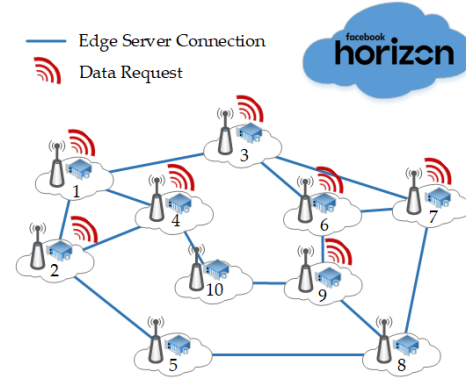


Fig. 1. An example EDD scenario

servers³. There are many possible strategies for distributing the VR video onto those 7 edge servers. A straightforward EDD strategy is to transmit this VR video from the cloud to each individual edge server directly. We refer to such data transmissions as C2E (cloud to edge server) transmissions hereafter. Alternatively, the VR video can first be transmitted from the cloud onto one of the edge servers, which then transmits the VR video onto other edge servers via the high-speed links between them. The data transmissions between edge servers are referred to as E2E (edge server to edge server) transmissions hereafter. A third possible EDD strategy is similar to the second one, but the VR video is first transmitted from the cloud to several of the edge servers instead of one. Given the same amount of data to transmit, E2E transmissions cost less than C2E transmissions because of the much shorter distance between adjacent edge servers and the zero burden caused by E2E transmissions on the internet backbone [23]. Therefore, different EDD strategies incur different costs.

From Facebook's perspective, it is critical to formulate a cost-effective data distribution strategy that minimizes the data distribution cost. While pursuing low data distribution cost, the time taken to distribute the VR video onto all the 7 edge servers must also be considered. As discussed above, low latency is one of the major objectives of edge computing [24]. Thus, an EDD strategy must also fulfill Facebook Horizon's time constraint⁴.

3 PROBLEM FORMULATION

In this section, we first formulate the EDD problem as a constrained optimization problem (COP), then prove the \mathcal{NP} -hardness of this problem based on the Steiner Tree problem. The notations used in this paper are summarized in Table 1.

3.1 Problem Statement

Edge computing is significantly different from cloud computing which facilitates content-centric network and content

3. When different VR videos are to be cached, their distribution processes are not correlated in terms of transmission cost and transmission delay. Thus, their corresponding EDD strategies are formulated individually.

4. Please note that the time constraint for EDD varies from application to application.

2. <https://www.oculus.com/facebookhorizon>

TABLE 1
Summary of Notations

Notation	Description
c	cloud node
d_{limit}	delay limit defined by app vendor
d_v	delay that edge server v obtain data after data arrives the edge server network
\mathcal{D}_v	depth of v , equal to $d_v + 1$
\mathcal{D}_{limit}	depth limit, equal to $d_{limit} + 1$
E	set of links between edge servers
$e_{u,v}$	edge/link between edge server u and v
G	graph presenting a particular area
\mathcal{H}	latency limit defined by app vendor
\mathcal{R}	set of destination edge servers
γ	the ratio of data transmission cost of $C2E$ and a 1-hop transmission cost of $E2E$
S	set of binary variables indicating the selection of the initial transit edge servers
s_v	binary variable indicating whether v is an initial transit edge server
\mathcal{T}	set of binary variables indicating the data distribution path
T_{ce}	tree with root c with edges $e_{c,v}, \forall v \in \{T_{ms} - c\}$
T_{edd-a}	tree returned by Algorithm 2
T_{ms}	tree returned by Algorithm 1
$\mathcal{T}_{u,v}$	binary variable indicating data transmitted from u to v
V	set of edge servers
v	edge server v
u	edge server u

delivery network. In an edge computing environment, adjacent edge servers deployed at different base stations and access points can communicate with their neighbor edge servers and share their storage resources via high-speed links [7], [22]. Thus, the edge servers in a particular area constitute an *edge server network*, which can be modeled as a graph where a node represents an edge server and an edge represents the link between two edge servers.

In this research, the n edge servers in a particular area are modeled as a graph G . For each edge server v , graph G has a corresponding node. For each pair of linked edge servers (u, v) , graph G has a corresponding edge $e_{u,v}$. We use $G(V, E)$ to represent the graph, where V is the set of nodes in G and E is the set of edges in G . In the remainder of this paper, we will speak inter-changeably of an edge server and its corresponding node in graph G , denoted as $v, \forall v \in V$. Let \mathcal{R} denote the set of *destination edge servers* in graph G , i.e., the edge servers to which the data are to be transmitted from the cloud.

Example 1. As discussed above, the edge server network in Fig. 1 can be modeled as the graph G presented in Fig. 2, while the destination edge servers are presented as black nodes and others are white nodes. In graph G , there are 10 edge servers with 14 edges in total, where $\mathcal{R} = \{1, 2, 3, 4, 6, 7, 9\}$.

The fees for data transmissions charged by different cloud service providers, e.g., Amazon and Google, are dif-

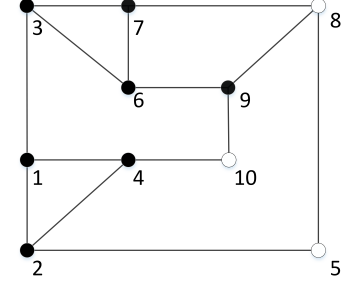


Fig. 2. Graph structure of EDD scenario in Fig. 1

ferent. Amazon even has different pricing models in its different regions. Similarly, edge infrastructure providers usually have different pricing models for their E2C transmissions and E2E transmissions. Thus, we use a ratio γ to indicate the difference between the C2E transmission cost and the E2E transmission cost generically. For example, $\gamma = 20$ indicates that a C2E transmission costs 20 times as much to transmit a data than an E2E transmission - C2E transmissions are usually more expensive than E2E transmissions as discussed in Section 2. In addition, the data transmission latency between two edge servers is measured by the number of hops between them in graph G . Thus, the C2E transmission cost can be converted to γ times of the 1-hop E2E transmission cost. This way, the optimization objective and the corresponding constraints in the EDD problem can be modeled in a more generic manner. Specific pricing models and network latency models can be easily integrated to calculate the actual EDD cost and EDD time consumption, i.e., the total cost and time of transmitting the data from the cloud to the destination edge servers, respectively.

There are two possible phases of EDD. 1) The *C2E* transmission, where the data is transmitted from the cloud to one or many of the edge servers in the area, which are referred to as the "initial transit edge servers" hereafter. 2) The *E2E* transmission, where the data is transmitted from the initial transit edge servers to the destination edge servers via other transit edge servers. Please note that an initial transit edge server is not necessarily a destination edge server. A destination edge server may also be a transit edge server because it may transmit the data further to other destination edge servers. Accordingly, an EDD strategy consists of two parts, a C2E strategy and an E2E strategy. A C2E strategy specifies the initial transit edge servers. It is denoted as a vector $S = \langle s_1, \dots, s_n \rangle$, where s_v ($1 \leq v \leq n$) indicates whether edge server v is selected as an initial transit edge server to receive the data from the cloud directly:

$$s_v = \begin{cases} 0 & \text{if } v \text{ is selected as an initial transit edge server} \\ 1 & \text{if } v \text{ is NOT selected as an initial transit edge server} \end{cases} \quad (1)$$

An E2E strategy is also represented by a vector $\mathcal{T}_{E2E} = \langle \mathcal{T}_{1,1}, \mathcal{T}_{1,2}, \dots, \mathcal{T}_{n,n} \rangle$, where $\mathcal{T}_{u,v}$ ($u, v \in V$) denotes whether

the data is transmitted through edge $e_{u,v}$ in G :

$$\mathcal{T}_{u,v} = \begin{cases} 1 & \text{if data is transmitted through edge } e_{u,v} \\ 0 & \text{if data is NOT transmitted through edge } e_{u,v} \end{cases} \quad (2)$$

Since a valid EDD strategy must connect each destination edge server $v \in R$ to an initial edge server in S through \mathcal{T}_{E2E} , constraint (3) must be fulfilled:

$$isConnected(v, S, \mathcal{T}_{E2E}) = true, \forall v \in R \quad (3)$$

The details to fulfil constraint (3) will be discussed later in Theorem 3.

As discussed above, the EDD time constraint is determined by the app vendor - i.e. application-specific. As discussed in Section 1, we formulate the EDD problem in a generic manner. The data transmission latency between two edge servers is measured by the number of hops between them in G . Let d_{limit} denote the app vendor's EDD time constraint. Please note that the EDD time constraint here does not include the C2E latency because it is ensured by the edge infrastructure provider and does not impact the formulation of the EDD strategy - it can never be avoided or reduced by an EDD strategy. Thus, each destination edge server v 's E2E latency, i.e., the data transmission latency between v and its connected initial edge server in S must not exceed this constraint:

$$0 \leq d_v \leq d_{limit}, d_v \in \mathbb{Z}^+, \forall v \in R \quad (4)$$

Example 2. Take Fig. 2 as an example. Let us assume that the app vendor's EDD time constraint is $d_{limit} = 2$. This means that it must not take more than two hops for a destination edge server to receive the data from an initial transit edge server. In Fig. 2, if node 3 is the only edge server selected as the initial transit edge server, one possible E2E strategy is to select edges $\{e_{3,1}, e_{3,6}, e_{3,7}, e_{1,2}, e_{1,4}, e_{6,9}\}$. This means that in \mathcal{T}_{E2E} there is $\mathcal{T}_{3,1} = \mathcal{T}_{3,6} = \mathcal{T}_{3,7} = \mathcal{T}_{1,2} = \mathcal{T}_{1,4} = \mathcal{T}_{6,9} = 1$. Accordingly, we can obtain the 7 destination edge servers' E2E latency: $d_3 = 0, d_1 = d_6 = d_7 = 1, d_2 = d_4 = d_9 = 2$.

Given an EDD time constraint d_{limit} , the app vendor's optimization objective is to minimize the EDD cost, which consists of the part incurred by the C2E transmission(s) and the E2E transmissions:

$$\text{minimize } Cost_{C2E}(S) + Cost_{E2E}(\mathcal{T}_{E2E}) \quad (5)$$

while fulfilling the EDD time constraint (4).

3.2 Problem Hardness

Now we prove that the EDD problem is \mathcal{NP} -hard by proving Theorem 1 and Theorem 2.

Theorem 1. The EDD problem is \mathcal{NP} .

Proof As there are no more than $(|V| + |E| + 2|R|)$ constraints in total, any solution to this EDD problem can be validated in polynomial time by checking whether the solution satisfies the constraints (1), (2), (3) and (4). Thus, the EDD problem is \mathcal{NP} . \square

Theorem 2. The EDD problem is \mathcal{NP} -hard.

Proof To prove the \mathcal{NP} -hardness of the EDD problem, we first introduce the classic Rooted Minimum Steiner Tree

(RMST) problem. The RMST problem is well-known to be \mathcal{NP} -hard [25], [26], and can be defined as follows. Given a graph $G = (V, E)$, a set of destination nodes \mathcal{N} in G , and a root node $root$ of the Steiner tree ST . For each edge $e \in E$, there is a variable \mathcal{Y}_e to indicate whether it is in ST ($\mathcal{Y}_e = 1$) or not ($\mathcal{Y}_e = 0$). Moreover, each edge e has its own weight \mathcal{W}_e . Function $path(n, root, ST)$ is used to obtain the possible path from $root$ to the node n through the edges in E . If node n is the root of ST or not in ST , there should not exist a path from $root$ to n , which means $path(n, root, ST) = null$. The formulation is presented below:

$$\text{object : } \min \sum \mathcal{Y}_e \cdot \mathcal{W}_e \quad (6a)$$

$$\text{s.t. : } \mathcal{Y}_e \in \{0, 1\} \quad (6b)$$

$$path(n, root, ST) \neq null, \forall n \in \mathcal{N} \quad (6c)$$

Now we prove that the RMST problem can be reduced to an instance of the EDD problem. The reduction can be done as follows: 1) add the cloud server as a node r into G to obtain a new graph G' ; 2) add the edges from node r to every other node in G' ; 3) relax the EDD time constraint d_{limit} to $|V|$. Given any instance $RMST(G, root, R, \mathcal{W})$, we can correspondingly construct $EDD(G', cloud, R, Cost_{C2E}, Cost_{E2E})$ with the reduction above in polynomial time where $|G| = |G'|$, while $Cost_{C2E}$ and $Cost_{E2E}$ can be treated as the weights of the edges. By the reduction, the constraint (4) can be relaxed properly. As the constraint (6b) in the RMST problem only considers the edge variables, we can convert constraint (1) to $S_v = \mathcal{T}_{c,v} \in \{0, 1\}$. By combining this with constraint (2), constraint (6b) is fulfilled. Additionally, both constraints (3) and (6c) ensure that all the nodes in R are connected to $root$. Moreover, objective (6a) of RMST is to obtain the minimum total weight of ST , which can be projected to (5) by mapping the $Cost_{C2E}$ and $Cost_{E2E}$ to the weights of edges.

In conclusion, any solution \mathcal{Y} always satisfies the RMST problem if \mathcal{Y} satisfies the reduced EDD problem. Therefore, the EDD problem is reducible from the RMST problem and it is thus \mathcal{NP} -hard. \square

4 EDGE DATA DISTRIBUTION STRATEGY FORMULATION

We first present an optimization approach, namely EDD-IP, to exactly solve the EDD problem formulated in the previous section. Then, we introduce an $O(k)$ -approximate approach named EDD-A to solve large-scale EDD problems approximately, followed by a theoretical analysis of its performance.

4.1 Optimization Approach

The solution to the EDD problem must minimize the EDD cost while fulfilling the app vendor's EDD time constraint d_{limit} . Thus, the EDD problem can be modeled as a constrained optimization problem (COP).

Following the methodology of the proof of Theorem 3, we use similar techniques to convert the EDD problem to an integer program model that can be solved by integer

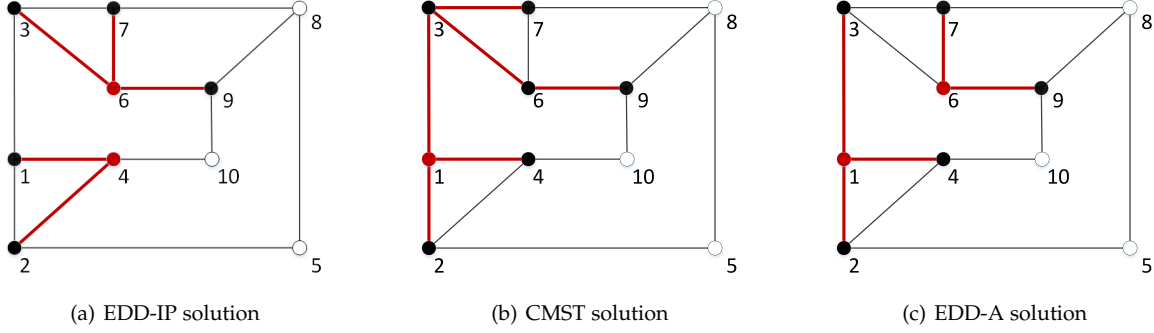


Fig. 3. EDD solutions

programming solvers, such as IBM CPLEX Optimizer⁵ and Gurobi⁶. Accordingly, this optimal approach is named EDD-IP.

Firstly, we add the cloud c into V , then add the edges from c to each edge server $v \in V \setminus c$ in graph G . Then, the C2E strategy $S = \langle s_1, \dots, s_n \rangle$ can be formulated by selecting edges in graph G , i.e., $\mathcal{T}_c = \langle \mathcal{T}_{c,1}, \mathcal{T}_{c,2}, \dots, \mathcal{T}_{c,n} \rangle$, where $\mathcal{T}_{c,v}$ ($v \in V \setminus c$) denotes whether the data is transmitted from the cloud c to v through the new edge $e_{c,v}$. Here, we combine the C2E strategy S and the E2E strategy \mathcal{T}_{E2E} as the data distribution strategy $\mathcal{T} = \langle \mathcal{T}_{c,1}, \dots, \mathcal{T}_{c,n}, \mathcal{T}_{1,1}, \dots, \mathcal{T}_{n,n} \rangle$, where variable $\mathcal{T}_{u,v} \in \{0, 1\}$ ($u \in \{c\} \cup [1, n], v \in [1, n]$) indicates whether edge $e_{u,v}$ is included in \mathcal{T} . Secondly, we implement the definition of depth in the Steiner tree to represent the order of transmitting the data. Denote \mathcal{D}_v as the depth of edge server v , where $\mathcal{D}_v = d_v + 1$ and $\mathcal{D}_c = 0$. Then, the EDD time constraint d_{limit} can be defined as a depth limit $\mathcal{D}_{limit} = d_{limit} + 1$.

After this, we define the variable for each edge server v :

$$I_v = \begin{cases} 0 & \text{if } v \text{ is visited during the EDD process} \\ 1 & \text{if } v \text{ is NOT visited during the EDD process} \end{cases} \quad (7)$$

Now, the COP model for the EDD problem is formally expressed as follows:

$$\min \gamma \sum_{v \in V \setminus c} \mathcal{T}_{c,v} + \sum_{v,u \in V \setminus c} \mathcal{T}_{u,v} \quad (8)$$

$$I_v = 1, \forall v \in R \quad (9)$$

$$\sum_{u \in V} \mathcal{T}_{u,v} = I_v, \forall u, v \in V \setminus c \quad (10)$$

$$\mathcal{T}_{u,v} \leq I_u \cdot I_v, \forall u, v \in V \quad (11)$$

$$I_v, \mathcal{T}_{u,v} \in \{0, 1\}, \forall u, v \in V \quad (12)$$

$$\mathcal{D}_c = 0 \quad (13)$$

$$\mathcal{D}_c < \mathcal{D}_v \leq \mathcal{D}_{limit}, \forall v \in V \setminus c \quad (14)$$

$$\mathcal{D}_v - \mathcal{D}_u = 1, \forall u, v \in V, \mathcal{T}_{u,v} = 1 \quad (15)$$

where γ is the ratio that generically indicates the ratio of the C2E transmission unit cost over the E2E transmission unit cost, as introduced in Section 3.1.

Example 3. Fig. 3(a) shows the EDD strategy formulated by EDD-IP with EDD time constraint $d_{limit} = 1$. The C2E

strategy specifies that nodes 6 and 4 are selected as the initial transit edge server. They receive the data from the cloud and then transmit it to all other destination edge servers. The EDD strategy selects edges $\{e_{c,4}, e_{c,6}, e_{6,3}, e_{6,7}, e_{6,9}, e_{4,1}, e_{4,2}\}$ for data transmissions. The total cost is $2\gamma + 6$ times of a 1-hop E2E transmission cost.

Theorem 3. EDD-IP computes an optimal solution to the EDD problem.

Proof Let \mathcal{C}_{C2E} and \mathcal{C}_{E2E} denote the unit costs of C2E data transmission and E2E data transmission, respectively. This way, objective (5) can be converted to $\mathcal{C}_{C2E} \cdot \sum_{v \in V \setminus c} \mathcal{T}_{c,v} + \mathcal{C}_{E2E} \cdot \sum_{u,v \in V \setminus c} \mathcal{T}_{u,v}$, with $Cost_{C2E}(S)$ calculated by $\mathcal{C}_{C2E} \cdot \sum_{v \in V \setminus c} \mathcal{T}_{c,v}$ and $Cost_{E2E}(\mathcal{T}_{E2E})$ calculated by $\mathcal{C}_{E2E} \cdot \sum_{u,v \in V \setminus c} \mathcal{T}_{u,v}$. Denote $\gamma = \frac{\mathcal{C}_{C2E}}{\mathcal{C}_{E2E}}$, objective (5) can be presented as $\mathcal{C}_{E2E} \cdot (\gamma \sum_{v \in V \setminus c} \mathcal{T}_{c,v} + \sum_{u,v \in V \setminus c} \mathcal{T}_{u,v})$. Since \mathcal{C}_{E2E} is a constant, objective (5) can be transformed to objective (8) by removing \mathcal{C}_{E2E} .

There are two situations in Eq. (10): 1) if v is not visited, any edge pointing to v will not be selected in the C2E strategy; 2) if v is visited, there must be exactly selected one edge that points to v . Constraints (9) and (10) ensure that all the destination edge servers in R are visited during the EDD process. Constraint (11) ensures that, if edge $e_{u,v}$ is selected, both edge servers u and v must be selected. Otherwise, $e_{u,v}$ can never be included into the E2E strategy.

Thus, constraints (9), (10), (11) and (12) collectively ensure that every destination edge server $v \in R$ is connected to the cloud server in G , fulfilling (3) in Section 3.1.

Constraint (13) makes sure that the EDD process always starts from the cloud. In addition, constraint (14) ensures that the EDD time constraint is fulfilled, while constraint (15) guarantee the the depth of u is always one less than that of v , if edge $\{u, v\}$ exists.

Thus, EDD-IP computes an optimal solution to the EDD problem. \square

As discussed in Section 3.1, specific cost models and latency models can be easily integrated to calculate the actual EDD costs and EDD time consumption in real-world EDD scenarios. For example, given a cost function $cost(u, v)$ that represents the transmission cost between u and v , the total EDD cost can be calculated by $\sum_{v \in V \setminus c} \mathcal{T}_{c,v} \cdot cost(c, v) + \sum_{u,v \in V \setminus c} \mathcal{T}_{u,v} \cdot cost(u, v)$. Given a specific latency constraint \mathcal{L}_{limit} and a latency function $\mathcal{L}(u, v)$ that represents

5. <https://www.ibm.com/analytics/cplex-optimizer>

6. <http://www.gurobi.com/>

the latency between u and v via $e_{u,v}$, constraints (13) (14) and (15) can be replaced by (16), (17) and (18) respectively:

$$\mathcal{L}_{\mathcal{T}}(c, c) = 0 \quad (16)$$

$$\mathcal{L}(c, v) \leq \mathcal{L}_{\mathcal{T}}(c, v) \leq \mathcal{L}_{limit}, \forall v \in V \setminus c \quad (17)$$

$$\mathcal{L}_{\mathcal{T}}(c, v) - \mathcal{L}_{\mathcal{T}}(c, u) = \mathcal{L}(u, v), \forall u, v \in V, \mathcal{T}_{u,v} = 1 \quad (18)$$

where $\mathcal{L}_{\mathcal{T}}(c, v)$ represents the total transmission latency between c and v via the path from c to v indicated by \mathcal{T} .

4.2 Approximation Algorithm

As proven in Section 3.2, the EDD problem is \mathcal{NP} -hard. Finding the optimal solution is intractable in large-scale EDD scenarios. To address this issue, this section presents an approximation approach, named EDD-A, for finding approximate solutions to large-scale EDD problems efficiently. The approximation ratio of EDD-A is $O(k)$, which means that the ratio of the EDD cost incurred by EDD-A and that incurred by the optimal solution is $O(k)$ in the worst case, where k is a constant.

Similar to the techniques used in Section 4.1, EDD-A is an approach designed based on the concept of Steiner tree by adding the cloud server c and the corresponding edges into G . There are two parts in EDD-A: 1) calculating an approximate minimum Steiner tree T_{ms} based on a simple but fast algorithm presented in Algorithm 6 (CMST); 2) splicing and pruning T_{ms} with the latency constraint $\mathcal{H} = \mathcal{D}_{limit}$, based on Algorithm 2.

We first introduce our CMST (Connectivity-oriented Minimum Steiner Tree) algorithm for calculating the approximation to the minimum Steiner tree. CMST is based on the algorithm proposed in [27] which is simple but effective. In our CMST algorithm, it first collects the nodes closest (with the lowest cost) to T_{ms} as a set, then selects the one with the highest connectivity (Lines 3-4 in Algorithm 1).

Algorithm 1 CMST Algorithm

- 1: **Input:** $G(V, E)$, R , c
 - 2: **Output:** A minimum Steiner Tree T_{ms}
 - 3: initialize a tree T_{ms} based on $G \cup \{cloud\}$, only consisting of the node $\{cloud\}$;
 - 4: return T_{ms} if all the destination edge servers in R have been added into T_{ms} , else go to step 3;
 - 5: find a set of edge servers C that are closest to T_{ms} , while $C \cap T_{ms} = \emptyset$
 - 6: find edge server v with the highest connectivity, then add v to T_{ms} ;
 - 7: go to step 2.
-

Example 4. Take Fig. 2 as an example. By applying CMST, edges $\{e_{c,1}, e_{1,2}, e_{1,3}, e_{1,4}, e_{3,6}, e_{3,7}, e_{6,9}\}$ are added into T_{ms} , as shown in Fig. 3(b). The total cost of T_{ms} is $\gamma + 6$. Let us assume that all E2E transmissions must be finished within one hop ($d_{limit} = 1$) to facilitate the following discussion. This means $\mathcal{H} = 2$. Thus, Nodes 6, 7 and 9 violate this limit. Thus, the EDD-A algorithm needs to fix such violations.

Algorithm 2 presents the pseudo code of EDD-A. It takes the minimum Steiner tree T_{ms} returned by Algorithm 1 as

input. Firstly, it initializes T_{edd-a} by T_{ms} and sets the parent of cloud server c as null (Line 3). Then, it initializes $parents[]$ for recording the parent of each node in T_{edd-a} , $d[]$ for recording the transmission latency between c and each node in T_{edd-a} , and $costs[]$ for recording the transmission costs between c and each node in T_{edd-a} . After that, the algorithm visits each node v that violates the latency limit \mathcal{H} and finds the minimum-cost path $[c - s - v]$. If path $[c - s - v]$ helps v eliminate the violation, EDD-A adds path $[c - s - v]$ into T_{edd-a} and updates $parents[]$, $d[]$ and $costs[]$ accordingly (Lines 11-17). If the latency limit is still violated, i.e., the sum of latency $\Delta d[s, v]$ and edge server s 's latency $d[s]$ exceeds the latency limit \mathcal{H} , v will be connected to c directly (Lines 19-21). Next, EDD-A visits each child u of v to update the shortest paths and the parents for both u and v (Lines 23-33). Finally, the algorithm prunes the unused edges in T_{edd-a} (Line 35), and returns T_{edd-a} as the final result.

Example 5. Continuing with Example 2, EDD-A selects node 6 to connect with the cloud node c directly by adding edge $e_{c,6}$. Now, node 9, i.e., the child of node 6 in T_{edd-a} , can obtain the data via 1 hop. After this, EDD-A visits node 7 and finds the shortest path $[c - 6 - 7]$. Thus, EDD-A adds edge $e_{6,7}$ into T_{edd-a} . After running EDD-A, the result is presented in Fig. 3(c). The total cost now is $2\gamma + 5$, and the EDD time constraint, $\mathcal{H} = 1$, is fulfilled. In this case, the EDD strategy formulated by EDD-A has the same cost as EDD-IP.

In the EDD-A algorithm, the computational overhead of finding the minimum Steiner tree T_{ms} is $O(|R|^2)$. It takes at most $O(|V|^2)$ to read each edge server in T_{edd-a} in DFS order and obtain the shortest path by the Dijkstra algorithm. Thus, the total computational overhead of EDD-A is $O(|R|^2 + |V|^3) = O(|V|^3) = O(n^3)$.

In the rest of this section, we prove that EDD-A is an $O(k)$ -approximation algorithm based on the following theorems and lemmas, where k is a constant.

Theorem 4. CMST is a 2-approximation algorithm to calculating the Steiner minimum tree.

Proof The original idea of CMST is the same as the algorithm proposed in [27]. The difference between them is the comparison in the connectivity between the nodes that have the same cost. This difference does not impact CMST's approximation ratio. Thus, CMST is a 2-approximation algorithm, the same as the approximation algorithm presented in [27]. \square

Let us assume a tree T_{ce} that consists of all the edge servers in T_{ms} and the root c with the edges $[c, v]$, $\forall v \in \{T_{ms} - c\}$. Denote $cost(T_{ce})$, $cost(T_{ms})$ and $cost(T_{edd-a})$ as the total cost of T_{ce} , T_{ms} and T_{edd-a} accordingly.

Theorem 5. For tree T_{edd-a} produced by EDD-A, the cost of T_{edd-a} is $\frac{2\gamma}{\mathcal{H}} + 1$ times of the cost of T_{ms} at most.

Proof Let $v_0 = c$, and v_i be the i^{th} edge server, where $i \in 1, \dots, m$, that introduces additional paths during the DFS traversal. Once the shortest path $[c - v_i]$, which is edge $[c, v_i]$, is added into T_{edd-a} , the cost is exactly $cost_{T_{ce}}(c, v_i) = \gamma$. Moreover, if the path from c to edge server v_i contains edge $[c, v_{i-1}]$ after updating the tree T_{edd-a} , we can obtain $cost_{T_{edd-a}}(c, v_i) \leq cost_{T_{ce}}(c, v_{i-1}) + cost_{T_{ms}}(v_{i-1}, v_i)$. However, if the direct path from c to v_i is

Algorithm 2 EDD-A Algorithm

```

1: Input:  $G(V, E), R, c, \mathcal{H}, T_{ms}$ 
2: Output: A low-cost Steiner Tree  $T_{edd-a}$  within  $\mathcal{H}$ 
3:  $T_{edd-a} \leftarrow T_{ms}, \text{parents}[c] \leftarrow \text{null}$ 
4: For each edge server  $v \in G$ , set the parent of  $v$  in  $T_{edd-a}$ 
   as  $\text{parents}[v]$ , the data retrieval latency of edge server  $v$ 
   in  $T_{edd-a}$  as  $d[v]$  where  $d[c] \leftarrow 0$ , and the cost from  $v$  to
    $c$  in  $T_{edd-a}$  as  $\text{costs}[v]$ 
5: for each edge server  $v$  in  $T_{edd-a}$  in DFS order do
6:   if  $v \notin R$  or  $d[v] \leq \mathcal{H}$  then
7:     continue
8:   end if
9:   find the edge server  $s \in \{T_{edd-a} - c\}$  that minimizes
   the cost of path  $[c - s - v]$ .
10:  if  $\Delta d[s, v] + d[s] \leq \mathcal{H}$  then
11:    update  $\text{parents}[]$  and  $\text{costs}[]$  for edge servers on
    path  $[c - s - v]$ , add path  $[s - v]$  into  $T_{edd-a}$  and
    update  $d[]$ 
12:    for each edge server  $u \in R$  do
13:      if  $\text{costs}[u] > \text{costs}[v] + \text{cost}(v, u)$  then
14:         $\text{costs}[u] \leftarrow \text{costs}[v] + \text{cost}(v, u)$ 
15:        add path  $(v, u)$  into  $T_{edd-a}$  and update  $d[]$ 
16:      end if
17:    end for
18:  else
19:     $\text{parents}[v] \leftarrow c$ 
20:     $\text{costs}[v] \leftarrow \text{cost}(c, v)$ 
21:    update  $d[]$ 
22:  end if
23:  for each child  $u$  of  $v \in T_{edd-a}$  do
24:    if  $\text{costs}[u] > \text{costs}[v] + \text{cost}(v, u)$  then
25:       $\text{parents}[u] \leftarrow v$ 
26:       $\text{costs}[u] \leftarrow \text{costs}[v] + \text{cost}(v, u)$ 
27:    end if
28:    if  $\text{costs}[v] > \text{costs}[u] + \text{cost}(u, v)$  then
29:       $\text{parents}[v] \leftarrow u$ 
30:       $\text{costs}[v] \leftarrow \text{costs}[u] + \text{cost}(u, v)$ 
31:    end if
32:    update  $d[]$ 
33:  end for
34: end for
35: prune unused edges in  $T_{edd-a}$  based on  $\text{parents}[]$ 
36: return  $T_{edd-a}$ 

```

added into T_{edd-a} , it means that $d[v_i]$ exceeds \mathcal{H} , and there is $\text{cost}_{T_{edd-a}}(c, v_i) \geq \gamma + \mathcal{H} = (1 + \frac{\mathcal{H}}{\gamma}) \cdot \text{cost}_{T_{ce}}(c, v_i)$. Thus, we can obtain the following equation:

$$(1 + \frac{\mathcal{H}}{\gamma}) \cdot \text{cost}_{T_{ce}}(c, v_i) \leq \text{cost}_{T_{edd-a}}(c, v_i) \leq \text{cost}_{T_{ce}}(c, v_{i-1}) + \text{cost}_{T_{ms}}(v_{i-1}, v_i) \quad (19)$$

Summing (19) for all the m edge servers, we can obtain:

$$(1 + \frac{\mathcal{H}}{\gamma}) \sum_{i=1}^m \text{cost}_{T_{ce}}(c, v_i) \leq \sum_{i=1}^m (\text{cost}_{T_{ce}}(c, v_{i-1}) + \text{cost}_{T_{ms}}(v_{i-1}, v_i, T_{ms})) \quad (20)$$

Because of $\sum_{i=1}^m \text{cost}_{T_{ce}}(c, v_i) \geq \sum_{i=1}^{m-1} \text{cost}_{T_{ce}}(c, v_i)$, there is:

$$\frac{\mathcal{H}}{\gamma} \text{cost}(T_{ce}) \leq \sum_{i=1}^m \text{cost}_{T_{ms}}(v_{i-1}, v_i) \quad (21)$$

where $\text{cost}(T_{ce}) = \sum_{i=1}^m \text{cost}_{T_{ce}}(c, v_i)$.

For each edge server v changing the path in T_{edd-a} but not adding path $[c, v]$, the update cost, $\text{cost}_{update}(v)$, must be less than $\text{cost}_{T_{ce}}(c, v)$. Thus, the total cost after constructing T_{ms} cannot be more than $\sum_{i=1}^m \text{cost}_{T_{ce}}(c, v_i)$.

Based on the DFS traversal, each edge is visited twice. Thus, the total cost of $\text{cost}_{T_{ms}}(v_{i-1}, v_i)$ is no more than twice of $\text{cost}(T_{ms})$:

$$\sum_{i=1}^m \text{cost}_{T_{ms}}(v_{i-1}, v_i) \leq 2 \cdot \text{cost}(T_{ms}) \quad (22)$$

Thus, the total cost of T_{edd-a} should be bounded by:

$$\text{cost}(T_{edd-a}) \leq \text{cost}(T_{ce}) + \text{cost}(T_{ms}) \leq (\frac{2\gamma}{\mathcal{H}} + 1) \cdot \text{cost}(T_{ms}) \quad (23)$$

□

Theorem 6. EDD-A is an $O(k)$ -approximation algorithm.

Proof As discussed in Theorem 4, the cost of T_{ms} is at most twice the cost of the minimum Steiner tree T . However, the cost of the optimal solution of the EDD problem, OPT , cannot be less than that of the minimum Steiner tree. Thus, we can obtain:

$$\frac{\text{cost}(T_{edd-a})}{\text{cost}(T_{OPT})} \leq \frac{\text{cost}(T_{edd-a})}{\text{cost}(T)} \leq 2(\frac{2\gamma}{\mathcal{H}} + 1) = \frac{4\gamma}{\mathcal{H}} + 2 \quad (24)$$

From (24), the approximation ratio of EDD-A is $2 + \frac{4\gamma}{\mathcal{H}}$. Let $k = 2 + \frac{4\gamma}{\mathcal{H}}$. As both γ and \mathcal{H} are constant inputs, k is a constant. Thus, EDD-A is an $O(k)$ -approximation algorithm where k is a constant. □

Similar to EDD-IP, specific cost and latency models can also be easily integrated into the EDD-A algorithm. Let $\{\gamma_1, \gamma_2, \dots, \gamma_n\}$ denote the C2E costs, $\{\alpha_{1,1}, \alpha_{1,2}, \dots, \alpha_{n,n}\}$ as the E2E costs, and $\mathcal{L}(u, v)$ as the latency model. Cost functions $\text{cost}(c, v)$ and $\text{cost}(u, v)$ can be replaced by γ_v and $\alpha_{u,v}$, respectively, in Algorithm 2, and the latency function $\Delta d[s, v]$ can be calculated by $\mathcal{L}(u, v)$. Now we prove that EDD-A is still an $O(k)$ -approximation algorithm in real-world EDD scenarios with specific cost and latency models.

Theorem 7. EDD-A is an $O(k)$ -approximation algorithm with specific cost and latency models.

Proof We denote $\gamma_{max} = \{\gamma_1, \gamma_2, \dots, \gamma_n\}$ as the maximum C2E cost, $\alpha_{min} = \{\alpha_{1,1}, \alpha_{1,2}, \dots, \alpha_{n,n}\}$ as the minimum E2E cost, \mathcal{L}_{E2E}^{max} as the maximum E2E latency and \mathcal{L}_{C2E}^{min} as the minimum C2E latency. In this case, a specific latency limit \mathcal{L}_{limit} is given by the app vendor to replace \mathcal{H} . Let $v_0 = c$, and v_i ($i \in \{1, \dots, m\}$) be the i^{th} edge server that introduced additional paths during the DFS traversal in Algorithm 2. Once edge $[c, v_i]$, is added into T_{edd-a} , the cost is exactly $\text{cost}_{T_{ce}}(c, v_i) = \gamma_i$. If the path from c to edge server v_i contains edge $[c, v_{i-1}]$ after updating tree T_{edd-a} , we can obtain:

$$\text{cost}_{T_{edd-a}}(c, v_i) \leq \text{cost}_{T_{ce}}(c, v_{i-1}) + \text{cost}_{T_{edd-a}}(v_{i-1}, v_i) \quad (25)$$

However, if the direct path from c to v_i is in T_{edd-a} , it means $d[i] > \mathcal{L}_{limit}$. Given α_{min} and \mathcal{L}_{E2E}^{max} , the ratio of cost over latency for any E2E edge is more than or equals to $\frac{\alpha_{min}}{\mathcal{L}_{E2E}^{max}}$. Denote $\mathcal{H}' = \frac{\alpha_{min}}{\mathcal{L}_{E2E}^{max}}(\mathcal{L}_{limit} - \mathcal{L}_{C2E}^{min})$, we can obtain:

$$cost_{T_{edd-a}}(c, v_i) \geq \gamma_i + \mathcal{H}' = (1 + \frac{\mathcal{H}'}{\gamma_i}) \cdot cost_{T_{ce}}(c, v_i) \quad (26)$$

Combing (26) and (25), (27) stands:

$$(1 + \frac{\mathcal{H}'}{\gamma_i}) \cdot cost_{T_{ce}}(c, v_i) \leq cost_{T_{ce}}(c, v_{i-1}) + cost_{T_{ms}}(v_{i-1}, v_i) \quad (27)$$

Summing (27) for all the m edge servers, we can obtain:

$$\begin{aligned} & \sum_{i=1}^m (1 + \frac{\mathcal{H}'}{\gamma_i}) cost_{T_{ce}}(c, v_i) \\ & \leq \sum_{i=1}^m (cost_{T_{ce}}(c, v_{i-1}) + cost_{T_{ms}}(v_{i-1}, v_i)) \end{aligned} \quad (28)$$

Since γ_i is always lower than or equals to γ_{max} , we can obtain:

$$(1 + \frac{\mathcal{H}'}{\gamma_{max}}) \sum_{i=1}^m cost_{T_{ce}}(c, v_i) \leq \sum_{i=1}^m (1 + \frac{\mathcal{H}'}{\gamma_i}) cost_{T_{ce}}(c, v_i) \quad (29)$$

Because of $\sum_{i=1}^m cost_{T_{ce}}(c, v_i) \geq \sum_{i=1}^{m-1} cost_{T_{ce}}(c, v_i)$ and (29), there is:

$$\frac{\mathcal{H}'}{\gamma_{max}} cost(T_{ce}) \leq \sum_{i=1}^m cost_{T_{ce}}(v_{i-1}, v_i) \quad (30)$$

where $cost(T_{ce}) = \sum_{i=1}^m cost_{T_{ce}}(c, v_i)$.

Based on Theorem 4, we can obtain $k = 2 + \frac{4\gamma_{max}}{\mathcal{H}'}$. The corresponding process is omitted here because it is the same as in Theorems 5 and 6. Thus, Theorem 7 holds. \square

5 EXPERIMENTAL EVALUATION

We have experimentally evaluated the performance of EDD-IP and EDD-A. All experiments were conducted on a Windows-10 machine equipped with Intel Core i7-8665U processor (4 CPUs, 1.90GHz) and 8GB RAM.

5.1 Simulation Settings

5.1.1 Approaches in Comparison

In our experiments, we evaluate the performance of EDD-IP and EDD-A against three representative approaches:

- **EDD-IP**: This approach finds the optimal EDD solutions by solving the COP defined in Section 4.1 with IBM's CPLEX CP Optimizer. Specifically, Ilo-Constraint⁷ is used to implement the constraints in EDD-IP, including constraint (11) with the product terms of binary variables.
- **EDD-A**: This approach finds near-optimal EDD solutions with Algorithm 2 described in Section 4.2.
- **Minimum-cost Multi-cast Routing (MMR)** [28]: This approach deals with the data routing problem in

communication networks. It is also based on Steiner tree and presented as Algorithm 1 in [28].

- **Greedy Connectivity (GC)**: In this approach, we define the connectivity of edge server as the number of edge servers in R that have yet to receive the data. This approach always selects the edge servers with the highest connectivity to receive data from the cloud, which will then transmit the data to other destination edge servers in R , until all the destination edge servers in R can receive the data within the EDD time constraint d_{limit} .
- **Random**: This approach randomly selects edge servers to receive the data from the cloud, which then transmit the data to other destination edge servers in R , one after another, until all the destination edge servers in R receive the data within the EDD time constraint d_{limit} .

5.1.2 Experiment data

Two sets of experiments are conducted on a widely-used EUA dataset⁸ [29]. This dataset contains the geographical locations of 1,464 real-world base stations in Melbourne, Australia. As discussed in Section 3.1, γ is dependent on specific edge infrastructure providers. In the experiments, we set $\gamma = 20$. The links between edge servers are randomly generated and to ensure a connected graph, based on the widely-used Erdős Rényi random graph model [30].

5.1.3 Experiment parameters

To simulate different EDD scenarios, four parameters that impact the performance of EDD-IP and EDD-A are varied in the experiments.

- **The number of edge servers (n) in G** . This parameter impacts the size of graph G .
- **Edge density ($density$)**. We define the edge density with $density = |E|/n$. This parameter impacts the density of graph G .
- **Ratio of destination edge servers ($ratio$)**. This ratio is calculated by $ratio = |R|/n$. It determines the number of destination edge servers in graph G .
- **EDD time constraint ($limit$)**. Measured by the number of hops, this parameter indicates the app vendor's preference for the time taken by the EDD process.

As mentioned in Section 4.2, finding the optimal solutions is intractable in large-scale EDD scenarios. Thus, we limit the maximum running time (in seconds) of EDD-IP in Set #2.

- **Maximum running time (T_{limit})**. EDD-IP will stop and return the optimal solution among all the solutions that have been found within T_{limit} .

Table 2 summarizes the parameter settings. There are two main sets of experiments, Set #1 of small-scale experiments and Set #2 of large-scale experiments. Every time the value of a parameter varies, the experiment is repeated for 100 times and the results are averaged. The last two columns in Table 2 are the number of variables ($3n + dn + 2$),

7. https://www.ibm.com/support/knowledgecenter/SSSA5P_12.8.0/ilog.odms.studio.help/pdf/usrcpoptimizer.pdf

8. <https://github.com/swinedge/eua-dataset>

TABLE 2
Parameter Settings

	n	d	$ratio$	$limit$	T_{limit}	$ variables $ in EDD-IP	$ constraints $ in EDD-IP
Set #1.1	10, 15, ..., 35	1.0	0.6	2	∞	42, 62, ..., 142	67, 100, ..., 232
Set #1.2	20	1.0, 1.2..., 2.0	0.6	2	∞	82, 86, ..., 102	133, 141, ..., 173
Set #1.3	20	1.0	0.2, 0.4 ..., 1.0	2	∞	82	125, 129, ..., 141
Set #1.4	20	1.0	0.6	1, 2, ..., 5	∞	82	133
Set #2.1	200, 300, ..., 700	2.0	0.6	2	10	1002, 1502, ..., 3502	1721, 2581, ..., 6021
Set #2.2	200	2.0, 2.4, ..., 4.0	0.6	2	10	1002, 1082, ..., 1402	1721, 1881, ..., 2521
Set #2.3	200	2.0	0.2, 0.4, ..., 1.0	2	10	1002	1641, 1681, ..., 1801
Set #2.4	200	2.0	0.6	1, 2, ..., 5	10	1002	1721
Set #2.5	200	2.0	0.6	2	2, 4, ..., 10	1002	1721

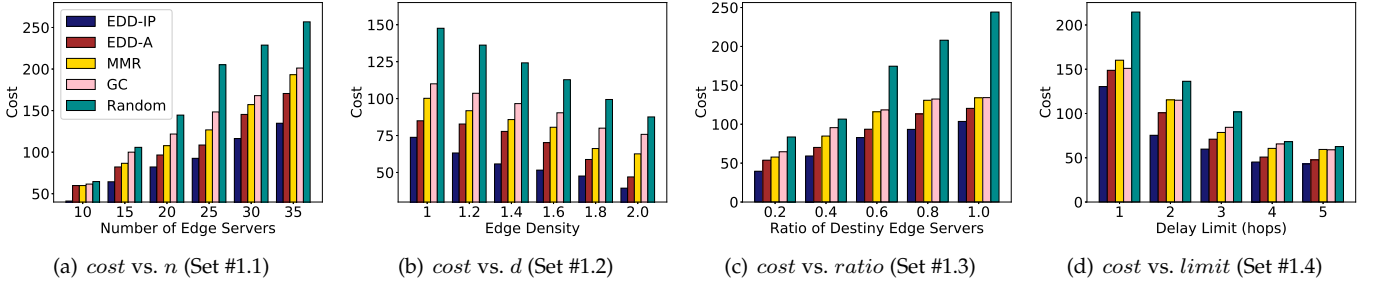


Fig. 4. Effectiveness comparison in Set #1

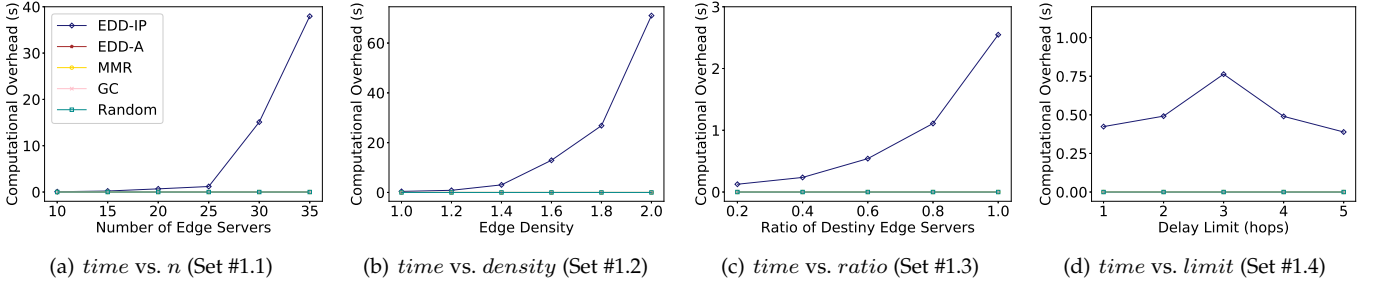


Fig. 5. Efficiency comparison in Set #1

consisting of $I(n+1)$, $\mathcal{D}(n+1)$ and $\mathcal{T}(dn+n)$, and the number of constraints $(4n+2dn+ratio \cdot n+1)$ based on (9), (10), (11), (13), (14) and (15) in the EDD-IP model presented in Section 4.1.

5.1.4 Performance Metrics

The objective of the EDD problem is to minimize the EDD cost. Thus, this *cost* is a significant metric for evaluating the effectiveness of EDD-IP and EDD-A. In addition, as discussed in Section 1, the applications in the edge computing environment are latency-sensitive. It must not take too much time to find an EDD solution. Thus, the computational overhead is selected to evaluate the efficiency of EDD-IP and EDD-A.

- **EDD cost (*cost*)**, calculated by (5), the lower the better.
- **Computational overhead (*time*)**, measured by the time taken by an approach to find the solution, the lower the better.

5.2 Experimental Results

5.2.1 Experiment Set #1

Through comparison with MMR, GC and random, Fig. 4 demonstrates the effectiveness of EDD-IP and EDD-A in experiment Set #1 and the impacts of the four parameters. It can be seen that **the EDD strategies formulated by EDD-IP can distribute the data at the lowest cost**, followed by EDD-A. Across the four subsets of experiments, the average advantages of EDD-IP are 18.22% over EDD-A, 28.01% over MMR, 32.54% over GC and 48.34% over Random. The average advantages of EDD-A are 11.96% over MMR, 17.62% over GC and 36.87% over Random.

Effectiveness. Fig. 4(a) shows the effectiveness results of experiment Set #1.1. When the number of edge servers n increases from 10 to 35, the costs of the EDD strategies formulated by all five approaches increase, from 41.2 to 134.8 by 227.18% for EDD-IP, from 59.8 to 170.6 by 185.28% for EDD-A, from 59.8 to 193.2 by 223.08% for MMR, from 61.6 to 201.2 by 226.62% by GC, and from 64.6 to 256.8 by 297.52% for Random. **Of all the five approaches, EDD-A**

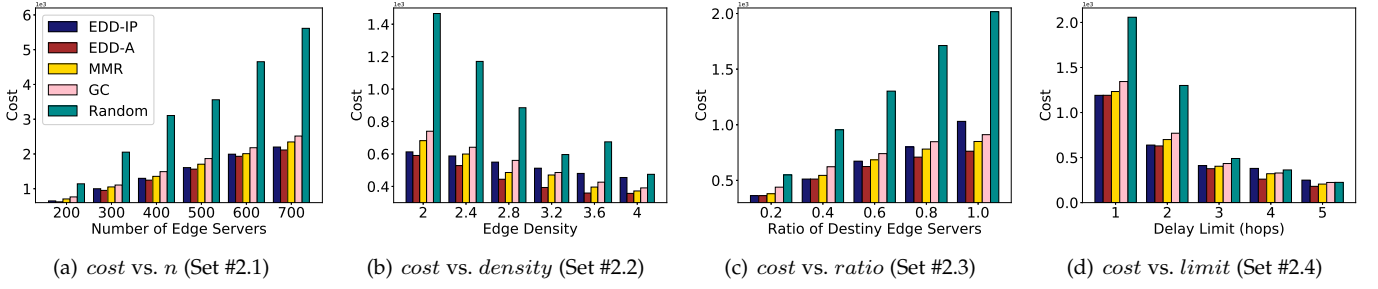


Fig. 6. Effectiveness comparison in Sets #2.1 - #2.4

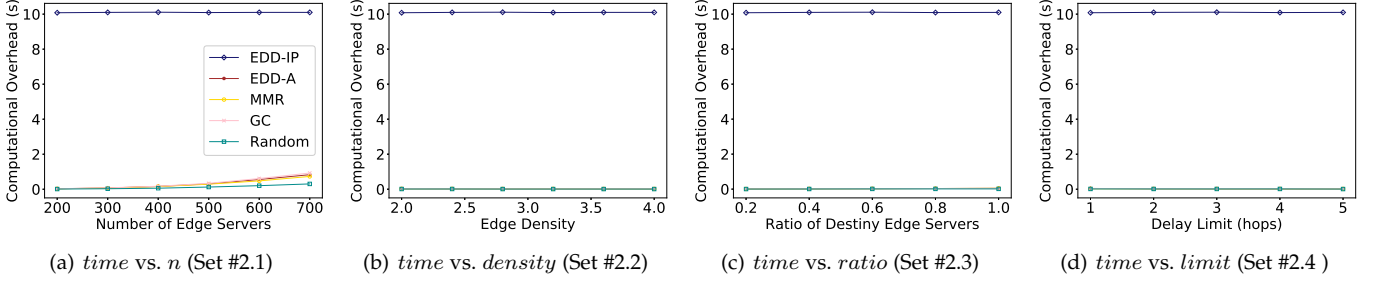


Fig. 7. Efficiency comparison in Sets #2.1 - #2.4

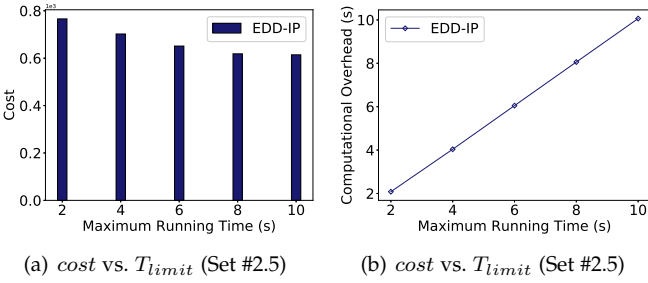


Fig. 8. Effectiveness and efficiency of EDD-IP in Set #2.5

has the lowest overall increase.

Fig. 4(b) shows the results of experiment Set #1.2. Again, **EDD-IP and EDD-A outperform other approaches** with significant margins. The average advantages of EDD-IP are 21.38% over EDD-A, 31.97% over MMR, 40.43% over GC and 53.17% over Random, while the numbers for EDD-A are 13.46% over MMR, 24.23% over GC and 40.44% over Random. As the edge density d increases from 1.0 to 2.0, the costs decrease for all the approaches. This is because, with the number of edge servers n fixed, a higher edge density d gives destination edge servers higher chances to receive the data within the EDD time constraint. This reduces the cost incurred by C2E because few destination edge servers have to receive the data directly from the cloud.

Fig. 4(c) shows the effectiveness results of experiment Set #1.3, where **EDD-IP and EDD-A achieve the best and second best performance**, respectively. The advantage of EDD-IP over EDD-A is 16.09%. The advantages of EDD-A over MMR, GC and Random are 13.79%, 17.24% and 44.77%, respectively. As *ratio* increases from 0.2 to 1.0, all five approaches need more costs to distribute the data. This is expected because a larger number of destination edge servers will certainly incur higher costs of C2E and/or E2E

transmissions.

Fig. 4(d) shows the results of experiment Set #1.4. **EDD-IP outperforms EDD-A** by 15.56%, while EDD-A outperforms MMR, GC and Random by 11.27%, 11.79% and 28.20%, respectively. As *limit* increases, the costs of all five approaches decrease. The main reason is that a less stringent EDD time constraint relies less on C2E transmissions which are faster but more expensive than E2E transmissions.

Efficiency. The efficiency results of Set #1 is presented in Fig. 5. As demonstrated, **EDD-IP is much more computationally expensive than all other approaches**. This validates the \mathcal{NP} -hardness of the EDD problem - excessive computational overheads are inevitable for finding the optimal solutions to large-scale EDD problems. As demonstrated in Fig. 5(a), in largest-scale EDD scenarios with 700 edge servers, EDD-IP takes 39.96 seconds to find the optimal solution in Set #1.1. Moreover, EDD-IP takes up to 71.03 seconds in Set #1.2. When the edge density increases from 1.0 to 2.0, the size of the solution space for EDD-IP to explore becomes larger quickly. Thus, **its computational overhead increases significantly with the increase in edge density**. Similar phenomena are observed in Fig. 5(c). Interestingly, the computational overhead of EDD-IP in Fig. 5(d) increases when the EDD time constraint *limit* increases from 1 to 3, then decreases after that. With *limit* > 3, EDD-IP can find the optimal solution that requires as few as 1 initial transit edge servers. This eases the EDD-IP's pain in inspecting the possible solutions that require multiple initial transit edge servers. As a result, EDD-IP's computational overhead decreases.

Compared with EDD-IP, **the computational overheads of EDD-A stay at a very low level**, taking less than 8.06 seconds in average to find a solution in the entire Set #1. To further evaluate the performance of EDD-A, we present and discuss the results of Set #2, i.e., large-scale experiments, in Section 5.2.2.

5.2.2 Experiment Set #2

Effectiveness. Fig. 6 demonstrates the EDD costs achieved by EDD-IP, EDD-A, MMR, GC and Random in experiment Sets #2.1 to #2.4. Overall, their trends in achieving a low cost are similar to Fig. 4 with the same reasons for their performance changes as discussed in Section 5.2.1. Since the maximum running time of EDD-IP is limited in Set #2, its solution is not always the real optimal solution. Thus, EDD-A achieves the best performance in the entire Set #2. In Fig. 6(a), the costs increase from 650.3 to 2,200.1 by 238.82% for EDD-IP, from 623.4 to 2,115.0 by 239.27% for EDD-A, from 706.2 to 2,346.2 by 232.23% for MMR, from 764.6 to 2,515.8 by 229.03% for GC, and from 1,142.0 to 5,614.6 by 391.65% for Random. Fig. 6(b) shows that the advantages of EDD-A are 29.86% over EDD-IP, 11.08% over MMR, 17.63% over GC and 49.26% by Random on average in experiment Set #2.2 where the edge density d increases from 2.0 to 4.0. The performance differences between the five approaches demonstrated in Fig. 6(c) and Fig. 6(d) are similar to those demonstrated in Fig. 4(c) and Fig. 6(d). Thus, it is not discussed in detail here. Fig. 8(a) depicts that the cost achieved by EDD-IP decreases in Set #2.5 when the running time limit T_{limit} increases. This is because given more running time, EDD-IP can search for more possible solutions to achieve a lower cost.

Efficiency. Fig. 7 depicts the efficiency of each approach in experiment Sets #2.1 to #2.4. In such large-scale experiments, EDD-A, MMR, GC and Random can still find their solutions very fast. In Set #2.1, EDD-A takes a little more time than MMR and Random when the number of edge servers increases. This is the performance price to pay for EDD-A's advantages over these approaches in terms of effectiveness as shown and discussed above. With the significant advantages of EDD-A, especially where there are more edge servers, a higher edge density, a higher ratio of destination edge servers and a lower EDD time constraint, it is worth running EDD-A in real-world applications. As shown in Fig. 8(b), the computational overheads of EDD-IP are slightly higher than its running time limit. The reason is that after EDD-IP stops searching for possible solutions when T_{limit} is reached, it still needs some time to find the best solution among those possible solutions.

5.2.3 Conclusion

The experimental results demonstrated and discussed above indicate that EDD-IP is suitable for solving EDD problems of reasonable sizes. To solve large-scale EDD problems, EDD-A is more practical for its high efficiency in finding solutions very close to the optimal ones.

5.3 Threats to Validity

5.3.1 Construct Validity

The main threats to the construct validity are threefold: 1) the comparison with MMR, GC and Random may not suffice to comprehensively evaluate EDD-IP and EDD-A; 2) the dataset used in the experiments may not represent all real-world scenarios exactly; 3) the performance of our approaches in real-world EDD scenarios may not be exactly the same as in our experiments. To minimize these threats, we varied setting parameters in both sets of experiments,

as summarized in Table 2, to simulate a broad range of various EDD scenarios. This has allowed us to evaluate our approaches more comprehensively. Moreover, we evaluated EDD-IP and EDD-A by not only the comparison with three representative approaches but also the demonstration of how the changes in the setting parameters impacted their performance. In this way, the experimental results can be used as guidelines on the estimation of the performance of our approaches in real-world applications.

5.3.2 External Validity

The main threat to the external validity of the evaluation is whether EDD-IP and EDD-A can be generalized and applied in other application scenarios in the edge computing environment. To tackle this threat, we modeled the problem and evaluated the performance of EDD-IP and EDD-A in a generic manner - using the number of hops to represent the data transmission latency between edge servers and a ratio γ to indicate the difference between the C2E transmission cost and the E2E transmission cost. In this way, the evaluation results can be interpreted with specific latency and cost models. We also varied parameters to change the size and the complexity of the EDD problem. This way, the representativeness and comprehensiveness of the evaluation are ensured. The above mitigates the threat to external validity.

5.3.3 Conclusion Validity

The lack of statistical tests, e.g., chi-square tests, is the major threat to conclusion validity in our paper. To compensate this threat, we have conducted comprehensive and intensive experiments to cover various scenarios in different size and complexity. In addition, every time a parameter changes, we repeat the experiment for 100 times and calculate the averaged results. This led to a large number of test cases, which tend to result in a small p-value in the chi-square tests and lower the practical significance of the test results [31]. For example, in experiment Set #1, there were a total of 2,200 runs. This number is not even close to the number of observation samples that concern Lin et al. in [31]. This way, the threat to the conclusion validity due to the lack of statistical tests might be high but is not significant.

6 RELATED WORK

Edge computing was proposed by Cisco in 2012 as a new computing paradigm. As an extension of cloud computing, edge computing distributes cloud-like computing resources and services to the edge of the cloud [24]. Applications, services and data can now be deployed on edge servers to offer end-users ultra-low latency. It offers new opportunities and in the meantime raises many new challenges, e.g., edge server placement, edge user allocation, computation offloading, edge application deployment, edge data caching and edge data distribution.

Edge server placement is a fundamental problem in edge computing. In [32], the authors focused on minimizing the cost incurred during edge server deployment. They designed a cost-effective method that employs integer programming to help edge infrastructure providers make decisions on edge server placements. Similarly, Yin et al. [33]

presented a decision support framework based on flexible placement, namely Tentacle. It aims to minimize the cost of edge infrastructure deployment while maximizing the overall system performance.

The edge user allocation problem in the edge computing environment was first studied in [29]. The authors of [29] modeled this problem as a variable sized vector bin packing problem to maximize the number of allocated app users, while minimizing the cost of hiring edge servers. He et al. [3] tackled a similar problem in edge user allocation with the aim to find a near-optimal solution in an efficient manner. They proposed EUAGame, a game-theoretic approach that employs a decentralized algorithm to find the Nash equilibrium of the game as the solution to the problem.

The problem of computation offloading has been intensively studied with consideration of edge servers' energy efficiency, offloading cost and joint service with caching [5], [32], [34], [35]. Xu et al. [5] proposed an online algorithm, namely OREO, to efficiently improve offloading performance jointly with service caching. OREO was developed based on Lyapunov optimization to reduce computation offloading latency while keeping energy consumption low. In [36], Wang et al. considered the computation offloading problem in wireless cellular networks with mobile edge computing. They modeled this problem as a convex problem and then decomposed it to be solved in a distributed manner.

Application deployment is another problem in the edge computing environment that has attracted increasing attention from researchers. A number of approaches have been proposed to determine optimal deployment strategies with different objectives, such as maximizing the user or request coverage [37], minimizing the deployment cost [38], and maximizing the profit [39]. For example, Wang et al. [38] focused on an application migration problem and proposed a Markov decision process based framework for migrating application instances between edge-clouds, with the aim to minimize the average migration cost and the transmission cost over time. Mahmud et al. [39] proposed a new pricing model deploying applications on fog instances. They also proposed a user compensation method based on SLA violation. Based on the new pricing model and the user compensation method, an approach was proposed to find optimal application deployment strategies that fulfil resource constraints like processing cores and memory.

In recent years, researchers have started to propose and investigate new ideas and techniques for data caching in the edge computing environment. Cao et al. [14] presented an optimal auction mechanism to maximize service provider's revenue based on cache allocation and user valuation reports. They proposed computationally-efficient approaches to apply the auction mechanism based on data retrieval and delivery costs. The authors of [11] proposed a caching system named Cachier for recognition of applications in an MEC environment. Cachier coordinates the loading balance between edge servers and the cloud to minimize the data retrieval latency in a dynamical manner. Breitbach et al. proposed a data management system for edge computing environments by decoupling data placement based on task scheduling [40]. The system adjusted the data replica placement cost to achieve the balance between data management

overhead and execution delay. In [41], the authors focused on data-intensive IoT workflows in a collaborative edge and cloud computing environment. They also formulated the problem as a 1-0 integer programming model and provided a variant of the intelligent swarm optimization algorithm to solve the problem.

However, existing research has not considered the fact that transmitting the data on cloud and edge computing infrastructure is also a large component in app vendors' cost structure in the edge computing environment. Without considering this component, app vendors will not be able to realistically evaluate the costs of caching their app data on edge servers. To the best of our knowledge, this paper makes the first attempt to solve the edge data distribution (EDD) problem from the app vendor' perspective in the edge computing environment. Its aim is to minimize the cost of distributing data from the cloud to edge server, with consideration of the costs incurred during C2E and E2E transmissions, while fulfilling the app vendor's time constraint for data distribution.

7 CONCLUSION

In this paper, we formulated the edge data distribution (EDD) problem in the edge computing environment as a constrained optimization problem from the app vendor's perspective. We proved that the EDD problem is \mathcal{NP} -hard. To solve this problem, we proposed an optimal approach named EDD-IP based on the Integer Programming technique to minimize the cost incurred during data distribution. As the EDD problem is \mathcal{NP} -hard, we also provided an approximation approach named EDD-A for finding approximate solutions to large-scale EDD problems efficiently. Extensive experiments were conducted on a widely-used real-world dataset to evaluate the performance of the proposed approaches. The results showed that our approaches significantly outperformed the representative approaches in various EDD scenarios.

This research has established the foundation for the EDD problem and opened up a number of future research directions. In our future work, we will consider the robustness and fault-tolerance of EDD strategies, and more dynamic and heterogeneous aspects of edge servers.

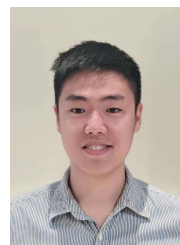
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