Evaluation of Fog Topologies in Fog Planning for IoT Task Scheduling

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ABSTRACT

In this paper, we investigate the impact of different fog topologies in fog planning on provisioning diverse IoT tasks under an integrated cloud and fog framework (iCloudFog). Two Integer Linear Programming (ILP) models are proposed for ring and star topologies, respectively. Note that similar issue for fully-connected mesh topology has been addressed in our previous work[2], which will be used as a benchmark in the performance comparison. Numerical analyses and comparisons are conducted in terms of the CAPEX, OPEX and average hops for different topologies.

CCS CONCEPTS

• **Networks** → **Network architectures**; **Layering**; *Network simulations*; *Network services*; *Cloud computing*; Wired access networks; Wireless access networks;

KEYWORDS

fog computing, cloud computing, IoT, in-fogs topology, network planning, layered architecture, real-time, mobility

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1 INTRODUCTION

The current datacenters in cloud are fixed and distant from the IoT end devices and thus are short of providing real-time services as well as addressing the issues induced by IoT task mobility. Regarding this, fog computing was coined with the motivation of provisioning IoT tasks by edge devices in their vicinity, mostly with one-hop distance, so as to reduce the transmission latency and achieve the goal of real-time services.

In the past years, great progresses have been made in fog computing in various aspects, such as fog planning [1, 2, 4, 5], energy consumption, fog application in various fields, emerging fog computing with 5G , etc.

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Nonetheless, very few of them has addressed the issue of mapping huge IoT tasks to dynamic fog networks with different topologies. In our previous work, we have addressed the fog planning issue based on fully-connected mesh [2] and as a subsequent work, we will explore the impact of different fog topologies on the iCloudFog performance, by means of proposing integer linear programming models (ILP) for star and ring topologies, respectively. In developing the ILP models, we take into consideration of diverse QoS requirements of IoT tasks, such as real-time and mobility, and the network attributes in terms of the resource availability status of different fogs, so as to optimize the overall performance.

The rest of this paper is structured as follows. In section 2, iCloudFog framework with topological fogs are introduced. In section 3, we introduce the proposed ILP models dedicated for star and ring topologies, respectively. The numerical results of the proposed ILP models based on AMPL are given and analyzed in section 4. Section 5 concludes this paper.

2 ICLOUDFOG FRAMEWORK

The integrated Cloud-Fog (iCloudFog) framework consists of three layers, i.e., the cloud, the fog and the IoT end layers from top to bottom. In the fog layer, a fog may consist of only wireless, only wired, or both of wireless and wired edge devices, therefore, we classify the fogs into three types, namely wireless fog (WLF), wired fog (WDF), and hybrid fog (HBF), respectively [3].

IoT devices in the IoT layer generate a large number of heavyweight or lightweight IoT tasks that would require services from fogs and/or cloud. Note that there is no direct connection between IoT end layer and cloud layer. Any IoT task must bypass some wired fog node to access the resources in the cloud, if needed.

We mainly consider the requirements of real-time and mobility. A mobile IoT task can only be connected to a wireless fog node, and thus can be served by WLF or HBF; a real-time IoT task can be connected to any wireless or wired fog node which is located in a fog consisting of at least one wireless fog node, and thus can also be served by WLF or HBF; general IoT tasks with no real-time and mobility requirement can be uploaded to any fog and the cloud.

We consider the fog planning cost (i.e., CAPEX) due to constructing different types of fogs and the fog utilization cost (i.e., OPEX) induced by serving IoT tasks on planned fogs. The CAPEX cost of constructing a homogeneous fog, i.e., WLF or WDF, is the same and less than that of a heterogeneous one, i.e., HBF; the OPEX utilization overhead of WDF is the least, followed by HBF, WLF, and cloud in an increasing order. For WLF, WDF, and HBF, we consider topologies of ring, star and fully-connected mesh.

3 ILP MODELS

In this section, we propose two integer linear programming (ILP) models to investigate the impact of star and ring topologies of WLF, WDF, and HBF on iCloudFog performance. Readers who are interested in fully-connected mesh topology are referred to [2].

3.1 Sets and Parameters

The sets and parameters of the two ILP models are given as follows.

- IT: Set of IoT tasks
- FN: Set of fog nodes, which could be wireless (WL) and wired(WD)
- CF: Set of cloud, WL, and WD nodes
- IC_i: Number of computing resource units required by IoT task i, $i \in IT$
- IS_i: Number of storage resource units required by IoT task i, $i \in IT$
- IM_i: Binary parameter. One indicates IoT task i requires mobility; zero, vice versa, $i \in IT$
- IR_i: Binary parameter. One indicates IoT task i requires real-time; zero, vice versa, $i \in IT$
- FC_j: Number of available computing resource units in fog node j, $j \in FN$
- FS_j: Number of available storage resource unit s in fog node j, $j \in FN$
- FT_j: Binary parameter. One indicates fog node j is wireless one; zero indicates fog node j is wired one, $j \in FN$
- $DC_{h,k}$: CAPEX cost of deploying links between fog nodes h and k, $h, k \in FN$
- $UC_{i,l}$: OPEX cost of using fog node or cloud node l to serve any IoT tasks i, $i \in IT, l \in CF$
- N: Number of nodes that can participate in constructing a fog
- α: Lower bound of fog nodes that will be selected to form fogs
- β: Upper bound of fog nodes that will be selected to form fogs
- $D_{jj'}$: The set of distances in kilometers between fog nodes j and j', $j, j' \in FN$
- γ: Average hops of IoT tasks traverse in a fog
- $\mathbf{M}$: A coefficient to balance the average hops and the total Cost
- θ: Weight value of general objective

3.2 Decision variables

The decision variables of the two ILP models are given as follows.

- x_{ij}: Binary variable. One indicates IoT task i is successfully served by fog node j; zero, vice versa $i \in IT$ & $j \in FN$
- $y_{jj'}$: Binary variable. One indicates the link between fog node j and fog node j' is deployed; zero, vice versa; $j, j' \in FN$ & $j \neq j'$
- z_{ij}: Binary variable. One indicates IoT task i is handled by the cloud node j; zero, vice versa; $i \in IT$ & $j \in WD$
- u_j: Binary variable. One indicates fog node j is selected to form a fog types; zero, vice versa; $j \in FN$

3.3 Objective

The objective of the proposed two models are given in (3), which is a weighted objective of (1) and (2).

Minimize (Total_Cost):

$$Minimize(\sum_h \sum_k DC_{h,k} + \sum_i \sum_l UC_{i,l}) , \quad i \in IT, h, k \in FN, l \in CF , \tag{1}$$

*Minimize (**M** * average hops):*

$$Minimize(\mathbf{M} * p) , \quad p \in \gamma . \tag{2}$$

Minimize (General_Objective):

$$Minimize(Total\_Cost + \theta * \mathbf{M} * average\ hops) . \tag{3}$$

The objective in Equation (1) is to minimize the total CAPEX and OPEX cost, where the first item, say $\sum_h \sum_k DC_{h,k}$, indicates CAPEX cost due to deploying a link between fog nodes $\boldsymbol{h}$ and $\boldsymbol{k}$; while the second item, say $\sum_m \sum_n UC_{i,l}$, indicates OPEX cost due to serving IoT task $\boldsymbol{i}$ via cloud or fog node $\boldsymbol{l}$. The specific calculations of the two items are given as follows in Equations (4) and (5).

Equation (2) aims at minimizing the number of average hops required by a fog node to offload tasks to other fog nodes in the same planned fog. When the number of fog nodes in a fog type is $\boldsymbol{N}$, the average hop count of a star is $\frac{2(N-1)^2}{N^2}$. For a ring, the average hop count is $\frac{N^2-1}{4N}$ and $\frac{N}{4}$ when $\boldsymbol{N}$ is odd and even, respectively. For the fully-connected mesh, the average hop count to serve the offloading task between fog nodes (if necessary) of a planned fog is $\frac{N-1}{N}$, which is approaching one when $\boldsymbol{N}$ is big enough. The coefficient value $\mathbf{M}$ here is used to balance objective (2) and objective (3).

Equation (3) is the multi-weighted objective, where a weight value of θ is used to integrate objective (1) and objective (2).

$$\sum_h \sum_k DC_{h,k} = \sum_{j}^{j \in FN} \sum_{j'}^{j' \in FN} y_{jj'} * \begin{pmatrix} DC_{WL,WD} * \left(FT_j * (1 - FT_{j'}) + (1 - FT_j) * FT_{j'} \right) \\ + DC_{WL,WL} * FT_j * FT_{j'} \\ + DC_{WD,WD} * (1 - FT_j) * (1 - FT_{j'}) \end{pmatrix}, \tag{4}$$

$$\sum_i \sum_l UC_{i,l} = \sum_{i}^{i \in IT} \sum_{j}^{j \in FN} (IC_i + IS_i) * \begin{pmatrix} x_{ij} \begin{pmatrix} UC_{i,WD} * (1 - FT_j)) \\ + UC_{i,WL} * FT_{j'} \end{pmatrix} \\ + z_{i,j} * UC_{i,cloud} \end{pmatrix} . \tag{5}$$

3.4 Constraints on Fog Planning

The constraints of fog planning based on the star and ring topologies are given in the following, respectively.

3.4.1 Constraints on Star and Ring Topologies.

$$\frac{N-1}{N} * \sum_{j}^{j \in FN} u_j = \sum_{j}^{j \in FN} \sum_{j'}^{j' \in FN} y_{jj'} , \tag{6}$$

$$u_j + u'_j \geq 2 * y_{jj'} , \quad \forall j, j' \in FN , \tag{7}$$

$$\alpha * \sum_{j}^{j \in FN} j \leq \sum_{j}^{j \in FN} u_j \leq \beta * \sum_{j}^{j \in FN} j , \tag{8}$$

$$(N-2) \geq \sum_{j''}^{j'' \in FN} (y_{jj''} + y_{j'j''}) * y_{jj'}\,, \quad \forall j, j' \in FN\,. \tag{9}$$

$$\sum_{j}^{j \in FN} u_j * \frac{N}{N} = \sum_{j}^{j \in FN} \sum_{j'}^{j' \in FN} y_{jj'}\,, \tag{10}$$

$$u_j * 2 - \sum_{j'}^{j' \in FN} y_{jj'} = 0\,, \quad \forall j \in FN\,, \tag{11}$$

$$u_j + u'_j \geq 2 * y_{jj'}\,, \quad \forall j, j' \in FN\,, \tag{12}$$

$$\alpha * \sum_{j}^{j \in FN} j \leq \sum_{j}^{j \in FN} \leq \beta * \sum_{j}^{j \in FN} j\,. \tag{13}$$

Constraints (6) and (10) ensure the conservation of the total number of links needed in a star and a ring, respectively. Constraints (7) and (12) ensure that if a link is selected in constructing a star or a ring, the fog nodes at both ends of the link must be selected too. Constraints (8) and (13) ensure that the system needs at least α (%) and at most β (%) fog nodes to participate in constructing a star or a ring. Constraints (9) and (11) ensures that the planned fogs are based on star and ring topologies, respectively. In constraints (9) and (11), j, j' and j" are not equal. Readers are referred to [2] for the related constraints on the fully-connected mesh topology.

3.4.2 Constraints on IoT Tasks Provisioning.

$$\sum_{j}^{j \in FN} (x_{i,j} + z_{i,j}) = 1\,, \quad \forall i \in IT\,, \tag{14}$$

$$x_{ij} + z_{ij} \leq u_j\,, \quad \forall j \in FN\,, \tag{15}$$

$$\sum_{j}^{j \in FN} x_{ij} * FT_j \geq IM_i\,, \quad \forall i \in IT\,, \tag{16}$$

$$\sum_{j}^{j \in FN} \sum_{j'}^{j' \in FN} x_{ij} * (FT_j + y_{jj'} * FT_{j'}) \geq IR_i\,, \quad \forall i \in IT\,, \tag{17}$$

$$z_{ij} \leq (1 - IR_i) * (1 - IM_i) * (1 - FT_j)\,, \quad \forall i \in IT,\ j \in FN\,, \tag{18}$$

$$FC_j + \sum_{j'}^{j' \in FN} y_{jj'} * FC_{j'} \geq \sum_{j'}^{j' \in FN} \sum_{i}^{i \in IT} (x_{ij} + x_{ij'} * y_{jj'}) * IC_i\,, \quad j \in FN,\ j \neq j'\,, \tag{19}$$

$$FS_j + \sum_{j'}^{j' \in FN} y_{jj'} * FS_{j'} \geq \sum_{j'}^{j' \in FN} \sum_{i}^{i \in IT} (x_{ij} + x_{ij'} * y_{jj'}) * IS_i\,, \quad j \in FN,\ j \neq j'\,. \tag{20}$$

Constraint (14) ensures that an IoT task must be connected to a fog node, so that it can be either served by a fog or by the cloud. Constraint (15) restricts that if an IoT task is served by a fog node, the fog node should be selected in a planned fog. Constraint (16) indicates that any IoT task with mobility requirement should be directly connected to a wireless fog node in a WLF or HBF and cannot be uploaded to the cloud. Constraint (17) indicates that an IoT task with real-time requirement must be served by a either a WLF or a HBF consisting of wireless fog node(s). Constraint (18) indicates that if an IoT task is uploaded to the cloud for processing, it must not be an IoT task with real-time or mobility requirement, and the fog node connecting it must be a wired one. Constraints (19) and (20) ensure that the number of computing/storage resources of each fog being planned must be greater than the total number of resources required by all IoT tasks to be served in this fog.

4 NUMERICAL RESULTS

4.1 Network Environment

We assume there are sufficient computing/storage resources in the cloud layer. In the middle fog layer, we assume there are 6 wired and 6 wireless fog nodes, which can be freely selected to form WDF, WLF, and HBF. The number of candidate fog nodes allowed in a potential fog type is set to be 3, i.e. $N = 3$. The number of available computing and storage resource units of all wired and wireless candidate fog nodes are randomly fall in the range of 20 to 30, i.e., FC_j or FS_j. The number of computing and storage resource units required by IoT tasks are randomly set in the range of 5 to 9, i.e., IC_i or IS_i. We assume that the CAPEX cost between fog nodes h and k, i.e., $DC_{h,k}$, for homogeneous (i.e., WL&WL or WD&WD) and heterogeneous fog types (i.e.,WL&WD) are numerically set to 100 and 200, respectively. The OPEX cost to serve IoT tasks i on different fog nodes, i.e., $UC_{i,WL}$ and $UC_{i,WD}$, are 2 and 3 for wireless and wired fog nodes, respectively. The cost of accessing cloud resource units to serve IoT task i is set to 25, i.e., $UC_{i,cloud}$.

The total number of IoT tasks is set to 36, with a ratio of 50% requiring real-time services and a ratio of 50% requiring mobility services. An IoT task may simultaneously have the two requirements, one of them or none of them. A ratio of 25% to 50% IoT tasks requires neither real-time nor mobility services. We define α and β as the lower and upper boundaries of candidate fog nodes that should participate in the overall fog planning and their values are set to be 40% and 80%, respectively. The coefficient and weight values, i.e., **M** and θ, respectively, in the multi-weighted objective of (3) are set to 7000 and 1 by default, which can be modified according to the importance of the average hop counts and the cost.

4.2 Numerical Results and Analyses

Fig. 1 shows the total cost under different numbers of candidate fog nodes for fully-connected mesh, ring and star fogs. Since the upper bound of β is set to 80% for a total of twelve candidate fog nodes, a total number of nine fog nodes are selected in the fog planning. With this setting, all the three different topologies achieve the optimal performance in terms of total cost when $N = 3$. The total cost of all the three topologies increases dynamically until N=5, and decrease after that due to the fact that when N=5, four fog nodes out of nine cannot participate in forming any fog and a lot of tasks are offloaded to cloud. When N>5, the participation ratio of candidate fog nodes is increased and thus lead to decreased total cost. Among all the three topologies, star performs the best in terms of the total cost, followed by ring, and fully-connected mesh.

Figs. 2 and 3 show the impact of real-time and mobility requirements of IoT tasks on the performance of total cost for star and

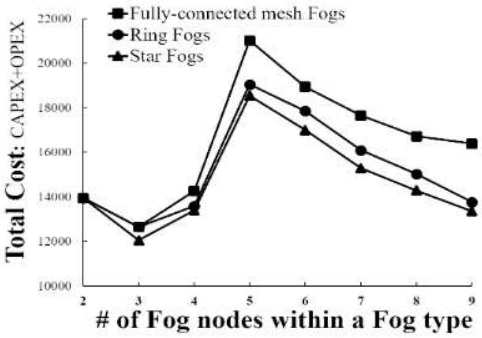

Figure 1: Total cost of three different topologies under different Ns.

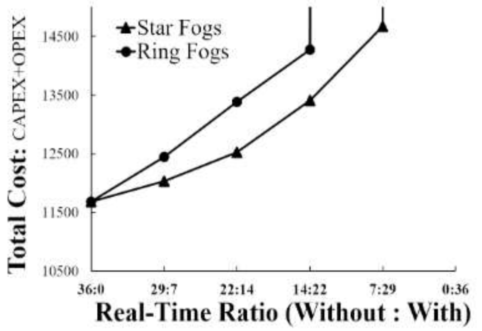

Figure 2: Total cost of ring and star topologies under different ratios of real-time IoT tasks.

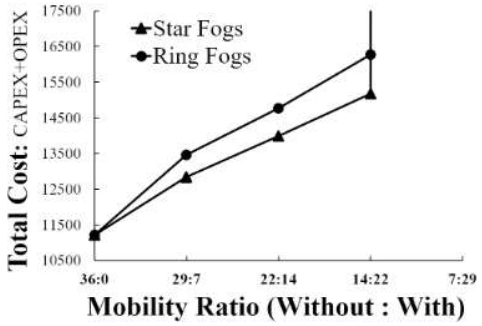

Figure 3: Total cost of ring and star topologies under different ratios of mobility IoT tasks.

ring topologies. From the results we can see that the star topology performs slightly better in serving both of real-time and mobile IoT tasks since it requires less total cost. The total costs for serving real-time IoT tasks are less than that when serving mobile IoT tasks for both topologies, due to the fact that real-time IoT tasks can be offloaded into fogs via both wired or wireless fog nodes, but mobile IoT tasks can only be offloaded to wireless fog nodes.

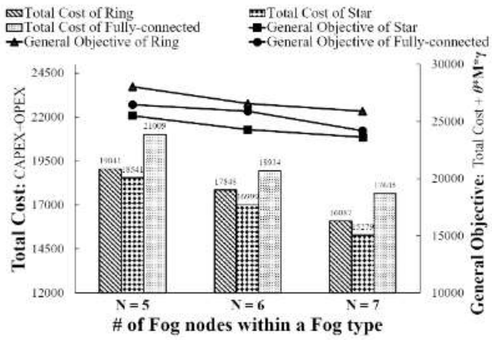

Figure 4: Multi-weighted objective in Equation (3) under different Ns.

Fig. 4 shows the performance for the total cost and the multi-weighted general objective. From the results, we can see that star performs the best in terms of the total cost, followed by ring, and fully-connected mesh. For the general objective, star performs the best, followed by fully-connected mesh and ring. Although fully-connected mesh fogs have the largest number of links in planning a fog, it is superior to ring, due to the fact that the number of average hops in a ring increases more dynamically with increasing N than that of fully-connected mesh.

5 CONCLUSIONS

In this paper, we investigated the impact of different fog topologies, i.e., fully-connected, star, and ring, in fog planning on the performance of CAPEX and OPEX cost under the framework of iCloudFog. Specifically, we proposed two ILP models, with the objective of minimizing the total cost by considering the average hop count. Numerical simulations were carried out and the results were compared with the fully-connected mesh in our previous work. Results showed that fully-connected mesh topology had the highest cost and star topology performed the best in serving real-time and mobile IoT tasks.

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