Edge Network Extension Based on Multi-domains Fusion and LEO Satellite

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Abstract. The explosion of heterogeneous devices needs an extended version of edge network. Physical factor, such as time delay and energy cost, is usually used to facilitate resource sensing and neighbor nodes' networking. In fact, other factors from multiple domains may seriously affect the resource selection and edge network extension. Thus, this paper uses multi-domains fusion connect more nodes from multiple domains and expand edge network. In the proposed edge network model, nodes can thus be selected and combined from a single domain to multi-domains. Moreover, low earth orbit (LEO) satellite can act as a relay node providing excess connection for different domains, and further expands the edge network. To formulate the domains fusion, a two-dimensional matrix is used for each domain. The abscissa and ordinate of the matrix exactly correspond to the tasks and nodes of the offloading process in one domain. Finally, the edge network matrix (selected matrix) can be expanded (increasing of non-zero elements) after the fusion operation. Our analysis and numerical results demonstrate that multi-domains fusion and cooperating with LEO effectively extend the edge network with about 9%.

Keywords: LEO satellite · Multi-domains fusion · Edge network extending introduction

1 Introduction

Terminal devices, that can be used for computing, are embracing an explosively increasing number [1]. The Internet of Things (IoT) network continues to expand with heterogeneous devices, which may serve as massive computing resources. Most distributed devices in the IoT have low computing demand and urge for edge computing services. An efficient method to enjoy edge computing service is offloading tasks to other nodes with enough computation resources.

The commonly used methods to select nodes are based on one performance or several related metrics such as time delay and energy cost [2–8]. Most of these metrics belong to physical domain. However, the number of nodes sensed in physical domain may be limited to finish a hug instantaneous task. Can we break away the limitation of a single domain and reexamination the question in view of multi-domains? Besides the physical domain, other domains like social domain and information domain exist in edge network. These domains include various nodes condition and connection information. For example, the owner's willing is the typical factor in social domain. If the

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owner of a device has no interest to release his device, the node cannot be selected. Therefore, making full advantage of these nodes' information from multiple domains may help extend edge network and finish instantaneous huge computation.

In practical, the issue is how to sense and connect these nodes from multiple domains. Edge computation needs a high speed and low delay connection between nodes, but mobile network may not cover some remote area and important region. The service range of cellular connection is limited by many factors, such a wide range connection's building and low earth orbit (LEO) satellite provides a new choice to serve wide range with low delay and high speed. Starlink and Oneweb have been used in practical to provide a high-speed connection. This paper proposes LEO satellite-based method to find and build connection over large area and extend edge network from one domain to multi-domains.

Node selection for edge computing has careful researched in [2–8]. The authors of Ref. [2] propose an algorithm to offload tasks based on increasing utilization of the network. These related works are able to efficiently utilize the released computation resource from other layers to balance the uneven distribution of computation resources in space, which are also known as task offloading [3−5] or task migration [6–8]. In recent years, there are also some papers trying to integrate the knowledge of multi-domains and to deal with the information of different domains in a unified way. Papers [9] begin to introduce people's part of speech into people's attitude judgment, combining the information domain of people's emotional judgment with domain of humanity emotion. Also, Ref. [10] combined humanity and society to build a system of smart city. In the field of satellite communication, some papers point out that LEO satellite can be used to assist communication by establishing fast and stable links or being a node in edge network. But these are not enough to effectively expand the scope of the edge network because they cannot make full use of all nodes from multi-domains and wide area.

If the nodes' information and connection from multiple domains are fully used, the number optional nodes will be further increased. At the same time, the consideration of multi-domains factors can also reduce the one-sidedness of node selection. The selected nodes may also have a better performance in the macroscopic view.

This paper attempts to describe the information of different domains into three domains, including: physical domain (**PD**), which represents some physical constant parameters like occupying time. Social domain (**SD**), which represents human's attitude or emotion. Information domain (**ID**), which represents some variable parameters of network likes delay. Each domain contains the connect information between nodes and tasks. Such a one-to-one correspondence is suitable to be described by two-dimensional matrix. Through multi-domains fusion, the number of nodes in the edge network increases and the edge network is expanded. After cooperating with the LEO satellite, the non-zero elements will be further increased, and the network will be further expanded. In the actual fusion process, because of the information association between different domains, it will lead to the repeated calculation of part of the information, so this paper reduces the covariance between the information of different domains to 0, so that there is no correlation between different domains. Finally, independent domain information is obtained. The accuracy of fusion is ensured.

In summary, the distinctive feathers and contributions of this paper are as follows:

1. This paper solves the problem of narrow edge network caused by selecting edge network nodes from a single domain, proposes multi domain to expand the scope of edge network, and gives the fusion mode of multi domain information.
2. This paper proposes a LEO satellite-based method to incorporate more nodes and expand the edge network.

2 System Model

The whole system is composed of three different domain information and remote node information connected by satellite. The three domains: **ID**, **SD**, and **PD** are fused to form a selected matrix (**SM**), which contains the information from all the three domains.

Nodes in **PD** can cooperate or offload tasks to other nodes but sometime with the limited information only from **PD** can't provide a good offload plan. For example, some owners don't want their device to serve for the edge computing, but **PD** doesn't contain such an information. Such a condition will cause an invalid offloading. So fusing information from other domains can not only solve these incorrect connections but also can provide some additional node information to extend edge network. Please see Fig. 1.

In order to further expand the network, we need to mine more node information. Because of the limitations of network coverage, remote equipment is always ignored. Some devices are not connected to other domains through wired networks, nor are they covered by wireless networks. If these devices can be found and connected, it will bring more choices for edge computing.

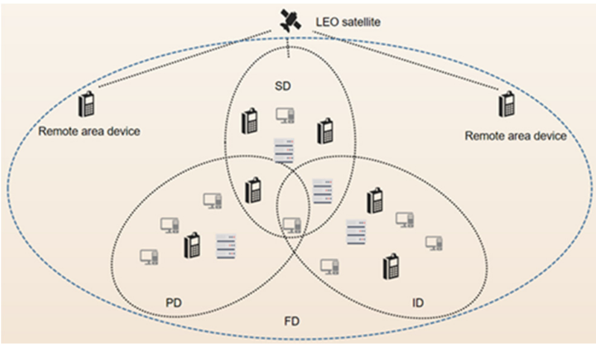

Fig. 1. System model with domains fusion

2.1 Modeling the Three Domains

In edge computing, the computing ability of nodes and task volume are the key parameters. But it doesn't make sense to only measure computing ability or task volume. If the computing ability of a node is very weak, but the volume of computing tasks is also very small, then the node can complete the calculation task. Therefore, the ratio of task volume to computing ability is more meaningful for node selection, which we call occupying time.

Thus, in **PD** computing ability of the nodes donated by c*ompute* (in CPU cycles per-second) and the volume of computing tasks donated by $volume_m$ (in CPU cycles). Therefore, in an edge internet with N nodes and M tasks, the **PD** can be described as a $M*N$ matrix called **PD**. Each element in **PD** describe the time that task m can be finished by node n $(m \in M, n \in N)$. Before the multi-domains fusion, if the node and the task are not in one domain, set the $\mathbf{PD}_{m,n}$ into 0. The unit of $\mathbf{PD}_{m,n}$ is millisecond.

$$\mathrm{D}_{m,n} = \frac{volume_m}{compute_n} \tag{1}$$

$$\mathrm{PD}_{M*N} = \begin{pmatrix} PD_{1,1} & PD_{1,2} & \ldots & PD_{1,N} \\ PD_{2,1} & PD_{2,2} & \ldots & PD_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ PD_{M,1} & PD_{M,2} & \ldots & PD_{M,N} \end{pmatrix} \tag{2}$$

The network condition between nodes changes with time, which may lead to the change of connection quality. Delay and BER are the key parameters to describe the network condition. In the edge computing, it can represent the effective calculation proportion in the edge computing. Because delay and *BER* are both negatively correlated with network condition. The smaller the delay and *BER* the better the network condition.

We use $\mathbf{ID}_{m,n}$ to describe network condition. $\mathbf{ID}_{m,n}$ represents the average transmission delay of per error bit. When the value is lower, the current network is in good condition. These data make up a new matrix **ID**. Each element in **ID** describes the network condition between the task m and node n $(m \in M, n \in N)$. $BER_{m,n}$ represents the BER between the task m and node n. $T_{m,n}$ represents the delay between task m and node n. and the unit of $\mathbf{ID}_{m,n}$ is millisecond.

$$ID_{m,n} = BER_{m,n} \times T_{m,n} \tag{3}$$

$$\mathbf{ID}_{M*N} = \begin{pmatrix} ID_{1,1} & ID_{1,2} & \ldots & ID_{1,N} \\ ID_{2,1} & ID_{2,2} & \ldots & ID_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ ID_{M,1} & ID_{M,2} & \ldots & ID_{M,N} \end{pmatrix} \tag{4}$$

Humanity attitude plays a key role in practical application, because the owner of a device may not be willing to release his device completely for edge computing. This is a factor that we must consider, and it is also the most important humanistic factor in edge computing. Owner's will cannot be simply regarded as willing or unwilling. Sometimes there are other influencing factors, such as the compensation of computation and occupation time. Maybe only when the reward is high and the occupation time is short, the owner is willing to release the node.

So, we describe the owner's will as a probability's reciprocal, that is, the probability that the owner will release the existing device for edge computing. The stronger the will of the owner, the greater the probability. All probability values form a new matrix **SD**. Each element in **SD** describe the owner's willing of device n release the device to compute for task m. O_{pre} means the exception occupying time of the node owner. $I_{m,n}$ represents the income of node n compute for the task m and I_{pre} means the exceptional income of the node owner. $(m \in M, n \in N)$.

$$\text{if},\ PD_{m,n} > O_{pre}, SD_{m,n} = 0$$

$$\text{else}\ SD_{m,n} = \frac{2}{1 + \frac{I_{m,n}}{I_{pre}} - \frac{PD_{m,n}}{O_{pre}}} \tag{5}$$

$$\mathbf{SD}_{M*N} = \begin{pmatrix} SD_{1,1} & SD_{1,2} & \cdots & SD_{1,N} \\ SD_{2,1} & SD_{2,2} & \cdots & SD_{2,N} \\ \vdots & \vdots & \ddots & \cdots \\ SD_{M,1} & SD_{M,2} & \cdots & SD_{M,N} \end{pmatrix} \tag{6}$$

2.2 Extended Edge Network with LEO Satellite

Nodes in remote areas are easy to be ignored. Some nodes cannot be covered by the wired network and wireless network, which makes them difficult to connect with other nodes. For example, airplanes and devices on some islands. In recent years, LEO satellites have been able to provide low delay and wide range of network service. This is very important to help these remote nodes establish connections with other nodes. The connection service with low delay can guarantee the good connection performance of these nodes for edge computing. The wide range of LEO satellite services can provide more nodes to expand the edge network (Fig. 2).

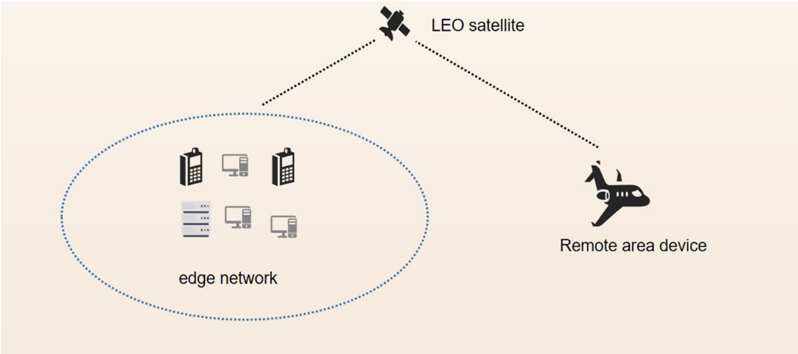

Fig. 2. LEO satellite build a connection between remote device and edge network.

In this model, we divide the device into two parts, one is the local edge network, the other is the remote area equipment. The process we need to describe is to add these remote devices to the local edge network. We define the fusion domain as selected matrix (**SM**), which is defined in the next chapter.

We assume that there are r remote devices that connect to the local edge network via satellite. The information between these r devices and M tasks is stored in matrix **R**.

$$\mathbf{R}_{M*r} = \begin{pmatrix} R_{1,1} & \cdots & R_{1,r} \\ \vdots & \ddots & \vdots \\ R_{M,1} & \cdots & R_{M,r} \end{pmatrix} \quad (7)$$

The elements in **R** are calculated in the same way with **SM**, which is defined in the following.

2.3 Domains Fusion

Multi domain fusion in edge computing is to integrate the information of multiple domains to expand the scope of edge network. And comprehensively consider the influencing factors in each domain. In order to comprehensively consider the multi-domain factors, after the numerical calculation of the factors of the three domains, the matrix of the three fields should be weighted and calculated. The importance of the selected nodes is weighted according to the information of each domain. This means that the three parameters are variable. When the environment of the problem changes, the value of the parameters can be adjusted to change the ratio of the three domains.

$$\mathbf{SM} = (\alpha\mathbf{PD} + \beta\mathbf{ID}) * \delta\mathbf{SD}, \quad (8)$$

where $*$ is hamard product between two same matrices.

Finally, **SM** is obtained. Each element in the **SM** corresponds to the value of multi-domain factors when a task is offloaded to the node. The smaller the value is, the better the performance will be after integrating the factors of the three domains. When this value is 0, it means that the task cannot be offloaded to the node because it does not meet the owner's expectation the node cannot complete the calculation task.

2.4 Reduce the Relevance

When there is correlation between domains, which will cause too much calculation of one factor in the process of fusion. In order to eliminate the data correlation between different domains, we need to preprocess the data. So that the matrix can store the correct irrelevant information.

One of the quantities that describe the association between data is covariance.

$$Cov(a,b) = \frac{1}{M \times N}\sum\nolimits_{i=1}^{M}\sum\nolimits_{j=1}^{N} a_{i,j}b_{i.j}, \tag{9}$$

where $a_{i,j}$ and $b_{i,j}$ represents the elements of any two of the three domains. When the covariance between them is 0, it means that they are not related.

In order to clearly describe the relationship between any two domain elements, we select the corresponding elements in the two domains to form a new contrast matrix **Y**(M*N) × 2.

$$\mathbf{Y}_{(M*N)*2} = \begin{pmatrix} a_{1,1} & b_{1,1} \\ \vdots & \vdots \\ a_{M,1} & b_{M,2} \end{pmatrix} \tag{10}$$

So, we continue to create a covariance matrix $\mathbf{C}_{(M*N)} \times {}_{(M*N)}$ to describe the covariance of elements in any number of each two domains.

$$\mathbf{C} = \mathbf{Y}\mathbf{Y}^{\mathrm{T}} \tag{11}$$

The next step is to diagonalize the covariance matrix, so that the off diagonal elements will become zero. The dimensions of the corresponding data matrix are no longer related. Here we assume that the new covariance matrix after diagonalization is **Q**. The data matrix **Y** is transformed into a new matrix **Z**, which is independent of all domains of data.

$$\mathbf{Z} = \mathbf{P}\mathbf{Y} \tag{12}$$

And **P** is the transformation matrix.

$$\boldsymbol{P} = \frac{1}{\boldsymbol{M} * \boldsymbol{N}}\mathbf{Z}\mathbf{Z}^{T} \tag{13}$$

$$\mathbf{Q} = \mathbf{P}\mathbf{C}\mathbf{P}^{T} \tag{14}$$

According to Formula (9), the eigenvalues λ of the matrix can be obtained. Finally, we get the eigenvalue matrix **E**. Matrix **E** meets the condition:

$$\mathbf{Z} = \mathbf{E}\mathbf{Y} \tag{15}$$

3 Numerical Results

According to the above model, we need to analyze the network expansion after multi domain fusion. We assume an edge network with ten nodes and ten tasks. The node information is stored in different domains. In the actual network, the state of the network is often random, and the owner's attitude towards whether to release the node changes with the change of the task. We use randomly generated matrices instead of data in three fields. In order to make the data easier to process, we set the parameter as the reciprocal of the maximum value of the local value to normalize the data.

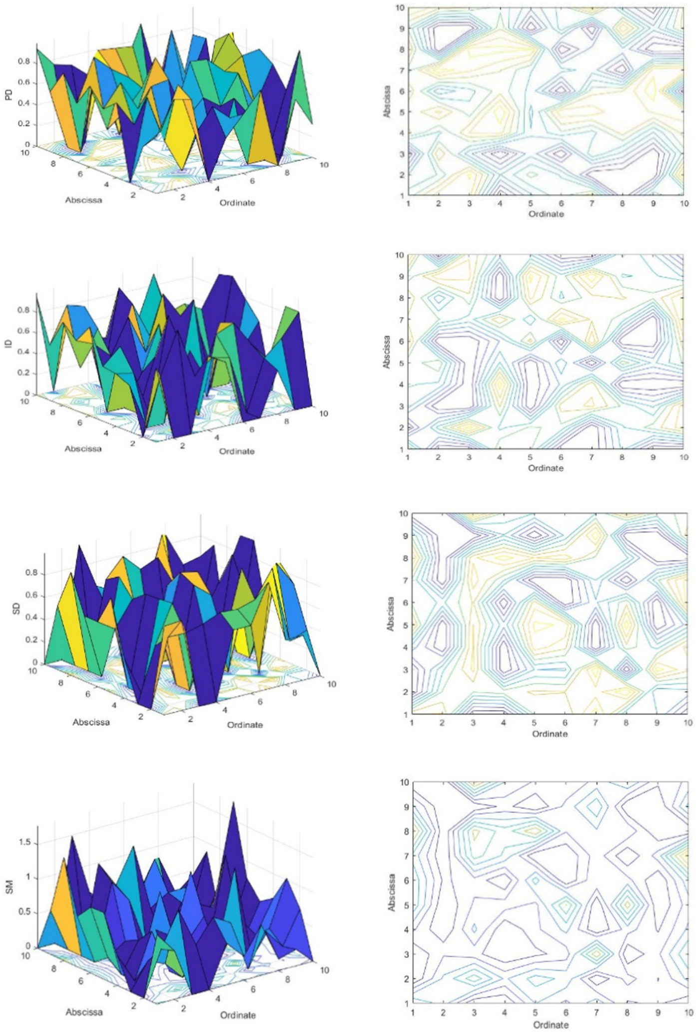

Fig. 3. Numerical results of multi-domains fusion, each picture represents the changing value of elements in each domain. Non-zero element represents a selected node.

Each matrix will generate 30% zero-elements to stimulate the nodes can't be connected in the field. The non-zero values represent the nodes that can be selected in edge computing (Fig. 3).

There are more non-zero elements in **SM** than in **PD** and **ID**, which means that the number of edge nodes that can be selected is increased through multi-domains fusion. Compared with **SD**, because **SD** plays a decisive role in the fusion process (when an element in **SD** is zero, the owner is not willing to release the node), the number of nodes does not increase compared with **SD**. At that time, it was still very important to fuse the information in **SD**, because the introduction of **SD** enabled us to exclude some nodes that could not be released and increase the accuracy of offloading. After three times repeat of these processes, the selected nodes in **SM** is about 9% more than **PD** and **ID**.

When devices in remote areas are connected to the edge network through LEO, the edge network is further expanded. The number of nodes in the network increases further (Fig. 4).

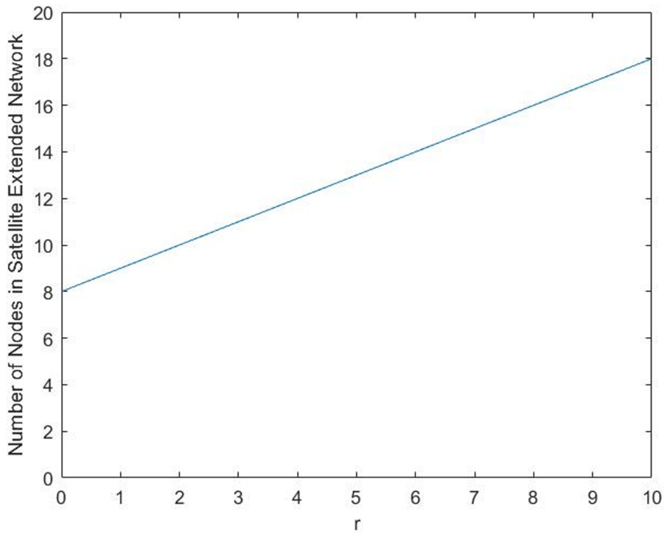

Fig. 4. The number of selected nodes is increasing with more remote devices connect with LEO satellite. The x-coordinate describes the increase of remote device and the y-coordinate describes the number of selected nodes in satellite extended network.

The figure shows the number of devices from remote areas connected to LEO satellite increases, the number of nodes in edge network increases and the edge network is expanded further. Since the zero elements in the matrix are randomly generated according to a certain probability, the non-zero elements in each domain approach to a constant (the probability of generating a non-zero element) after repetitive calculations. When more remote nodes connect edge network by LEO satellite, the number of selected nodes increases and edge network is extended. The selected nodes in LEO extended edge network is formed by the nodes form fusion domain and nodes from remote area. There is a linear relationship between the growth trend of selected nodes and the number of remote nodes.

4 Conclusion

To solve the problem that there are not plenty of nodes in edge network to realize large scale edge computing, this paper fuses the information in different domains. By extending the edge network from a single domain to multi domain, the number of nodes in the edge network is increased and the network is expanded. In addition. This paper also proposes to cooperate with LEO satellite to further expand the edge network and increase the number of optional nodes in the edge network by connecting devices in remote areas. The final numerical results also show that multi-domains fusion and cooperating with LEO satellite can effectively increase the number of nodes in the edge network and expand the network. The research on multi-domains is still in the initial stage and the edge offloading strategy in multi-domains will be studied in the future.

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