Virtual network embedding in cross-domain network based on topology and resource attributes

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Abstract. Aiming at the network architecture ossification and the diversity of access technologies issues, this paper researches the cross-domain virtual network embedding algorithm. By analysing the topological attribute from the local and global perspective of nodes in the virtual network and the physical network, combined with the local network resource property, we rank the embedding priority of the nodes with PCA and TOPSIS methods. Besides, the link load distribution is considered. Above all, We proposed an cross-domain virtual network embedding algorithm based on topology and resource attributes. The simulation results depicts that our algorithm increases the acceptance rate of multi-domain virtual network requests, compared with the existing virtual network embedding algorithm.

1. Introduction

The multi-domain converged substrate network (MD-CSN) is composed of heterogeneous wireless access network, optical backbone network and data center. Each network layer has specific physical resource, such as wireless resource block, wireless backhaul bandwidth, optical spectrum and computing resource. The traditional network architecture is segregative and fossilized between layers, hence it can’t meet the requirements of the emerging businesses [1].

Virtualization technology decouples the traditional network framework into substrate network (SN) and virtual network (VN), multiple virtual networks which are parallel running and isolated are deployed on the same substrate network simultaneously [2].

So far, there are still few studies on cross-domain virtual network embedding. In [3], a virtualized multi-domain network architecture based on LTE wireless access technology was proposed. The backbone network adopts time shared optical network (TSON) architecture, which can efficiently decrease network energy consumption and delay. In [4], an ILP research model was established based on the 5G converged network. Whereas the ILP method is only limited for small-scale network. Besides, a hierarchical multi-domain virtual network embedding algorithm was proposed.

2. Network model and problem statement

2.1. Multi-domain converged substrate network model

The multi-domain converged substrate network is abstracted as undirected weighted diagram and denoted as \( G^S = (N^S, L^S, C^S_N, C^S_L) \), where \( N^S \) is the physical node set including the set of heterogeneous wireless access nodes \( N^S_{AP} \), the set of optical switching nodes \( N^S_{OS} \), and the set of...
data centers $N^S_{DC}$ and $L^S$ is the physical link set including wireless backhaul set $L^S_{WL}$ and optical link set $L^S_{OL}$. Moreover, $C^S_N$ and $C^S_L$ depict the attributes of physical node $n^S(n^S \in N^S)$ and physical link $l^S(l^S \in L^S)$ respectively. The attributes of physical node $n^S$ include the wireless resource block $RB(n^S_{AP})$ of heterogeneous wireless access nodes, the computing resource $CPU(n^S_{OS})$ of optical switching nodes, and the computing resource $CPU(n^S_{DC})$ of data centers. The attributes of physical link $l^S$ include the bandwidth $BW(l^S_{WL})$ of wireless backhaul links and the bandwidth $BW(l^S_{OL})$ of optical links.

**Figure 1.** Cross-domain converged network embedding architecture

2.2. Multi-domain virtual network request model

Multi-domain virtual network request (MD-VNR) is modeled as undirected weight diagram and can be denoted as $G^V = (N^V, L^V, R^V_N, R^V_L)$, where $N^V$ is the virtual node set. $L^V$ is the virtual link set. $R^V_N$ and $R^V_L$ depict the service requirements of virtual node $n^V(n^V \in N^V)$ and virtual link $l^V(l^V \in L^V)$. The service requirement of virtual node can be wireless resource block request, computing request. The location of virtual node is labeled as $Loc(n^V)$. The service requirement of virtual link mainly consider the wireless bandwidth request and optical bandwidth request. We can denote the k-th MD-VNR as a triple VNR(k)$G^V, t_g, t_d$), where $t_g$ is generate time, and $t_d$ is duration time for MD-VNR in substrate network. Figure 1 shows the multi-domain converged substrate network and virtual network request.
2.3. Problem analysis
The local expand resource of node is defined as the total link bandwidth connected with the node divided by adjoin link number.

\[
E(n) = \sum_{i \in L(n)} \frac{BW(l)}{a_i(n)} \quad (1)
\]

Where \( L(n) \) is the total adjoin link of node, \( a_i(n) \) is the link number of \( L(n) \).

To manifest load distribution of physical links, link resource price is defined as the reciprocal of link bandwidth.

\[
\text{price}(l^s) = \frac{\eta}{BW(l^s)} \quad (2)
\]

Where \( \eta \) is regulation factor of link resource price, we generally set the value as 1.

3. Multi-attributes of network node analysis
Firstly, we introduce the node centrality theory. The node centrality is an epidemic concept in social network which can measure the node importance [5]. Here are the primary evaluation indexes of node centrality.

Degree centrality (DC) is defined as the adjacent links connecting the node. The node degree centrality only considers the local information and neglects the importance impact of adjacent nodes.

Betweenness centrality (BC) is defined the ratio of shortest paths between total node pairs to the shortest paths cross the node. It can measure the node load capacity when information transmission.

Closeness centrality (CC) depicts the capacity of information transmission between nodes. The node with large closeness centrality could establish easily the transmission with other nodes.

3.1. Multi-attributes of virtual node analysis
The degree centrality of virtual node depicts the local importance in network, virtual node with fairly high degree value possesses more adjacent nodes and links, it could bear more resource requirement. The virtual node degree centrality is defined as the total adjacent virtual links.

\[
DC^v(n_i) = \sum_{i \rightarrow m_i} l^v(i) \quad (3)
\]

The betweenness centrality incarnates the virtual node global importance, virtual node with high betweenness centrality value is situated more critical position and could bear more resource request. The betweenness centrality value of virtual node is defined as follows.

\[
BC^v(n_i) = \frac{P_i}{P} \quad (4)
\]

Where \( P_i \) is the number of shortest path crossing virtual node \( n_i \) between the total node pairs in virtual network, \( P \) is the number of shortest path between the total node pairs in virtual network.

The affecting attributes of virtual node in mapping process are node resource requirement, local bandwidth requirement, degree centrality and betweenness centrality. We set the virtual node number as \( t \). The multi-attributes evaluation matrix of substrate nodes named \( MP^v \) is as follows.

\[
MP^v = \begin{bmatrix}
mp_{11} & mp_{12} & \cdots & mp_{1n} \\
mp_{21} & mp_{22} & \cdots & mp_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
mp_{m1} & mp_{m2} & \cdots & mp_{mn}
\end{bmatrix} = \begin{bmatrix}
R^v_{11} & E^v_{12} & DC^v_{13} & BC^v_{14} \\
R^v_{21} & E^v_{22} & DC^v_{23} & BC^v_{24} \\
\vdots & \vdots & \vdots & \vdots \\
R^v_{m1} & E^v_{m2} & DC^v_{m3} & BC^v_{m4}
\end{bmatrix}
\]
Based on MP^V, we adopt principal component analysis (PCA) to establish the principal component matrix H^V which is the initial indexes on the new principal component indexes. Establish the principal component indexes evaluation matrix with weight q which is W^V.

\[
W^V = \begin{bmatrix}
  w_{11} & w_{12} & \cdots & w_{1p} \\
  w_{21} & w_{22} & \cdots & w_{2p} \\
  \vdots & \vdots & & \vdots \\
  w_{m1} & w_{m2} & \cdots & w_{mp}
\end{bmatrix} = \begin{bmatrix}
  h_{11} \cdot q_1 & h_{12} \cdot q_1 & \cdots & h_{1p} \cdot q_p \\
  h_{21} \cdot q_1 & h_{22} \cdot q_1 & \cdots & h_{2p} \cdot q_p \\
  \vdots & \vdots & \vdots & \vdots \\
  h_{m1} \cdot q_1 & h_{m2} \cdot q_1 & \cdots & h_{mp} \cdot q_p
\end{bmatrix} \quad (6)
\]

Then we calculate the node importance value with technique for order preference by similarity to ideal solution (TOPSIS). Calculate the relative proximity between indexes and ideal solution which is C^V, subsequently, The embedding priority of virtual node is defined as follows.

\[
EP^V = C_i^V = \frac{D_i^-}{D_i^- + D_i^+}, \quad 0 \leq EP^V \leq 1 \quad (7)
\]

### 3.2. Multi-attributes of substrate node analysis

The node with higher closeness centrality may not be situated in the central position in network, while it has preferable connectivity with other network nodes. Considering the node resource, the shortest hookup distance of node pair and the local expand bandwidth, the closeness centrality computing model of substrate node is as follows.

\[
CC^S(n_i) = \sum_{j=1}^{n} \frac{\left( \frac{d(i,j)}{MinBW^S(i,j)} \right)^{-2}}{a_i(n_j)} \quad (8)
\]

Where \(d(i,j)\) is the hookup distance of the shortest path between \(n_i\) and \(n_j\). \(MinBW^S(i,j)\) is the real-time available resource of the shortest path between \(n_i\) and \(n_j\). \(a_i(n_j)\) is the adjacent links of node \(n_i\).

The affecting attributes of substrate node include the node resource, the local expand bandwidth of node, degree centrality, closeness centrality and distance between embedded nodes. The substrate node number is t. The evaluation matrix of substrate nodes named MP^S is as follows:

\[
MP^S = \begin{bmatrix}
  mp_{11} & mp_{12} & \cdots & mp_{1k} \\
  mp_{21} & mp_{22} & \cdots & mp_{2k} \\
  \vdots & \vdots & \vdots & \vdots \\
  mp_{t1} & mp_{t2} & \cdots & mp_{tk}
\end{bmatrix} = \begin{bmatrix}
  C_{11}^S & E_{12}^S & DC_{13}^S & CC_{14}^S & DI_{3k}^S \\
  C_{21}^S & E_{22}^S & DC_{23}^S & CC_{24}^S & DI_{2k}^S \\
  \vdots & \vdots & \vdots & \vdots & \vdots \\
  C_{t1}^S & E_{t2}^S & DC_{t3}^S & CC_{t4}^S & DI_{tk}^S
\end{bmatrix} \quad (9)
\]

Then we calculate the node importance value with PCA and TOPSIS based on MP^S. Calculate the relative proximity between indexes and ideal solution which is C^S, subsequently, The embedding priority of substrate node is defined as follows.

\[
EP^S = C^S \quad (10)
\]

### 4. The cross-domain virtual network embedding based on topology and resource attributes

By analysing the node centrality and resource, we propose a cross-domain virtual network embedding algorithm based on topology and resource attributes (TARA). TARA has two steps including node mapping and link mapping.
First all the virtual nodes are in descending order with the embedding priority $EP^V$. Similarly, the whole substrate nodes are in descending order with the embedding priority $EP^S$. The substrate node with highest $EP^S$ is selected to deploy the selected virtual node with highest $EP^V$.

In the selection phase of substrate path, the k-shortest path algorithm with the weight of link resource price is adopted to choose the bearing substrate path with fewer hops and affluent bandwidth.

5. Simulink results and analysis
In this section, we evaluate and validate the effectiveness of our proposed algorithm by conducting extensive simulations. In order to verify preferably the performance of the TARA, we get the derived TARA-bw by modifying the criterion of substrate path selection. TARA-bw chooses the substrate path with maximal bandwidth within k shortest path set. In addition, the state-of-the-art algorithm which called as Greedy-shortest path (G-SP) [6] is compared with our proposed algorithm.

5.1. Experimental parameter setting and environment modeling
Physical nodes are generate randomly in separate areas including 50 heterogeneous wireless access nodes, 10 optical backbone network nodes, and 5 data centers. The physical resources of each substrate network layer are real numbers uniformly distributed as table 1 shows.

To embedding MD-VNRs more flexibly and effectively, we classify multifarious service requests with delay, resource requirement and SLA. Table 2 presents the partitioned service request types.

| Resource type | Wireless resource Block (block) | Wireless backhaul bandwidth (Mb/s) | Optical backbone CPU (unit) | Optical backbone bandwidth (Mb/s) | Data center CPU (unit) |
|---------------|---------------------------------|-----------------------------------|-----------------------------|----------------------------------|------------------------|
| Resource scope | 50-70                            | 60-80                             | 120-140                     | 140-160                          | 200-240                |

| Layer & Request class | Wireless resource block (block) | Wireless backhaul bandwidth (Mb/s) | Optical backbone CPU (unit) | Optical backbone bandwidth (Mb/s) | Data center CPU (unit) |
|----------------------|---------------------------------|-----------------------------------|-----------------------------|----------------------------------|------------------------|
| Mobile Internet      | Flow/Session                     | 1-5                               | 1-5                         | 3-5                              | 5-10                   |
|                      | Interaction                      | 3-5                               | 3-7                         | 5-10                             | 3-7                   |
|                      |                                  | 5-7                               | 5-7                         | 10-15                            | 10-15                  |
| Massive Internet of things | Collection                     | 10-15                             | 5-7                         | 10-15                            | 7-10                   |
|                      | Controller                       | 5-10                              | 7-10                        | 10-15                            | 15-20                  |
| High reliability/ low delay | IoV                            | 10-15                             | 13-17                       | 10-15                            | 13-17                  |
|                      | Telemicine                       | 5-10                              | 10-15                       | 10-15                            | 10-15                  |

The MD-VNRs arrive following a Poisson distribution with a mean of five requests in 100 time units. The runtime of each MD-VNR is 1000 time units. The number of virtual nodes is randomly engendered by a uniform distribution between 3 and 8. We run all of our simulations for 20000 time units.

5.2. Experimental result and performance analysis
As illustrated in Figure 2, the acceptance ratio of TARA is 5% higher than TARA-bw, and 20% higher than G-SP. The primary cause is our proposed TARA analyses the topological connectivity of nodes
and network resource attributes from the local and global perspective. Furthermore, we adopt k-shortest path based on real-time link resource price to grabble substrate path with least hop and affluent bandwidth for deploying virtual link. Therefore, the resource consumption is efficiently decreased, the holistic acceptance ratio is improved.

![Figure 2. Acceptance ratio](image)

6. Conclusion
To consolidate the virtualization and resource sharing of 5G network infrastructure, we proposed a cross-domain virtual network embedding algorithm. Based on topology and resource attributes of nodes in virtual network and substrate network, this paper establishes the node multi-attributes evaluation model, and then measures the embedding priority of nodes with PCA and TOPSIS to match the appropriate substrate nodes and virtual nodes. Furthermore, we set the link resource price to manifest the load distribution, hence we can choose the substrate path with fewer links and ample bandwidth for virtual links. The simulation results indicates TARA improves the acceptance rate of multi-domain virtual network requests, compared with the existing virtual network embedding algorithm.

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