topology of this subnetwork. However, each subnetwork will not expose the details of its internal structure to the outside. Instead they will only advertise some aggregated routing information made by the process of topology aggregation (TA). As a result the quantity of routing information exchanged in the whole network will descend greatly and the running complexity of the routing protocol may grow linearly of the scale of network.

It is clearly that TA process will play a very important role in hierarchical routing and has a great influence on the routing performance. Generally, a communication network can be modeled as a directed graph with different weight on each directed link. Such directed graph is called asymmetric graph or asymmetric network. The weight of directed link may represent such parameters as cost, delay, attenuation and so on. So in this paper, we will address the issue of TA in hierarchical routing network and focus on the TA algorithm for asymmetric network.

In the past years many efforts have been made on TA for undirected network and lots of methods have been given. W.C Lee present a spanning tree method [3], Bartal suggests a tree representation for graph whose average distortion is O(logn),where n is the node num in graph [4]. In the work [5] of Yi Du, some spanning tree schemes are compared and minimum spanning tree (MST) was seen to yield good network performance. However TA for asymmetry network is more difficult and few solutions are given. Baruch presented a method with undirected transformation in [6] and T.Korkmaz put forward a source-oriented TA scheme in [7]. In the Baruch's scheme, undirected transformation can lead to the loss of asymmetry information in the origin graph, while Korkmazd's scheme may cause more inaccurate information. So in this paper we propose a novel SHEF (Source-oriented Heavy Edge First) algorithm to aggregate the asymmetric graph. The routing information complexity of SHEF is $O(2b)$ and the routing performance of SHEF is proved to be better than conventional methods by simulations.

The rest of this paper is organized as follows. In the next section basal rules to aggregate the asymmetric graph are depicted. Then the SHEF algorithm is described in detail. In the fourth section, we will show the detailed simulation results and performance analysis. Finally, the concluding remarks are given.

2. TOPOLOGY AGGREGATION

2.1. Conventional Methods

Generally, a subnetwork can be represented by a graph G(V, E), V is the set of vertexes and E is the set of edges. B is the collection of border nodes that have connection with nodes in other subnetworks. G may be directed or undirected. To aggregate an undirected graph G, two conventional steps can be followed, as shown in figure 1.

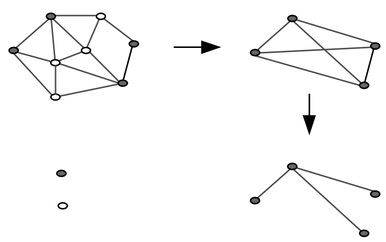


Fig. 1 Aggregate an undirected graph

However, when an outside node can reach a subnetwork through m border nodes of that subnetwork, the node will totally receive m different tree presentations of the subnetwork. For the convenience of process, it is suggested in [7] that only the first received tree is accepted and saved while the other presentations are discarded. The method is proposed with the assumption that the path along which the first received presentation is propagated and the corresponding reverse path are both the shortest. It is a correct assumption in symmetric network but may be incorrect in asymmetric networks. So the source-oriented scheme may lead to routing inaccuracy in asymmetric networks.

3. TOPOLOGY AGGREGATION WITH SHEF ALGORITHM

Based upon the schemes depicted above, we propose a novel TA algorithm called SHEF for asymmetric networks. In SHEF source-oriented method is efficiently integrated with the minimum spanning tree (MST) method to solve the TA problem. With the heavy-edge-first rule of simplification SHEF can avoid the loss of asymmetry information which is caused by undirected transformation in conventional Baruch scheme. At the same time MST is used in SHEF to represent the internal topology of subnetwork, so the routing inaccuracy of source-oriented scheme can be minimized.

3.1. Minimum Spanning Tree

For two graphs G(V,E) and G'(V',E'), if V=V' and $E' \subseteq E$ then G' is called spanning graph of G. Furthermore, G' is defined as the spanning tree of G if G' is a tree graph. G' is the minimum spanning tree (MST) of weighted G only when G' has the smallest weight among all the spanning trees of G. MST can be used for TA and is proved to be effective due to its special characteristic.

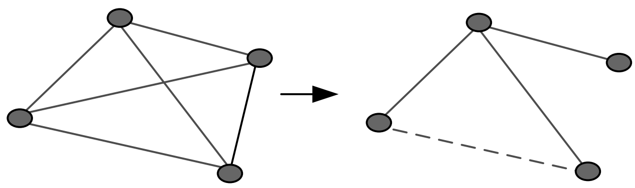


Fig. 3 A MST T for weighted graph F

Figure 3 illustrates a weighted graph F and its MST T. Assume that Er is the collection of edges which are removed from F to build T. e_{ij} is edge from node i to node j in E_r. Since T has the minimum weight, the weight w_{ij} of e_{ij} will be not less than the weight $w(e_{mn})$ of any link e_{mn} on the unique path P_{ij} from node i to node j in T, i.e.

$$w_{ij} \geq \max_{e_{mn} \in P_{ij}} \{w(e_{mn})\} \qquad (1)$$

If F is a full mesh representation of another network, F will satisfy the principle of shortest path. So w_{ij} is not more than the weigh $w(P_{ij})$ of P_{ij}, i.e.

$$w_{ij} \leq \sum_{e_{mn} \in P_{ij}} w(e_{mn}) \qquad (2)$$

estimate $w(e_{uv})'=\frac{w(P_{uv})+w^*}{2}$ and $w(e_{vu})'=w(e_{uv})'/\rho_a$.

If $w(P_{uv})<w^*< w(P_{vu})$ or $w^*= w(P_{uv})$, $w(e_{vu})$ must be larger than $w(e_{uv})$, then $w(e_{vu})$'s estimate $w(e_{vu})'=\frac{w(P_{vu})+w^*}{2}$ and $w(e_{uv})'=w(e_{vu})'/\rho_a$.

Otherwise it can not be judged which one out of $w(e_{uv})$ and $w(e_{vu})$ is larger, then $w(e_{uv})'= w(e_{vu})'=\frac{\max\{w(P_{uv}),w(P_{vu})\}+w^*}{2\sqrt{\rho_a}}$.

Figure 4 and 5 illustrate the SHEF algorithm with node A being the source. The topology aggregation shown in the figures is made by node B. In figure 4, F is simplified based on heavy-edge-first principle to form the F^-. In figure 5, F^- is transformed to a MST T and a tree T' whose root is node B and leaf nodes are node C, D and E. Finally M is created by combining T with T'. M along with correlative parameters will be advertised to subnetwork S_2 by node B. The similar process will be pursued by other border nodes. On receiving these routing information node A will rebuild the F' of S_1 with the steps above.

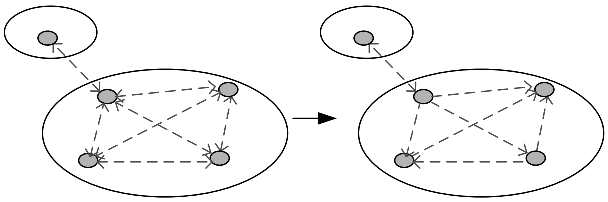


Fig. 4 Full mesh presentation with heavy-edge-first principle

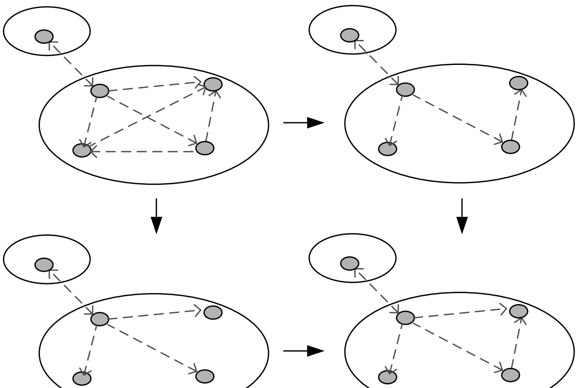
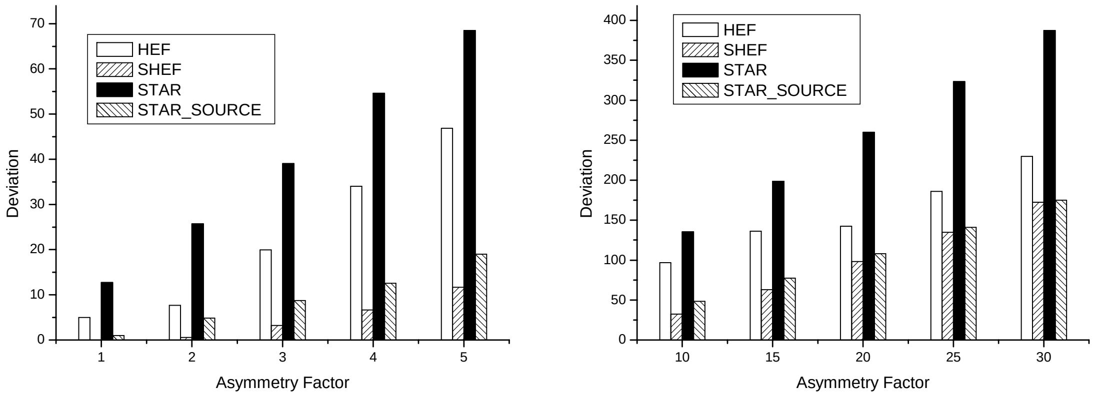


Fig. 5 Construct M out of F^-

By SHEF the original G can be reduced to a simpler graph M. If there are b border nodes in G, at most 2(b-1) data pairs ($w(e_i)$, ρ_i) and an average AF ρ_a are advertised, i.e. the routing information complexity of SHEF algorithm is $O(2b)$. So the SHEF is algorithm with good scalability. At the same time SHEF can yield outstanding routing performance as proved in

S2
A
S1
B
C
D



(a) (b)

Fig. 7 DWSP versus AF in scenarios of: (a), smaller AF; (b), larger AF

Figure 7(a) and 7(b) show the simulation result. It is clearly that the performance of heavy-edge-first algorithm is better than that of conventional star scheme. The introduction of source-oriented method can also reduce the DWSP and the accuracy of aggregated topology is enhanced. So SHEF has less DWSP than STAR in both smaller AF scenarios and larger AF scenarios. Averagely SHEF can reduce the DWSP by 75 percent than conventional STAR algorithm.

5. CONCLUSION

Topology aggregation is very important for hierarchical networks. SHEF is a novel TA algorithm for asymmetric digraph. The simplification of asymmetric network by heavy-edge-first principle can avoid the loss of asymmetry information caused by undirected transformation in conventional method. SHEF can also give a more accurate estimation to the original graph than conventional methods since SHEF takes full advantage of both MST scheme and source-oriented scheme. It can be concluded from the simulation results that SHEF can reduce the DWSP caused by topology aggregation greatly and yield outstanding routing performance. Since the total num of advertised values is $O(2b)$, scalability of SHEF is very good. So the good performance together with simplicity of SHEF algorithm makes it a very attractive candidate for use in practice.

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