KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS VOL. 5, NO. 2, February 2011

Topology Aggregation for Hierarchical Wireless Tactical Networks

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Received October 25, 2010; revised December 13, 2010; accepted January 18, 2011;
published February 28, 2011

Abstract

Wireless tactical network (WTN) is the most important present-day technology enabling modern network centric warfare. It inherits many features from WMNs, since the WTN is based on existing wireless mesh networks (WMNs). However, it also has distinctive characteristics, such as hierarchical structures and tight QoS (Quality-of-Service) requirements. Little research has been conducted on hierarchical protocols to support various QoS in WMN. We require new protocols specifically optimized for WTNs. Control packets are generally required to find paths and reserve resources for QoS requirements, so data throughput is not degraded due to overhead. The fundamental solution is to adopt topology aggregation, in which a low tier node aggregates and simplifies the topology information and delivers it to a high tier node. The overhead from control packet exchange can be reduced greatly due to decreased information size. Although topology aggregation is effective for low overhead, it also causes the inaccuracy of topology information; thus, incurring low QoS support capability. Therefore, we need a new topology aggregation algorithm to achieve high accuracy. In this paper, we propose a new aggregation algorithm based on star topology. Noting the hierarchical characteristics in military and hierarchical networks, star topology aggregation can be used effectively. Our algorithm uses a limited number of bypasses to increase the exactness of the star topology aggregation. It adjusts topology parameters whenever it adds a bypass. Consequently, the result is highly accurate and has low computational complexity.

Keywords: Hierarchical QoS routing, partial optimization, topology aggregation

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This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency (NIPA-2010-(C1090-1021-0011)).

DOI: 10.3837/tiis.2011.02.006

1. Introduction

Network centric warfare connects each element distributed geographically through wireless network technology. A wireless tactical network (WTN) should support self-establishment and self-management for a wireless backbone without any help of infrastructure. It should be robust under high mobility and dynamic topology. It also should provide tight QoS support capability, such as throughput and end-to-end delay.

The size of WTN can be very large i.e. usually tens to hundreds of kilometers and sometimes upto thousands of kilometers. Moreover, the WTN can consist of a very large number of nodes. In such a network, if we adopt flat network concepts, we can suffer from serious problems, such as excesive control overhead in routing setup and management. Recent research has proposed the use of hierarchical network structures for WTN [1][2][3][4][5].

If we adopt the hierarchcial network structure with multiple tiers, the routing overhead can be distributed into tiers, so the total routing overhead can be much reduced when *minimum hop count based routing protocols* are used. However, the hierarchical network structure cannot reduce control overhead efficiently when we find routing path that satisfies given QoS constraints. In this case, we require QoS parameters of each link instead of simple connectivity between nodes. Then, we can still suffer from serious overhead from supporting QoS [6][7][8].

The fundamental solution to decrease control overhead is to shrink the information size. Topology aggregation can be the most promising solution for hierarchical routing. In topology aggregation, a cluster header in a low tier gathers the cluster topology information and QoS parameters for links. Then, it aggregates links and the topology information to reduce their size. After aggregation, the information is delivered into a high tier node and other cluster headers. The cost to exchange routing control information and routing search time are decreased greatly, since routing setup and maintenance are performed based on this simplified information. However, the uncertainty of information increases during aggregation, in contrast. This can deteriorate QoS capability support.

In this paper, we propose a new topology aggregation algorithm. It achieves almost the same information aggregation time compared to previous algorithms but it outperforms them in terms of exactness. It can work efficiently for WTNs due to these features, without suffering from frequent change of network topology.

The remainder of this paper is organized as follows. In Section 2, we briefly introduce the related work for WTNs, routing protocols and topology aggregations. In Section 3, we describe our proposed algorithm termed *partial optimzation with bypass links*. We present the simulation and analysis results for the performance evaluation in Section 4. Section 5 concludes our paper.

2. Related Work

2.1 Wireless Tactical Network

There are many similarities between WTN and WMN, since a WTN is based on a WMN. However, a WTN also has distinct features, such as low throughput, strict QoS support capability, high mobility and high robustness [4][5].

2.1.1 Characteristics of wireless tactical networks

The link bandwidth of WTNs is relatively small compared to WMNs. For example, a WiFi based WMN can support up to 54 Mbps link bandwidth. In contrast, a WTN can achieve only 20~64 Kbps on VHF (Very High Frequency) / UHF (Ultra High Frequency) bands. Researchers are trying to increase the throughput of WTNs through repetitive system upgrades to adopt the latest wireless technologies. It is expected that WTN can support almost the same data throughput to that of the current WiFi based WMNs by the middle of 2010s, as shown in **Table 1**.

Table 1. Performance comparison of WTN.

Country		1990	2000	2013
US	Switching	Circuit	Packet (ATM)	Packet (IP)
	User	Voice (24 Kbps)	Voice/data	Voice/data/multimedia
	Backbone	64 Kbps	2 Mbps	32 Mbps
France	Switching	Circuit	Packet (ATM)	Packet (IP)
	User	16 Kbps	64 Kbps	Voice/data/multimedia
	Backbone	64 Kbps	64 Kbps ~ 8 Mbps	32 Mbps
Korea	Switching	Circuit	Packet (ATM)	Packet (IP)
	User	19.2 Kbps	56 Kbps	Voice/data/multimedia
	Backbone	1 Mbps	4 Mbps	45 Mbps

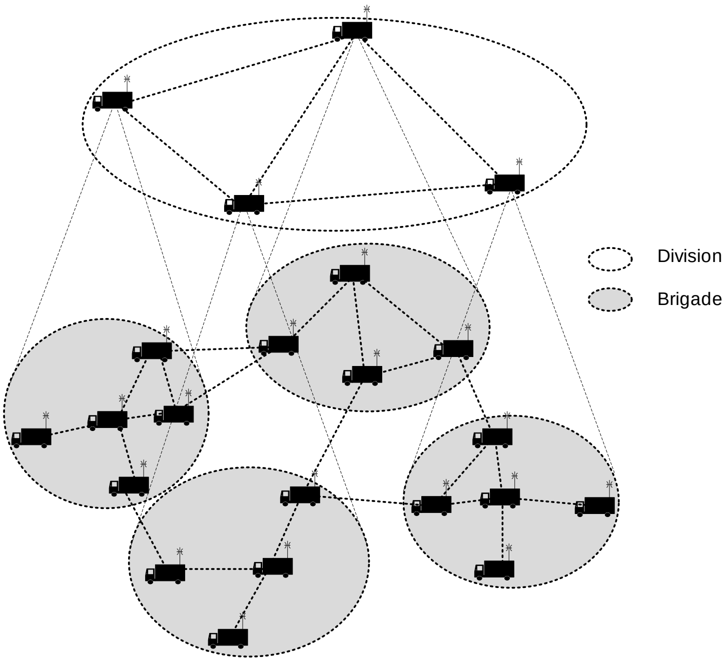

Fig. 1. Hierarchical wireless tactical network.

In WMNs, researchers usually assume that an inter-node distance is about 100 m. Conversely, in WTNs, the distance is very long and sometimes can reach 30 km to cover total battlefields. Moreover, a WMN does not consider mobile routers, although it can have mobile clients. However, since a WTN node can be a soldier, a car, a tank, a airplane or a ship, it can have various levels of mobility.

The hierarchical network structure can be applied for WTN easily and efficiently due to the military's hierarchical structure. Recent research adopts a hierarchical network for WTNs [1][2].

2.1.2 QoS requirement

Supporting QoS in WMNs is not a major issue but it is a manadatory requirement in WTNs. WTNs should support various QoS requirements according to data types. **Table 2** shows the QoS requirements currently being considered [5].

Table 2. WIN-T Data exchange requirement.

Information type	% Completion within data information exchange requirement		Data information exchange requirement	
	Threshold	Objective	Threshold	Objective
Alerts, warnings, sensor-shooter data between Army echelons (survival information)	90%	95%	< 5 sec	< 4 sec
Intelligence and fire support information between Army echelons	90%	95%	< 15 sec	< 8 sec
Combat reporting between Army echelons	90%	95%	< 30 sec	< 15 sec
Logistical and administrative reports between Army echelons	90%	95%	< 15 min	< 8 min

2.2 Hierarchical routing protocol

Routing protocols can be classified into flat or hierarchical routing according to network structures. Generally, flat routing has poor scalability due to costs of routing path establishment and maintenance increasing as network size increases.

Hierarchical routing has high scalability by dividing an entire network into several smaller networks, termed clusters. Hierarchical routing can be divided into two operations: intra and inter cluster routing. General flat routing protocols, such as TBRPF (Topology Broadcast based on Reverse-Path Forwarding) [9], AODV (Ad-hoc On-demand Distance Vector routing) [10] and DSR (Dynamic Source Routing) [11], can be used for intra cluster routing.

Some selected routers of the network, i.e. cluster headers participate in inter cluster routing. Only one cluster header exists in each cluster. It has a speciallized responsibility for the inter cluster routing. It constructs a virtual network that consists of itself and virtual links that exists only if there is at least one link between two clusters. When the destination router does not belong to a current cluster, the packet is delivered into its cluster header. Then, the cluster header determines the next cluster and sends the packet to a border router that belongs to the current cluster and has one or more links to the next cluster. The packet is delivered into the next cluster using intra cluster routing. This procedure is repeated until the packet reaches a cluster belonging to the destination router. If it reaches the final cluster, it is delivered to the destination by an intra cluster routing protocol. The control overhead of the intra routing protocol in each cluster can be greatly reduced and inter routing overhead is also reduced due to the small cluster header network size. However, it has some deficits, such as a non-optimal routing path and high overhead for QoS support.

2.3 Topology Aggregation

Assume that any two routers have N paths between them. Let's denote the i th intermediate router in k th path as L_i^k where $1 \le k \le N$. We also assume that we have only two QoS parameters, expressed by ,(w, d) where w is bandwidth and d is delay[1]. We denote this as $w\left(L_i^k\right)$ and $d\left(L_i^k\right)$ for bandwith and delay for L_i^k, respectively.

Then the range of QoS supported between two routers can be given as follows.

$$\left\{\left(w^k, d^k\right) \middle| w^k = \min_i \left\{w\left(L_i^k\right)\right\}, d^k = \sum_i d\left(L_i^k\right), k = 1, 2, \ldots, N\right\}. \tag{1}$$

Since (1) determines two dimensional areas and they can be simplified and expressed with one or two values acccording to aggregation schemes. This is called a link aggregation and they can be classified into *approximated line*, *single path parameter*, *best case of multiple path parameters* and *worst case of multiple path parameters link aggregation.* These are marked as I, P, Q and R, respectively in **Fig. 2** [12].

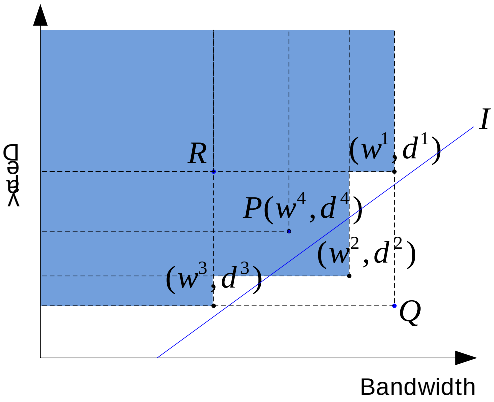

Fig. 2. Link aggregation types when N =4.

Using link aggregation, we can simplify the total network topology. One topology aggregation can be obtained by applying link aggregations for all border routers. This aggregation is termed full mesh topology aggregation. It is known as the most exact topology aggregation but the information complexity can be given as $O(b^2)$, where b is the total number of border routers.

To decrease the complexity, Star topology aggregation was proposed [5][6]. in the star topology aggregation, we assume that a center router exists in the network and all border routers are connected with the router. Information complexity can be reduced to $O(b)$ but its exactness can be also decreased. We can add some bypass links that provide a direct connection between two border routers to trade-off complexity and exactness. If we use more bypass links, we can get better exactness but the data size increases more. To avoid increasing

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[1] We assume that a link is symmetric for easy explanation, and it can be extended to h QoS parameters easily.

size, the maximum number of bypass links is carefully selected. Currently, the complexity of this approach is set to $O(2b)$, since the maximum number of bypass links is set to b. Star topology aggregation uses bypass links to the b border router pairs that have the worst exactness.

3. Proposed Algorithm

Our algorithm is a star topology aggregation with bypass links that has a better exactness without significantly increased computational cost. The basic idea of the algorithm is adjusting some links whenever a bypass link is added. This approach can decrease the maximum error size, as well as total average error size, compared to the full mesh topology aggregation. Features such as the low computational overhead and the improved exactness are essential factors for WTNs. We briefly introduce the system model to explain our algorithm.

3.1 System Model and Notation

Each cluster is modeled by $G(V,E)$, where V and E are sets of routers and bidirectional links in the cluster, respectively. We denote a set of border routers among V as B, and e_{ij} represents a uni-directional link from routers i to j, where $i, j \in B$. We use e_{ij}^{f} and e_{ij}^{s} for the full mesh and the star topology aggregation, respectively, to avoid confusion. In star topology aggregation, routers i and j are not connected directly, so e_{ij}^{s} denotes the serial connection from e_{in}^{s} to e_{nj}^{s}. This is simply represented as $e_{in}^{s} + e_{nj}^{s}$.

As mentioned earlier, the full mesh topology is the most exact aggregation scheme. Therefore, the difference between proposed scheme and the full mesh topology aggregation shows the exactness of the proposed algorithm. We denote the difference by $\Delta\left(e_{ij}^{f}, e_{ij}^{s}\right)$[2] where $i, j \in B$. If we add a bypass link between routers $i, j \in B$, the difference becomes zero.

3.2 Optimized Star Topology Aggregation

A star topology aggregation is optimal when the star topology is composed of links from the set of links $\hat{E}$, where $\hat{E}$ is defined as follows.

$$\hat{E} = \arg\min_{E} \left\{ \sum_{\forall i, j \in B, i \neq j} \Delta\left(e_{ij}^{f}, e_{ij}^{s}\right) \right\}, \tag{2}$$

where $E = \left\{ e_{ij}^{s} \mid \forall i, j \in B, i \neq j \right\}$.

For any two border routers $i, j \in B$, we can derive $\hat{e}_{in}^{s}$ and $\hat{e}_{nj}^{s}$ from (2), where $\hat{e}_{in}^{s}$ and $\hat{e}_{nj}^{s}$ are defined, respectively, as follows.

$$\hat{e}_{in}^{s} = \arg\min_{e_{in}^{s}} \left\{ \sum_{\forall k \in B, k \neq i} \Delta\left(e_{ik}^{f}, e_{in}^{s} + e_{nk}^{s}\right) \right\}, \tag{3}$$

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[2] The detailed description of $\Delta\left(e_{ij}^{f}, e_{ij}^{s}\right)$ can be found in *Definition 5* of [6].

$$\hat{e}^s_{nj} = \arg\min_{e^s_{nj}} \left\{ \sum_{\forall h\in B, h\neq j} \Delta\left(e^f_{hj}, e^s_{hn}+e^s_{nj}\right)\right\} . \tag{4}$$

We also verify easily that $\hat{e}^s_{in}, e^s_{nj} \in \hat{E}$ and we term (3) and (4) as the partially optimized condition. It is very difficult to obtain the optimized star topology and this takes much time. However, it is relatively easy to find the partially optimized star topology due to its loose conditions.

3.3 Partial Optimization with Bypass Link

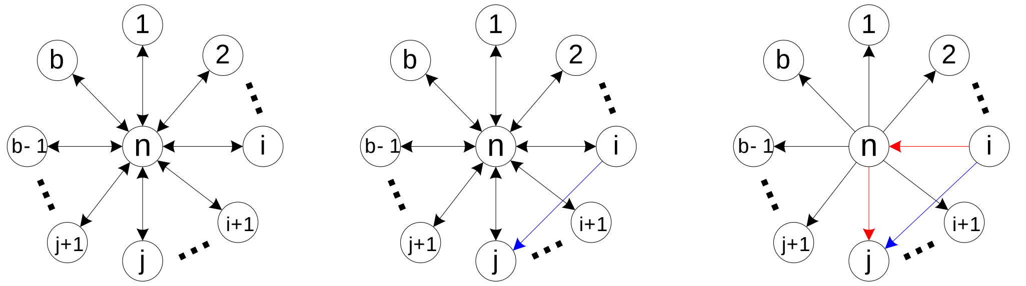
In **Fig. 3**, each circle represents each router in the network and the number in the circle shows its ID (Identification number). Since the link between center and border routers is bi-directional but the bypass link is uni-directional, we uses lines with arrow(s) to show its direction as shown in **Fig. 3**.

When we add a bypass link between routers $i, j \in B$, as shown in **Fig. 3-(c)** can be expressed as

$$\arg\min_{e^s_{in}} \left\{ \sum_{\forall k\in B, k\neq i, k\neq j} \Delta\left(e^f_{ik}, e^s_{in}+e^s_{nk}\right)\right\} .$$

In initial star topology, the link from node i to node j is represented as $e^s_{in}+e^s_{nj}$. After adding a bypass from node i to j, e^s_{in} and e^s_{nj} do not need to represent the link, so that e^s_{in} and e^s_{nj} can be adjusted to improve the overall exactness of the network aggregation.

After adding a bypass link, we should recalculate all links to satisfy (2). We use the repetitive partial optimization, instead of the optimal optimization, due to the high cost. The topology does not satisfy the partially optimal condition either due to the added bypass link.



(a) Initial star topology **(b)** Adding bypass from *i* to *j* **(c)** Links related to the bypass

Fig. 3. Star topology aggregation with a bypass link.

Let's define $\tilde{e}^s_{in}$ and $\tilde{e}^s_{nj}$ respectively, as follows.

$$\tilde{e}^s_{in} = \arg\min_{e^s_{in}} \left\{ \sum_{\forall k\in B, k\neq j} \Delta\left(e^f_{ik}, e^s_{in}+\hat{e}^s_{nk}\right)\right\} , \tag{5}$$

$$\tilde{e}^s_{nj} = \arg\min_{e^s_{nj}} \left\{ \sum_{\forall h\in B, k\neq i} \Delta\left(e^f_{hj}, \hat{e}^s_{hn}+e^s_{nj}\right)\right\} . \tag{6}$$

Now, we will show that topology aggregation becomes more exact when $\tilde{e}^{s}_{in}$ and $\tilde{e}^{s}_{nj}$ are used.

$$\begin{aligned}
&\sum_{\forall h,k\in B,h\neq k} \Delta\left(e^{f}_{hk},\hat{e}^{s}_{hk}\right) \\
&= \sum_{\forall h,k\in B,h\neq k,h\neq i,k\neq j} \Delta\left(e^{f}_{hk},\hat{e}^{s}_{hk}\right) + \sum_{\forall k\in B,k\neq j} \Delta\left(e^{f}_{ik},e^{s}_{in}+e^{s}_{nk}\right) + \sum_{\forall h\in B,h\neq i} \Delta\left(e^{f}_{hj},e^{s}_{hn}+e^{s}_{nj}\right) \qquad (7)\\
&> \sum_{\forall h,k\in B,h\neq k,h\neq i,k\neq j} \Delta\left(e^{f}_{hk},\hat{e}^{s}_{hk}\right) + \sum_{\forall k\in B,k\neq j} \Delta\left(e^{f}_{ik},\tilde{e}^{s}_{in}+e^{s}_{nk}\right) + \sum_{\forall h\in B,h\neq i} \Delta\left(e^{f}_{hj},e^{s}_{hn}+\tilde{e}^{s}_{nj}\right)
\end{aligned}$$

From (7), we can guarantee that the topology aggregation error can be decreased by recalculating e^{s}_{in} and e^{s}_{nj} to satisfy (5) and (6). Moreover, the calculation complexity is very low. $\sum_{\forall k\in B,k\neq j} \Delta\left(e^{f}_{ik},\tilde{e}^{s}_{in}+\hat{e}^{s}_{nk}\right)$ and $\sum_{\forall h\in B,h\neq i} \Delta\left(e^{f}_{hj},\hat{e}^{s}_{hn}+\tilde{e}^{s}_{nj}\right)$ in (7) are independent of each other, so it is possible to calculate them separately. Although we consider only one bypass link case, this can be extended to the multi bypass link case easily. Let's define $E(k)$ as the set of end routers of bypasses in which the start router is k and $S(h)$ as the set of start routers of bypasses in which the end router is h. Then, (5) and (6) can be rewritten, respectively, as

$$\tilde{e}^{s}_{in} = \arg\min_{e^{s}_{in}} \left\{ \sum_{\forall k\in B-E(j)} \Delta\left(e^{f}_{ik},e^{s}_{in}+\hat{e}^{s}_{nk}\right) \right\}, \qquad (8)$$

$$\tilde{e}^{s}_{nj} = \arg\min_{e^{s}_{nj}} \left\{ \sum_{\forall h\in B-S(i)} \Delta\left(e^{f}_{hj},\hat{e}^{s}_{hn}+e^{s}_{nj}\right) \right\}. \qquad (9)$$

It is very difficult to solve (8) and (9) due to the complicated definition of $\Delta\left(e^{f}_{ij},e^{s}_{ij}\right)$. To make the problems tractable, we define $\delta\left(e^{f}_{ij},e^{s}_{ij}\right)$, instead of $\Delta\left(e^{f}_{ij},e^{s}_{ij}\right)$, as follows.

$$\delta\left(e^{f}_{ij},e^{s}_{ij}\right) = \left(w^{f}_{1,ij}-w^{s}_{1,ij}\right)^{2} + \left(d^{f}_{1,ij}-d^{s}_{1,ij}\right)^{2} + \left(w^{f}_{2,ij}-w^{s}_{2,ij}\right)^{2} + \left(d^{f}_{2,ij}-d^{s}_{2,ij}\right)^{2},$$

where $e^{f}_{ij} = \left[\left(w^{f}_{1,ij},d^{f}_{1,ij}\right),\left(w^{f}_{2,ij},d^{f}_{2,ij}\right)\right]$ and $e^{s}_{ij} = \left[\left(w^{s}_{1,ij},d^{s}_{1,ij}\right),\left(w^{s}_{2,ij},d^{s}_{2,ij}\right)\right]$ [3] when $[p,q]$ denotes the line connecting two points, p and q.

In (8),

$$\begin{aligned}
\tilde{e}^{s}_{in} &= \arg\min_{e^{s}_{in}} \left\{ \sum_{\forall k\in B-E(j)} \Delta\left(e^{f}_{ik},e^{s}_{in}+\hat{e}^{s}_{nk}\right) \right\} \\
&\approx \arg\min_{e^{s}_{in}} \left\{ \sum_{\forall k\in B-E(j)} \delta\left(e^{f}_{ik},e^{s}_{in}+\hat{e}^{s}_{nk}\right) \right\} \qquad (10)\\
&= \arg\min_{e^{s}_{in}} \left\{ \sum_{\forall k\in B-E(j)} \delta\left(e^{f}_{ik}-\hat{e}^{s}_{nk},e^{s}_{in}\right) \right\}.
\end{aligned}$$

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[3] For easy explanation, we assume that the approximated line approach is used.

To find $\tilde{e}^s_{in}$ in (10),

$$\frac{\partial}{\partial w^s_{1,in}} \sum_{\forall k \in B-S(i)} \delta\left(e^f_{ik} - \hat{e}^s_{nk}, e^s_{in}\right) = -\sum_{\forall k \in B-S(i)} 2\left(w^f_{1,ik} - w^s_{1,nk} - w^s_{1,in}\right) = 0. \qquad (11)$$

From (11), we can obtain

$$w^s_{1,in} = \frac{\sum\limits_{\forall k \in B-S(i)} \left(w^f_{1,ik} - \hat{w}^s_{1,nk}\right)}{\left|B - S(i)\right|},$$

where $\left|S\right|$ is the total number of elements in set S.

In the same way, we can find $\tilde{e}^s_{in}$, $\tilde{e}^s_{nj}$, respectively, as follows.

$$\tilde{e}^s_{in} = \frac{1}{\left|B - S(i)\right|} \sum_{\forall k \in B-S(i)} \left[\left(w^f_{1,ik} - \hat{\hat{w}}^s_{1,nk}, d^f_{1,ik} - \hat{\hat{d}}^s_{1,nk}\right), \left(w^f_{2,ik} - w^s_{2,nk}, d^f_{2,ik} - d^s_{2,nk}\right)\right], \qquad (12)$$

$$\tilde{e}^s_{nj} = \frac{1}{\left|B - E(j)\right|} \sum_{\forall h \in B-E(j)} \left[\left(w^f_{1,hj} - \hat{\hat{w}}^s_{1,hn}, d^f_{1,hj} - \hat{\hat{d}}^s_{1,hn}\right), \left(w^f_{2,hj} - w^s_{2,hn}, d^f_{2,hj} - d^s_{2,hn}\right)\right]. \qquad (13)$$

Algorithm 1 shows the detailed algorithm.

Algorithm 1. Partial optimization algorithm.

```
FOR $n$=1 TO $b$
    Choose border router pair $i, j$ with the highest error.
    Add a bypass link to the pair.
    Calculate $\tilde{e}^s_{in}$ with (12).
    Calculate $\tilde{e}^s_{nj}$ with (13).
END_FOR
```

4. Performance Comparison

We consider 2-tier network as shown in Fig. 1 again to evaluate the performance. We assume that the entire network consists of five division routers. Each division is composed of 10 or 20 brigade routers and half of them is border router, respectively according to simulation scenarios. Each brigade router has connection with at least 3 brigade routers. Each link has bandwidth and delay which are randomly selected from ranges of 1 to 4 Mbps and 0.1 to 1 sec, respectively. In the simulation, we perform topology aggregation for each low-tier brigade network and then the results are transferred into a high-tier division router. Division routers calculate the difference between aggregated topology information and actual topology information.

We consider two star topology aggregation schemes, source oriented and error least star topology aggregations [6][7]. For each star topology scheme, each link has a random QoS parameter value for star topology aggregation. We also use various link aggregations. We focus on the sum of Δ for all pairs of border routers, when Δ is the difference between full mesh and star topology aggregation, to compare the exactness of the aggregation. For a more exact evaluation, we also compare the maximum Δ among all Δ. The total Δ represents the overall exactness and the maximum Δ shows the maximum error of topology aggregation. Good aggregation should have small total Δ and the maximum Δ. We show the ratio of the values, i.e. the total Δ sum and the maximum Δ after and before adding bypasses to measure the improvement from using bypasses.

Fig. 4 to **7** show that the total Δ and the maximum Δ of our scheme are reduced compared to existing schemes when four link aggregation methods, such as approximated line (represented as *LINE* in **Fig. 4** to **7**), single path parameter (*SINGLE*), best case of multiple path parameters (*BEST*), and worst case of multiple path parameters link aggregation (*WORST*), are used

We use the following steps for the previous star topology aggregation. First, we perform full mesh topology aggregation, and then, create a star topology network from the full mesh topology aggregation. Finally, select b router pairs with the maximum errors and add the bypass links.

The computational complexity for error least star topology aggregation is given as $O(b^2 \log(b))$; for source-oriented star aggregation, it is given as $O(b)$. Therefore, the total complexities are $O(b^2 \log(b) + b^2) = O(b^2 \log(b))$ and $O(b + b^2) = O(b^2)$ when our algorithm is used for error least and source oriented star topology aggregations, respectively. We can see that our approach achieves more accurate topology aggregation for all the cases in the simulation. For all cases, the total number of bypasses equals to that of border routers as described in [6].

As shown in **Fig. 4**, we can see that our scheme decreases total Δ by 12 %, 44%, 21% and 66 % compared with approximated line, single path parameter, best case of multiple path parameters and worst case of multiple path parameters link aggregation, respectively. In **Fig. 5**, our scheme decreases maximum Δ by 32%, 50%, 79% and 27% compared with with approximated line, single path parameter, best case of multiple path parameters and worst case of multiple path parameters link aggregation, respectively. In **Fig. 8** to **7**, the improvements are 29%, 28%, 26% and 35% for total Δ and 24%, 5%, 19% and 30% for maximum Δ, respectively, for each link aggregation scheme. From these results, we can say that our scheme is very effective to improve both of total Δ and maximum Δ simultaneously.

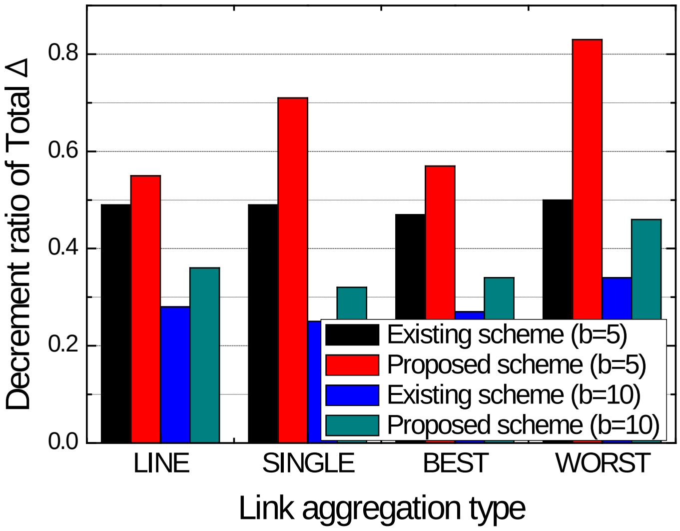

Fig. 4. Decrement ratio of Total Δ for error least star topology aggregation.

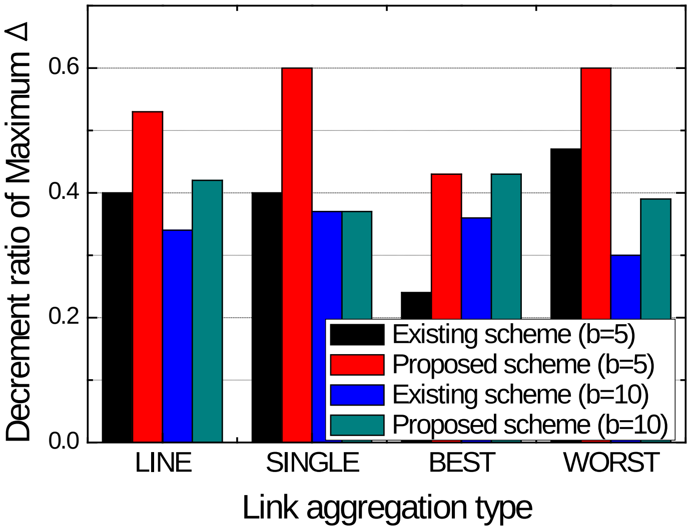

Fig. 5. Decrement ratio of Maximum Δ for error least star topology aggregation.

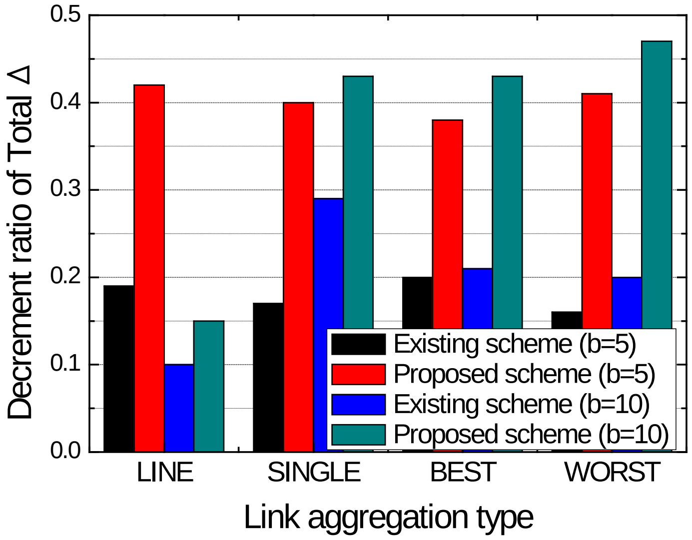

Fig. 6. Decrement ratio of Total Δ for error least star topology aggregation.

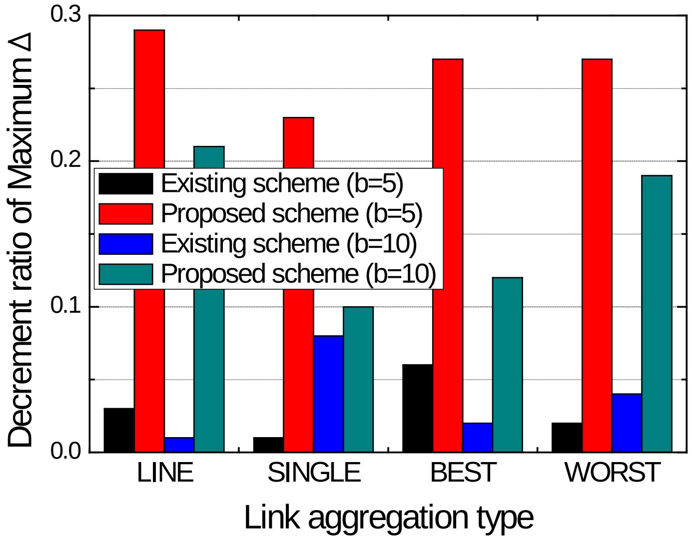

Fig. 7. Decrement ratio of Maximum Δ for error least star topology aggregation.

To evaluate the performance according to total number of bypasses used, we measured the decreament ratio of total when the number increases from 0 to *b* (total number of border routers). Since it shows almost the same results regardless of topology and link aggregation algorithms, we show the results only for error least star topology aggregation and worst case of multiple path parameters link aggregation in **Fig. 8** to **9**. As we can see, we have better performance with more bypasses for all cases. Also, the performance gap between proposed and existing schemes increases according to total number of bypasses. It means we should always use *b* bypass links for the best performance. When we use 5 bypasses in Fig. 8, our proposed scheme can outperform the existing scheme by 45 %. For 10 bypasses as shown in

Fig. 9, the improvement is 20 %. Since the total number of nodes are smaller than 10 in WTN, the improvement is quite higher than 20 % in real WTN environments.

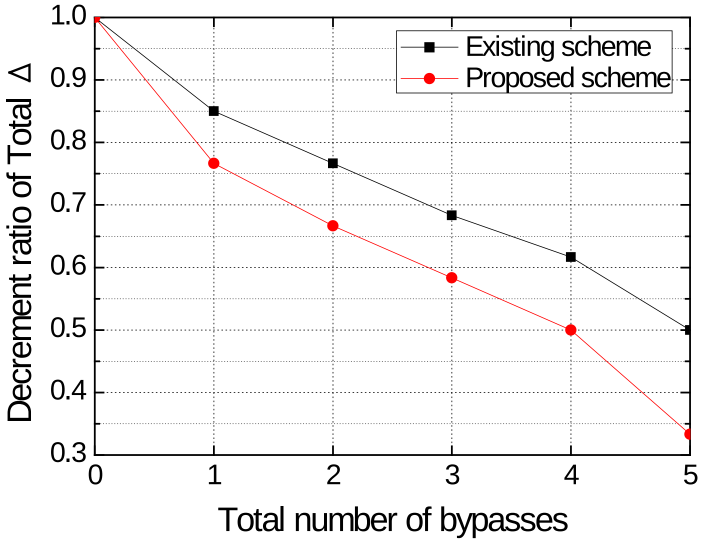

Fig. 8. Decrement ratio of Total Δ according to total number of bypasses when *b*=5 where error least star topology aggregation and worst case of multiple path parameters link aggregation are used.

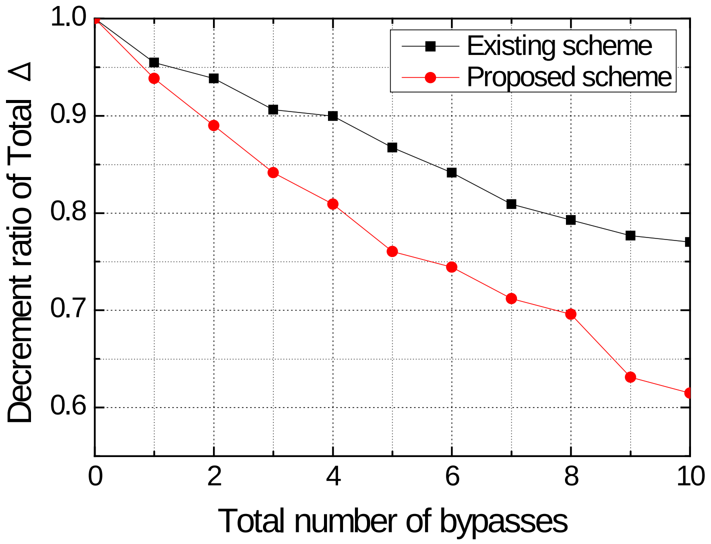

Fig. 9. Decrement ratio of Total Δ according to total number of bypasses when *b*=10 where error least star topology aggregation and worst case of multiple path parameters link aggregation are used.

5. Conclusion

In this paper, we suggested the partial optimization scheme to improve the exactness of general and source-oriented star topology aggregations with bypass links. We verified that it increased the exactness level of aggregation. The simulation of various network topologies showed that our scheme performs well. Moreover, our optimization method can be combined with existing aggregation schemes to achieve the higher performance due to its flexibility.

References

[1] J. Liu, X. Hong, J. Kong, Q. Zheng, N. Hu and P. G. Bradford, "A hierarchical anonymous routing scheme for mobile ad-hoc networks," in *Proc. of IEEE Military Communications Conference (MILCOM)*, pp. 1-7, October 2006. Article (CrossRef Link).

[2] J. Wei and X. Zhang, "Mobile multi-target tracking in two-tier hierarchical wireless sensor networks," in *Proc. of IEEE Military Communications Conference (MILCOM)*, pp. 1-6, October 2009. Article (CrossRef Link).

[3] L. Li and T. Kunz, "Efficient mobile networking for tactical radios," in *Proc. of IEEE Military Communications Conference (MILCOM)*, pp. 1-7, October 2009. Article (CrossRef Link).

[4] H.-L. Koo, N.-H. Roh, Y.-K. Park, S.-E. Kim and Y.-S. Kim, "Data delivery with end-to-end QoS guarantee in tactical network interconnected with wireless ad-hoc network and heterogeneous networks," in *Proc. of International Conference on Advanced Communication Technology (ICACT)*, vol.1, pp. 804-809, February 2009. Article (CrossRef Link).

[5] "Warfighter information network - tactical (WIN-T)," http://www.fas.org/man/dod-101/sys/land/docs/WIN-T5NOV.htm, November 1999.

[6] K. -S. Lui, K. Nahrstedt and S. Chen, "Routing with topology aggregation in delay-bandwidth sensitive networks," *IEEE/ACM Transactions on Networking*, vol. 12, no. 1, pp. 17-29, February 2004. Article (CrossRef Link).

[7] T. Kormaz and M. Krunz, "Source-oriented topology aggregation with multiple QoS parameters in hierarchical ATM networks," *IEEE International Workshop on Quality of Service (IWQoS)*, pp. 137-146, May 1999. Article (CrossRef Link).

[8] W. Pak. and S. Bahk, "Partial optimization method of topology aggregation for hierarchical QoS routing," *IEEE International Conference on Communications (ICC)*, vol. 2, pp. 1123-1127, April 2002. Article (CrossRef Link).

[9] R. Ogier, F. Templin and M. Lewis, "Topology dissemination based on reverse-path forwarding (TBRPF) RFC 3684," February 2004, Category: Experimental, work in progress. http://www.ietf.org/rfc/rfc3684.txt.

[10] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," *IEEE Workshop on Mobile Computing Systems and Applications*, pp. 90-100, February 1999. Article (CrossRef Link)

[11] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," *Springer Mobile Computing*, T. lmielinski and H. Korth, Eds., Ch. 5, Kluwer, vol. 353, pp. 153-181, 1996. Article (CrossRef Link).

[12] W. C. Lee, "Spanning tree method for link state aggregation in large communication networks," in *Proc. of IEEE International Conference on Computer Communications (Infocom)*, vol.1, pp. 297-302, April 1995. Article (CrossRef Link).

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