# Organization-Aware Routing in Mission Critical Networks

Yuanzhu Peter Chen
Department of Computer Science
Memorial University of Newfoundland
St. John's, NL Canada
Email: yzchen@cs.mun.ca

Lijun Qian
Department of Electrical and Computer Engineering
Prairie View A&M University, Texas A&M University System
Prairie View, Texas 77446
Email: liqian@pvamu.edu

***Abstract*— In a large mission critical wireless ad hoc network, heterogeneous nodes with different capabilities and nodes from different organizations may be deployed within the same geographical area. This is typical for many mission critical applications such as military networks. For such applications, on one hand, a node from one organization may collaborate with the nodes from a different organization for better survivability and efficiency. On the other hand, it is important to keep cross-organization data transfer at the lowest possible level for minimal disruption of the traffic within each organization and for security reasons. We propose a novel routing metric that both maximizes the benefits from the collaboration of heterogeneous nodes and takes the organizational constraints into account. Furthermore, we propose a novel routing protocol that may accommodate this new organization-aware metric, while backward compatible with the most popular routing protocols for general MANET, such as the optimized link state routing protocol (OLSR). Simulation results demonstrate that the proposed method provides the much needed survivability and efficiency in battlefield environment while keeping the cross-organization data transfer at a low level.**

## I. Introduction

Mission Critical Networks (MCNs) are under intensive research recently due to its wide-spread applications such as in military operations, disaster relief, etc. Usually an MCN requires fast deployment as well as elimination of infrastructure support. This makes the wireless ad hoc networking technology a promising candidate for MCNs. In an MCN, multiple organizations are typically involved and they are deployed to the same geographical area, each focusing on a potentially different task. For example, many troops, UAVs, and wireless sensor networks are deployed in the same battlefield. One unique challenge in an MCN, as well as opportunity, is that multiple organizations may collaborate, and yet such collaboration should introduce minimum disruption to each organization's own operations.

In this work, we consider a heterogeneous mobile ad hoc network (MANET) deployed within the same geographic area, and assume that all the nodes are inter-operable. Specifically, we focus on the routing problem in scenarios where nodes that belong to one organization could transport traffic for nodes from another organization. This is crucial for maintaining survivability and efficiency in a harsh environment.

An illustrative example is shown in Fig. 1, where the ground vehicles (horizontal gateways), UAVs (vertical gateways), the soldiers, and the sensors belong to different organizations and their radios are inter-operable. Assume that a soldier B4 is out of the radio range of its own network. Then B4 can only communicate with other soldiers through the horizontal gateway A2 or the vertical gateway D2. Moreover, significant resource savings and high efficiency can be achieved by collaborations among multiple organizations. For example, in Fig. 1, if sensor node C10 has very limited energy left, it would be desirable to relay the sensed data through a shortcut with the help of soldier B2, instead of a long route (C7-C8-C9-Fusion Center).

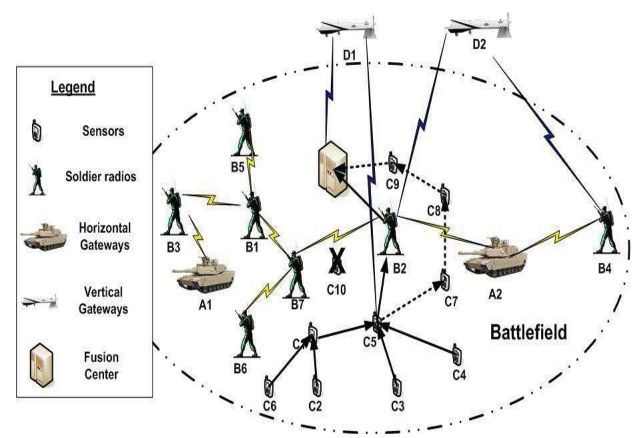


Fig. 1. Collaborations in an organization-aware mobile ad hoc network

Although there are considerable benefits for different organizations to collaborate, it is also important that the incurred additional overhead to the helping organization will not disrupt its own operation. For instance, suppose network B is tied up with its own organizations, then it may not be appropriate for network B to relay traffic for network C (the sensor nodes). Instead, the vertical gateway D1 may function as a relay of the sensed data. These concerns can be modeled as organization induced constraints.

In this work, we are particularly interested in how much benefit and overhead can be yielded when different organizations collaborate to support critical applications across each other without violating organization induced constraints. As a first step toward this goal, in our previous work [1], a new metric is defined to model different levels in an organization-aware network using hierarchical addresses, and organizationally shortest path (OSP) is defined. Note that

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users from different organizations can be defined as users at different levels in a "global" organization-aware network using hierarchical addresses. Thus, this framework applies to all scenarios involving multiple organizations.

In this paper, we extend our previous results by proposing a generic routing metric incorporating organization induced constraints in existing routing metrics. Specifically, the proposed metric addresses the tradeoff between the benefits (due to collaboration) and the cost (due to cross-organization traffic flow). In order to find the optimal path efficiently using the new routing metric, a novel routing protocol that accommodate the new organization-aware metric by modifying the optimized link state routing protocol (OLSR) [2], called *generic hierarchical OLSR*, or ghOLSR for short, is proposed based on our study. We perform extensive simulations using ns-2 to demonstrate the effectiveness of the proposed scheme and to evaluate the tradeoff between organizational and topological requirements.

The rest of this paper is organized as follows. In Section II, the system model and the organization-aware link metric are given. The proposed generic routing metric and routing protocol are described in Section III. Section IV is dedicated to simulation studies and our findings out of these experiments. Related works are discussed in Section V. Section VII contains the concluding remarks.

## II. Organization-aware link metric

In an organization-aware network (OAN), a fundamental challenge is how to achieve efficient communications and maintain "chain of command" at the same time. In our previous work [1], a new metric is defined to model different levels in an organization-aware network by using hierarchical address, and organizationally shortest path (OSP) is defined. In this work, we extend our previous results by considering the tradeoff between the benefits due to collaboration (which may be measured by path quality such as number of hops, data rate or delay) and the cost due to organization induced constraints.

### A. Organization-aware paths

We denote the set of nodes in the network by $V$. For each node $v$ in $V$, it has a hierarchical address of $h$ levels, denoted by $\langle v_1, v_2, \dots, v_h\rangle$, where each component is taken from a countable set, such as an octet of the IP address. As a convention, we use the right most address component for the deepest (lowest) level in the hierarchy. We assume that the addresses are unique in the network. Given two nodes $u = \langle u_1, u_2, \dots, u_h\rangle$ and $v = \langle v_1, v_2, \dots, v_h\rangle$, we define the *bond* of them, $b(u, v)$ or simply $b$ when there is no confusion, as the maximum index $b$ in their addresses such that $u_i = v_i$, for $i = 1, 2, \dots, b$, but $u_{b+1} \neq v_{b+1}$. That is, nodes $u$ and $v$ belong to the same unit as deep as level $b(u, v)$. Specifically, when $b = 0$, these nodes belong to two different units at the highest level; when $b = h-1$, they belong to the same lowest-level unit. For example, the network in Fig. 2 has 9 nodes which belong to two different units, indicated by their colors. The bond of nodes $A$ and $D$ is 1 while it is 0 for $A$ and $B$.

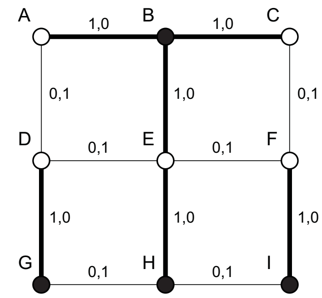


Fig. 2. Paths in a 2-level network

In a network of nodes with hierarchical addresses defined as above, it is usually required that traffic flows are kept "as low as possible" in terms of the organizational unit. Formally, we can use an undirected graph $G = (V, E)$ to represent the network, where $V$ is the set of nodes and $E$ is the set of communication links between neighboring nodes. Given a simple path $P = e^1 e^2, \dots, e^l$ between source $s$ and destination $t$ in $G$, we define the bond of a path as

$$b(P) = \min_{i=1}^{l} \left\{ b(u, v) | e^i = (u, v) \right\}.$$

That is, the bond of $P$ is the highest level of common unit that it traverses. For instance, path $ADG$ in Fig. 2 has a bond of 0 while path $ADE$ has 1. For a pair of source and destination, $s$ and $t$, we would want to identify paths connecting them with the maximum bond. In addition, among these paths, we should use the shortest one(s) for data transportation. The shortest path defined in this sense is called an *organizationally shortest path* (OSP for short).

Note that a link metric is necessary for calculating the length of a path, which should also reflect the "level" of the link, i.e., the bond of its endpoints. Here, such a metric can be based on any traditional link weight notion. For example, a unit link weight can be employed so that the path length is essentially the hop count. Alternatively, we can also use more informative metrics such as the Expected Transmission Count (ETX) [3] and the Expected Transmission Time (ETT) [4]. In order to define the metric of a given link $e = (u, v)$ of positive weight $w$, we adopt an $h$-dimensional vector notation, $\langle w_1^e, w_2^e, \dots, w_h^e\rangle$. Specifically, $w_{i+1}^e$ is set to $w$ if $i = b(u, v)$ and to 0 otherwise. The links in Fig. 2 are labeled as such. As a result, the length of path $P = e^1 e^2, \dots, e^l$ is $\mathcal{W} = \langle W_1, W_2, \dots, W_h\rangle$, where $W_i = \sum_{e \in P} w_i^e$ $(i = 1, 2, \dots, h)$. To compare the "lengths" of two paths in the organizational sense, we use the lexicographical order of vectors so that lower-level paths are always favored over higher-level ones. That is, given two paths $P$ and $P'$ with lengths $\mathcal{W} = \langle W_1, W_2, \dots, W_h\rangle$ and $\mathcal{W}' = \langle W_1', W_2', \dots, W_h'\rangle$, respectively, we say that $\mathcal{W} < \mathcal{W}'$ ($\mathcal{W} > \mathcal{W}'$, resp.) if $W_i = W_i'$ for $i = 1, 2, \dots, j-1$ and $W_j < W_j'$ ($W_j > W_j'$, resp.) for some $j$ $(1 \leq j \leq h)$; if no such $j$ exists, we say $\mathcal{W} = \mathcal{W}'$. For example, consider nodes $A$ and $C$ in Fig. 2. Path $ABC$ has a length of $\langle 2, 0\rangle$

and path $ADEFC$ has a length of $\langle 0, 4\rangle$). Thus, the latter is considered to be a "shorter" path in the organizational sense. In fact, it is the OSP between these two nodes. Therefore, such a definition of path length and comparison constitutes a total order among all paths to find the OSP in a network with hierarchical addresses. Observe that, given a pair of nodes in the same network, an OSP and a shortest path in the topological sense (denoted by *TSP*) can be as large as the number of the nodes in the network in extreme cases [1].

### B. Preliminary experiments

This organization-aware link metric was first devised in our earlier work [1]. To test the effectiveness of this metric using a packet simulator, we compared routes adopted by some routing protocols in ad hoc networking to those calculated globally and studied their relative topological and organizational lengths. Four kinds of paths were investigated there, i.e., the topologically shortest paths (TSP), organizationally shortest paths (OSP), paths used by AODV, and those used by DSR. The TSP and OSP were calculated using global information as references for AODV and DSR. Our findings indicated that this metric captures the organizational notion in path length very well. In addition, in various network sizes and node distributions, an OSP usually has a considerably smaller organizational length than that of the TSP connecting the same pair of nodes, while its topological length is merely slightly greater than that of the TSP.

## III. Generic Hierarchical Routing

In this section, we first formulate a routing problem as a composite shortest path problem. The proposed formulation addresses the tradeoff between the benefits due to collaboration (which may be measured by path quality such as number of hops, data rate or delay) and the cost due to the organization awareness overhead. In other words, the proposed routing metric provides flexibilities on balancing communication efficiency and organizational requirement. Then we introduce ghOLSR as a baseline routing protocol for finding the composite shortest path efficiently.

### A. Tradeoff OSP and TSP

Define a weight vector $\rho = \langle \rho_1, \rho_2, \ldots, \rho_h \rangle$ that representing how important each level is (due to chain of command, etc.). In addition, a cost reflecting link quality such as delay and resource consumptions such as power is denoted by $d_e$ and the path cost will be $d_P = \sum_{e \in P} d_e$. The total cost (including the organization-aware cost and the link quality and resource cost) of a path $P$ can be defined by

$$C_P = \eta_1[\rho \cdot W_P] + \eta_2 d_P, \tag{1}$$

where $\rho \cdot W_P$ denotes the inner product of the two vectors, and $0 < \eta_1 < 1$, $0 < \eta_2 < 1$, $\eta_1 + \eta_2 = 1$. The goal of the proposed optimal organization-aware routing is

**(P1)**

$$\min_P C_P \tag{2}$$

In other words, for any given source destination pair, find the path such that the total cost of the path is minimized.

Note that the parameters $\eta_1$ and $\eta_2$ determine the tradeoff between emphasis on organization level constraints and path quality and resource cost. The vector $\rho$ provides further flexibility of specifying the relative importance among each levels.

### B. ghOLSR

The goal of our routing protocol is to find short paths using the organization-aware link metric that also satisfy the side constraints. To do that, we believe that a proactive link-state routing protocol is the most suitable choice even without these constraints. The reasons are two-fold. First, an on-demand routing protocol is not suitable for this purpose due to its confined route search space and to its duplicate avoidance features. Second, a distance-vector routing protocol's loop avoidance component prevents good paths from being identified. Thus, we build our routing protocol atop OLSR for its savings in routing overhead, dubbed *generic hierarchical OLSR* (ghOLSR). (For a taxonomy of the essential routing protocols in ad hoc networks, the readers are referred to the excellent review of Royer and Toh [5].)

OLSR is a proactive link-state routing protocol standardized in RFC 3626 [2]. It improves traditional link-state routing by significant reduction of routing overhead using the notion of MPR, i.e., *MultiPoint Relay*. In OLSR, each node appoints a subset of its neighbors as its MPRs. In essence, the MPRs form a dominating set in the 2-hop neighborhood of this node. As a result, for this node to broadcast a message within its 2-hop neighborhood, only its MPRs need to forward the message, which avoids a large number of duplicate messages. This is the first aspect of overhead reduction. Second, in OLSR, link-state information is only generated by nodes elected as MPRs. Thus, a potentially smaller number of nodes are sources of link-state broadcasting. Third, an MPR may choose to report only links between itself and its MPR selectors, i.e., the neighbors that have selected it as MPR. Consequently, a link-state broadcast message can contain a smaller number of link-state entries.

With an identical view of the entire network reconstructed using the OLSR link-state messages, a node calculates the shortest path tree in this reconstructed topology to all other nodes rooted at itself. Note that OLSR in its original form is not able to calculate the OSP to each destination even if the hierarchical addresses are added to the link-state messages. The reason is that the second and third savings discussed above prevent some links from being broadcast. This leads to an incomplete topology gathered by each node. To address this issue, ghOLSR, the organization-aware enhancement of OLSR, requires the following modification to OLSR.

- The hierarchical address of the origin of link-state messages is included.
- A numerical link weight is associated with each link-state entry.
- All nodes must broadcast link-state messages as origin.
- All links must be included in the link-state messages.

These modifications imply that the second and third types of overhead savings are not possible in ghOLSR. However, the first and primary form of overhead reduction via MPR forwarding is still effective. Once a node has collected the above information, it calculates the generic link costs incorporating the tradeoff parameters and executes Dijkstra's single-source shortest path algorithm to populate the forwarding table.

## IV. Simulation Study

In this section, we investigate the performance of ghOLSR using ns-2, an open source packet level simulator. The proposed ghOLSR is implemented based on UM-OLSR [6], the ns-2 module by University of Murcia, and is integrated to ns-2.33. We use the default two-ray PHY model and IEEE 802.11 MAC settings in ns-2, which translates to a transmission range of 250 meters in a 2-dimensional space. Although from version 2.33 the package starts to ship with two new MAC/PHY extensions, which include more advanced features such as fading simulation, we still use the default 802.11 implementation as in earlier versions. The reason is that our focus is on routing, and a simple and predictable MAC/PHY helps us to understand the protocol better.

### A. Grid

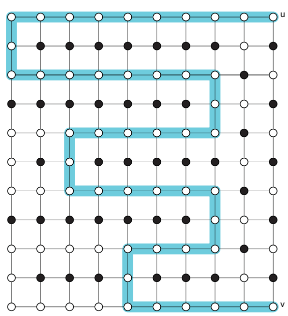


Fig. 3. 11×10 grid

First, we study how ghOLSR works in a grid network. In this scenario, there are 11×10 nodes in the grid, and the distance between neighboring nodes is 200m (Fig. 3). Every node has a unique low-level address and belongs to one of two organizations, as indicated by the solid and hollow circles in the diagrams. That is, the network has a 2-level hierarchical addressing system and the top level address can have value 0 or 1. We focus on the node pair $u$ and $v$ and observe how the "shortest" path changes as we tune $\eta_1$, $\eta_2$, $\rho$, and $d$. Apparently, the TSP between $u$ and $v$ is the vertical path of 10 hops with a hierarchical weight of $W = \langle 10, 0\rangle$, while the OSP is the highlighted path of 44 hops with $W = \langle 0, 44\rangle$. The TSP can be returned by ghOLSR via making all links carry an equal scalar weight, say setting $\rho_1 = \rho_2 = 0.5$ and $d = 0$. The OSP can be returned via setting $\rho_1 = 1$, $\rho_2 = 0$, and $d = 0$. In either case, we set $\eta_0 = \eta_1 = 1$. By doing so, we can focus on the relative values of the $\rho$ components.

To trace the actual path used for data forwarding between $u$ and $v$ for a given set of tradeoff parameters, we employ a pair of tracer UDP flows between them. Each flow carries a CBR (constant-bit rate) traffic of 500B/pkt at 1pkt/sec. After routing stabilizes, we record the routes taken by the CBR segments. We find that three other medium paths (Figs. 4 to 6) are also possible depending on the parameter settings. Indeed, the OSP, the medium paths, and TSP (Fig. 7), represent the different tradeoffs between the organizational and topological requirements. That is, these five paths have an increasing (decreasing, resp.) topological (organizational, resp.) requirement. We consider two cases,

- $d = 0$, where tradeoff is completely controlled by the relative values of the $\rho$ components, and
- $d = 0.1$, where the actual link weights are also important.

We know that, in either case, when $\rho_0/\rho_1$ is large, the routing agent is more organization-aware, so it tends to use an OSP. When $\rho_1/\rho_2$ is small, it tends to use a TSP. Assume that $\rho_1 + \rho_2 = 1$ without loss of generality. We are interested in the phase points as the ratio increases when

1) path in Fig. 3 reduces to that in Fig. 4 ($T_1$),
2) path in Fig. 4 reduces to that in Fig. 5 ($T_2$),
3) path in Fig. 5 reduces to that in Fig. 6 ($T_3$), and
4) path in Fig. 6 reduces to that in Fig. 7 ($T_4$).

The thresholds of ratio $\rho_1/\rho_2$ are summarized in rows 2 and 3 in Table I. From these values, we observe that even a slight contribution of $d$ suppresses the organizational requirement to a large degree. Row 4 is the hop length of the paths and row 4 is the hierarchical weight of these paths.

TABLE I
PHASE CHANGE THRESHOLDS

| $\rho_1/\rho_2$ thresholds | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|
| $d = 0$ | 8.0 | 6.0 | 4.0 | 2.0 |
| $d = 0.1$ | 29.0 | 13.0 | 6.1 | 2.7 |
| Resultant path length | 30 | 20 | 14 | 10 |
| $W_P$ | $\langle 2, 28\rangle$ | $\langle 4, 16\rangle$ | $\langle 6, 8\rangle$ | $\langle 10, 0\rangle$ |

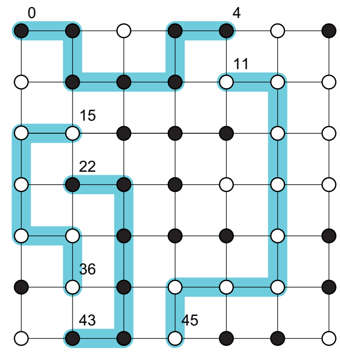


Fig. 8. Grid with random addresses

Next, we test ghOLSR in a 7×7 grid with the same neighbor separation distance. Nodes belong to two groups as before, indicated by the solid and hollow circles in Figure 8. Here, we are interested in the routes output by the routing protocol between random node pairs. In particular, we focus on the node

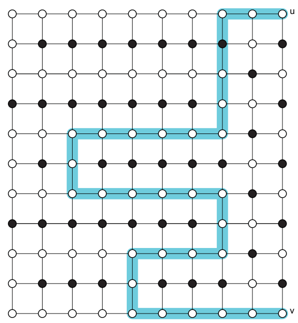

Fig. 4. Reduction 1

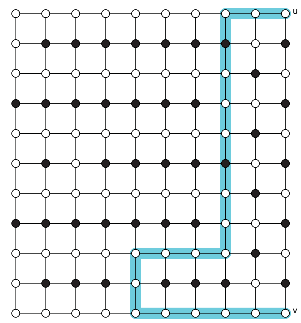

Fig. 5. Reduction 2

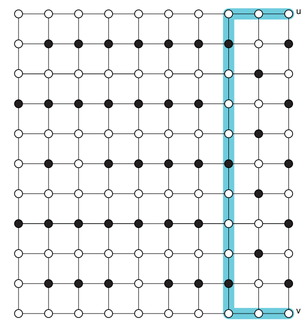

Fig. 6. Reduction 3

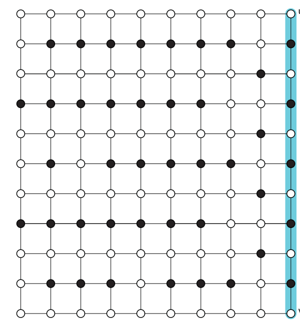

Fig. 7. Reduction 4

TABLE II
RANDOM NODE PAIRS IN A GRID

| Paths | $L_{\mathrm{TSP}}$ | $W_{\mathrm{TSP}}$ | $L_{\mathrm{OSP}}$ | $W_{\mathrm{OSP}}$ |
|---|---|---|---|---|
| $0 \rightleftharpoons 4$ | 4 | $\langle 2, 2\rangle$ | 6 | $\langle 0, 6\rangle$ |
| $15 \rightleftharpoons 36$ | 3 | $\langle 2, 1\rangle$ | 5 | $\langle 0, 5\rangle$ |
| $22 \rightleftharpoons 43$ | 3 | $\langle 2, 1\rangle$ | 5 | $\langle 0, 5\rangle$ |
| $11 \rightleftharpoons 45$ | 6 | $\langle 2, 4\rangle$ | 8 | $\langle 0, 8\rangle$ |

pairs of $(0 \rightleftharpoons 4)$, $(15 \rightleftharpoons 36)$, $(22 \rightleftharpoons 43)$, and $(11 \rightleftharpoons 45)$ by tracing the datagrams assigned between each pair after stabilization. Regardless the tradeoff parameters, there can only be two feasible paths between each node pair, i.e. the OSP and TSP. The lengths and hierarchical weights of these paths are summarized in Table II. Note that for a given pair, the OSP is always 2 hops longer than the TSP. In addition, we during the simulation, when we change the parameter settings, the switch for the routing agent to output from an OSP to a TSP is always simultaneous for these 4 node pairs. We report one set of results here when we set $\eta_1 = \eta_2 = 0.5$. In Table III, we list the phase change thresholds of the $\rho_1/\rho_2$ ratio for various given values of $d$. Notice that, when $d = 1$, $\rho_1 = 1$ and $\rho_2 = 0$ must be set for phase path switch to be possible.

TABLE III
$\rho_1/\rho_2$ VS. $d$

| $d$ | $\rho_1/\rho_2$ |
|---|---|
| 0 | 2.0 |
| 0.1 | 2.7 |
| 0.4 | 4.0 |
| 0.7 | 9.0 |
| 1 | $\infty$ |

### B. Random location

The next set of experiments are carried out over a randomly generated network of 100 nodes in a $1500 \times 1500$ square (Fig. 9). Again, these nodes belong to two groups, as indicated by the solid and hollow circles in the figure. In this particular example, 57 nodes are in group 1 (hollow) and 43 in group 0 (solid). Based on the MAC/PHY parameters, the transmission range is 250m, but we do not include the wireless links in the diagram for the ease of reading. We assign bi-directional pilot flows between nodes of the same group at the beginning of our 50-second simulation. Comparison is made between hOLSR and OLSR. Here, we focus on 4 pairs of nodes, i.e., $(42 \rightleftharpoons 63)$, $(41 \rightleftharpoons 95)$, $(29 \rightleftharpoons 83)$, and $(26 \rightleftharpoons 73)$. Similar to the previous experiments, we first summarize the convergence time and exemplar OSPs/TSPs with their lengths in Table IV. These node pairs represent different cases when considering TSP and OSP between a given pair of nodes in the network. For each node pair, the OSP always involves intermediate nodes in the same group. We describe our observations from the simulation as follows.

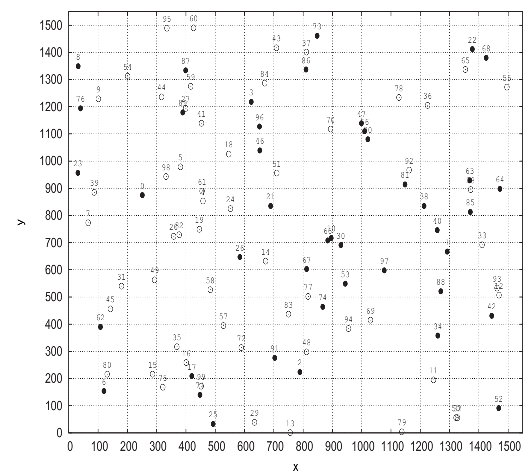

Fig. 9. Random deployment in square region

- $(42 \rightleftharpoons 63)$: Nodes 42 and 63 belong to group 0 (solid). There are multiple TSPs of 3 hops between these two nodes, some of which only involve intermediate nodes of the same group, e.g. 63.40.88.42, while others include nodes of group 1, e.g. 63.33.88.42. From the simulation, OLSR first identifies the former as TSP from node 63 to 42, but switches to the latter a few seconds after. In the other direction, OLSR always identifies 42.88.40.63 as the OSP. In contrast, the only OSP in between is 42.88.40.63, also of 3 hops, which is identified by hOLSR right after convergence.
- $41 \rightleftharpoons 95$: These end nodes belong to group 1 (hollow).

TABLE IV
RANDOM DEPLOYMENT

| Senarios | $42 \rightleftharpoons 63$ | $41 \rightleftharpoons 95$ | $29 \rightleftharpoons 83$ | $26 \rightleftharpoons 73$ |
|---|---|---|---|---|
| TSP (length) | 42.88.33.63 (4) | 41.87.95 (3) | 29.91.83 (3) | 26.21.46.84.73 (4) |
| OSP (length) | 42.88.40.63 (4) | 41.59.95 (3) | 29.99.57.83 (4) | 26.21.46.3.86.73 (5) |
| Time in OLSR (sec) | 4.6 | 4.5 | 4.5 | 9.1 |
| Time in hOLSR (sec) | 5.5 | 4.5 | 5.0 | 8.6 |

Both TSP (e.g. 41.87.95) and OSP (e.g. 41.59.95) are 2 hops long. For such short paths, OLSR and hOLSR quickly identify and stabilize at these two paths for either direction.

- $29 \rightleftharpoons 83$: Nodes 29 and 83 belong to group 1 (hollow). The TSP (e.g. 29.91.83) in between is 2 hops but the OSP (e.g. 29.99.57.83) is 3 hops. For this pair, OLSR quickly finds the the former as the TSP for both directions. It takes hOLSR about 1.5 seconds to settle from the TSP to OSP. Once it finds the OSP, it stays with it for the rest of the simulation.
- $26 \rightleftharpoons 73$: These end nodes, in group 0 (solid), are relatively far apart from each other, and it takes both protocols a few seconds longer to identify a path between them. The TSP between them (e.g. 26.21.46.84.73) is 4 hops while the OSP (e.g. 26.21.46.3.86.73) is 5 hops. On one hand, since there is only one OSP between nodes 26 and 73, hOLSR stabilizes at it right after it finds this path in both directions. On the other hand, we observe that OLSR's belief in the TSP drifts sometimes during the simulation. In particular, it first finds 26.21.46.84.73 as TSP after 9 seconds into the simulation. After another approximately 10 seconds, it indicates that the TSP becomes the longer 26.24.52.70.86.73. A closer look into the trace suggests that this is caused by a temporary link outage. This lasts for about 5 seconds before OLSR falls back to the shorter 26.24.46.84.73. It further changes to 26.21.46.84.73 after a few more seconds, which is the path it discovered at the beginning.

From this set of experiments, we observe that OLSR and hOLSR are able to find TSPs and OSPs in a network with randomly deployed nodes, respectively, in a short time. In addition, they respond to transient network changes quickly and converges to the optimum adaptively. Furthermore, in many cases, hOLSR identifies OSPs which are of the same length of or slightly longer than TSPs. In other words, hOLSR satisfies the "lowest possible level" at a very small cost.

## V. Related Work

There are a number studies on inter-domain routing for both wired and wireless networks, such as BGP [7] and HLP [8] for the Internet and [9] for wireless ad hoc networks, just to name a few. However, those studies consider a fairly different scenario where different networks are also in different geographical/logical areas and there are pre-defined gateway nodes between different networks. Typically each network is defined as an autonomous system (AS) and nodes in different ASes will not mix and communicate directly. For instance, the primary function of a BGP system is to exchange network reachability information with other BGP systems. The information is then used to construct a graph of AS connectivity from which routing loops can be pruned and policy decisions can be enforced. The traffic flows are *intentionally* across multiple ASes rather than the collaborations in MCNs considered in this paper. Although the organization ID of the nodes is considered in [9], again, the ad hoc networks are located in different geographical areas and the traffic flows are meant to cross different networks. Furthermore, the level constraint is not considered in [9].

## VI. Discussion

### A. Constrained Routing

Problem **(P1)** is essentially an unconstrained optimization problem. In many practical situations, certain QoS constraints such as end-to-end delay bound may be necessary. In addition, there may exist strict organization security constraints, such as no traffic beyond a certain level is allowed. Hence, we define the following constrained optimization problem:
**(P2)**

$$\min_{P} C_P \tag{3}$$

such that

$$d_P \le d_P^{tar} \tag{4}$$

$$W_P \le W_P^{tar} \tag{5}$$

where $d_P^{tar}$ and $W_P^{tar}$ are target upper bounds for delay and organization security, respectively.

It worth noting that since $d_P$ represents link quality such as delay and resource consumptions such as power, it is a function of traffic flow [10].

Problem **(P2)** can be re-written as the following problem:
**(P3)**

$$\min_{P} \left[ \eta_1 \sum_{i=1}^{h} \rho_i \left( \sum_{(j,k)\in P} W_i^{(j,k)} \right) + \eta_2 \sum_{(j,k)\in P} d^{(j,k)} \right] \tag{6}$$

such that

$$\sum_{(j,k)\in P} d^{(j,k)} \le d^{P,tar} \tag{7}$$

$$\sum_{(j,k)\in P} W_i^{(j,k)} \le W_i^{P,tar} \; \forall i = 1, 2, \cdots, h. \tag{8}$$

The above constraints $\sum_{(j,k)\in P} W_i^{(j,k)} \le W_i^{P,tar}$ $\forall i = 1, 2, \cdots, h.$ states the fact that there is possibly a constraint at

each level. If there is no constraint at some level $m$, we may simply set $W_m^{P,tar} = \infty$. The above **(P3)** can be formulated as the following network flow problem with integer constraints and side constraints:
**(P4)**

$$\min_{(j,k)\in E} \left[ \eta_1 \sum_{i=1}^{h} \rho_i \left( \sum_{(j,k)\in E} W_i^{(j,k)} x^{(j,k)} \right) + \eta_2 \sum_{(j,k)\in E} d^{(j,k)} x^{(j,k)} \right] \quad (9)$$

such that

$$\sum_{\{k|(j,k)\in E\}} x^{(j,k)} - \sum_{\{k|(k,j)\in E\}} x^{(k,j)} = \begin{cases} 1 & \text{if } j = s \\ -1 & \text{if } j = t \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

$$0 \le x^{(j,k)} \le 1, \ \forall (j,k) \in E \quad (11)$$

$$\sum_{(j,k)\in E} d^{(j,k)} x^{(j,k)} \le d^{P,tar} \quad (12)$$

$$\sum_{(j,k)\in E} W_i^{(j,k)} x^{(j,k)} \le W_i^{P,tar} \ \forall i = 1, 2, \cdots, h. \quad (13)$$

where $(j,k)$ is the link/edge from node $j$ to node $k$ and $E$ is the set of all edges.

Note that this generic path metric degenerates to a few forms depending on the values of $\eta_1$, $\eta_2$, $\rho$, and $d$. These degenerated cases models a number of differing application requirements. Table V summarizes these cases.

TABLE V
DEGENERATION BY DIFFERENT PARAMETER SETTINGS

| | Pure OSP | Hop Count | Informative |
|---|---|---|---|
| $\eta_1$ | 1 | 0 | 0 |
| $\eta_2$ | 0 | 1 | 1 |
| $d$ | any | 1 | ETX, ETT, etc. |
| $\rho$ | heavy-head $\rho_i$ | homogeneous $\rho_i$ | any |

It is also interesting to notice that there are multiple parameter settings as well as that changing the target value of the constraints may result in the same optimal path. For example, there are at least two ways to obtain the TSP assuming that the problem P4 is feasible: 1) $\eta_1 = 0$ ; $\eta_2$ can take any positive value; and $d$ is the same for all links. 2) $d^{P,tar} = d^{TSP}$.

Such a constrained optimization problem is not solvable in polynomial time [11]. There exist several sub-optimal algorithms such as the flow augmentation algorithm [10], etc. that could solve the problem efficiently. Although it would be interesting to study the specific structure of this constrained optimization problem and find corresponding efficient algorithms tailored to it, it is not the concern of this paper and we leave it for our future research. Instead, we have incorporated this new routing metric (Equation (1)) in ghOLSR and focused on studying the tradeoff between organization constraints and benefits of collaborations.

### B. Overhead Reduction

Note that ghOLSR needs large amount of information propagated through the network, thus introducing burden on the control plane. We can create a MPR for propagating information efficiently using the concept of Connected Dominating Set (CDS). CDS can be calculated efficiently using only local information [12]. Detailed scheme will be designed in our future research.

### C. QoS and Security/Policy Concerns

There are QoS and security/policy requirements of traffic flows as well as node-specific needs. These requirements are orthogonal to the organizational requirements raised in this paper, and can be solved by other means, e.g. [13], thus ommitted in this paper.

## VII. Conclusions and Future Work

In this paper, we consider a novel generic routing metric to address one of the salient issues in mission critical and organization-aware networks, i.e. the tradeoff between collaborations and organizational constraints. We also propose a novel routing protocol, ghOLSR, that may accommodate the new routing metric, while backward compatible with OLSR. Simulation results demonstrate the flexibility of the proposed routing metric and the effectiveness of the proposed ghOLSR.

As we pointed out in Section VI-A, it is desirable to satisfy hard QoS constraints as well as hard organizational constraints at the same time by solving the constrained optimization problem **(P.4)**. This will be one of our future efforts. In addition, the effects of node mobility on the proposed routing protocol will also be studied.

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