Towards Interoperability of Adaptive Social-Aware Routing at the Tactical Edge

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***Abstract*—In military operations at the tactical edge, mobile networking systems are crucial for warfighters to ensure rapid situational response to the surrounding environments. Traditional routing protocols for tactical mobile networking systems assume end-to-end wireless connectivity among warfighters, but may experience serious performance degradation in practical Disconnected, Intermittent, and Limited-bandwidth (DIL) environments where such network connectivity is usually unavailable. Node mobility is instead exploited to ensure efficient data delivery following the methodology of "carry-and-forward", in particular, by investigating the information about social relationship between warfighters. It is hence important to maintain the interoperability between the carry-and-forward routing schemes and traditional Link State Routing (LSR) protocols, so as to improve the communication efficiency without incurring significant upgrade cost. Such interoperability will also improve the data delivery performance and network scalability by addressing the unavailability of routing paths in LSR protocols, without requiring global network information. In this paper, we propose a novel approach to maintaining such interoperability by investigating the diverse wireless connectivity among mobile nodes that varies over time. Our basic idea is to opportunistically enable LSR whenever temporary multi-hop connectivity exist between nodes, and to further integrate the locally maintained network link states into the calculation of social-aware routing metrics among disconnected nodes. Extensive simulation results show that our scheme could significantly improve the routing performance in various network scenarios.**

I. Introduction

Mobile networking systems which do not rely on persistent wireless infrastructure are crucial for warfighters at the tactical edge to maintain their situational awareness to the surrounding environments, and to ensure rapid situational response and adaptive operations [2]. Development of efficient routing protocols in such mobile networking systems at the tactical edge has received much attention from the U.S. Army, such as the Army's Warfighter Information Network - Tactical (WIN-T) [3] and DARPA's Content-Based Mobile Edge Networking (CBMEN) program [1]. These protocols are based on the traditional Mobile Ad-Hoc Networks (MANETs) and assume end-to-end wireless connectivity between warfighters [31].

Such connectivity, however, is usually unavailable in practical Disconnected, Intermittent, and Limited-bandwidth (DIL) environments at the tactical edge [28], [27], which are also known as Disruption Tolerant Networks (DTNs) [12]. The environmental dynamics and warfighter mobility in such environments lead to opportunistic and intermittent network disconnection, and make it difficult to maintain end-to-end communication links or global network information. Warfighters can only communicate when they move into the communication range of others' wireless radios, referred to as *contact*. As a result, the performance of traditional distance-vector [24] or link-state [18] MANET routing protocols are expected to be significantly degraded in such DIL environments, due to the unavailability of end-to-end routes. Instead, researchers adopt the idea of "carry-and-forward" [23]: node mobility is exploited to let nodes physically carry messages as relays, which forward messages when they opportunistically contact other nodes. The key problem is hence how to make effective forwarding decisions, to ensure that the messages are carried by relays with the best chance to contact their destinations.

Interoperability, in such cases, becomes a key challenge hindering the practical integration of a large number of legacy military communication devices, which operate LSR protocols, into the real theater at the tactical edge. Redeployment of opportunistic carry-and-forward routing protocols, on the other hand, requires significant investment and long time period for system upgrade and maintenance. In this paper, we present a novel scheme which synergistically integrate LSR and opportunistic routing protocols into the same application domain, so as to maintain the vital interoperability for routing in tactical DIL environments. Our basic idea is to investigate the transient characteristics of warfighters' contact patterns that would be heterogeneous in both temporal and spatial dimensions, as well as the subsequent diverse network connectivity among warfighters. As a result, we opportunistically enable LSR in tactical DIL environments whenever transient multi-hop connectivity exists between mobile nodes.

More specifically, we have made the following detailed contributions:

- We experimentally investigate the characteristics of transient node contact patterns over realistic DIL network traces, and further validate the diverse network connectivity among mobile users.
- We formally define the social-aware routing metrics considering the existence of temporary multi-hop wireless connectivity among warfighters, and further provide analytical methods calculating such metrics in practice.
- We develop a hybrid routing scheme which adaptively applies LSR protocols and social-aware opportunistic routing protocols into different network scenarios.

The rest of this paper is organized as follows. Section II briefly reviews the existing work. Section III motivates the necessity of maintaining the aforementioned interoperability in tactical DIL environments and highlights the big picture of our proposed solutions. Section IV describes the details of our proposed approach. Section V presents the results of performance evaluation, and Section VI concludes the paper.

II. Related Work

The major challenge of designing efficient routing protocols in MANETs is the unpredictable node movement and frequent end-to-end route failures. To minimize the overhead of repetitive route probing and reconstruction, researchers proposed to adopt the idea of reactive routing, which only invokes a route discovery procedure when a data source requests to send data to specific destinations. The route remains valid until either the data arrives the destinations or the route becomes unavailable. Route discovery can be done in either a distance-vector [24] or a link-state [18] manner. In particular, representative link-state routing protocols, such as Interior Gateway Routing Protocol (IGRP) [17] or Open Shortest Path First (OSPF) [22], have been widely adopted for MANET routing.

However, as noted in [6], the MANET environment at the tactical edge is usually volatile, such that links between nodes are unreliable and intermittently connected due to the battlefield terrain, node mobility, lack of infrastructure, and jamming effects. Instead, the research on carry-and-forward routing protocols in DIL environments originates from Epidemic routing [32] which floods the entire network. Later studies develop forwarding strategies to approach the performance of Epidemic routing with lower cost, which is measured by the number of data copies created in the network. While the most conservative approach [30] always keeps a single data copy and Spray-and-Focus [29] holds a fixed number of data copies, most schemes do not limit the number of data copies and forward data by comparing the nodes' routing metrics. In Compare-and-Forward [9], a relay forwards data to another node whose routing metric is higher than itself. Delegation forwarding [11] reduces the cost by only forwarding data to the node with the highest metric.

The routing metrics generally evaluate the capability of a mobile node to forward data to the specified destinations, and various metrics can be applied to the same strategy for different performance requirements. Some schemes predict such capability by estimating the co-location probabilities of mobile nodes based on their mobility patterns in different ways [33]. Node contact process, on the other hand, is also exploited, as abstraction of node mobility, to calculate nodes' routing metrics. The nodes' capability of contacting others in the future is predicted, based on their cumulative contact records from the past. Then, routing metrics have been proposed to estimate node contact probability in the future [4].

Node contact process can also be exploited for routing from a social network perspective. Most schemes exploit sociological centrality metrics [20] for relay selections. SimBet routing [7] uses an ego-centric betweenness metric, and BUBBLE Rap [16] considers node centrality in a hierarchical manner based on social community knowledge. In both schemes, the network contact graph is binary and hence cannot differentiate the contact frequency of various pairs of mobile nodes. Gao et al. [14] proposes to use Cumulative Contact Probability (CCP) as the centrality metric based on the cumulative node contact rates and the assumption of exponential distribution of pairwise node inter-contact times (ICTs). However, they assume that the node contact characteristics are stable over time and did not consider interoperability with traditional link-state-based MANET routing protocols.

Topology table

	0	1	2	3	4	5
0	0	1	0	0	0	0
1	1	0	1	1	0	0
2	0	1	0	0	1	1
3	0	1	0	0	1	0
4	0	0	1	1	0	1
5	0	0	1	0	1	0

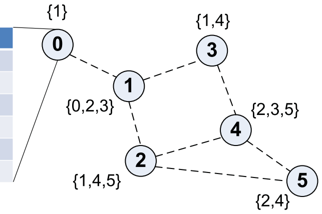


Fig. 1. An example of topology table built based on the link state packets. Dijkstra's algorithm is then used to find the shortest path.

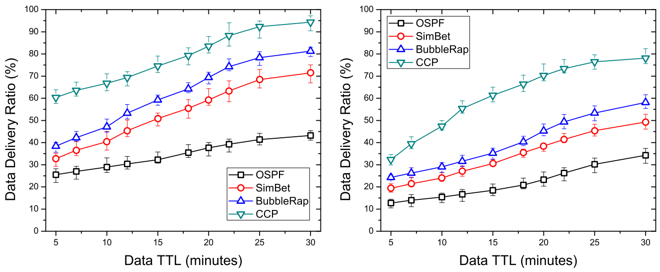
III. Motivation

In this section, we demonstrate the various aspects of performance degradation that link state routing (LSR) protocols may experience in practical DIL environments at the tactical edge, from both empirical and experimental perspectives. These perspectives then together highlight the importance of introducing social-aware opportunistic routing protocols into tactical mobile networks, and motivate our proposed research on maintaining the interoperability between these routing protocols and traditional LSR protocols.

A. Empirical Thoughts

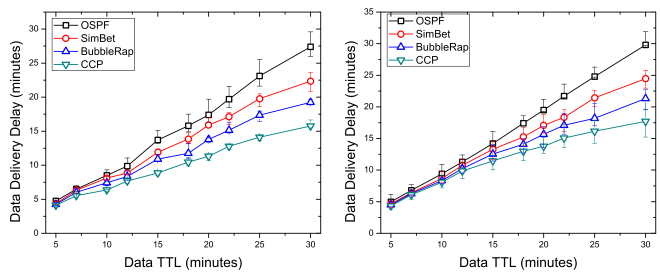
The process of discovering and maintaining routing paths in a highly mobile network requires generating routing control messages such as those used by the link state routing (LSR) protocols. In LSR protocols, each node in the network always tries to discover every other node in the network by using neighbor discovery and topology control messages, and then selects the optimal path. This process of route discovery and maintenance in MANET networks presents scalability challenges for the LSR protocols. Multiple field tests indicate that, even when faced with moderate levels of node mobility, increase in routing protocol exchange messages would prevent tactical MANETs from scaling beyond 30-40 nodes. This is due to the fact that LSR protocols such as OSPF [22], which are successfully deployed in the Internet for many years, are not easily extensible to tactical environments. Despite elaborated refinements and tweaks to OSPF, link state updates due to node movements tend to overwhelm wireless links when the number of nodes in a network grows beyond a few dozen. Most of these challenges are due to the mobility of nodes and the DIL nature of MANET networks, which results in frequent topology changes. As nodes move in the network, LSR protocols generate frequent update messages. Even though many techniques to reduce this overhead exist, the challenge still remains open.

As illustrated in Figure 1, the aforementioned process of knowing every node in the network at all times incurs tremendous amount of overhead traffic to be generated by the network. The topology table is created based on combinations of hello packets that each node generates and distributes locally, as well as the link state update packets which need to be distributed throughout the network. This takes away the network bandwidth that could otherwise have been utilized for sending user information. Additionally, the table from which the shortest path is calculated using the Dijkstras algorithm



(a) Dense network (b) Sparse network

Fig. 2. Data delivery ratio



(a) Dense network (b) Sparse network

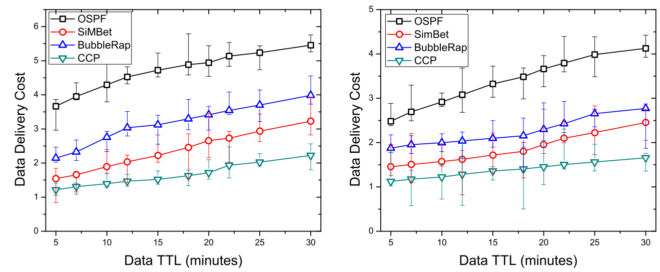
Fig. 3. Data delivery delay

needs to be accurate and consistent across all the nodes in the network. In cases when such table is inaccurate or inconsistent, many routing errors and loops can occur. These cases, unfortunately, could be quite common in tactical DIL environments due to the unexpected node mobility, wireless link disconnection, and the subsequent unavailability of global network information.

B. Experimental Investigations

In order to further demonstrate the performance degradation of link-state routing protocols in a DIL mobile networking environment at the tactical edge, we performed experimental comparisons between a link-state routing protocol, i.e., OSPF [22], and various social-aware DTN routing protocols, namely SimBet [7], BubbleRap [16] and the CCP [14]. The tactical network scenario used in our experiments is described in Table I. The network traffic was generated with random source and destinations. One data item is generated every minute and the time to live (TTL) for that data item varied from 5 minutes to 30 minutes. The size of the data item was small enough to be transmitted during every single contact, and every node is assumed to have sufficient buffer to relay all the data items. The following evaluation metrics are used in our experiments, and each experiment result is averaged over 200 simulation runs with random data source and destinations.

- **Data delivery ratio**, which is the percentage of data items being delivered before expiration.
- **Data delivery delay**, which is the average time for the destinations to receive the unexpired data.
- **Data delivery cost**, which is the average number of times that a data item is forwarded before being delivered to the destination. The data item includes the routing overhead which is converted to the number of data replicates.



(a) Dense network (b) Sparse network

Fig. 4. Data delivery cost

The simulation results for the dense and sparse network scenarios are shown in Figures 2 to 4, corresponding to the data delivery ratio, delay, and cost, respectively. From these results, we conclude that the link state routing protocol is generally ineffective in finding the right path for data delivery in a DIL networking environment, and hence the data delivery radio of OSPF is below 45% and 35% for the dense and sparse networks, respectively. Data delivery of OSPF also takes up to 20% longer delay and unnecessarily forwards data up to 70% more times over ineffective paths. Comparatively, the performance gain of various social-aware routing protocols is due to the fact that these protocols do not require complete and accurate knowledge about the network topology at individual network nodes. Instead, various social network concepts, such as centrality and community, are exploited for developing routing metrics and selecting the most appropriate nodes as relays. Therefore, integrating social-aware carry-and-forwarding routing protocols with traditional link-state routing protocols not only introduces crucial information about the network principles into relay selection, but also provide us key insights into addressing practical networking challenges at the tactical edge, by selecting the most appropriate ways of data delivery and reducing the data delivery cost.

TABLE I
LIST OF VARIOUS PARAMETERS USED IN THE NETWORK SCENARIO

Number of nodes	50
Communication range	5 nodes have 500m range; rest have 250m
Mobility model	Levy-walk model [25]
Duration of scenario	12 hours
Dense network	
Avg. node mobility	10m/sec
Avg. cumulative ICT	1.32 minutes
Avg. pairwise ICT	4.67 minutes
Sparse network	
Avg. node mobility	3m/sec
Avg. cumulative ICT	4.28 minutes
Avg. pairwise ICT	11.22 minutes

IV. OUR APPROACH

In this section, motivated by the empirical studies and experimental investigations in Section III, we present our approach to maintaining the interoperability between social-aware opportunistic routing protocols and traditional LSR protocols in tactical DIL mobile networks. Being different from conventional wisdom which suggests that user contacts in DIL environments are homogeneously distributed over time

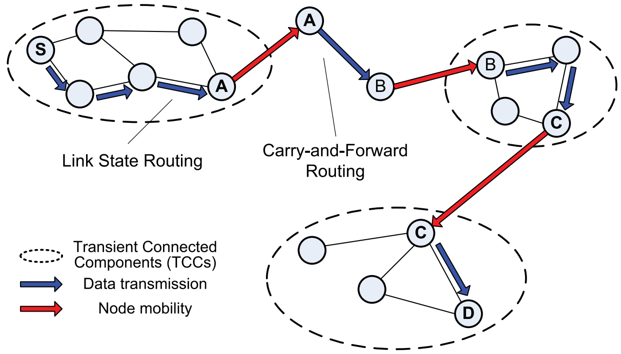


Fig. 5. Big picture of maintaining interoperability. Network link states are maintained and used for routing within individual TCCs, while relays are selected to carry-and-forward data between TCCs.

and describe the characteristics of a contact process between two warfighters by the cumulative distribution of their pairwise ICTs [5], our basic idea is to investigate the transient characteristics of warfighters' contact patterns that are heterogeneous in both temporal and spatial dimensions, and to further integrate LSR and opportunistic routing protocols in the same application domain by exploiting the diverse network connectivity among warfighters, a result of their transient contact patterns.

The big picture of maintaining such interoperability is illustrated in Figure 5. Although persistent end-to-end network connectivity is generally unavailable between warfighters, we consider that some nodes in tactical DIL environments may remain connected with each other during specific time periods to form Transient Connected Components (TCCs). For example, a group of warfighters may remain connected with each other when they form platoons for a specific tactical mission in urban areas. As a result, network link states could be effectively maintained and exploited for routing within individual TCCs, while relays will be opportunistically selected to carry and forward data between disconnected TCCs. In particular, by exploiting the existence of TCCs, we are also able to efficiently support multimedia traffic within TCCs, which requires real-time streaming and used to be considered as impossible in DIL environments without persistent network connectivity.

A. Network Modeling

Opportunistic contacts among nodes are described by a network *contact graph* $G(V, E)$, where stochastic contact process between a node pair $i, j \in V$ is modeled as an edge $e_{ij} \in E$. We assume that node contacts are symmetric; i.e., node j contacts i whenever i contacts j, and the network contact graph G is therefore undirected. The characteristics of an edge $e_{ij} \in E$ are mainly determined by the properties of ICTs among nodes. Similar to previous work [4], [34], we consider the pairwise node ICTs as exponentially distributed. Contacts between nodes i and j then form a Poisson process with contact rate λ_{ij}, which is calculated in real time from the cumulative contacts between nodes i and j. In the rest of this paper, we call a pair of nodes i, j as *contacted neighbors* if $\lambda_{ij} > 0$, and call the node set $\{j|\lambda_{ij} > 0\} \subseteq V$ as the *contacted neighborhood* of node i.

B. Transient Connected Components

We validate the existence of TCCs in practical DIL networks through experimental investigations over various realistic DIL network traces. As described by Table II, these traces collect contacts among mobile users at university campus (MIT Reality [10], UCSD [21]) and conference site (Infocom [5]). The existence of TCCs is validated from two aspects. First, we observed that the transient contact patterns among mobile users in these traces are highly heterogeneous over different time periods. As shown in Figure 6(a), the temporal distributions of user contacts in different traces are highly skewed over time. For example, over 50% of the contacts in the MIT Reality trace happen between 12:00 and 16:00, while only about 7% of the contacts happen between 22:00 to 7:00. Second, we observed that there are a large portion of contacts with non-negligible durations in all traces. As shown in Figure 6(b), in the MIT Reality trace, there are over 20% of the contacts with durations longer than one hour, and this percentage in the UCSD trace is around 30%. These observations, together, validate that a large portion of mobile nodes in DIL networks may remain connected during specific time periods, during which the multi-hop LSR routing is feasible.

TABLE II
TRACE SUMMARY

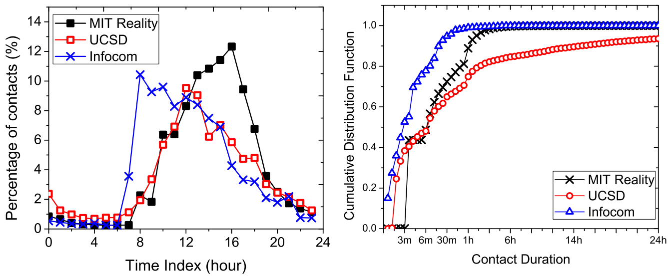
Trace	MIT Reality	UCSD	Infocom
Network type	Bluetooth	WiFi	Bluetooth
Number of devices	97	275	78
Number of internal contacts	114,046	123,225	182,951
Duration (days)	246	77	4
Contact detection period (secs)	120	20	120
Pairwise contact freq. (per day)	4.6	0.024	7.52
Average contact duration (hours)	0.57	10.45	0.142

In practice, the TCCs may dynamically evolve, and the size of TCCs that different nodes belong to may also vary over time. Each node detects the TCC it belongs to whenever it directly contacts another node, by broadcasting a beacon message. In order to detect the TCC in a multi-hop range, such message is broadcasted among the nodes within the TCC, and each node having received the message acknowledges to the original sender. The TTLs of both beacon and acknowledgement messages are controlled at the level of point-to-point wireless communication (e.g., a magnitude of milliseconds) that is much shorter than the ICTs between mobile nodes. These messages contain the identity of the sender for receivers to update their maintained list of TCC members, as well as the centrality value of the sender.

As a result, the network link states between mobile nodes within the same TCC could then be updated and maintained by these beacon messages. Since the time needed for transmitting a beacon message is generally much shorter than the contact duration, we ensure that TCCs can be accurately characterized. Since the broadcasting of beacon messages is only triggered by node contacts and the sizes of beacon messages and acknowledgements are very small, such TCC detection only produces little data transmission overhead.

C. Social-Aware Routing Metrics

In order to select the most efficient relays to forward data between isolated TCCs, we will need to further extend the social-aware metrics used in existing carry-and-forward routing protocols, so as to take the existence of TCCs into account. More specifically, we use node centrality as the



(a) (b)

Fig. 6. Validating the existence of TCCs: (a) Skewed contact distributions over time, (b) distribution of contact durations

routing metric, and measure the centrality of a node as the expected number of nodes to which it can deliver data within the given data TTL. Since the centrality of node i is calculated every time when a relay contacts i, we use C_i to indicate the centrality of node i at the current time t_c.

C_i is calculated in an accumulative manner, such that

$$C_i = \sum\nolimits_{j\in\mathbb{N}} c_{ij}, \tag{1}$$

where $\mathbb{N}$ denotes the set of nodes in the network and c_{ij} indicates the expected number of nodes which can receive data from i within the data TTL through i's contact with j. Conventional wisdom only considers direct contacts among mobile nodes in DIL networks, in which c_{ij} is equivalent to the probability for i to directly contact j within the data TTL. Instead, when taking the TCCs into account, i can deliver data to all the nodes which belong to the same TCC with node j by contacting node j.

As a result, by taking TCCs into account, we evaluate the centrality C_i of node i as

$$C_i = \sum\nolimits_{j\in\mathbb{N}} \int_{t_c}^{t_e} \hat{c}_{ij}(t) N_{TCC}^{j}(t)dt, \tag{2}$$

where t_c is the current time, t_e is the time when data expires, $\hat{c}_{ij}(t)$ is the probability that node i directly contacts node j at t, and $N_{TCC}^{j}(t)$ is the number of nodes belongs to the same TCC with node j at t. On one hand, the practical calculation of $\hat{c}_{ij}(t)$ depends on the modeling of pairwise ICTs among nodes. For example, if the pairwise ICTs are assumed to be exponentially distributed as suggested by [4], [13], we have

$$\hat{c}_{ij}(t) = 1 - e^{-\lambda_{ij}(t-t_c)}. \tag{3}$$

On the other hand, each node j autonomously characterizes the features of its own $N_{TCC}^{j}(t)dt$, by re-estimating the parameters of $N_{TCC}^{j}(t)dt$ at run-time with the up-to-date information of TCC members that is obtained as described in Section IV-B. Without loss of generality, we adopt the Gaussian Mixture Model (GMM) [19], which could be used to approximate any log-concave or elliptically symmetric density form, to the formulation of $N_{TCC}^{j}(t)dt$, such that

$$N_{TCC}^{j}(t)dt = \sum\nolimits_{m=1}^{M} s_{jm}\mathcal{G}[t, \mu_{jm}, \sigma_{jm}^2], \tag{4}$$

where $\mathcal{G}[\cdot]$ denotes Gaussian density form. The parameters of $N_{TCC}^{j}(t)dt$ could be efficiently re-estimated using the Expectation-Maximization (EM) algorithm [8], and we have

$$\begin{aligned} C_i &= \sum_{j\in\mathbb{N}} \sum_{m=1}^{M} \frac{s_{jm}}{\sigma_{jm}\sqrt{\pi}} \cdot \int_0^T (1-e^{-\lambda_{ij}t}) \cdot e^{-\frac{(t-\mu_{jm})^2}{\sigma_{jm}^2}} dt \\ &= \sum_{j\in\mathbb{N}} \sum_{m=1}^{M} \frac{s_{jm}}{2} \Big(\mathrm{erf}(\frac{T-\mu_{jm}}{\sigma_{jm}}) + \mathrm{erf}(\frac{\mu_{jm}}{\sigma_{jm}}) - e^{\frac{1}{4}\lambda_{ij}^2\sigma_{jm}^2} \cdot \\ &\Big(\mathrm{erf}(\frac{\lambda_{ij}\sigma_{jm}^2 + 2T - 2\mu_{jm}}{2\sigma_{jm}}) - \mathrm{erf}(\frac{\lambda_{ij}\sigma_{jm}^2 - 2\mu_{jm}}{2\sigma_{jm}}) \Big) \Big) \end{aligned} \tag{5}$$

where $T = t_e - t_c$, and $\mathrm{erf}(x)$ is the Gaussian error function.

D. Hybrid Routing Scheme

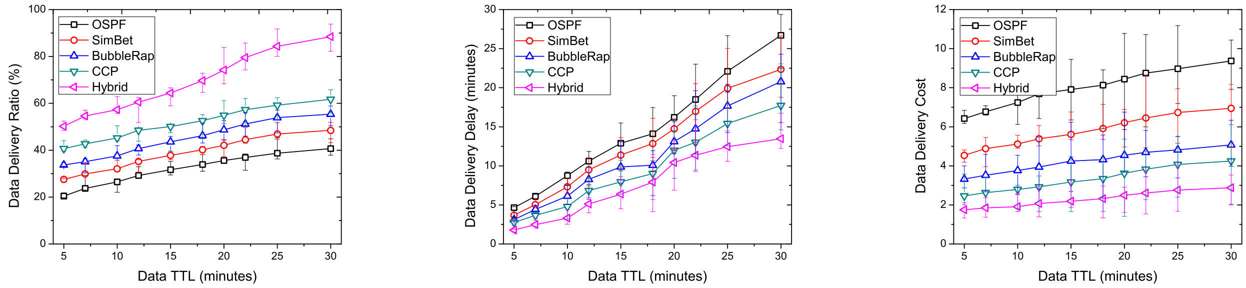
We present a hybrid routing scheme in tactical DIL environments that adaptively integrates both LSR protocols and social-aware opportunistic routing protocols into the same application domain. In general, the LSR protocols are operated within individual TCCs during the lifespan of these TCCs, and each node in a TCC follows the LSR protocol to maintain the network states to all the other nodes within the same TCC. Whenever a node leaves or a new node joins a TCC, the topology table will be updated accordingly. Afterwards, when a data source S wants to send data to a destination D, the data forwarding process consists of the following two parts:

- If S and D are within the same TCC when data is generated at S, S simply employs the LSR protocol to send data to D within the local TCC. According to Figure 6(b), the delay of such multi-hop wireless communication within a TCC is much shorter than the durations of contacts between nodes in the TCC. As a result, the chance for the pre-established route between S and D in the TCC to be disconnected due to node mobility is negligible during the data forwarding process.
- If S and D are within different TCCs, the data is routed in a hierarchical manner. First, S determines the "local" data destination within the TCC that S belongs to, and sends data to this local destination, say D_L, via LSR protocols. D_L will be the node with the highest centrality in the TCC, where the centrality values of mobile nodes are calculated following Eq. (5). Second, D_L, after having received data from S, continues to carry data in the network and forwards data to other relays upon contacts, following the social-aware opportunistic routing protocols such as Simbet [7] or BubbleRap [16]. More specifically, every time when a relay R contacts another node A, R will check over all the other nodes within A's TCC. If D is within the same TCC as A, data could be delivered from A to D via LSR protocols. Otherwise, if there is another node B that is in the same TCC with A but has higher centrality than A, B will also become the relay.

In practice, S may select multiple local data destinations in order to expedite the data delivery, and hence has the flexibility to balance between the data delivery performance and cost.

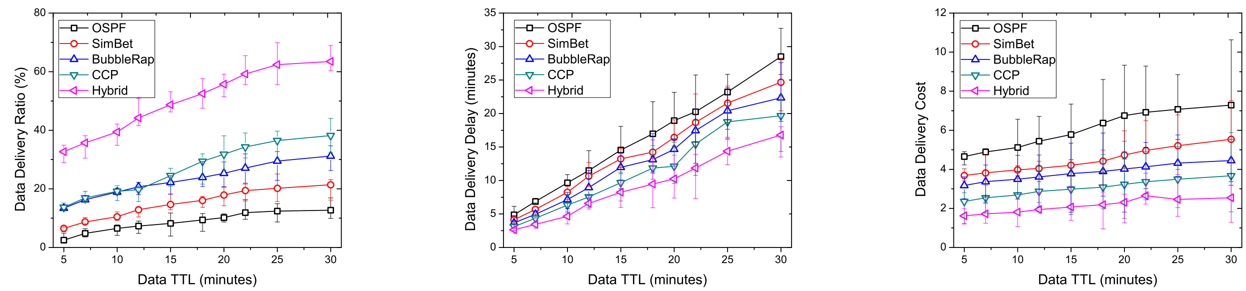
V. Performance Evaluation

In this section, we evaluate the performance of our proposed hybrid routing scheme with the following existing LSR protocols, i.e., OSPF [22], and social-aware opportunistic routing protocols, i.e., SimBet [7], BubbleRap [16], and CCP [14], in practical DIL environments.



(a) Data Delivery Ratio (b) Data Delivery Delay (c) Data Delivery Cost

Fig. 7. Performance of the hybrid routing scheme in dense tactical DIL network environments



(a) Data Delivery Ratio (b) Data Delivery Delay (c) Data Delivery Cost

Fig. 8. Performance of the hybrid routing scheme in sparse tactical DIL network environments

TABLE III
LIST OF PARAMETERS USED IN PERFORMANCE EVALUATION

Number of nodes	50
Communication range	5 nodes have 500m range; rest have 250m
Mobility model	RPGM model [15]
Duration of scenario	12 hours
Avg. no. nodes per group	10
Dense network	
Avg. node mobility	10m/sec
Max. distance from the group leader	150m
Avg. cumulative ICT	1.68 minutes
Avg. pairwise ICT	5.32 minutes
Sparse network	
Avg. node mobility	3m/sec
Max. distance from the group leader	350m
Avg. cumulative ICT	4.92 minutes
Avg. pairwise ICT	12.75 minutes

A. Simulation Setup

We evaluate the performance of our proposed hybrid routing scheme using the same performance metrics as we used in Section III-B. The tactical network scenario used in our experiments is described in Table III. To simulate the transient connectivity in practical tactical scenarios, we adopt the Reference Point Group Mobility model [15] which extends the famous Nomadic mobility model [26] and separates the mobile nodes into groups. Each group exists during a specific time period and has a leading node (which will be the one with longer communication range) determining the mobility behavior of the entire group. Therefore, it is obvious to see that noticeable TCCs could be observed in such network scenarios.

We use the same experiment settings as in Section III-B, such that one data item is generated every minute and the data TTL varies from 5 minutes to 30 minutes. We first randomize the data generation time, and then randomly pick data sources and destinations. For our proposed hybrid routing scheme, Compare-and-Forward [9] routing strategy is applied to our developed centrality metric in Section IV-C to opportunistically forward data between TCCs. Each experiment is repeated 500 times for statistical convergence.

B. Performance Comparison

The performance evaluation results in the dense and sparse network scenarios are shown in Figure 7 and Figure 8, respectively. Generally speaking, since our proposed hybrid routing scheme is able to efficiently utilize the transient multi-hop connectivity among mobile nodes and adaptively route data with the TCCs, it is able to significantly improve the routing performance in terms of data delivery ratio and delay. In both network scenarios, the data delivery ratio has been generally improved by over 40% in all cases with different values of data TTL, compared to existing LSR and social-aware opportunistic routing protocols. Correspondingly, such exploitation of transient connectivity is also able to reduce the data delivery delay by up to 25%, as shown in Figure 8(b). In particular, when the data TTL is longer than 20 minutes, the reduction of data delivery delay is especially noticeable.

At the same time, being aware of the existence of transient connectivity in DIL environments also avoids unnecessary replication of data among intermittently connected mobile users. Instead, data is forwarded instantaneously between mobile nodes along the temporarily available routing paths within individual TCCs. Such interoperability leads to a 30% reduction of data delivery cost, as shown in Figure 8(c). Note that, being consistent with our experimental investigations in Section III-B, social-aware opportunistic routing protocols also

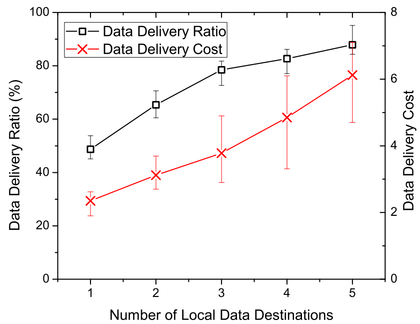


Fig. 9. Experimental investigations of the tradeoff between routing performance and cost in dense network scenario

exhibit better performance than regular LSR protocols in the traces, due to their better efficiency of relay selection.

C. Tradeoff between Performance and Cost

Section IV-D described that a data source may select multiple local data destinations within its local TCC, so as to further improve the routing performance by producing a large number of data replicates. In this section, we experimentally investigate such tradeoff between the routing performance and cost in the dense network scenario described in Table III. The data TTL is set to 20 minutes and the number of local data destinations selected by each data source varies from 1 to 5.

The experiment results are shown in Figure 9. When the number of local data destinations increases from 1 to 5, the data delivery ratio increases accordingly from 48% to 88%, because each additional data replicate increases the chance for the data destination to receive the data on time. However, the data delivery cost also increases, because more relays would be involved into the routing process. In particular, when the number of local data destinations is small (≤ 3), we observe significant improvement of the data delivery ratio with relatively smaller increase of routing cost. In contrast, when such number is larger than 3, the further improvement of routing performance becomes limited and cannot compensate the increase of routing cost. Such results suggest us to adaptively choose the number of local data destinations for routing according to the specific application scenarios.

VI. Conclusions

In this paper, we present a novel scheme to maintain the interoperability between traditional LSR protocols and social-aware opportunistic routing protocols in tactical DIL environments. Our basic idea is to investigate the transient characteristics of warfighters' contact patterns, and further to exploit the diverse network connectivity among them to adaptively apply LSR whenever possible. Simulation results show that our proposed solution could significantly improve the routing performance in various practical network scenarios.

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