Evacuation Assisting Strategies in Vehicular Ad Hoc Networks

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***Abstract*—Recent natural and man-made disasters such as Sandy (2012) and Fukushima nuclear power plant (2011) make efficient evacuation route planning and routing more important than ever. Conventional sign-based evacuation route and its information are limited to use in a life-threatening environment. In this paper, we first investigate a least travel time based shortest path approach to minimize the evacuation time in a Vehicular Ad hoc Network (VANET). Since the travel time changes in the presence of time-varying traffic congestion, frequent and timely updates of the shortest path during the evacuation period are essential. Thus, we also investigate an evacuation assistant VANET to efficiently update the shortest path on wheel by using Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications. Then we propose evacuation assisting schemes, *V2RSU* and *V2RSU+V2V*. We also implement the shortest path based schemes to work in VANETs, *Lowerbound* and *W/O_Update*. We compare the performance of four schemes as a function of the number of congestions, sources, destinations, and vehicles and different network sizes. The simulation results indicate that the proposed schemes integrated with a VANET can reduce the evacuation time significantly.**

***Index Terms*—Congestion, evacuation assistance, vehicle-to-infrastructure, vehicle-to-vehicle, vehicular ad hoc networks.**

I. Introduction

With increasing risks from natural and man-made disasters, efficient evacuation plans play a critical role for life-saving in disaster and emergency preparedness. For example, a tsunami caused by a 9.0 earthquake damaged three nuclear reactors at the Fukushima Daiichi nuclear power plant in 2011. Over 170,000 people were evacuated and dispersed from the surrounding areas [1]. Global warming impacts the creation of super storms like Hurricane Katrina (2005), Rita (2005), and Sandy (2012). Recent Hurricane Sandy affected East Coast and 24 U.S. states, particularly damaged New York City, which is the largest city in U.S., and called mandatory evacuations for over 375,000 people residing in seashore and low-lying areas [2]. Although several U.S. states (i.e., Louisiana, Mississippi, Florida, Texas, etc.) primarily use a signed evacuation route, which simply shows a direction and radio channels for information, its effectiveness is very limited in a life-threatening environment.

For efficient evacuation route planning and routing, contraflow (or lane reversal) based approaches have been investigated to increase the outbound evacuation route capacity and ultimately minimize the evacuation time. Researchers in academia and U.S. Department of Transportation (US-DOT) have investigated how to operate and manage contraflow (i.e., changing or merging lanes and roads, controlling traffic lights, etc.) for maximizing the utilization of already-built infrastructures [3], [4]. On the other hand, diverse algorithms [5], [6], [7], [8], [9], [10] have also been proposed to find the evacuation routes requiring the minimized computation in the presence of multiple sources (i.e., locations where evacuees evacuate from) and destinations (i.e., shelters where evacuees drive to). In addition, an intelligent highway infrastructure is proposed to support planned evacuations [11], where evacuation information is disseminated based on a Vehicular Ad hoc Network (VANET) via limited Vehicle-to-Infrastructure (V2I) and/or Vehicle-to-Vehicle (V2V) communications. Note that since traffic condition is often time-varying during an evacuation period, frequent and timely updates of evacuation information to evacuees are critical.

In this paper, we investigate an evacuation assistant VANET to minimize the evacuation time by efficiently updating each vehicle's shortest path to the evacuation routes. A VANET is an instance of a Mobile Ad hoc Network (MANET) and consists of a set of mobile vehicles equipped with computing and communicating capabilities. A VANET flexibly supports either V2I or V2V communications and it is well suited for facilitating flexible accessibility and information availability. Due to rapid advances in high speed wireless Internet, being connected on wheel without interruption has been already realized. Our contribution is two-fold:

- We propose a least travel time based shortest path approach to minimize the evacuation time in a VANET environment, where a transportation network is modeled as a graph form. The proposed technique is extended to further reduce the evacuation time by integrating V2I and V2V communications.
- We develop a customized simulator and implement the proposed approach integrated with V2I and V2V communications to work in VANETs: *V2RSU* and *V2RSU+V2V* schemes. For performance comparison, we also implement two additional schemes: *Lowerbound* and

W/O_Update schemes.

We compare the performance of four schemes in terms of number of congestions, sources, destinations, and vehicles and different network sizes through extensive simulation study. The proposed V2RSU and V2RSU+V2V schemes can reduce the evacuation time significantly and are a viable approach for expediting the evacuation.

The rest of this paper is organized as follows. Prior study is reviewed and analyzed in Section II. A system model and the proposed techniques are presented in Section III. Section IV is devoted to performance evaluation and analysis. Finally, we conclude the paper with future direction in Section V.

II. Related Work

A. Evacuation Route Planning and Routing

Due to the size of the transportation network and evacuation factors, a heuristic approach is often used to produce a sub-optimal and efficient evacuation plan. Unlike prior heuristic approach in which the shortest distance from a source to the closest destination is calculated, time-varying route capacity constraints are considered to compute an evacuation route in Capacity Constrained Routing Planner (CCRP) [5], [6], [7] and its extension (CCRP++) [12], and their variations [13], [9]. In [9], a scalable evacuation routing algorithm is proposed based on synchronized flows. The synchronized flows are the paths of evacuees from sources to destinations, and the evacuees are distributed over the paths. Virtual evacuees are also added to the synchronized flows to balance the evacuation time.

A good number of algorithms have been proposed for contraflow-aware evacuation route planning to minimize the evacuation time by increasing the outbound evacuation route capacity. Researchers in academia and US-DOT have been focusing on the operating and managing lanes and roads and controlling traffic lights [3], [4] but they cannot flexibly incorporate with diverse evacuation factors. [8] defines a contraflow problem based on graph theory and proposes heuristic algorithms by considering road capacity constraints, multiple sources, congestion factors, and scalability. A contraflow evacuation routing algorithm is proposed based on the reverse shortest path and maximum throughput flow [10]. A single running of reverse shortest path can find a set of shortest paths from all sources to the destinations. Then the maximum throughput flow scheme allocates as full as available route capacity to the shortest paths for minimizing the evacuation time.

B. Evacuation Assistant Vehicular Ad hoc Network

Drivers can monitor and share real-time traffic condition, transceive Emergency Warning Messages (EWMs), and avoid an accident (e.g., an intersection collision or a chain collision) in VANETs. Diverse applications and operations built for VANETs are available in both short and extended communication ranges[1]. To realize and disseminate these techniques, government, industry, and academic community have been putting a lot of efforts.

VANET has been integrated with evacuation operations. For example, an intelligent highway infrastructure is proposed to support a planned evacuation [11] by embedding piezoelectric pressure sensor belts in the road at regular intervals. Since traffic condition is often time-varying during evacuation period, frequent and timely updates of evacuation information to evacuees are critical. Vehicles can communicate with the belts by uploading and downloading traffic-related information. Roadside units (RSUs) [15] or access points (APs) are also combined with the belts to disseminate the information to the vehicles when they pass over the belts.

RSUs play an important role in the evacuation process by disseminating information and assisting communications between vehicles and the Internet in VANETs. Here, a RSU can be mounted on the top of a signal light, a road lamp, a gas station, or an intersection, and it is connected with a wired network and operates as a router for vehicles to connect to the Internet. Compared to the third generation (3G) and satellite networks, RSUs can provide location-dependent and real-time information with high bandwidth but low deployment cost. [15] proposes several scheduling schemes for data access between vehicles and RSUs. In [16], a data dissemination scheme is proposed by periodically broadcasting data to the vehicles. This scheme is further improved by buffering and broadcasting data at the RSUs that are installed at intersections. Thus, vehicles isolated from others or later arriving vehicles can still access available data.

In summary, relatively little effort has been made in developing communication protocols and related techniques for assisting evacuation route planning and routing in VANETs.

III. The Proposed Evacuation Assistant Vehicular Ad Hoc Networks

We first present a system model and then propose a least travel time based shortest path approach for evacuation assistant VANETs.

A. System Model

In VANET, vehicles are powered by their own built-in battery and execute computing and communicating operations without concern of energy conservation. Vehicles are equipped with communication facilities such as an IEEE 802.11-based Dedicated Short Range Communication (DSRC) transceiver. Thus, vehicles can communicate with other vehicles and the Internet flexibly through V2I or V2V communications. In

[1] In the short range, a real time traffic condition monitoring, a toll collection, a gas payment, data transfer (e.g., downloading and uploading a map, a MP3 file, or a video clip), and a rental car processing are potential applications. In the extended range, the driving safety related operations are expected including a vehicle warning signal (e.g., work-zone or, highway and rail intersection, or road condition warning), an intersection collision avoidance, and an inter-vehicle communication (e.g., sending and receiving an EWM of the vehicle's sudden stop or slow speed) [14].

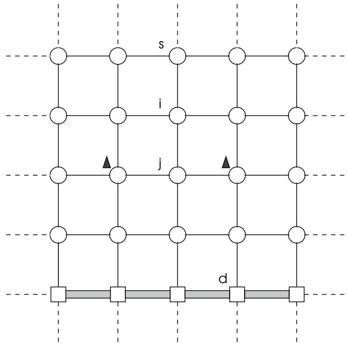

Fig. 1. A graph representation for a subset of transportation network. A road, an intersection, and a RSU are represented as a solid line, a circle, and a shaded triangle respectively. An evacuation route and its entrance point is represented as a shaded thick line and a rectangle located at the bottom.

the V2I communication, vehicles are limited to a single-hop communication with a RSU. For example, bypassing vehicles can pour their data into a RSU that can temporarily store and forward it to the following vehicles for improving data delivery. In the V2V communication, however, vehicles can communicate with other vehicles directly or indirectly through a multi-hop message relay without the assistance of any fixed infrastructure [15]. Vehicles also equip a built-in navigation system integrated with a Global Positioning System (GPS), in which a digital map is loaded to show the roads around the current location and direction, e.g., the shortest path to the destination or location-dependent information. Vehicles are able to monitor real-time traffic conditions, transceive EWMs, and avoid accidents. Due to high speed, vehicles may experience frequent disconnections or isolations from the RSUs or other vehicles. The movement of vehicles is restricted by underlying fixed roads with speed limits and traffic lights.

In Fig. 1, a subset of transportation network is represented as a graph form in terms of edges and vertices. In this paper, we consider a mesh network for the sake of simplicity. A set of RSUs can be installed at intersections for sharing traffic and evacuation information. An evacuation route is located at the bottom with the number of entrance points. Upon evacuation, vehicles located in the multiple sources drive to the multiple entrance points. In addition, a macroscopic network flow model is deployed to model the movement of vehicles, represented as a flow on the graph. This macroscopic model is preferred because it is effective to represent most capacity of a given transportation network such as road density, weighted mean speed, etc. [8].

B. Least Travel Time based Shortest Path

During the evacuation period, a set of evacuation routes and its related information will be disseminated to vehicles through the 3G network. The information contains evacuation routes (e.g., state or interstate highways), available entrance points, and a set of destinations (e.g., shelters). Note that not all the entrance points may be available to vehicles because either lanes or roads can be changed or merged to expedite the evacuation. Evacuation routes can be calculated by recent evacuation route planning algorithms [8], [9], [10], [12], [13] to achieve the minimized evacuation time in a given disaster area. Since the algorithms consider diverse factors including road size, capacity, contra-flow, traffic condition, weather, etc., evacuation routes are often pre-calculated in an off-line fashion and ready for dissemination not to delay the evacuation. Thus, evacuation routes are seldom changed or updated in a real-time fashion.

We first investigate how quickly each vehicle can reach to one of entrance points of evacuation routes with the minimized evacuation time in a given transportation network. Here, an entrance point can be an entrance of interstate, if it is a part of evacuation routes. Note that the evacuation time is measured from when the first vehicle leaves a source to when the last vehicle arrives at one of entrance points of evacuation routes. Any evacuation time elapsed after reaching entrance points of evacuation routes is not considered. In the transportation network, each road is characterized by its road capacity (c_{road}) and travel time (T_{trav}). The road capacity is measured by the number of travel vehicles per unit period. As shown in Fig. 1, when the number of vehicles ($n_{vehicle}$) located at a source (v_s) moves to a destination (v_d), the evacuation time (T_{evac}) can be calculated by following equation [13].

$$T_{evac} = T_{trav} + \lceil \frac{n_{vehicle}}{c_{road}} \rceil - 1. \quad (1)$$

Eq. 1 is designed for single source in the transportation network. In case of multiple sources, however, roads can be simultaneously used by vehicles arrived from different sources and thus, Eq. 1 may not accurately calculate the evacuation time. In this paper, we consider a delay of waiting the road that is currently occupied by vehicles arrived from different sources in the evacuation time.

Under the macroscopic methodology, the road capacity can be modeled by two methods: (i) continuous entering and (ii) occupy and empty [8]. In the continuous entering method, the number of vehicles equal to the road capacity travels on the road as long as the road is available. In occupy and empty method, however, the number of vehicles equal to the road capacity occupies the road for the travel time. During the travel period, the road is not available to other vehicles. In this paper, we deploy the continuous entering method because it represents the movement of vehicles more realistically.

When a vehicle receives an evacuation notice, it sets up a path from the current location to one of entrance points in the evacuation routes using a shortest path algorithm. Here, a shortest path can be displayed in a pre-loaded area map in a navigation system. Because of diverse road capacities in the network, a shortest path based on the physical distance between source and destination is not considered. Instead, the least travel time will be considered by using the Dijkstra's algorithm. The algorithm is terminated as soon as the next vertex is the destination. The pseudo code of the least travel time based shortest path algorithm is shown in Fig. 2.

• G_t: A transportation graph consisting of vertices and edges for a given evacuation area.
• v_s, v_d: Source and destination vertices where vehicles evacuate from and drive to respectively.
• $T_{trav}[i,j]$, $T_{known}[i,j]$: Travel time from v_i to v_j and known travel time from v_i to v_j.
• $L_{i,j}$: A list of paths from v_i to v_j.
◇ When a vehicle, located in v_s, initially receives an evacuation notice through the 3G network:

for each $v_i \in G_t$ **do**
  $T_{trav}[s,i] = T_{known}[s,i]$;
$T_{trav}[s,s] = 0$; $L_{s,d} = \emptyset$;
enqueue v_s into $L_{s,d}$;
for each $v_i \in G_t$ except v_s **do**
  find the smallest travel time in $T_{trav}[s,i]$;
  if ($v_i == v_d$) **then**
    break;
  for each one-hop neighbor v_j of v_i **do**
    $t = T_{trav}[s,i] + T_{trav}[i,j]$;
    if ($t < T_{trav}[s,j]$) **then**
      $T_{trav}[s,j] = t$;
    enqueue v_j into $L_{s,d}$;
  end do
end do

Fig. 2. The pseudo code of calculating the shortest path based on the least travel time.

C. V2I and V2V Communications Assistance

The aforementioned least travel time based shortest path is calculated before vehicles move to a destination. Then the path is never updated during the evacuation period. One of implicit assumptions in this approach is that the travel time is fixed. However, the travel time can frequently be changed during the evacuation period because of traffic congestion. Thus, we also investigate how a VANET can assist in calculating least travel time based shortest path approach and achieve the minimized evacuation time in the presence of time-varying traffic congestion in a given transportation network.

We consider both V2I and V2V communications in which vehicles can communicate with a RSU to update their shortest path. In V2I communication, as shown in Fig. 3, when a vehicle (e.g., n_p) is located in the communication range of a RSU, it sends a *Request* message piggybacked with recorded travel times to the RSU. Upon receiving the message, the RSU replies an *Update* message containing updated travel times of paths in the transportation network. Then the vehicle can recalculate the shortest path from the current location to the destination based on the updated travel times. The vehicle will replace its pre-calculated shortest path with the updated path, if the travel time can be reduced. A possible drawback of this approach is that if a vehicle does not meet any RSU during the evacuation period, it cannot update the shortest path. To increase the chance of updating the shortest path, V2V communication is also considered in which vehicles located far away from a RSU can still update their shortest path through multi-hop relays. In Fig. 3, when a vehicle (e.g., n_q) is approaching to a RSU, it can receive an *Update* message from the RSU after two hop relays. Thus, the vehicle can update its shortest path and avoid traffic congestion early. The pseudo code of updating the current shortest path algorithm is shown in Fig. 4.

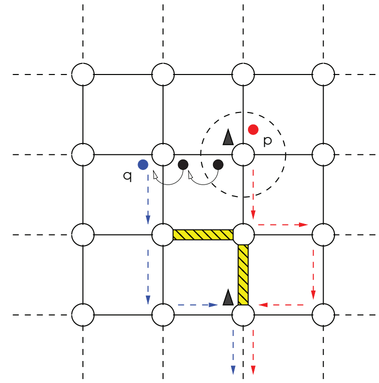

Fig. 3. Both V2I and V2V communications assist in updating the shortest path. Here, a vehicle (e.g., n_p, represented as a small shade circle) located in the communication range of a RSU can directly access the updated travel times. A vehicle located far away from the RSU (e.g., n_q) can still access the updated travel times through multi-hop relays, which are represented as a solid arrow. Then n_p and n_q can update their shortest path and avoid traffic congestion, represented as a rectangle with a diagonal pattern.

• $T_{update}[i,j]$: Updated travel time from v_i to v_j, piggybacked in the *Update* message.
◇ When a vehicle, located in $v_{s'}$, receives an *Update* message from either a RSU directly or a vehicle indirectly via multi-hop relays:

for each $v_i \in G_t$ except $v_{s'}$ **do**
  find the smallest travel time in $T_{update}[s',i]$;
  if ($v_i == v_d$) **then**
    break;
  for each one-hop neighbor v_j of v_i **do**
    $t = T_{update}[s',i] + T_{update}[i,j]$;
    if ($t < T_{update}[s',j]$) **then**
      $T_{update}[s',j] = t$;
      $L_{s',j} = \emptyset$;
      enqueue $v_{s'}$ into $L_{s',j}$;
      v_k = dequeue from $L_{s',i}$;
      enqueue v_k into $L_{s',i}$;
      while (v_k = dequeue from $L_{s',i}) \neq v_{s'}$ **do**
        enqueue v_k into $L_{s',j}$;
        enqueue v_k into $L_{s',i}$;
      end while
    end if
  end do
end do
broadcast the *Update* message for any following vehicle;

Fig. 4. The pseudo code of updating the current shortest path based on the updated travel time.

IV. Performance Evaluations

A. The Simulation Testbed

In this paper, we develop a customized simulator to conduct our experiments. We use a simple mesh network to model a transportation network. A set of different size mesh networks is deployed, where the number of vehicles is allocated to multiple sources located in the middle of network. Two evacuation routes with multiple entrance points are located

TABLE I
SIMULATION PARAMETERS

Parameter	Values
Number of congestions	2, 4, 6, 8, 10, 12, 14, 16
Number of sources	2, 4, 6, 8, 10, 12, 14, 16
Number of destinations	4, 6, 8, 10, 12, 14, 16
Number of vehicles	200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000
Network sizes	10 × 10, 14 × 14, 18 × 18, 20 × 20, 22 × 22, 24 × 24, 26 × 26, 28 × 28

in the top and bottom of the network respectively. Upon evacuation, vehicles move to one of entrance points in the evacuation routes based on the least travel time in the presence of different number of traffic congestions. We measure the evacuation time by changing the number of congestions, sources, destinations, and vehicles and network sizes. Here, we generate a congestion by reducing the road capacity so that vehicles experience an extended travel time. The simulation parameters are summarized in Table I.

B. Simulation Results

To compare the proposed approaches, we first evaluate an ideal case where there is no traffic congestion. This case will achieve the minimum evacuation time based on the shortest path and it is used as the performance lower bound, denoted as *Lowerbound*. Second, we consider a case where each vehicle follows an initial shortest path without updating its path during the evacuation period in the presence of traffic congestion, denoted as *W/O_Update*. Third, we also consider a case where each vehicle updates an initial shortest path whenever it has a chance to communicate via V2I, denoted as *V2RSU*. Finally, a combination of V2I and V2V communications is considered to update the shortest path directly or indirectly through multi-hop relays, denoted as *V2RSU+V2V*. Here, unless otherwise specified, we use eight congestions and sources, four destinations, and 2,000 vehicles in the network.

1) Impact of Number of Congestions: We first compare the evacuation time by changing the number of congestions in Fig. 5. Since the performance of Lowerbound scheme is not affected by the number of congestions, as an ideal case, it shows a stable and the lowest evacuation time. However, the W/O_Update scheme is congestion sensitive and shows a steep increase of the evacuation time, as the number of congestions increases. Both V2RSU and V2RSU+V2V schemes show the low evacuation time because they can avoid traffic congestion by updating the initial shortest path. The V2RSU+V2V scheme shows lower evacuation time than that of the V2RSU scheme. This is because vehicles can opportunistically update the shortest path, whenever they meet either the RSUs or multi-hop relayed *Update* messages during the evacuation period. Unlike the V2RSU+V2V scheme, the V2RSU scheme may not update the original shortest path in case of missing the RSUs.

2) Impact of Number of Sources and Destinations: Second, we compare the evacuation time by changing the number of

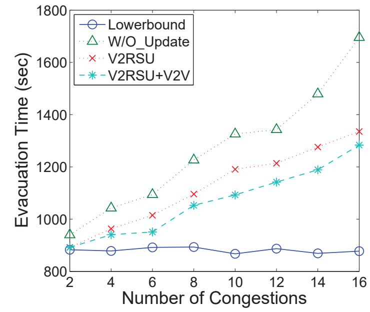

Fig. 5. Evacuation time against the number of congestions.

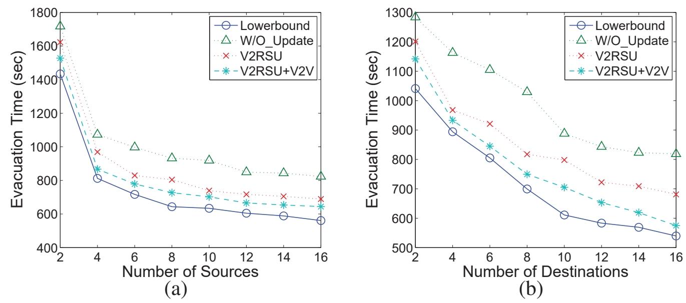

Fig. 6. Evacuation time against the number of sources and destinations.

sources and destinations in Fig. 6. As the number of sources and destinations increases, the less number of vehicles shares the same evacuation routes and thus, the evacuation time reduces. Both V2RSU and V2RSU+V2V schemes show lower evacuation time than that of the W/O_Update scheme. The evacuation time is more sensitive to the number of sources than the number of destinations. For example, as shown in Subfig. 6(a), the evacuation time is significantly reduced when the number of sources increases from two to four. This is because vehicles are spread out in the transportation network, as the number of sources increases.

We also compare the performance of V2RSU and V2RSU+V2V schemes by changing the number of sources and destinations for given number of congestions in Figs. 7 and 8 respectively. In Fig. 7, the equal number of vehicles is allocated to the designated number of sources. As the number of sources increases, the evacuation time decreases because vehicles are spread into the network. Thus, the less number of vehicles is conflicted during the evacuation period. Both V2RSU and V2RSU+V2V schemes show a similar performance trend as the number of sources increases. When the number of congestions increases but the number of sources decreases, the performance gap between V2RSU and V2RSU+V2V schemes increases. The V2RSU+V2V scheme shows lower evacuation time than that of the V2RSU scheme for entire number of sources and congestions.

In Fig. 8, since the destination is one of entrance points of the evacuation routes, each vehicle sets up its shortest path from the current location to the closely located destination. As the number of destinations increases, each vehicle has more chances to choose the shortest path with less evacuation time to the destination, and thus the evacuation time decreases. The evacuation time is more sensitive to the number of congestions.

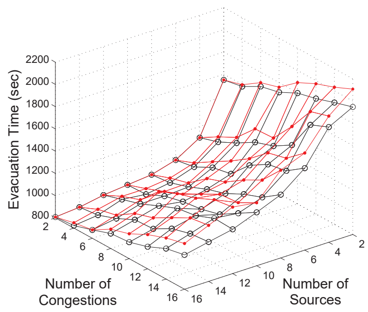

Fig. 7. Evacuation time against the number of congestions and sources. Here, the V2RSU and V2RSU+V2V schemes are marked by dot and empty circle respectively.

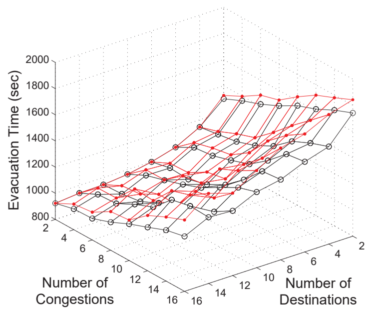

Fig. 8. Evacuation time against the number of congestions and destinations.

Comparing the performance in Figs. 7 and 8, the overall evacuation time is more affected by the number of sources rather than the number of destinations. Thus, it is critical to spread initial traffic in the network to achieve the reduced evacuation time.

3) Impact of Number of Vehicles: Third, we compare the evacuation time by changing the number of vehicles in Subfig. 9(a). A set of vehicles is allocated to multiple sources located in the middle of network before initiating the evacuation. Based on the macroscopic flow model, the movement of vehicles is represented as a flow. As the number of vehicles increases, the evacuation time increases due to the limited capacity in the network. The performance gap between the W/O_Update scheme and both V2RSU and V2RSU+V2V schemes slightly increases as the number of congestion increases.

4) Impact of Different Network Sizes: Finally, we compare the evacuation time by changing the network size in Subfig. 9(b). As the network size increases, the evacuation time increases almost linearly. The W/O_Update scheme shows the highest evacuation time for entire network sizes because of no update on the shortest path. Both V2RSU and V2RSU+V2V schemes show a competitive performance compared to the Lowerbound scheme. Here, due to the number of congestions (default eight congestions), smaller network sizes are not considered.

V. Conclusion and Future Research Direction

In this paper, we investigated a least travel time based shortest path approach to minimize the evacuation time in VANETs. The proposed V2RSU and V2RSU+V2V schemes

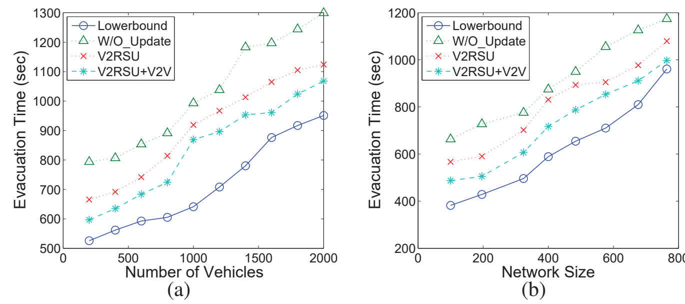

Fig. 9. Evacuation time against the number of vehicles and different network sizes.

have shown that they can reduce the evacuation time significantly and show a competitive performance compared to the Lowerbound scheme. We plan to extend the proposed techniques by considering a prediction mechanism for time-varying traffic congestions. Since a RSU is not always available in every intersection, vehicles may not update their shortest path frequently or in a timely manner. When vehicles meet the RSU, they predict traffic congestions based on the updated travel times and update their shortest path accordingly.

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