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Traffic Information Dissemination in Vehicular Ad Hoc Networks

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1. Introduction

Today, cars are equipped with all kind of on-board sensors and microcomputers that are able to measure geolocation, speed, tire pressure, raindrops on the windshield, etc., and based on these information Intelligent Transportation Systems (ITS) are built. The ITS applications are intended to ease the everyday life of drivers by reducing the risk of accidents, improving safety, increasing road capacity and reducing traffic jams. Many research papers, for example Torok et al. (2008) and Sormani et al. (2006), pointed out that a significant reduction of traffic jams can be achieved through the use of vehicular ad-hoc networks (VANETs). Vehicles could serve as Traffic and Travel Information (TTI) collectors and transmit this information to other participants in the vehicular network Laborczi et al. (2006). The ITS applications could utilize this information to actively relieve traffic congestion. Practically, vehicles could detect traffic congestion automatically when the usual (historical) characteristics of traffic patterns drastically change, i.e. the number of neighboring vehicles is high and/or the average speed is too low. Then this information should be relayed, disseminated to the vehicles approaching the congested area; thus, they will have enough time to choose alternative routes.

Due to their inherent characteristics, viable communication is harder to support in ITS scenarios than in conventional wireless networks. Vehicles are usually moving much faster than traditional mobile nodes; moreover, a vehicular network might be very heterogeneous in terms of node density, becoming fragmented in many cases. Reliability is also compromised due to the usually high interference in urban scenarios. Thus, there is a need to reconsider the wireless ad hoc communication networking protocols, and to use new concepts that fit better the specificities of ITS applications.

Traffic and Travel Information (TTI) spreading in vehicular ad hoc networks is achieved by the means of a flooding mechanism. To overcome network fragmentation the vehicles usually maintain and carry a copy of the packets, which is disseminated along the road segments Zhao & Cao (2006), Burgess et al. (2006), Tian et al. (2004). The frequency of subsequent transmissions will control the quality of the TTI reports, in terms of delay and accuracy. If the frequency of TTI transmissions is high, the time necessary for the information to reach the outer bounds of the geographic area is lower. The accuracy of TTI also varies in function of the amount of communication involved in the travel information gathering and transmission. Frequent information exchange leads to a more accurate picture about the traffic situation, but also to superfluous dissemination. Superfluous forwarding can be reduced by using adaptivity in the flooding mechanisms. Adaptivity can be introduced by controlling the

frequency of information exchange (timely manner) or limiting the dissemination only to areas where the TTI is really necessary (spatial manner).

Besides the presentation of the most important spatial TTI dissemination protocols we also investigate the problem of determining the areas of interest of traffic jams. As we argue, the presented spatial dissemination protocols fail to properly define the places where the TTI is useful. These solutions are only effective when are employed with additional mechanisms, which provide context-aware information to calculate the areas of interest of specific traffic jams.

2. Literature review

This section presents protocols related to spatial adaptivity-based TTI dissemination, which can be achieved pro-actively, using a data-push model Sormani et al. (2006), Leontiadis & Mascolo (2007), or based on a data-pull model Dikaiakos et al. (2007), when the information is obtained on-demand. In the first case the data is usually disseminated from the traffic incidents towards the outer inbound road segments, while in the second case the data is pulled to the locations of interest on-demand. In both cases the question is how to control and limit the traffic information dissemination only to places where the respective information is useful.

2.1 Spatial adaptivity by using data-push protocols

2.1.1 Dissemination restricted through publish/subscribe

The possibility of restricting the TTI dissemination to certain areas is investigated in Leontiadis & Mascolo (2007). In their proposal the authors present a publish-subscribe method, as the members of the traffic will receive only messages of their interest. The solution works well with methods employing the data-push model, for example the one described in Sormani et al. (2006). The publish-subscribe process starts with a vehicle subscribing to a topic (e.g. traffic congestion information). When a vehicle publishes a message, the area of interest and validity time of the message is determined. Vehicles subscribed to the given topic will receive the message if they are within the area of interest and the message is still valid. The basic idea is to maintain the message in the notification area, so every vehicle approaching the area where the message was generated (for example a traffic accident) gets the notification and has a chance to consider its reaction to the event (e.g. taking an alternate route to its destination). This is achieved by generating a fixed number of replicas of the message, which means that only those vehicles will broadcast the message which have a replica of the message. This way the load of the communication network is reduced compared to the general flooding mechanism, where every node of the network retransmits the received message, resulting in a broadcast storm. If a vehicle carrying a replica of the message is leaving the notification area, then it hands over the replica to an other vehicle, preferably driving the opposite direction, to keep the message replica in the desired area.

There are two questions regarding the message replicas. How many replicas should be there, and who should carry them? Before the replica owner broadcasts the message, it poll its neighbouring vehicles regarding the topic of the message. There are three possible answers to this poll:

- Informed: The answering vehicle is already received a notification for the given topic (e.g. if the topic is parking spots, this vehicle already knows where are free parking spaces).
- Interested: This vehicle is subscribed to the topic.

- Not interested: The vehicle is not subscribed.

If there are interested vehicles the carrier broadcasts the message. Also if the carrier is leaving the designated area, it selects a new carrier heading for the notification area, with the most interested vehicles in its vicinity. The aim of this selection method is to get the message replica where the most uninformed vehicles come from. This mechanism results in the replicas converging to areas where the information is needed, and if there are two replicas in the same area, one of them will move to an other area where the message is needed.

The number of the replicas is determined adaptively. Every replica carrier keeps the result of the last k polls, and based on these statistics the following options are possible:

- If there was at least one uninformed subscriber in the last k polls, the replica is kept.
- If there were at least k uninformed subscribers then a new replica is generated and forwarded to a vehicle, determined by the new carrier selection mechanism.
- If there are no uninformed subscribers, the replica is marked for deletion. In order to avoid deleting replicas simultaneously, the replicas are merged and are deleted only if the carrier receives a broadcast from an other carrier.

This way the number of replicas are adapted to the demand for the message, and they are forwarded to areas with the most subscribers.

However, due to the carrier selection and TTI replication mechanisms, it is not always guaranteed that the information carriers will meet their subscribers. The chance that a replica survives insensitivity, and meets proper subscribers, depends on the estimate of the replica's necessity, which is represented by the number of last k polls. Thus, the successful outcome of the protocol highly depends on the topological context and the fine tuning of the system. For example, considering the simulation results presented in Figure 1 for a scenario where two intersections are interconnected through two one way roads (one with traffic jam), it turns out that the fraction of cars entering the jammed road depends highly on the frequency of TTI disseminations (Timer), respectively on the number of transmissions until a TTI remains alive (TTL). If the frequency is too high then the TTI message is not transported until the intersection where the vehicles must be informed, even considering higher values for TTL. This can be attributed to the fact that the TTI replication and propagation was determined based on the interest of other neighboring vehicles, and in this particular case all the vehicles are heading outwards the jammed area; thus, they are uninterested about this particular jam. In order to overcome such problems additional context information regarding the road infrastructure has to be taken in consideration.

2.1.2 Dissemination restricted through propagation functions

In Sormani et al. (2006) the authors investigate methods on how to propagate the traffic messages to areas where the respective information is useful. They outline a scenario, where an accident occurs on a highway. A message broadcast happens within one mile of the accident, telling the vehicles to slow down. A second message is delivered to key points of the highway, where drivers can take alternative routes, in this scenario these points are the highway exits. This method can be considered as a data-push model, where the message is disseminated even if the information wasn't requested by an entity. The main idea is the definition of a propagation function, which restricts the message propagation to areas where the message is important. For our example this represents the highway, there is no point in disseminating the message outside this area. This propagation function has minimum points at the target zones, and its value is increasing as the distance from the target zones increase.

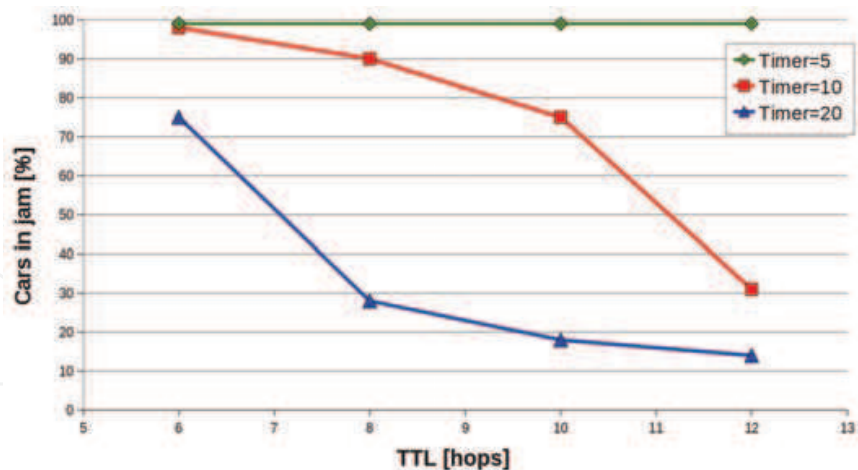


Fig. 1. Effect of TTI replication on alternative route selection

The message, originated the place of an event (e.g. a traffic accident), is always forwarded to a vehicle whose position results in the lowest value in the propagation function. This way the message will be routed towards the minimum of the propagation function, the target zone. The shape of this function is determined to follow the road network, where the vehicles can disseminate the message. The propagation function is either computed by the originator of the message, taking into account the current traffic situation and the road network in the vicinity, or it can be precomputed for important areas.

The authors consider some basic protocols to disseminate the traffic message in order to evaluate the effects of the propagation function. The most basic protocol is a modification of the flooding mechanism, where the received message is rebroadcasted only for the first time it has been seen and the value of the propagation function at the receiving vehicle is lower than at the sender of the message (One Zero Flooding, OZF). An other basic protocol is a further modification, taking into account the distance between the sender and the receiver (Distance Driven Probabilistic Diffusion, DDPD). This distance is used for probabilistic message forwarding, where the probability of forwarding is the distance between the vehicles divided by the communication range (approximately 200 meters for 801.11 capable devices). This way the surplus message retransmissions can be avoided. A more advanced protocol takes into account the shape of the propagation function (Function Driven Probabilistic Diffusion, FDPD). In this case the probability of forwarding is zero at the sender's position and is increasing as the value of propagation function decreases, and takes the value of one at the lowest value of the propagation function inside the communication radius of the sender of the message. This method yields to a more accurate routing, as a lower value of the propagation function is not enough, the algorithm tries to find the lowest possible value. The authors propose some store & forward variations of these algorithms, where after receiving a message the vehicle not only retransmits it immediately but carries it for some time and rebroadcasts the message periodically. The first store & forward variant (Function Driven Feedback-augmented Store & Forward Diffusion, FD-FSFD) is based on FDPD with the addition of a feedback augmented store & forward mechanism. The feedback augmentation means, if the carrier receives a message from a vehicle whose position results in a lower value of the propagation function, then the further broadcasts are cancelled as the message already reached a lower point of the propagation function. The second store & forward algorithm (Direction-aware Function Driven Feedback-augmented Store & Forward

Diffusion, DFD-FSFD) is an extension of FD-FSFD by taking into account the direction of movement of the nodes. This means that only nodes moving towards lower points of the propagation function are used to carry the message. These methods are useful in sparse networks where the connection between clusters of vehicles is not guaranteed.

Unfortunately, there are no methods presented to calculate the propagation function, i.e., the locations where the information should be propagated. Therefore, this protocol is not ready to be applied for TTI dissemination in urban scenarios.

2.2 Spatial adaptivity by using data-pull protocols

In Dikaiakos et al. (2007) the authors outline an application-layer communication protocol (Vehicular Information Transport Protocol, VITP), which could be used in VANETs to disseminate location based information. Such location based information can be traffic information regarding road conditions (e.g. slippery road or congestion), or some kind of roadside service information (e.g. fuel prices at gas stations or menus of restaurants). These kinds of information are typically requested by someone; thus this method can be called as the data-pull model. The authors introduce the concept of virtual ad-hoc servers (VAHS), which means that an information request is processed by a number of peers at the target location of the request, and the result is sent back to the originator of the query. For example, if a vehicle wants to know the traffic condition on a road segment in its path, it sends a request to that road segment. When a vehicle in the target area receives the query, it attaches the requested information to the message, and retransmits the message, so other vehicles can contribute to the reply. The ones contributing to the reply constitute the virtual ad-hoc server. After a certain threshold is met, for example ten vehicles attached their velocity information to the message, the last vehicle generates the reply from the gathered data, and sends it back to the originator vehicle. This way the answer can be more accurate, than in the case where only one vehicle made the reply, or when separate replies were generated by multiple vehicles. The data-push method is also supported by the proposed protocol as it is favorable in some cases, for example in case of an accident. The vehicles couldn't be forced to constantly generate queries for accidents, instead the information is "pushed" to them. The described protocol is also capable of caching the information in some cases, so a reply could be made before the query reaches the target location, speeding up the process. The effect of caching is further elaborated in Dikaiakos et al. (2010), and it is shown that significant improvements can be achieved in both the data-pull and the data-push cases.

2.3 Aggregation scheme for roadside unit placement

The authors of Lochert et al. (2008) present a method for optimization of roadside unit placement in order to minimize the required bandwidth for traffic information dissemination. A domain specific aggregation scheme is presented, then a genetic algorithm is proposed to identify the most appropriate positions for the roadside units. The aggregation scheme is conceived in a hierarchical fashion: the farther away a region is, the coarser will be the information on its traffic situation. By using this scheme a vehicle traveling along the road network will obtain coarser and coarser approximations about the traffic situation, travel times will be summarized in regions that are farther and farther away. Thus, the aggregation scheme will allow to limit the bandwidth requirements for TTI dissemination, by reducing the network capacity necessary for information spreading. The aggregation scheme is based on the definition of special multi-level landmarks, which will cover the hierarchy of the road networks. The higher levels are constituted by highways or junctions of main

roads, while the lower levels will include all higher level landmarks plus more and more intersections of smaller streets. Thus, cars can make investigations about the travel times between neighboring landmarks, which information will be disseminated in the surroundings of the respective road segment. A coarser picture, calculated from travel times between landmarks of higher levels, will be disseminated to a larger area, which leads to a summarized view of the travel times in the area. Roadside units are placed to form a backbone network, allowing them to exchange the TTI to be disseminated. In order to use a very limited number of roadside units the authors propose a toolchain for placement optimization. Since the identification of the optimal subset of roadside unit locations is a difficult optimization problem a genetic algorithm based approximation method is used to obtain a good result subset. The toolchain is composed from a network and traffic simulator (ns-2 and VISSIM), respectively from a closely interacting application simulator and the genetic algorithm. The application simulator is used to process the log file of the network-traffic simulator, perform the specific aggregation methods, decide about the dissemination of TTI beacons. At the level of the network simulator all the possible roadside unit locations are simulated, all of them transmit the periodic beacons. The non-existing roadside units are ignored at the level of the application simulator, the received beacons are not considered when its knowledge base is updated by the genetic algorithm. Thus, with the separation of movement and network issues from application behavior travel time savings are achieved by calculating the vectors of active roadside unit locations. These savings are used as a fitness metric, making the application-centric optimization through the genetic algorithm. The viability of the approach is confirmed through simulations by applying the proposed solution to a large-scale city scenario.

3. Spatially-aware congestion elimination (SPACE)

In this section the SPatially-Aware Congestion Elimination algorithm (SPACE) is designed. An algorithm is given to determine the locations, domain of interests, where a possible event (e.g. traffic jam) on a certain road influences the route choice of the driver. To illustrate the problem, a small example is presented, then we formulate it as a graph theoretical optimization problem. Both a heuristic and a linear programming optimization solution are provided. Thus, we give a well defined area (the Domain of Interest, DoI) where information about a specific traffic jam is useful.

3.1 Example

First let us consider an example of one way roads from left to right (Figure 2), which represents a subset of a larger road network.

We assume that a vehicle enters the network at node 1, its destination is at node 10. The vehicle has route decisions at nodes 2,3,4 and 5, respectively. It can take either Route A, Route B, Route C or Route D to reach its destination. Route A is shortest and fastest; consequently, the vehicle takes the middle route in the default case. If route A at road segment 6-7 is congested, this information has to be disseminated throughout the road network.

The *Domain of Interest (DoI)* is defined as the set of road segments, where the information about a traffic jam influences the route choice of the driver, i.e., the roads where the information should be disseminated. At these places, the vehicles are still able to change their routes, without a drastic deterioration in their travel time. However, if the vehicle leaves a critical junction, enters in the *zone of no return*, where is no possibility to avoid the traffic jam, or only with a major increase in the travel time. Our scope is to optimize the area of DoI in order to

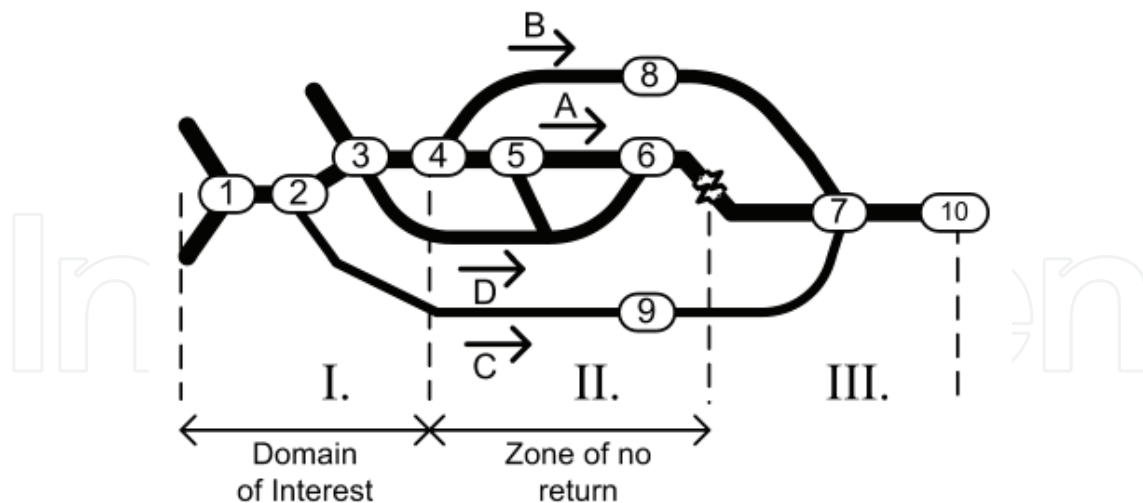


Fig. 2. Example road network

reduce the amount of TTI flooding and at the same time to achieve as low vehicle travel times as possible.

Traditional flooding methods disseminate this information towards any directions. However, in the example this information is only interesting at the decision point 4 (optimized DoI), since the second best choice is route B. It is useless to deliver the TTI further than junction 4, as vehicles are heading towards junction 4, anyway. There is no sense in providing this information to the whole DoI, like (1,2,3,8,9). However, if both routes A and B would be congested, this information should be provided to an earlier decision point (junction 2, segment 1-2), where both routes can be avoided by the by-pass route C. This means that the DoI can also present characteristics varying over the time.

3.2 Problem formulation

The road network is represented by a directed and weighted graph $G(\mathcal{V}, \mathcal{E})$ with representation described in Speicys & Jensen (2008), using two types of edges \mathcal{E}_r and \mathcal{E}_t ($\mathcal{E}_r \cup \mathcal{E}_t = \mathcal{E}$, $\mathcal{E}_r \cap \mathcal{E}_t = \emptyset$). \mathcal{E}_r is a directed edge representing a road between two intersections. One-way roads are represented with directed edges, while two-way roads with two opposite directed edges. The set of \mathcal{E}_t represents the turning regulations, i.e., an edge from $n_1 \in \mathcal{V}$ to $n_2 \in \mathcal{V}$, where n_1 is the destination node of e_1 while n_2 is the origin node of e_2 , is included in the graph if and only if a turn is allowed from e_1 to e_2 . The weight of an edge represents the travel time on the corresponding road, or turning.

The event (traffic jam) is associated to a set of failed roads \mathcal{E}_f , which is a subset of the roads ($\mathcal{E}_f \subseteq \mathcal{E}$). We assume that the set \mathcal{E}_f contains the core of the problem, where the actual speed decreases to a fraction of the normal speed.

We also assume that an estimated Origin-Destination (OD) function for the road network is known. The OD function $OD(n, m)$ represents the average amount of vehicles traveling from node $n \in \mathcal{V}$ to $m \in \mathcal{V}$. If the OD function is not known then it can be assumed that it has uniform distribution, i.e., $OD(n, m) = 1$ for each $n, m \in \mathcal{V}$.

The output of the algorithm is an Impact Vector $I_{\mathcal{E}_f}(e)$ that shows whether an event on edges of \mathcal{E}_f has an impact on the route choice of vehicles travelling on edge e , and if yes, in what extent. The value of $I_{\mathcal{E}_f}(e)$ is zero if it has no impact on edge e , non-zero if it has an impact.

The value $I_{\mathcal{E}_f}(e)$ expresses the average amount of vehicles on edge e , whose route choice is impacted by the knowledge about an event on roads of \mathcal{E}_f .

3.3 SPACE algorithm

In this section the proposed SPACE Algorithm is described, which generates the Impact Vector I . The algorithm simulates the impact of an event (obstacle, traffic jam) on a set of edges of the graph. For each affected optimal path p of the graph it is assumed that the travel time on edges of \mathcal{E}_f increases significantly. Then, the weights of the affected edges of \mathcal{E}_f are increased, or these edges are excluded from the graph temporarily, and a new optimal path (the by-pass route) is calculated by running the shortest path algorithm in the temporary graph, resulting in path p^* . We define three parts of the optimal route p , and illustrate it on Figure 2, where $p=(1,2,3,4,5,6,7,10)$, and the alternative route bypassing the edges with increased weights $p^*=(1,2,3,4,8,7,10)$:

Part I. Set of edges common with p^* , before the disjoint part: e.g., road (1,2,3),

Part II. Set of edges not included in p^* , before the event: e.g., road (4,5,6),

Part III. Set of edges after the event: e.g., road (7,10).

In this case, an event on edges in \mathcal{E}_f is important for the last X of edges in part I of p (in order to choose another route), and in the disjoint part before the event (part II.), in order to be informed about the obstacle (without the possibility of choosing the other route). These edges are called **relay** edges in the algorithm. For all these edges the impact vector I has to be increased with the amount of vehicles traveling on that route (or by 1, if an OD matrix is not available). The algorithm is summarized as follows:

Input: Directed Weighted Graph \mathcal{G} , OD matrix, Set of failed roads \mathcal{E}_f

Output: Impact Vector I

for all Pair of nodes $(n, m) \in OD$ **do**

 Calculate in \mathcal{G} the optimal path p from n to m ;

 Create a new temporary graph $\mathcal{G}_{\mathcal{E}_f}$: increase weights of edges of \mathcal{E}_f significantly;

 Calculate by-pass route p^* from n to m in $\mathcal{G}_{\mathcal{E}_f}$;

 Calculate the set of **relay** edges: $\mathcal{E}_R \subseteq \mathcal{E}$;

for all edge $e_r \in \mathcal{E}_R$ **do**

 Increase $I_{\mathcal{E}_f}(e)$ by $OD(n, m)$;

end for

end for

3.4 SPACE_ILP algorithm

In this subsection the problem of finding the optimal Domain of Interest (DoI) is formulated as an Integer Linear Programming (ILP) problem, as presented in Torok et al. (2010). Although, solving an ILP by a solver has a long running time, we emphasize that this formulation has the following motivations: the formulation gives an exact definition of the TTI dissemination problem and it allows a precise analysis of the problem compared to heuristic algorithms.

First, let us define the normal route of the vehicles. For each edge (i, j) , $i, j \in \mathcal{V}$, and origin and destination nodes $n, m \in \mathcal{V}$, we define the set of assignment variables, $\mathcal{X} = \{x_{ij}^{nm}\}$. The variable x_{ij}^{nm} takes value 1 if edge ij is used in the shortest path from n to m , and 0 otherwise.

The known flow conservation constraints for the default routes are as follows:

For each $j, n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$\sum_{i \in \mathcal{V}} x_{ij}^{nm} - \sum_{k \in \mathcal{V}} x_{jk}^{nm} = \begin{cases} -1 & \text{if } j \equiv n \\ 0 & \text{if } j \equiv m \\ & \text{otherwise} \end{cases} \quad (1)$$

Similarly, the by-pass route is defined for the vehicle. For each edge (i, j) , $i, j \in \mathcal{V}$, and origin and destination nodes $n, m \in \mathcal{V}$, we define the set of assignment variables, $\mathcal{Y} = \{y_{ij}^{nm}\}$. The variable y_{ij} takes value 1 if edge ij is used in the by-pass route from n to m , otherwise 0. The flow conservation constraints for the by-pass routes are as follows:

For each $j, n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$\sum_{i \in \mathcal{V}} y_{ij}^{nm} - \sum_{k \in \mathcal{V}} y_{jk}^{nm} = \begin{cases} -1 & \text{if } j \equiv n \\ 0 & \text{if } j \equiv m \\ & \text{otherwise} \end{cases} \quad (2)$$

Furthermore, in the formulation, both the normal and the by-pass routes are to be split in several pieces. For this, five more assignment variables are defined: a_{ij}^{nm} , b_{ij}^{nm} , c_{ij}^{nm} , d_{ij}^{nm} , f_{ij}^{nm} (for each edge (i, j) , $i, j \in \mathcal{V}$ and origin and destination nodes $n, m \in \mathcal{V}$) with following definitions:

- a_{ij}^{nm} is 1 if edge ij belongs to the common part of the normal and the by-pass route, 0 otherwise.
- b_{ij}^{nm} is 1 if edge ij belongs to the normal route after the fork of the normal route but before the traffic jam, 0 otherwise.
- c_{ij}^{nm} is 1 if edge ij belongs to the traffic jam $((i, j) \in \mathcal{E}_f)$, 0 otherwise.
- d_{ij}^{nm} is 1 if edge ij belongs to the normal route after the fork of the normal route but after the traffic jam, 0 otherwise.
- f_{ij}^{nm} is 1 if edge ij belongs to the by-pass route while not to the normal route, 0 otherwise.

For an example of these definitions see Figure 2 with origin=1, destination=10, optimal route (1,2,3,4,5,6,7,10) and by-pass route (1,2,3,4,8,7,10). $a_{ij}^{nm} = 1$ for roads (1,2),(2,3),(3,4) and (7,10). $b_{ij}^{nm} = 1$ for roads (4,5) and (5,6). $c_{ij}^{nm} = 1$ for road (6,7). $d_{ij}^{nm} = 0$ for all roads. $f_{ij}^{nm} = 1$ for roads (4,8) and (8,7).

The above definitions are ensured by the following equations:

For each $(i, j) \in \mathcal{E}$ and $n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$a_{ij}^{nm} + b_{ij}^{nm} + c_{ij}^{nm} + d_{ij}^{nm} = x_{ij}^{nm} \quad (3)$$

$$x_{ij}^{nm} + f_{ij}^{nm} \leq 1 \quad (4)$$

$$a_{ij}^{nm} + f_{ij}^{nm} = y_{ij}^{nm} \quad (5)$$

Furthermore, the part of the default route after the jammed link (d) has to be distinguished from the part before the jam (b) with the following constraint:

For each $j, n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$\sum_{i \in \mathcal{V}} d_{ij}^{nm} - \sum_{k \in \mathcal{V}} d_{jk}^{nm} = \begin{cases} -1 & \text{if } c_{ij}^{nm} = 1 \\ \geq 0 & \text{otherwise} \end{cases} \quad (6)$$

For each road (i, j) affected by the traffic jam $((i, j) \in \mathcal{E}_f)$ set c_{ij}^{nm} to 1 and y_{ij}^{nm} to 0, while for each other (not jammed) road $((i, j) \notin \mathcal{E}_f)$ set c_{ij}^{nm} to 0.

Next, the assignment variables for the propagation region are defined and we formulate the fact that vehicles does not by-pass the jam until they receive a message about it, i.e., the normal route and corresponding by-pass route are to be the same outside the propagation region. For each edge (pair of nodes) (i, j) , $i, j \in \mathcal{V}$, we define the set of assignment variables, $\mathcal{R} = \{r_{ij}\}$. The variable r_{ij} takes value 1 if edge ij is included in the propagation region, otherwise 0.

In order to ensure a propagation region that reaches all places where normal and by-pass routes are to be forked, the following constraints are defined:

For each $n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$r_{ij} \geq b_{ij}^{nm} \quad (7)$$

Finally, we define the objective by minimizing the weighted average of the length of all by-pass routes and the total length of the propagation region:

$$\min \sum_{(i,j) \in \mathcal{E}} \left(\alpha l'_{ij} \sum_{n,m \in \mathcal{V}} y_{ij}^{nm} + (1 - \alpha) l''_{ij} r_{ij} \right) \quad (8)$$

l'_{ij} denotes the cost (length, travel time, etc.) of travelling on road ij while l''_{ij} denotes the cost (e.g., road length, communication cost) of propagating information on road ij . Parameter α ($0 \leq \alpha \leq 1$) expresses the importance of minimizing the total length of all by-pass routes against the total propagation region.

In summary, for the ILP formulation we define constants: c_{ij}^{nm} , l'_{ij} , l''_{ij} ; binary variables x_{ij}^{nm} , y_{ij}^{nm} , r_{ij} , a_{ij}^{nm} , b_{ij}^{nm} , d_{ij}^{nm} , f_{ij}^{nm} ; objective: (8) and constraints: (1)-(7).

3.5 Query-based information gathering

As we presented above, in Dikaiakos et al. (2007) a query-based protocol is provided to achieve spatial adaptivity by the means of pull-based techniques. Unfortunately, there is no exact mechanism specified to calculate at what extent the queries, respectively the TTI reply/caching, should be propagated inside the road network. In the original paper the authors present simulations, where the queries are propagated only to a randomly selected value of 400-800 meters inside the road segments. This means that in certain situations the information will not be received in time to calculate the proper by-pass route. Therefore, additional mechanisms are necessary to determine the critical points until when the queries must be propagated, i.e., from where the TTI information has to be gathered. Considering a vehicle entering at junction 1 in the road graph of Figure 2, it is hard to decide when and how deep to inject the traffic information query in order to discover a possible traffic jam on route A. This problem is related to the calculation of the optimal DoI, and can only be solved by using additional information about the vehicle's context, i.e. the route graph traversed during the trip.

In Laborczi et al. (2010) an extension of the previous ILP formulation is given, with the aim to optimize the positions where vehicles along their routes should send query messages, in order to collect information about possible traffic jams. Thus, this formulation can be considered as an optimization of the query protocol presented in Dikaiakos et al. (2007). The numerical results of the formulation are presented in the following section.

The equations 1 - 6 from the previous section are the same also for the query-based information gathering.

In order to find an optimal point to send a query message, we have to define the following set of variables:

- s_{ij}^{nm} is 1 if edge ij belongs to the common part of the normal and the by-pass route and to the DoI as well.

With the following three constraints the properties of variables s_{ij}^{nm} are ensured:

For each $n, m \in \mathcal{V}$ where $OD(n, m) > 0$:

$$r_{ij} \geq b_{ij}^{nm} + s_{ij}^{nm} \quad (9)$$

$$s_{ij}^{nm} \leq a_{ij}^{nm} \quad (10)$$

Edges where s_{ij}^{nm} or b_{ij}^{nm} takes value 1 should be a coherent region, which ends at the traffic jam:

$$\sum_{i \in \mathcal{V}} (s_{ij}^{nm} + b_{ij}^{nm}) - \sum_{k \in \mathcal{V}} (s_{jk}^{nm} + b_{jk}^{nm}) = \begin{cases} \leq 1 & \text{if } \exists k c_{ik}^{nm} = 1 \\ \leq 0 & \text{otherwise} \end{cases}$$

Finally, the propagation delay of the distributed messages has to be taken into account. It takes some time for the query message to reach the jam, and the reply message to reach the originator. The query message should reach the begin of jam, collect information and the reply message should reach the vehicle before it reaches the optimal decision point expressed by the following constraint:

$$\sum_{(i,j) \in \mathcal{V}} \left(s_{ij}^{nm} \frac{l_{ij}}{v_{veh}} - (2b_{ij}^{nm} + s_{ij}^{nm}) \frac{l_{ij}}{v_{mess}} \right) \geq 0, \quad (11)$$

Where l_{ij} is the length of the ij road segment, v_{veh} is the velocity of the vehicle, v_{mess} is the velocity of the message propagation.

Finally, we define the objective by minimizing the weighted average of the length of all by-pass routes and the total length of the DoI:

$$\min \sum_{(i,j) \in \mathcal{E}} \left(\alpha l'_{ij} \sum_{n,m \in \mathcal{V}} y_{ij}^{nm} + (1 - \alpha) l''_{ij} r_{ij} \right) \quad (12)$$

where, l'_{ij} is the cost (length, travel time, etc.) of traveling on road (i, j) while l''_{ij} denotes the cost (e.g., road length, communication cost) of propagating information on road (i, j) . Parameter α ($0 \leq \alpha \leq 1$) expresses the importance of minimizing the total length of all by-pass routes against the total DoI.

In the next section, we use this formulation as follows. First, for each $n, m \in \mathcal{V}$ where $OD(n, m) > 0$ calculate shortest path and set variables x_{ij}^{nm} based on the result of the shortest path algorithm. Second, solve the following ILP problem: constants: x_{ij}^{nm} , c_{ij}^{nm} , l'_{ij} , l''_{ij} ; binary variables: y_{ij}^{nm} , r_{ij} , a_{ij}^{nm} , b_{ij}^{nm} , d_{ij}^{nm} , f_{ij}^{nm} , objective: (12) and constraints: (2)-(6) and (9)-(11).

4. Numerical analysis of the SPACE and SPACE_ILP algorithms

In this section we present the evaluation of the proposed heuristic and linear programming algorithms. All the simulations were effectuated on the same section of a digital map of Budapest.

4.1 SPACE

The output of the SPACE algorithm is demonstrated on Figure 3 for two roads of the Budapest test network. A main road (bridge, solid line), and a side road (from down-town, dotted line) were considered for analysis. The x-axis represents the domain of interest, i.e., the sum of road lengths on which the information about the event is disseminated, while y-axis represent the impact factor. The information is sent to roads (e) of higher impact factors ($I_{\mathcal{E}_f}(e)$), while roads with minor impact factors can be neglected. First, we assume that there is a traffic jam (obstacle) on the main road (depicted with solid line). If the TTI information is flooded to the whole domain of interest, then it should be spread to 16,000 meters. Therefore, a threshold (e.g., $TR = 4,000$) should be set in order to avoid superfluous forwarding. In this way the information is carried to the majority of vehicles (just 1,000 from more than 15,000 do not receive the information in time), while the domain of interest is decreased to 4,000 meters, instead of 16,000. Second, we consider an obstacle on a side street (dashed line). As expected, the impact factor of such streets is less, i.e., if the threshold is set to 1,000 then the domain of interest is 500 meters.

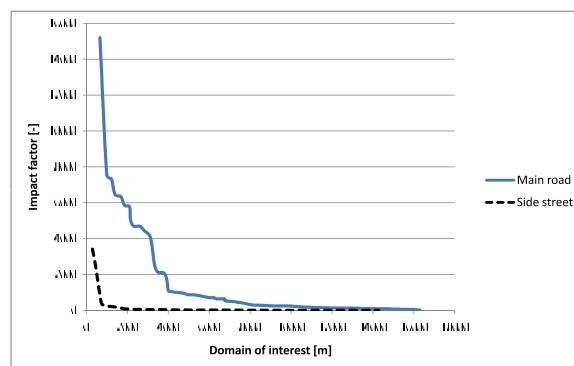


Fig. 3. Domains of Interest for different road types using the SPACE algorithm

4.2 SPACE_ILP

In order to have a better understanding, the results of the SPACE_ILP algorithm are presented below. A main road (bridge), and different side roads (from downtown area) were considered for analysis. The bridge graph represents averaged values for traffic demands initiated from both sides of the city, considering traffic jam on one of the bridge lanes. The downtown graph represents averaged values from different congested downtown roads (considering also the major roads leading to the bridge).

Figure 4 shows the Domain of Interest (DoI) depending on the parameter α (see Objective (8)). We recall that α ($0 \leq \alpha \leq 1$) expresses the importance of minimizing the total length of all vehicle by-pass routes against the importance of minimizing the propagation region (area of dissemination). The DoI is represented as the sum of the road segment lengths included in the propagation region.

It is obvious that for both graphs the DoI increases by increasing α . On the other hand, the figure shows that the two types of roads represent different dynamics considering their DoI. In case when the obstacle is on the bridge, the DoI increases steeply with the increase of α . This means that in order to reach all roads of the maximum DoI, higher efforts must be involved for TTI dissemination. However, after a limit ($\alpha \geq 0.6$) the DoI is not increasing significantly (only about 1 km). A crucial point for α is between 0.3 - 0.4, where the DoI increases significantly. Considering congestion on downtown roads the situation is different. It can be seen, that the

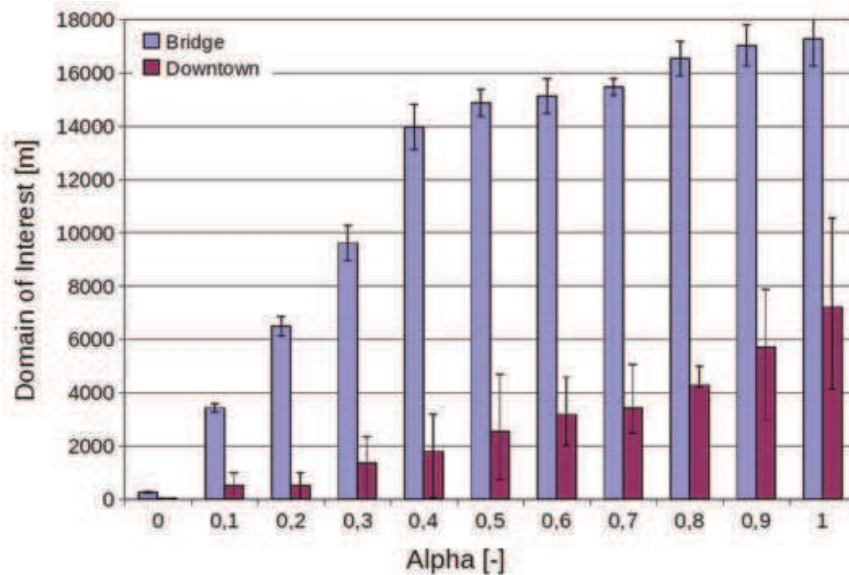


Fig. 4. Domains of interest in function of parameter α

variance of the DoI values is higher; however, the area of DoI for downtown scenarios is only a fraction of the values of the bridge scenarios.

These observations are also validated if we consider the length of alternative (by-pass) routes in function of α (Figure 5). As α increases, the length of by-pass routes will decrease, because more and more vehicles will be able to choose the ideal by-pass routes to avoid the congestion. For the bridge scenario the length of alternative routes decreases with about 30% if we disseminate TTI by employing $\alpha = 0.4$. In case of downtown congestions, we can observe that the length of alternative routes will not decrease significantly as we increase α , since the best by-pass routes are closer to the area of congestion. Thus, for downtown roads it is useless to disseminate the information further than the next couple of road segments (e.g. 200-300 meters), since the by-pass routes would not become shorter in any case.

Numerous analysis have been carried out that also show that the effect of α on the DoI and length of alternative routes is significant between 0.2 and 0.4 for most of the roads.

4.3 Query-based information gathering

In this section we present the numerical results of the generic query-based traffic information gathering protocol. The results were generated by creating a large amount of random source-destination route pairs on the road graph of Budapest. Optimal query locations were generated by solving the ILP formulation described in the previous section. A characteristic set of results, presenting interesting cases, were selected for presentation.

On Figure 6 the x-axis represents the distance of the source (n) of a vehicle from the traffic jam (while the destination (m) was fixed), while the y-axis represents the alteration in length of the respective metrics. The road length increase presents the difference between the original and the different by-pass routes ($\sum_{(i,j) \in \mathcal{E}} l'_{ij} (y_{ij}^{nm} - x_{ij}^{nm})$, for source n and destination m), while the query distance metric presents the distance from where the query is injected towards the point of interest ($\sum_{(i,j) \in \mathcal{E}} (l''_{ij} r_{ij})$, $l'_{ij} = l''_{ij} = \text{length of road } (i, j)$).

In case when the jam was on a bridge (diagrams noted with (B)), the length of the original route was 3300 meters. When the distance was less than 200 meters from the traffic incident, the increase in the by-pass route length was nearly 1600 meters, an increase of around 50% of

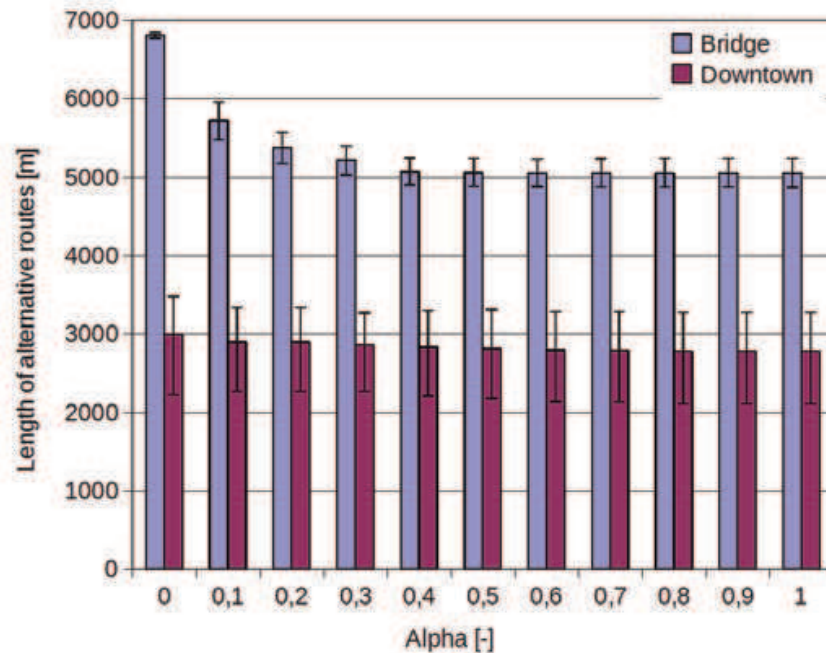


Fig. 5. Length of alternative routes in function of parameter α

the original route. As the source was generated further away from the traffic jam, the by-pass route length increase could be reduced significantly. The breakpoints in the graph are the points in the road network, where a new by-pass route could be taken. As we can see, the optimal query distance in this case is around 1000 meters. That is the point where the vehicles can take the shortest by-pass route according to the information contained in the returned TTI message.

On the diagrams noted with (M2), a major road in the city is displayed, where the length of the original route was 2500 meters. It can be seen that in case of short query distances the length of the by-pass routes could be as much as the double of the original route length. As the query distance is increased to 1000 meters, the by-pass route length decreases to around 600 meters, and with a query distance of 1200 meters, the route length increase is only 100 meters. This shows that finding the optimal query distance is really important, because the length of the by-pass route can be reduced significantly.

The diagrams noted with (M1) present a case when the traffic jam is on a main downtown road with plenty of nearby roads, which can be taken as by-pass routes. Thus, the query distance can be set to a small value, since the increase in by-pass route will become negligible.

4.4 Comparison of SPACE and SPACE_ILP

Until now we investigated the effect of traffic congestion on TTI dissemination separately studying the heuristic (SPACE) and the optimal (SPACE_ILP) Domain of Interest calculation algorithms. Considering the results from Section 4.1 and Section 4.2 we can affirm that the outcome of the algorithms present certain similarities. For example, from both approaches it turns out that the traffic jams can be classified in two major categories. One category is represented by traffic jams of main, crucial roads (e.g. bridge), with a large Domain of Interest and an increased length of the by-pass routes. The dissemination of TTI for such traffic incidents is extremely important, since the zone of no return of these traffic jams is also large. The second category of traffic jams is represented by downtown roads with small DoI

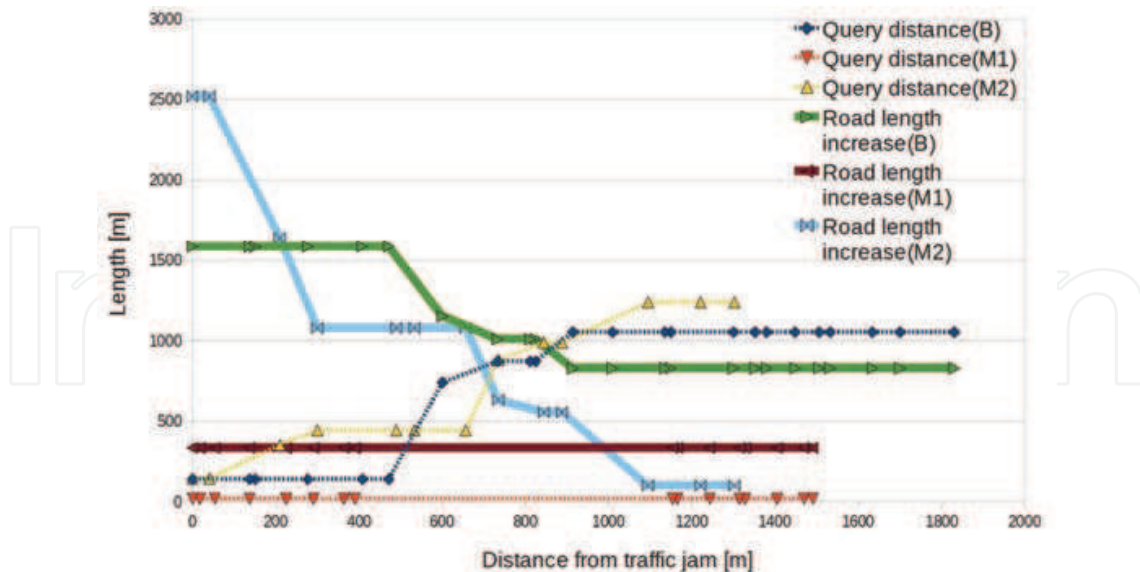


Fig. 6. Query results of different traffic jams

values. Such congestions can be avoided quite easily, since there is a large number of shorter by-pass routes around them.

Besides discovering resemblances of the algorithms' outcome it is also important to consider their potential benefits and differences. The main advantage of SPACE_ILP is the optimal size of DoI result sets for different parameters of the actual context (e.g. network load, reflected by parameter α). However, the SPACE_ILP algorithm can be employed only for the calculation of a limited number of DoI calculations, since its running time is relatively high; thus, it cannot be used to calculate the DoI for all the segments of a larger road network. That is where the SPACE algorithm comes into picture, because it presents much faster running times. Unfortunately, there is no method defined on how to select the most important road segments from the outcome of the SPACE algorithm. The impact factor metric gives us a good measure regarding the importance of different road segments, but it does not indicate a certain threshold, which would limit the DoI area for the respective result set. Therefore, the aim of this subsection is to provide a method, which provides a relationship, associates the results of the two DoI generator algorithms.

In order to find such a relationship we opted to compare and analyze the result sets of the two algorithms in a spatial manner. We designed and built an extension for our RUBeNS vehicular simulation environment Laborczi et al. (2006), which is able to load, store and analyze the DoI result sets of the algorithms. The extension is built in the PostgreSQL database management system and takes advantage of its geographic support, PostGIS and pgrouting. In this framework by using common map references we have an unified view of uploaded data, and through embedded functions we are able to define different spatial operations and methods for analyzing the uploaded result sets. For example, we can calculate the area or perimeter of DoIs, we can compare the DoI result sets regarding their spatial coverage and relationships, and we can design methods to intelligently reduce the area of SPACE DoIs.

For the reduction of SPACE DoI areas we implemented the following simple method. From the uploaded DoI sets of SPACE_ILP we selected certain cases, which represent characteristic DoIs (for large and small traffic jams). From these DoIs we get the optimized set of road segments, which in turn will be searched in the DoI set of the SPACE algorithm for the same traffic jam. Based on this we get a reduced set of road segments from the respective SPACE

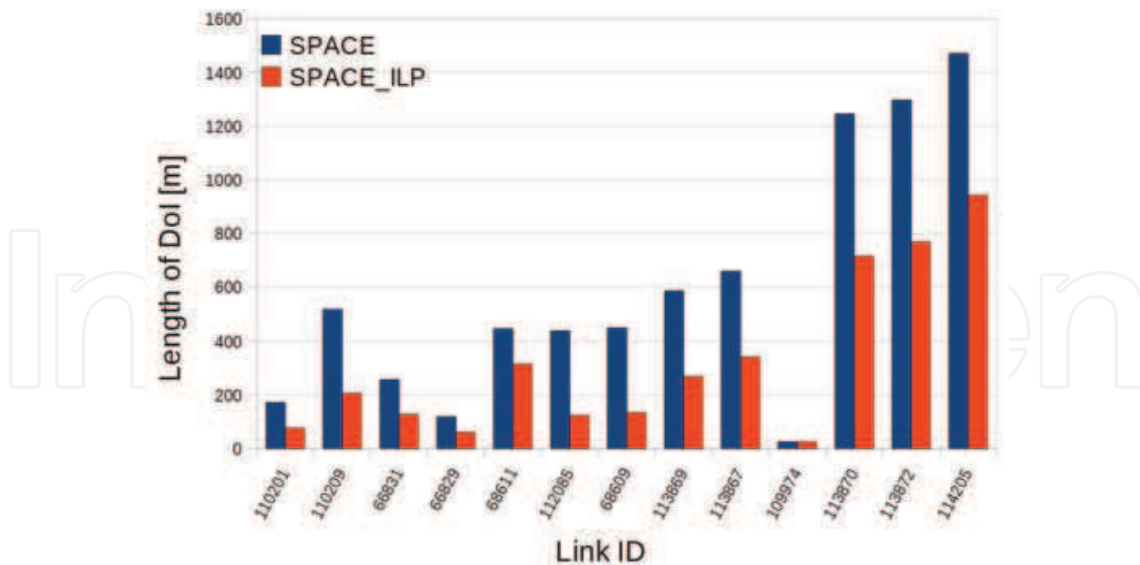


Fig. 7. Comparison of Domains of Interest of the SPACE and SPACE_ILP algorithms

DoI, for which the dissemination area is optimal. Then considering the impact factors and domain of interest lengths for this result set we calculate the derivative of the graph's slope. This will provide the threshold for limiting the area of other DoI result sets. For reducing the size of other SPACE DoI result sets we always select road segments until their graph's slope represents higher values than the calculated threshold. This would mean that these road segments are still important for TTI dissemination about the respective traffic incident. By using this calculation the size of all SPACE DoIs can be reduced; thus, a corresponding association between the two algorithms was identified.

The results of the method are presented on Figure 7, where we represent how the road segments with different relevance regarding the DoI are situated along a selected vehicle's route. A cross-bridge route was selected, where the length of DoI (considered only on this specific path) is represented in function of the link IDs along the path, the traffic jams were generated consecutively for the respective road segments. On the figure traffic jams with large influence (large DoI) can be observed between links with IDs 113870 and 114205 (critical part), where the DoI (along the route) of SPACE can reach even 1400 meters. This means that in case of a traffic jam situated along this critical part the TTI should be disseminated to a large part of the route, in order to avoid the traffic jam of the respective links with small by-pass routes. This critical part of the route contains also the bridge. For the rest of the route the congested links can be avoided easily, this is represented by small values for DoI.

It is important to observe that the results of DoI sets for SPACE and SPACE_ILP represent similar behavior, emphasizing the difference between the different kinds of traffic jams (with small, respectively large DoI values). The difference between the values of DoI length of the algorithm's output come from the fact that in the case of the SPACE algorithm we added a few more link segments (additional length increase), since we wanted to provide a larger zone for query and decision making during the trip along the respective route segment. The outcome of SPACE_ILP is a little bit to optimistic, since it does not take into account the delays of information propagation.

By applying the method for the whole set of uploaded SPACE DoIs (Figure 8) we can observe that size of DoIs (original, without reduction) shifts from the larger values towards much smaller ones (reduced DoIs). This can be attributed to the fact that only a few road segments

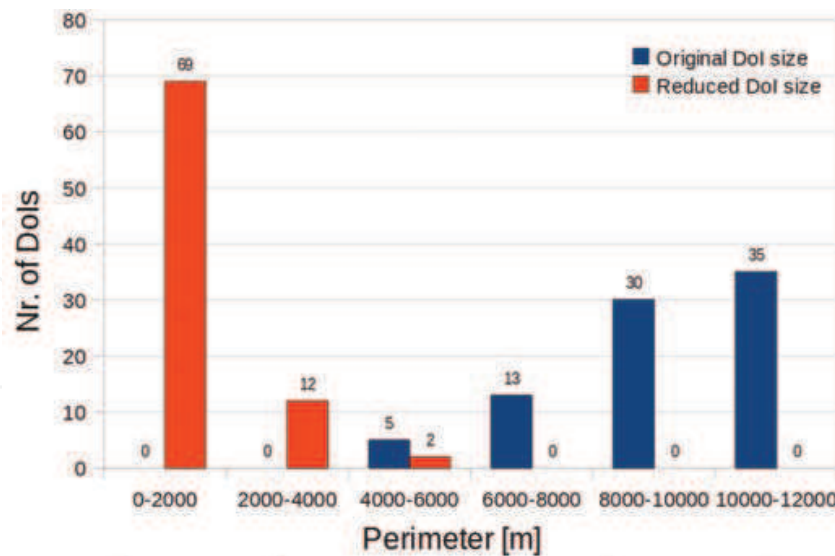


Fig. 8. Reshaping the Domains of Interest of the SPACE algorithm

are really important (large DoI areas), while the majority of traffic jams affect roads with small influence (from downtown areas). Similar results could be achieved by employing the SPACE_ILP algorithm for DoI calculations. Thus, the SPACE DoI reduction algorithm proves to be effective to determine the correct size of dissemination areas.

5. Conclusions

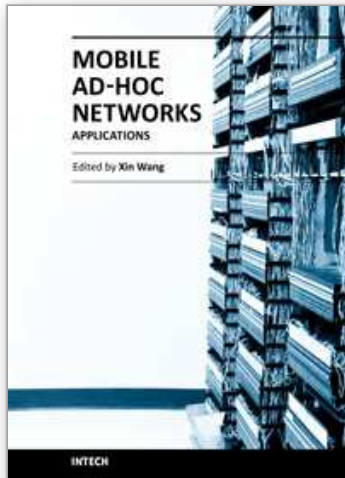
The current trends and problems of intelligent transportation systems have been presented in the beginning of this chapter. We presented a short overview of research on providing location-aware services in vehicular networks by disseminating information messages, for example regarding traffic congestion or fuel prices at a gas station, and maintaining these messages at key areas in the traffic network. This way the vehicles that traverse through these areas get informed about the content of the message and are able to alter their route accordingly. In the second part of the paper we presented SPACE, a heuristic algorithm to determine the domains of interest to a given event, for example a traffic jam, where the dissemination of the message is important. Following that we have given a linear programming formulation to determine the optimal domains of interest for a given traffic scenario. In the next section an extension of the linear programming formulation was described, to take the velocity of the vehicles and the message propagation delay into account. This allowed the extension of the DoI, so the vehicles could be notified before they reach the junction where the optimal alternative route starts. In the final section we evaluated the heuristic and the linear programming algorithms with different settings of the adjustable parameters using the RUBeNS simulation environment. It was shown, that the linear programming solution can be used to calibrate the heuristic algorithm, although SPACE does not presents the optimal solution like the linear ILP algorithm, but it runs significantly faster, thus it is more usable.

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Mobile Ad-Hoc Networks: Applications

Edited by Prof. Xin Wang

ISBN 978-953-307-416-0

Hard cover, 514 pages

Publisher InTech

Published online 30, January, 2011

Published in print edition January, 2011

Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: vehicular ad-hoc networks, security and caching, TCP in ad-hoc networks and emerging applications. It is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Attila Török, Balázs Mezny and Peter Laborczi (2011). Traffic Information Dissemination in Vehicular Ad Hoc Networks, Mobile Ad-Hoc Networks: Applications, Prof. Xin Wang (Ed.), ISBN: 978-953-307-416-0, InTech, Available from: <http://www.intechopen.com/books/mobile-ad-hoc-networks-applications/traffic-information-dissemination-in-vehicular-ad-hoc-networks>

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