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RESEARCH ARTICLE

An evaluation of routing in vehicular networks using analytic hierarchy process

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ABSTRACT

This paper presents a comprehensive study of the performance of routing protocols in distributed vehicular networks. We propose a novel and efficient routing protocol, namely cross-layer, weighted, position-based routing, which considers link quality, mobility and utilisation of nodes in a cross layer manner to make effective position-based forwarding decisions. An analytic hierarchy process approach is utilised to combine multiple decision criteria into a single weighting function and to perform a comparative evaluation of the effects of aforementioned criteria on forwarding decisions. Comprehensive simulations are performed in realistic representative urban scenarios with synthetic and real traffic. Insights on the effect of different communication and mobility parameters are obtained. The results demonstrate that the proposed protocol outperforms existing routing protocols for vehicular ad hoc networks, including European Telecommunications Standards Institute (ETSI's) proposed greedy routing protocol,greedy traffic aware routing protocol and advanced greedy forwarding in terms of combined packet delivery ratio, end-to-end delay and overhead. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS

position-based routing; vehicular ad hoc networks; cross-layer design; analytic hierarchy process

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1. INTRODUCTION

The rapid increase in the number of vehicles over the last decades has resulted in growing concerns about the adverse environmental impacts and safety issues in land transport systems [1]. Thus, intelligent transport systems (ITS) have emerged as promising solutions for the future effective and environment friendly transport systems. ITS aim to apply information and communication technologies to improve safety and efficiency as well as the passenger experience in modern transport systems. It is envisaged that dynamic vehicular networks, particularly vehicular ad hoc networks (VANETs), will be an important part of the future ITS. Unlike traditional mobile communication networks, VANETs are expected to be highly dynamic and distributed resulting in significant reliability issues for the communication protocols and routing protocols in particular. Motivated by this demand, this paper investigates the effects of different parameters on forwarding decisions and proposes an efficient distributed position-based routing protocol for VANETs.

1.1. Motivation and contributions

Several position-based unicast routing for VANETs have been proposed (Section 2) that can be categorised as follows: (i) greedy [2,3]; (ii) mobility assisted [4–10] or (iii) cross-layered [11–14]. However, simple greedy approaches do not perform well in dynamic networks such as VANETs, because of the presence of *local maximum* problem as explained later. Although algorithms that take into account mobility information improve the performance of the protocol in terms of received packets, they increase communication information exchange requirements. In addition, it is known that exploitation of cross-layer information can improve the performance of routing protocols. To the best of our knowledge, existing proposals do not consider the aforementioned factors within a coherent framework nor investigate the effects of communication and environment parameters on forwarding decisions, as discussed in detail in Section 2.

Therefore, herein, we propose a novel cross-layer, weighted, position-based routing (CLWPR) protocol, for vehicular environments. By employing cross-layer information from physical (PHY) and data link (MAC) layers, the proposed algorithm is able to estimate the link quality, which is then exploited by the routing algorithm. Moreover, information about node's position, speed and direction are used by a prediction scheme to increase position information accuracy. In addition, an adaptive 'HELLO' message exchange mechanism among neighbour nodes is adopted to reduce the signalling overhead required from the routing process. Navigation information, regarding the roads that vehicles are travelling, and direction are also considered in the forwarding selection in order to reduce end-to-end delay (E2ED). To cope with frequent link failures and network segmentations, mainly in sparse networks, a *carry-and-forward* mechanism is employed. To investigate the effects of the aforementioned parameters, an analytic hierarchy process (AHP) [15,16] approach is adopted in our proposed protocol for making routing decisions. Comprehensive performance analysis of the proposed routing protocol in a benchmark scenario [17], as well as in real city scenario [18] with realistic propagation model [19] is carried out in an NS-3 simulation environment. It is demonstrated that the proposed approach results in significant advantage in terms of packet delivery ratio (PDR) and communication overhead, without compromising E2ED despite a caching mechanism is employed.

The contributions of this paper can be summarised as follows:

- A novel and effective position-based routing protocol is proposed that takes into account all the major network and environment parameters from PHY, MAC and network layers. This work accounts for node reliability and the effect of carry-and-forwarded messages. These indicators have not been previously considered despite their significance in highly dynamic VANETs.
- AHP is employed to optimally combine multiple decision criteria involved in a fast forwarding mechanism with minimum computation overhead. This results in both qualitative and quantitative findings for the effects of mobility, link quality and node utilisation related information in forwarding decisions.
- Comprehensive performance analysis in representative urban scenarios is performed that takes into account realistic propagation models and real city scenario traffic.

To the best of our knowledge, this is the first time where the effects of multiple parameters (communication and environment related) on the performance of routing in VANETs are examined in a systematic framework.

1.2. Structure of paper

The remainder of the paper is organised as follows. Section 2 presents related work on routing protocols for VANETs. In Section 3, the system model and background information for vehicular communications are presented. Moreover, propagation models designed for simulation of urban vehicular communications are presented in this section. Section 4 proposes and analyses our routing protocol, alongside with the formulation of AHP in VANETs scenarios. In Section 5, the impact of communication and environment related parameters on the performance of routing is presented. Moreover, comprehensive simulation study of the proposed protocol and existing state-of-the-art is included in this section. Finally, Section 6 summarised the main conclusions of this paper.

2. RELATED WORK

Position-based or geographic routing protocols have emerged as promising solutions for routing in VANETs. Geographic routing protocols were initially introduced in the 1980s [20], but they were not adopted at the time because of their high cost and inaccuracy of positioning devices. However, with the proliferation of cheap and accurate position systems in the recent years, such as GPS, position-based routing became popular once again. Nowadays, it is standardised in ETSI ITS GeoNetworking [2]. These protocols combine some aspects of proactive routing protocols, where periodic broadcast messages are used for neighbour discovery (with neighbour being a node that can be directly communicated), with some aspects of reactive routing protocols, for discovering the geographical location of the destination nodes. In this section, we discuss some of the proposed routing protocols and their drawbacks. A more complete survey of position-based routing protocols for VANETs can be found in [21].

The basic geographic routing protocols implement greedy forwarding mechanisms based on different position related metrics. For example, in ETSI Greedy Forwarding (ETSI-GF) [2] and greedy perimeter stateless routing (GPSR) [3], a forwarding node sends a packet to the neighbour having the minimum geographical distance to the destination node. But in VANETs, such an approach exhibits poor performance [22]. Geographic routing protocols have an inherent drawback, which is manifested more in greedy forwarding. If the forwarding node is the closest to the destination and the destination node is outside its communication range, the routing protocols suffer a problem known as *local maximum*. There are several solutions to mitigate this problem such as the *perimeter forwarding* mechanism proposed in GPSR and the *right hand rule* proposed in [10], which forward the packet away from the destination increasing the number of hops. On the other hand, *carry-and-forward* mechanism used in [5,8], stores forwarded packets locally at the vehicle and therefore 'forwards' them with the vehicle's speed towards the destination. However, this approach may increase latency. Therefore, it has to be employed with caution and after considering the type of application employed.

In VANETs, where nodes are equipped with navigation systems and the mobility of the nodes is constrained by the road structure, different techniques can be employed to reduce the probability of observing *local maximum* problem. For example, Back-Bone-Assisted Hop Greedy Routing (BAHG) [4], greedy traffic aware routing (GyTAR) [5], Greedy Perimeter Coordinator Routing (GPCR) [10] and Connectivity-Aware Routing (CAR) [9] protocols use 'anchor' points through which packets have to be forwarded. These anchor points could be logical waypoints like the intersections through which packets are forwarded or actual vehicles identified at specific locations. The drawback in these approaches is potential increase in number of hops or network overhead required to identify these points. More sophisticated protocols use information obtained from the neighbour discovery mechanism to select nodes, which not only use the distance metric but also information about the direction of vehicles, optimised GPSR [7] or even predict the position of the neighbouring nodes to make more accurate forwarding decisions, vehicle assisted data delivery (VADD) [8] and Movement Aware Greedy Forwarding (MAGF) [6]. Other methods use information about the vehicle traffic density, for example, GyTAR, to forward packets to more dense road segments in order to increase the probability of finding a suitable next hop. All the aforementioned protocols base the next hop selection only on mobility and location related information and do not consider the effect of communication links or the reliability of the nodes, which can provide significant performance improvement.

More advanced techniques are proposed to take into account the information that can be learned from MAC and PHY layers. Using information about the received signal strength and inter-arrival time of packets at the PHY, authors in [11] proposed the Link Residual Time (LRT) metric. This is an indicator of the remaining time that the specific link can be used for transmission. LRT is 'exposed' to upper layers, such as routing. However, calculating LRT is not trivial requiring intensive signal processing. The advantage of this approach is that it is generic and PHY information can be used by other upper layers. PROMPT [12] on the other hand, is a cross-layer geographic routing protocol, which allows bi-directional information exchange. It is developed for vehicle-to-infrastructure applications and provides the following: (i) delay-aware routing through traffic statistics collected in MAC, and (ii) robust relay selection at MAC layer through mobility information from network. Hybrid location-based routing [13] is an enhancement of Adhoc On Demand Distance Vector-Expected Transmission Count (AODV-ETX), using location-based information. The focus of this protocol is to reduce overhead. Lastly, portable fuzzy constraint Q-learning (PFQ-AODV) [14] is another improvement of AODV. The protocol uses fuzzy logic to evaluate whether a wireless link is good or not by considering multiple metrics, which are, specifically, available bandwidth, link quality and relative vehicle movement.

3. BACKGROUND AND SYSTEM MODEL

In this section, we give a brief description of the system model architecture for vehicular communication systems, using as an example the framework for the DRIVE C2X project [23]. We present location services that can be used to find the geographical position of the destination. Finally, we discuss the relevant propagation models that capture the unique characteristics of vehicular communications.

3.1. System architecture

The reference architecture of communication protocols stack for vehicular communications is specified for DRIVE C2X in [24] in accordance with the ETSI specifications [25] and is depicted in Figure 1(a). The work presented in this paper relates to the network and access layers of this architecture. Most often the access layer is based on the PHY and MAC specifications of the IEEE 802.11p standard for ad hoc communication. However, 3G technologies can also be used for applications, management and testing purposes communicating with infrastructure. Additionally, GPS and sensor equipment are used to provide position

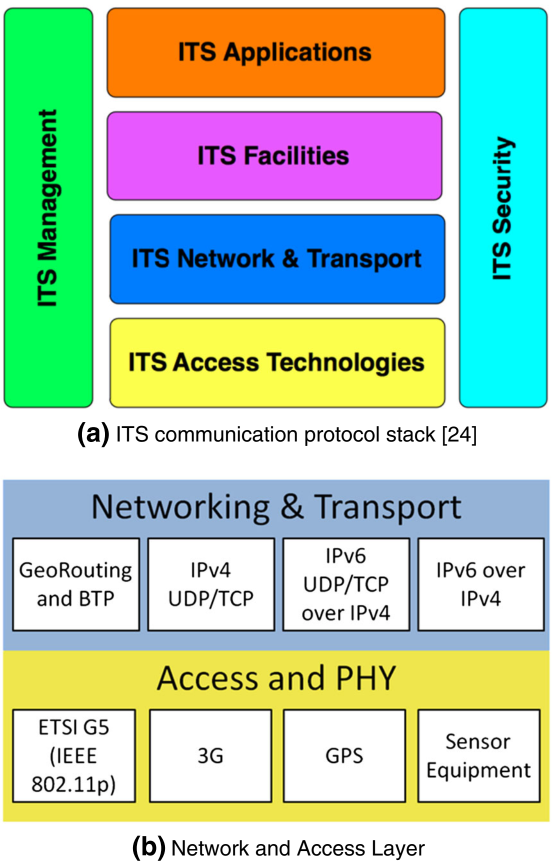

Figure 1. Intelligent transport systems (ITS) reference architecture (a) and Network layer and access layers (b).

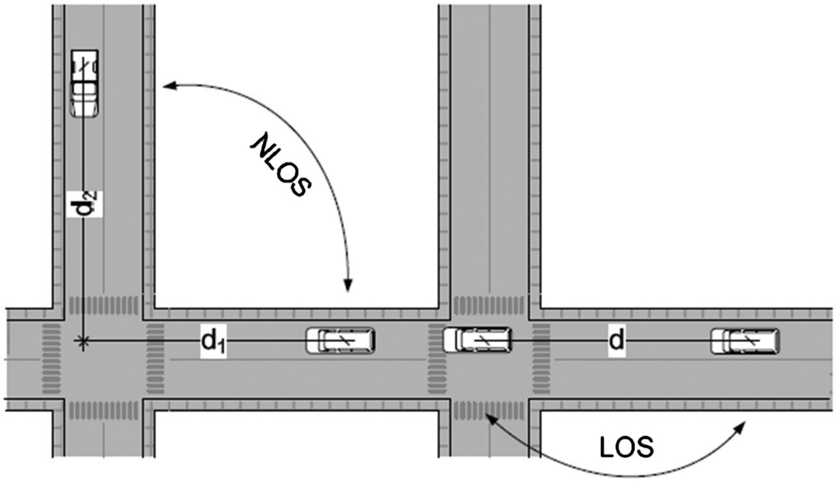

Figure 2. Propagation in urban scenarios with line-of-sight (LOS) and non-LOS (NLOS) components [19].

information and interface to real world. Networking and transport layers play a key role in the system because they are responsible to handle reliable delivery of messages across the network. These layers implement a number of functionalities, which are shown in Figure 1(b). User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) can be used for transport layer protocols. The basic transport protocol [26] is a UDP-like transport protocol commonly used with geographic routing. In addition, ITS specific transport protocols have been designed to cope with the characteristics of vehicular traffic, for example, vehicular transport protocol (VTP) [27] and Vehicular Information Transfer Protocol (VITP) [28]. Network layer implements functionalities such as routing, addressing, mobility management and other. Position-based routing is usually used for ad hoc communications among vehicles and roadside units (RSUs) and relies on geo-addressing scheme as specified in [2]. In addition, geo-addressing requires a 'translation' mechanism from IP addresses to geo-networking addresses. This is usually done by a GeoNetworking IPv6 Adaptation SubLayer [29]. In position-based routing protocols, each node maintains a local database which stores the position of its neighbours that is learnt through the neighbour discovery mechanism. Moreover, position-based routing relies on a location service to identify the position of a destination node. Each node can determine its own location and get navigation information from the facility layer in Figure 1(a). Finally, an important part of system's architecture, which spans alongside all layers, is security. The security requirements include aspects such as data integrity, authentication and privacy, as well as detection and resilience against attacks. The security mechanisms for the proposed system architecture are described in [30].

3.2. Location services

Location Services can be implemented in a distributed manner through collaboration of network nodes or in a centralised manner similar to the mobility management mechanism in cellular networks. Approaches like Distance Routing Effect Algorithm for Mobility (DREAM) [31], Location Aware Routing (LAR) [32] and ETSI Location Service (ETSI-LS) [2] flood the entire network with either position updates or queries, which causes severe network performance degradation. Alternatively, rendezvous-based LS select a number of special nodes that serve as location service providers. In these schemes, the location updates and queries are not broadcasted to every node, but they are directed to the location server nodes. A novel LS for VANETs is Region-based Location Service Management Protocol (RLSMP) [33], which utilises mobility patterns to increase scalability and employs message aggregation for reduced overhead in querying. Finally, Mobile group-based location service management (MG-LSM) [34] also uses mobility information to group nodes travelling in the same direction and assigning one of them as the location server. This ensures a longer lasting association of a node with a single server, therefore, reducing the signalling overhead.

3.3. Propagation models

In the previous section, we discussed the importance of PHY and MAC layer information in order to predict the link quality for cross-layer schemes. Because of the high cost of field experiments, research is primarily based on simulation evaluations. Therefore, proper care should be taken to model the channel characteristics. In VANETs, there are two types of propagation environments: highway and urban environments. In highway environment, nodes move mostly in straight lines, and usually a line-of-sight (LOS) model is sufficient. The challenge here is to model the Doppler effect caused by the high vehicles' speeds. In urban environments, on the other hand, the main challenge is to accurate model the obstacle-effect from buildings and other vehicles. Vehicles often do not have LOS with each other. An analytical model for the urban environments is presented in [35] that takes into account both LOS and non-LOS components of the signal (Figure 2). Extensive field trials have been performed in the *WINNER-II* project, where a series of vehicular scenarios are defined, and the appropriate channel models for link and system level simulations are investigated [19].

4. CROSS-LAYER, WEIGHTED, POSITION-BASED ROUTING

In this section, we propose a routing protocol named *CLWPR*. This section comprises four subsections with Section 4.1 describing the proposed routing protocol design. Then, Section 4.2 explains the operation of CLWPR with the aid of an example. Section 4.3 discusses the routing metric that is used for forwarding function. Finally, Section 4.4 specifies of the AHP approach used in this paper.

4.1. Protocol design

CLWPR is a distributed unicast, multi-hop, cross-layer protocol based on opportunistic forwarding. Unlike reactive routing protocols, it does not rely on route discovery. The selection of the next hop, during the forwarding process, is performed based on calculation of a decision metric for all neighbour nodes, called *weight* in this paper. The forwarding algorithm at the heart of the proposed routing protocol can be visualised with the flowchart in Figure 3. The algorithm first checks if the destination's position information is known. If not, a request is sent to a location service. When the information becomes available, the node calculates the weight of all its neighbours based on local information (neighbour list), as it will be described in Section 4.3. If the forwarding node faces the *local maximum* problem, namely it has the least *weight* among its neighbours, the packet is stored locally until a neighbour with less *weight* is found or until a timer expires. The forwarding algorithm relies on the neighbour discovery mechanism, which is based on one-hop 'HELLO' messages that every node periodically broadcasts. As summarised in Table I, these messages include positioning information (position, velocity) of the broadcasting node, the node's MAC related information and the number of cached packets due to *local maximum*. Each node updates its local list of neighbours with the information learnt from these messages. In addition, upon receipt of a 'HELLO' message, a node calculates the Signal to Interference and Noise Ratio (SINR) value of the received message and stores it with the rest neighbouring information. Then, it counts the consecutive 'HELLO' messages received from the same neighbour, as an indicator of neighbour reliability. In order to reduce the overhead of these broadcast messages, CLWPR employs a dynamic broadcasting scheme where the inter-arrival of the packets varies according to vehicle's speed. The information used for forwarding purposes comprises of three basic components: mobility, link quality and node utilisation.

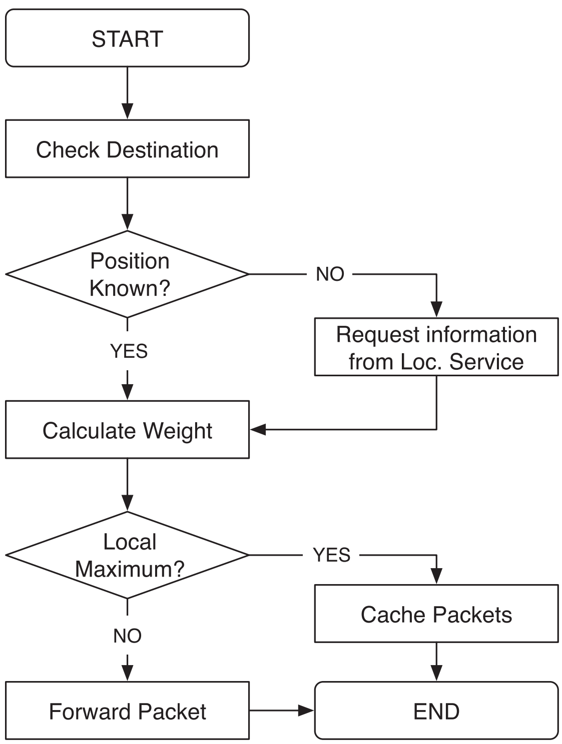

Figure 3. *Cross-layer, weighted, position-based routing* forwarding algorithm.

Table I. HELLO message information.

Information carried	Description
Node position	The position coordinates (x,y)
Node velocity	The velocity coordinates (x,y)
MAC frame error rate	The average number of collisions in unit of time
C'n'F indicator	The number of cached packets due to *local maximum* problem

4.1.1. Mobility related information.

Unlike greedy forwarding policies and other position-based protocols [2,3,8,18], CLWPR does not calculate the minimum geographic distance between two nodes. Instead, it determines the actual distance that a vehicle would have to travel in order to reach the destination, called *curvemetric* distance in this paper. The motivation for this design decision originates from the fact that the nodes are vehicles, and as such, their movement is restricted within the read boundaries. Packets have to be forwarded alongside roads to avoid propagation obstacles, such as buildings, that might block the direct path among communicating nodes. Thus, the distance of two vehicles is better described by the distance based on the road network layout rather than their minimum geographical (Euclidean) distance. In contrast to other protocols in [4,5,9,10], CLWPR does not use 'anchor' nodes at intersections like protocols through which a packet has to be forwarded; thus, it reduces the overhead for identifying these nodes. In order to be able to calculate the *curvemetric* distance, electronic maps should be available from the vehicles; for example , navigation systems. Then, the road that a vehicle is travelling on can also be identified. As discussed, when a message forwarded along the road that the destination is travelling, we maximise the probability to have LOS communication. Such a selection is performed close to junctions where more vehicles can be accessed. Then, those vehicles travelling along destination's road and approaching it are preferred. Finally, more frequent 'HELLO' messages can provide more accurate and up-to-date information of a node's position. However, such an approach increases network overhead. In our protocol, we use the information gathered from 'HELLO' messages, such as position, speed and heading (extrapolated from the velocity vector), to predict future positions of a node in order to reduce the frequency of broadcasted 'HELLO' messages. In addition, a dynamic broadcasting scheme is proposed where the interval varies with vehicle's velocity to further reduce overhead.

Dynamic 'HELLO' broadcast scheme: Most of the existing broadcasting schemes have fixed, very short period which results in increased overhead. Less frequent broadcasts in high vehicles' speeds, on the other hand, decrease network performance. We have analysed this in [36], where a prediction mechanism was used to cope with the poor performance with respect to PDR. To adjust broadcasting period to vehicle speed, we propose a dynamic broadcast scheme, where the period varies between a maximum rate, when vehicles travel faster than a certain maximum speed, and a minimum rate for nodes travelling slower than a certain minimum speed. One way of obtaining this is by using a step function-based approach as in (1). As a result, there is a minimum and a maximum HELLO broadcasting period and values between them determined by the selected granularity.

$$\text{HELLO Period} = P = \begin{cases} P_{min}, \text{ if } V \le V_{min} \\ P_{min} + i \cdot Thr, \text{ if } V_{min} + i \text{ step} < V \le V_{min} + (i+1) \text{ step}, \\ P_{max}, \text{ if } V > V_{max} \end{cases} \quad (1)$$

where threshold (*Thr*) can be calculated depending on the number of steps i (granularity) we want to use.

4.1.2. Link quality related information.

Because the communication links in vehicular environments are highly variable and perhaps short lived due to the dynamic nature of the network, cross-layer information from PHY and MAC layers will help select more reliable forwarding nodes. However, the cross-layer approaches discussed in Section 2 are not suitable for all VANETs scenarios because they rely on existence of infrastructures (e.g. [12]) or require complex calculations (e.g. [11]). Therefore, assuming channel reciprocity, we propose to use the SINR value of the received 'HELLO' messages as a metric of link quality. Moreover, we use the MAC layer errors, for example, contention errors, as another metric that will contribute to further increase the reliability of our routing protocol. Finally, the number of consecutive received 'HELLO' messages is used as an indicator of neighbour node reliability.

4.1.3. Node utilisation related information.

As mentioned in Section 2, geographical routing protocols suffer from the *local maximum* problem, especially in low density networks. This is also the case with CLWPR. We address this problem by adopting a *carry-and-forward* mechanism. This selection is based on the fact that, in VANETs, neighbour nodes vary frequently due to the high and constraint mobility. Such updates may result in new nodes that solve the *local maximum* problem. Therefore, it is preferred to cache the packet shortly than start a recovery mechanism like perimeter routing that would forward the packet away from the destination or drop the packet. This will occasionally result in higher E2EDs. However, in order to reduce the effect of caching packets locally, we 'penalise' those nodes with extra weight related to the number of cached packets.

4.2. Cross-layer, weighted, position-based routing operation with an example

An example demonstrating CLWPR forwarding algorithm can be viewed in Figure 4. In this example, there is one source (S) and two destination ($D1$ and $D2$) nodes. We assume that every node knows the position of the destinations through a location service mechanism and its neighbours through the 'HELLO' message exchange mechanism as listed in Table II. When S wants to sent a packet to either destinations, it looks into its neighbour list. If the Euclidean distance was used, S would be selected for $D2$ and B selected for $D1$. In both cases, such selection would not be efficient due to the *local-maximum* problem already discussed. With the use of *curvemetric* distance, however, node A will be selected without having to identify intersections and anchor points. The next hop selection from node A towards both destinations will be one of nodes C and D, which both have the same *curvemetric* distance. Because node C moves towards the destinations, whereas D is travelling away, it is preferred as the second hop.

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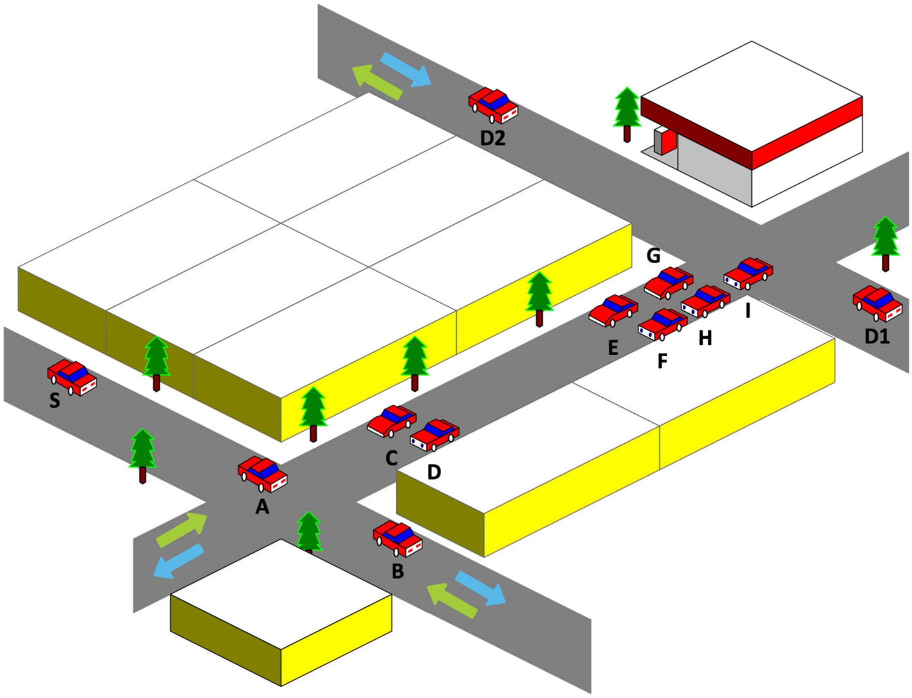

Figure 4. *Cross-layer, weighted, position-based routing* forwarding algorithm example.

Table II. Neighbour list for scenario in Figure 4.

Node ID	Neighbours ID
S	A , B
D1	G , H, I, D2
D2	G , H, I, D1
A	S, B, C, D
B	S, A, C, D
C	A, B, D, E, F, G, H, I
D	A, B, C, E, F, G, H, I
E	C, D, F, G, H, I
F	C, D, E, G, H, I
G	D1, D2, C, D, E, F, H, I
H	D1, D2, C, D, E, F, G, I
I	D1, D2, C, D, E, F, G, H

Then, node C will have to select the next-hop for the destinations among nodes $E - I$. Node I is the closest node to $D1$ but at the edge of the communication range of C, and therefore, it has a high probability of dropping a packet. In addition, this high traffic intersection will cause high contention among the nodes, so proper caution should be taken in the next-hop selection. For $D1$, the nodes with the least weight will be selected, and the packet will be delivered within four hops. However, $D2$ is out of the communication range of all nodes, which again results in *local-maximum* problem. Therefore, *carry-and-forward* mechanism is employed. If a different recovery mechanism was used (e.g. perimeter routing), packets would be forwarded away from the destination. If, for example, node G is selected as next-hop for $D2$, the packets will need to be cached. To avoid losing packets due to increased data flow to $D2$ and buffer overflow on node G, a different node will be selected when the number of cached packets is significantly increased.

4.3. Weighting function

A forwarding node i computes the *weight* of neighbour node j with respect to routing to destination node k, denoted by $W_{i,j}^{(k)}$, as follows:

$$W_{i,j}^{(k)} = f_M M_{i,j}^{(k)} + f_L L_{i,j} + f_\Gamma \Gamma_j \quad (2)$$

where

- f_X indicates the relative importance of parameter $X \in \{M, L, \Gamma, D, R, P, C, Ma, N\}$ in making forwarding decisions. These factors are calculated using the AHP algorithm as presented in Section 4.4.
- $M_{i,j}^{(k)}$ accounts for the impacts of mobility on routing decisions, given by

$$M_{i,j}^{(k)} = f_D D_{i,j}^{(k)} + f_R R_{j,k} + f_P P_{j,k} \quad (3)$$

where $D_{i,j}^{(k)}$ is the normalised *curvemetric* distance of neighbour j from destination node k, calculated at node i as follows:

$$D_{i,j}^{(k)} = \frac{D_{j,k} - D_{i,k}}{r} \tag{4}$$

Here, $D_{i,k}$ and $D_{j,k}$ are the *curvemetric* distance of forwarding node i and neighbour j from the destination k based on the current position of the corresponding nodes, and r is the nominal communication range of a node. The current position is estimated using the knowledge acquired from the most recent 'HELLO' message and the assumption that the node does not change direction between two consecutive 'HELLO' messages. If neighbour node j and destination node k are on the same road, $R_{j,k} = 0$, and $R_{j,k} = 1$, otherwise. Further $P_{j,k}$ indicates whether node j will be in a closer position or farther position to node k based on their current travelling paths. Assuming that the destination node k is fixed for a certain period of time, $P_{j,k}$ can be quantified by the cosine of the angle θ between the velocity vector of node $j\left(\overrightarrow{V_j}\right)$ and the vector starting at node j towards node k $(\overrightarrow{JK})$ as follows:

$$P_{j,k} = -\cos(\theta) = -\frac{\overrightarrow{V_j} \bullet \overrightarrow{JK}}{||\overrightarrow{V_j}|| \cdot ||\overrightarrow{JK}||} \tag{5}$$

- $L_{i,j}$ represents the link information between forwarding node i and neighbour node j, given by

$$L_{i,j} = f_C CSI_{i,j} + f_{Ma} M_j + f_N NR_{i,j} \tag{6}$$

where $CSI_{i,j}$ represents the quality of the channel between forwarding node i and neighbour node j. M_j indicates the level of contention in the area close to the neighbour node j represented by the average number of collisions, and $NR_{i,j}$ represents the reliability of the neighbour node j. This is calculated based on the number of consecutive 'HELLO' messages that node i received from a neighbour j on expected intervals, denoted by H_c. We choose the following values for $NR_{i,j}$ between zero, which indicates a highly reliable node, and one, which indicates a less reliable node:

$$NR_{i,j} = \begin{cases} 1, & \text{if } H_c \leq 2 \\ 0.5, & \text{if } 2 < H_c \leq 4 \\ 0, & \text{if } H_c > 4 \end{cases} \tag{7}$$

- Γ_j is the ratio of number of *carry-and-forward* packets at node j to the queue size. We take into account this parameter to reduce the chance of selecting next hop nodes that are facing local maximum problem.

Determining a good set of f_X parameters, which will optimise the performance of *CLWPR*, or providing insights of the effects of aforementioned parameters on the network performance, is a non-trivial problem. In this direction, an AHP-based methodology is described in the next subsection, to systemically approach this problem in a typical urban environment.

4.4. Analytic hierarchy process

AHP [15,16] is a general approach that has been used in multi-criteria decision analysis, similar to our approach in Section 4.3. The AHP decomposes the decision problem into elements, according to their common characteristics and hierarchy levels. The top level consists the 'goal' of the problem, and the rest levels correspond to relevant criteria and sub-criteria. AHP is then used to evaluate the relative importance between the criteria. Our AHP-based approach is implemented in three steps, following the methodology in [15].

4.4.1. Description of problem as a hierarchy.

We describe the multi-criteria forwarding decision, defined in (2), with an AHP hierarchy as shown in Figure 5. The goal of our approach is to calculate the *weight* of all individual nodes from the neighbour list and, subsequently, to select the neighbour with the minimum weight. The first level of hierarchy includes the high level decision criteria: mobility, link quality and node utilisation. The second level further expands these criteria into more detailed sub-criteria corresponding to (3) and (6).

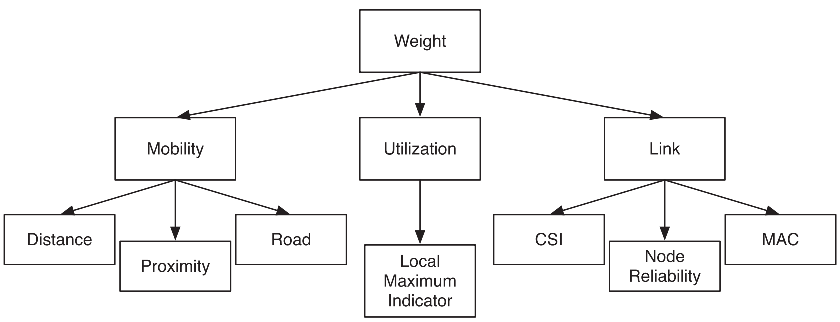

Figure 5. Analytic hierarchy process hierarchy for cross-layer, weighted, position-based routing weighting function.

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Table III. Scales of pairwise comparison.

Importance	Description
1	Equally important
3	Moderate importance
5	Strong importance
7	Extreme importance
9	Extremely more important
2,4,6,8	Intermediate values between adjacent scales

4.4.2. Construction of pair-wise comparison matrix.

The next step is to construct a comparison matrix for each level, denoted by C.

$$C = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,n} \\ c_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ c_{n,1} & \cdots & \cdots & c_{n,n} \end{bmatrix} \tag{8}$$

where n is the total number of criteria as each level, and $c_{i,j}$ represents the relative importance of criteria i to j constrained by the following rules: $c_{i,j} > 0; c_{i,j} = 1/c_{j,i}; c_{i,i} = 1$ for $\forall i$. The exact values of $c_{i,j}$ will be assigned according to the convention in Table III [15]. Note that each row and column of this matrix corresponds to one of the decision criteria given in (2), (3) and (6) in the specific AHP decomposition.

4.4.3. Calculation of f_X parameters.

According to the AHP approach, we first need to normalise the comparison matrix, C, as follows:

$$\overline{c_{i,j}} = \frac{c_{i,j}}{\sum_{i=1}^{n} c_{i,j}} \tag{9}$$

Then, if the f_X parameter, related to criteria X, corresponds to row and column k in our comparison matrix, it can be computed as follows:

$$f_X = \frac{\sum_{j=1}^{n} \overline{c_{k,j}}}{n} \tag{10}$$

5. PERFORMANCE ANALYSIS

In this section, we evaluate the performance of the proposed protocol. There are several metrics that can be used, but the most widely accepted are Packet Delivery Ratio (PDR), End-to-End Delay (E2ED) and overhead introduced by the routing protocol. PDR is calculated as the ratio of delivered data packets against the total number of sent data packets; E2ED is the average E2ED experienced by received data packets. As for overhead, we specify the ratio of the total amount of information used for signalling against the total size the information exchanged in the network.

Our simulation model examines two scenarios. In *Scenario* 1, we consider an urban area consisting of a Manhattan grid road network with 16 intersections, based on the reference area depicted in Figure 4, with edge size 2000 m. This is a well-known benchmark simulation scenario type used in the literature [17]. The mobility traces are generated using the Bonnmotion tool [37] for different vehicles densities within typical speed limits for urban areas (average speed, 50 km/h; standard deviation, 5 km/h). *Scenario* 2 simulates a real city environment with traces obtained from [18] for the urban area of 'Unterstrass' in Zurich (Figure 6). The propagation model in [19] is considered in this paper, which is suitable for both LOS and non-LOS communications. We consider two types of communications, namely Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V). For the first type, we employ a static RSU at the centre of the reference area to act as a server that consumes all the data traffic. For the second type, we assume simultaneous connections between randomly selected moving vehicles. The vehicles and RSUs are equipped with IEEE 802.11p communication units. The nominal communication range of the nodes is 500 m when there is no obstacle in the LOS communications path. We assume an ideal location service, which does not introduce any latency from the requests, in order to evaluate only the delay caused by the routing protocol. The simulation platform we use is NS-3.16, and the outcomes of the simulations are averaged over a set of independent runs. The most important simulation parameters are summarised in Table IV.

The rest of the section is organised as follows. In Section 5.1, we evaluate the impacts of different parameters in (2), (3) and (6) on the performance of the proposed routing protocol using *AHP*. This aims finding the optimal f_X values for *CLWPR*. Then, in Section 5.2, we compare the performance of the optimised CLWPR protocol with that of the ETSI proposal (ETSI-GF) that relies only on Euclidean distances between nodes. We also compare an advanced implementation of greedy forwarding, namely advanced greedy forwarding (AGF) [18], which supports *carry-and-forward* mechanism and a prediction policy (similar to VADD), and GyTAR. Finally, on Section 5.3, we discuss on the findings of the simulation campaign and other issues.

5.1. Impact of forwarding parameters

The use of AHP and particularly by means of the hierarchy structure can group similar parameters, for example, distance, proximity and road, and examine the effect of them as a whole (mobility group) against other groups and individually among the same group. The output we get is not just a set of optimal parameters for our protocol but insights of how such parameters affect the forwarding process. We carry out a number of simulations in order to

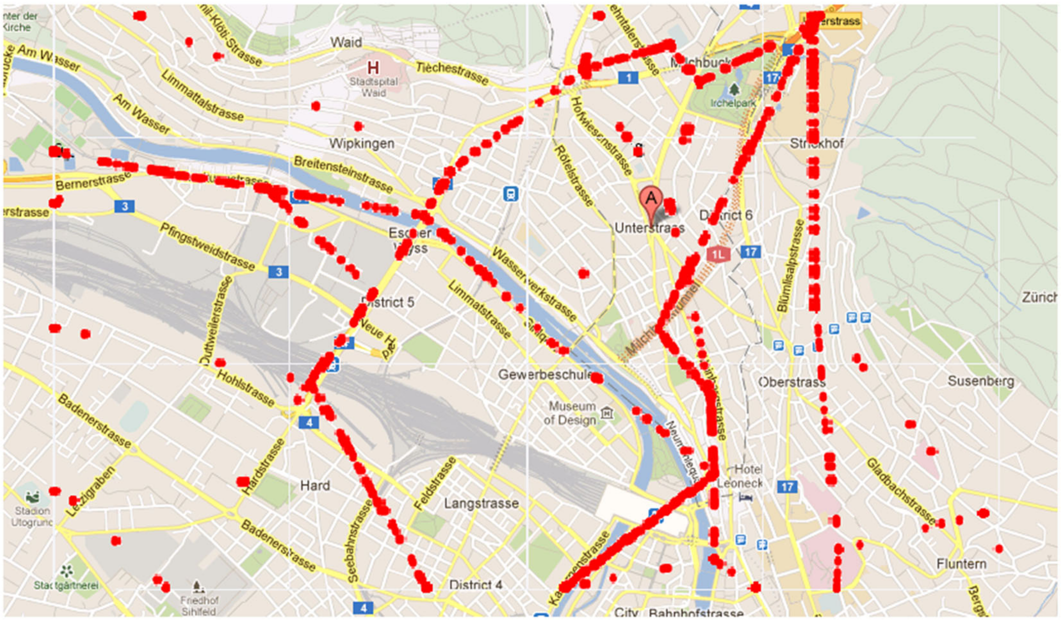

Figure 6. Vehicle traces overlaid on 'Unterstrass' area in Zurich (map taken from maps.google.com).

Table IV. Simulation parameters.

Parameter	Value
Nominal comm. range	500 m (at line-of-sight) [19]
Number/type of Connections	15 UDP, V2V & V2I
MAC/PHY protocol	IEEE 802.11p, 6 Mbps
Routing protocols	CLWPR, ETSI-GF, AGF, GyTAR
HELLO interval	1 s *
Caching limit	5 s

*For CLWPR, it is dynamic from 1 to 3 s.
CLWPR,cross-layer, weighted, position-based routing; AGF, advanced greedy forwarding; GyTAR, greedy traffic aware routing.

find a set of appropriate f_X parameters in (2), (3) and (6) that will optimise the performance of CLWPR for a typical urban area, represented by *Scenario* 1. This type of scenario with frequent LOS/non-LOS transitions poses one of the most adverse environments for a VANET routing protocol. We have performed a comprehensive analysis using an extensive number of configurations in order to suggest the most effective set of f_X parameters. However, because of page limitations, we only present the results for a typical medium density ($\sim$ 10 veh/km) scenario with an average node speed of 50 km/h and standard deviation 5 km/h, assuming V2V communication traffic. The observed trends for other configurations, not presented here, were very similar to those presented in this subsection.

First, we evaluate the impacts of f_M, f_L and f_Γ in (2). This indicates the importance of mobility, utilisation and link quality information in the forwarding decision. Following the AHP methodology, we construct the comparison matrix for these parameters as follows:

$$\begin{bmatrix} 1 & c_{M,L} & c_{M,\Gamma} \\ c_{L,M} & 1 & c_{L,\Gamma} \\ c_{\Gamma,M} & c_{\Gamma,L} & 1 \end{bmatrix} \tag{11}$$

where $c_{L,M}$ represents the relative importance of link quality related information to mobility related information, $c_{\Gamma,M}$ represents the relative importance of node utilisation related information to mobility related information, and $c_{\Gamma,L}$ indicates the relative importance of node utilisation to the link quality related information. These variables take values from the set $\{0.2, 0.33, 1, 3, 5\}$ according to Table III, which reflects the relative importance between pairs of criteria; for example, $c_{L,M} = 5$ means that link related information strongly more important than mobility related information, and $c_{M,L} = 0.2$, vice versa. In other words, the comparison matrix has three independent variables, each with five possible values, thus, giving a total of 125 different combinations. Each of these combinations result in a distinct set of $\{c_{L,M}, c_{\Gamma,M}$ and $c_{\Gamma,L}\}$ parameters. The rest of $c_{i,j}$ parameters are set to one. The main target is to find the combination which result in the best performance for CLWPR, and then compute the corresponding f_X parameters. Figure 7 shows the effects of $\{c_{L,M}, c_{\Gamma,M}, c_{\Gamma,L}\}$ parameters on PDR and E2ED using statistical analysis. It can be seen that there is a correlation between the selected weights and the performance of the protocol. First of all, the results suggest that $c_{L,M}$ and $c_{\Gamma,M}$ should be relatively small, meaning that link and utilisation related information are less important than mobility. In addition, $c_{\Gamma,L}$ should be given a relatively medium/high value. With these considerations in mind, we select the combination $\{0.2, 0.2\ , 3\}$

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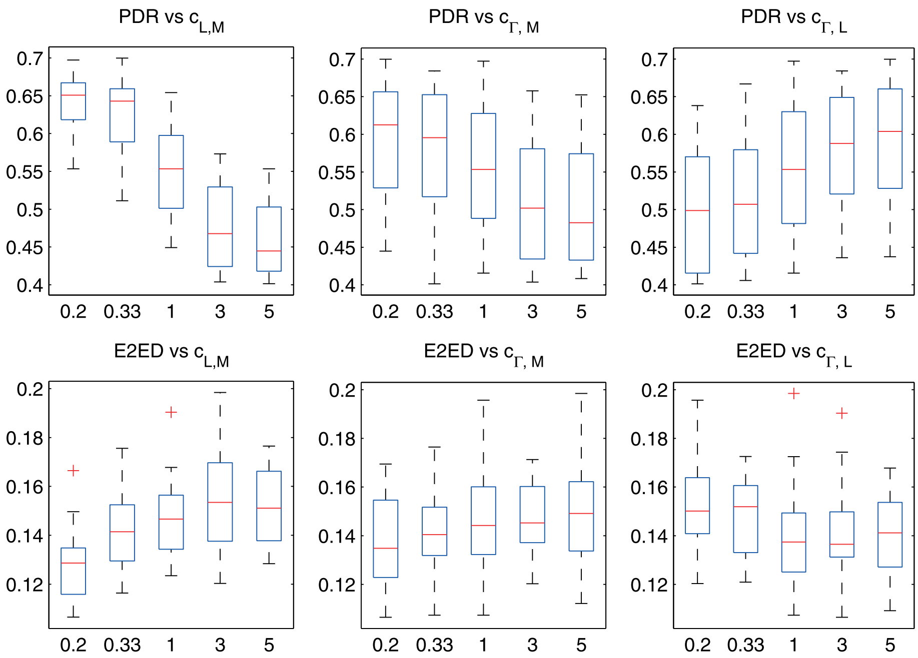

Figure 7. Performance of cross-layer, weighted, position-based routing protocol for different $\{c_{L,M}, c_{\Gamma,M}, c_{\Gamma,L}\}$ parameters. E2ED, end-to-end delay; PDR; packet delivery ratio.

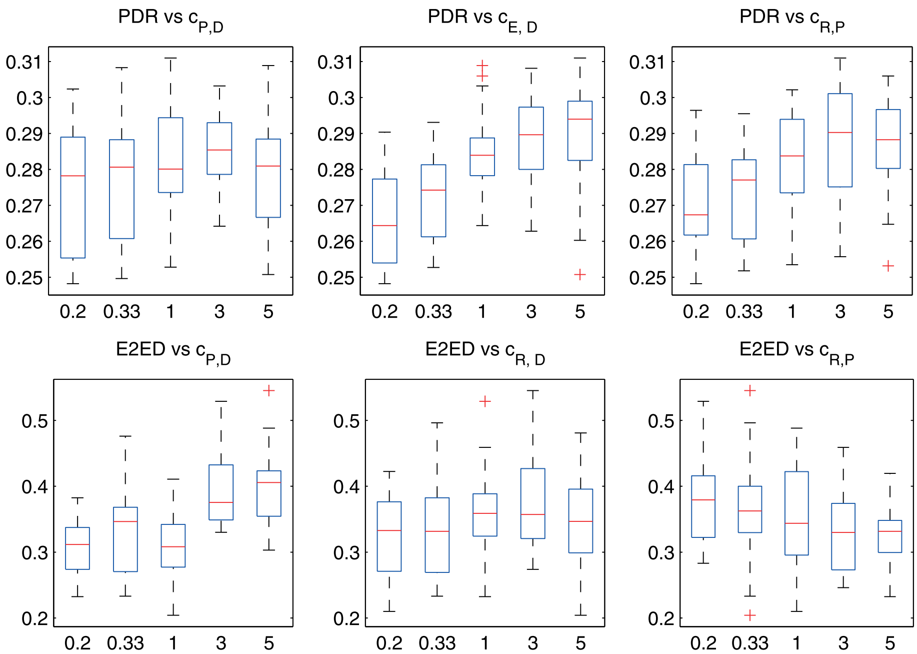

Figure 8. Performance of cross-layer, weighted, position-based routing protocol for different $\{c_{P,D}, c_{R,D}, c_{R,P}\}$ parameters. E2ED, end-to-end delay; PDR; packet delivery ratio.

for the relative importance coefficients. This set suggests that mobility related information is strongly more important than link quality related information ($c_{L,M} = 0.2$) and strongly more important than node utilisation related information ($c_{\Gamma,M} = 0.2$). Furthermore, link quality related information is moderate less important as node utilisation related information ($c_{\Gamma,L} = 3$).

Next, we evaluate the impacts of mobility related parameters f_D,f_R and f_P in (3). The comparison matrix for these parameters is

$$\begin{bmatrix} 1 & c_{D,P} & c_{D,R} \\ c_{P,D} & 1 & c_{P,R} \\ c_{R,D} & c_{R,P} & 1 \end{bmatrix} \quad (12)$$

where $c_{P,D}$ represents the relative importance of proximity related information to distance, $c_{R,D}$ represents the relative importance of road related information to distance, and $c_{R,P}$ the relative importance of road related information over proximity related information. Similar to the previous evaluation, these variables can take values from the set $\{0.2, 0.33, 1, 3, 5\}$, whereas the rest parameters are set to one; thus, another set of 125 distinct combinations is formulated. The results of these simulations are presented in Figure 8 together with the statistical limits. In this set, the selection is not clear; however, our approach is a performance trade-off between PDR and E2ED metrics. In other words, there might not be obvious difference for PDR versus $c_{P,D}$, but there is for E2ED. Similarly for the other parameters, the corresponding selected $\{c_{P,D}, c_{R,D}, c_{R,P}\}$ set is $\{1, 5, 3\}$, which suggests that proximity information is equally important as distance related information ($c_{P,D} = 1$), and moderate less important than road- related information ($c_{R,P} = 3$). Road related information on the other hand is more important than distance related information ($c_{R,D} = 5$).

Following the same approach, we evaluate the impact of link quality related factors, f_C,f_{Ma} and f_N on (6). We formulate the comparison matrix:

$$\begin{bmatrix} 1 & c_{C,M_a} & c_{C,N} \\ c_{M_a,C} & 1 & c_{M_a,N} \\ c_{N,C} & c_{N,M_a} & 1 \end{bmatrix} \quad (13)$$

where $c_{Ma,C}$ represents the relative importance of MAC to CSI related information, $c_{N,C}$ represents the relative importance of neighbour reliability to CSI related information, and $c_{N,Ma}$ is the relative importance of neighbour reliability to MAC related information. Keeping the other parameters to one, we set each parameter to have a value from the set $\{0.2, 0.33, 1, 3, 5\}$. Based on the similar analysis (with the results not shown due to page limitations), we conclude that the optimal configuration set is $\{0.33, 0.2, 0.2\}$. This means that MAC related information is less important than CSI related information ($c_{Ma,C} = 0.33$) and moderate more important than neighbour reliability ($c_{N,Ma} = 0.2$). CSI related information is moderate more important than neighbour reliability ($c_{N,C} = 0.2$).

Table V. Optimal values for cross-layer, weighted, position-based routing parameters.

Parameter	Value
f_M	0.0897
f_L	0.6070
f_Γ	0.3033
f_D	0.4796
f_P	0.4055
f_R	0.1150
f_C	0.1019
f_{Ma}	0.2121
f_N	0.6860

Finally, using the three sets for each group of relative importance parameters, we can calculate the set of optimal values for the f_X parameters using (10), as shown in Table V. It is noted that the results in this subsection also demonstrate the effects of different parameters on the performance of the forwarding mechanism. This reveals an important shortcoming of the existing works presented in Section 2; they only consider mobility related information in the forwarding mechanism. Mobility is found to be the most important parameter, however, others play non-negligible role. In addition, our simulation results indicate that when a realistic propagation model is considered, link quality related information such as SINR becomes important, similarly to mobility related information. Therefore, for efficient next-hop selection, it is not sufficient to consider only mobility information, but link quality and node utilisation is also needed.

5.2. Comparison with ETSI-GF, advanced greedy forwarding and greedy traffic aware routing protocol

With the optimal values for CLWPR identified in the previous subsection, we compare its performance against ETSI-GF, AGF and GyTAR. Our simulation scenarios comprise of low, medium and high vehicle densities of approximately 5, 10 and 20 veh/km, respectively.

Scenario 1. (Manhattan grid scenario with synthetic traffic). Figures 9 and 10 compare the performance of the aforementioned protocols in terms of PDR, E2ED and overhead for V2V and V2I connections. CLWPR is shown to outperform the other protocols with respect to PDR (up to $\sim 20\%$) and overhead (up to 50%), while it has the lowest E2ED among protocols employing *carry-and-forward* (up to $\sim$ 10%). While ETSI-GF has the lowest E2ED because it does not cache packets, it also has the lowest PDR and highest overhead compared with the other protocols. AGF takes advantage of *carry-and-forward* mechanism and position prediction to increase PDR, which results in relatively high E2ED. On the other hand, GyTAR is able to achieve higher PDR, lower E2ED and lower overhead than AGF because of the use of traffic information. However, it is the combined criteria used by CLWPR protocol that assist to further increase PDR (up to $\sim$ 10%) and reduce the negative effect of *carry-and-forward* mechanism on E2ED (up to $\sim$ 10%). In addition, cross-layer optimisation allows CLWPR to select more resilient nodes that reduce the probability of retransmissions and reduce E2ED. Finally, the dynamic 'HELLO' message exchange employed in CLWPR significantly reduces overhead compared with fixed broadcast interval in the rest protocols (up to 50%). The performance of all protocols is slightly improved for *V2I* communications scenarios as shown in Figure 10. This is due to the presence of fixed points

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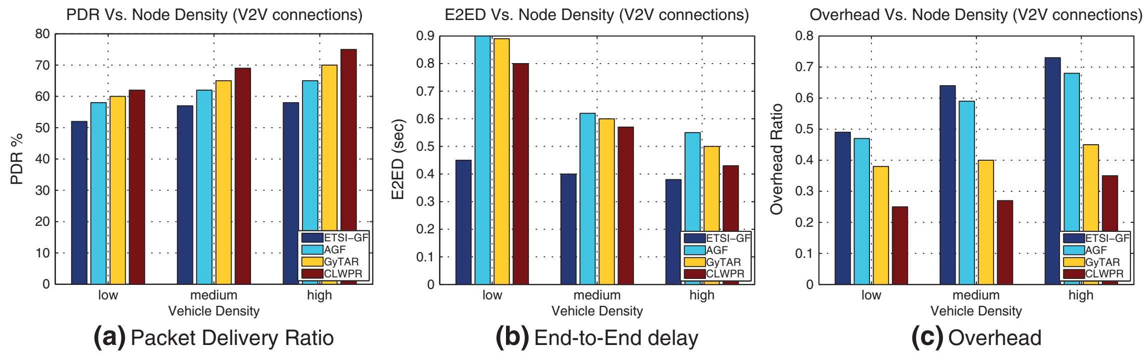

Figure 9. Performance comparison with V2V connections (*Scenario 1*). PDR; packet delivery ratio; E2ED, end-to-end delay; AGF, advanced greedy forwarding; GyTAR, greedy traffic aware routing protocol; CLWPR, cross-layer, weighted, position-based routing.

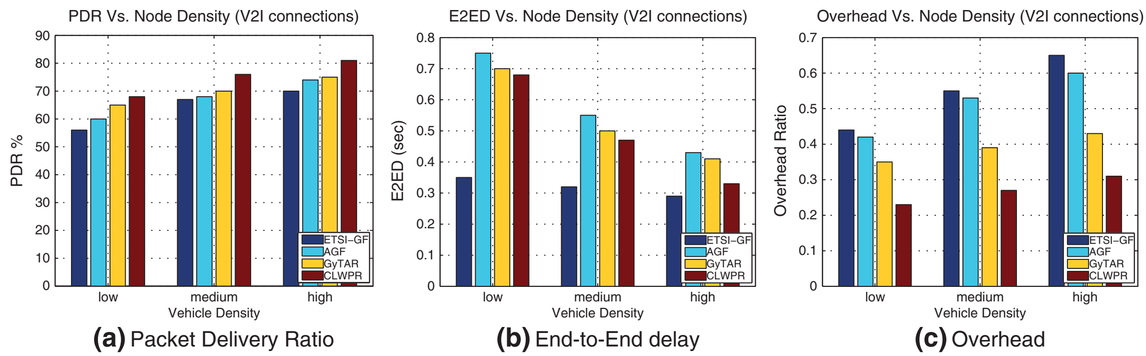

Figure 10. Performance comparison with V2I connections (*Scenario 1*). PDR; packet delivery ratio; E2ED, end-to-end delay; AGF, advanced greedy forwarding; GyTAR, greedy traffic aware routing protocol; CLWPR, cross-layer, weighted, position-based routing.

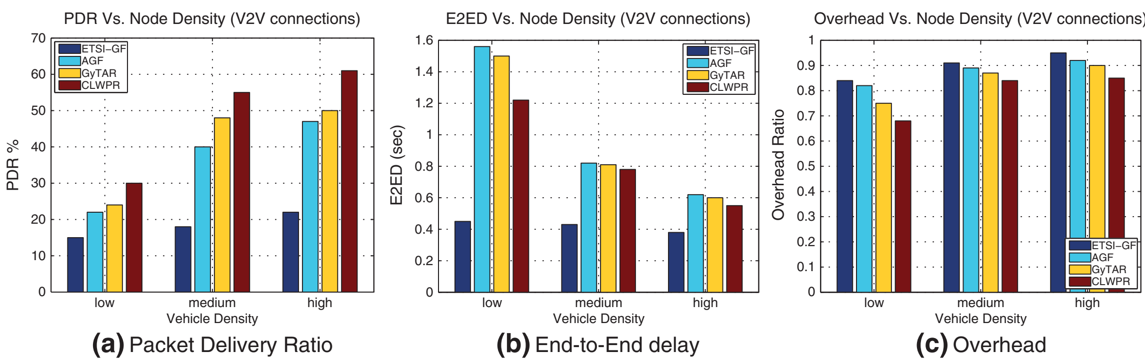

Figure 11. Performance comparison with real scenario with V2V connections (*Scenario 2*). PDR; packet delivery ratio; E2ED, end-to-end delay; AGF, advanced greedy forwarding; GyTAR, greedy traffic aware routing protocol; CLWPR, cross-layer, weighted, position-based routing.

resulting in less frequent path changes compared with moving destinations.

Scenario 2. ('Unterstass' city scenario with real traffic). This scenario simulates a large scale real city scenario (Figure 6), where the effect of *local maximum* problem is stronger. This is manifested by the relatively low PDR of ETSI-GF protocol and the relatively high E2ED in protocols with *carry-and-forward* mechanism (more cached packets) Figure 11. In addition, the average number of hops is significantly larger than those in *Scenario* 1 due to the longer distance between the end nodes in the flows, which increases E2ED. Furthermore, in this scenario, the overhead is substantially increased because of the higher number of nodes. Nevertheless, the trends in the results are similar to *Scenario* 1; CLWPR exhibits the highest PDR (up to 40%) and lowest overhead in general (up to ∼20%), while it has the lowest E2ED among the protocols with *carry-and-forward* mechanism.

5.3. Further discussion

As presented in the previous subsection, we use an AHP approach to tune the important parameters of the proposed protocol. The outcome is twofold: first, the optimised CLWPR protocol demonstrates significant advantages in performance over ETSI-GF, AGF and GyTAR protocols. Second, the insights we gain about the effects different environmental and communication parameters have on the performance of routing. From the results, it is concluded that mobility related information is not the only parameter to be accounted for in forwarding, buy a cross-layer approach should be considered. The proposed framework is evaluated using a fixed set of parameters, optimally adjusted for the two scenarios. However, dynamic f_X parameters could be used depending on the situation and should be re-adjusted based on additional information learnt by the system, like traffic information. Nevertheless, this would incur to additional overhead and complexity, which the current framework aims to minimise. With respect to complexity, the proposed protocol is based only on local information acquired by the neighbour discovery mechanism with relatively simple mathematical calculations. In addition, the use of *carry-and-forward* keeps the complexity low, compared with other recovery mechanisms, such as the perimeter forwarding that needs to calculate planar graphs.

Finally, with respect to the security and privacy issues concerned to the inherent ad hoc and broadcast nature of the protocol, CLWPR as well as most position-based routing protocols rely on location service to provide them with the position information of the destination. There is a possibility of malicious attacks, which is related to this process, that could potentially undermine the system by providing false information; thus, diverting the traffic away from the destination. Additionally, broadcasting periodically 'HELLO' messages imposes privacy concerns. Both of these issues are covered in principles by the security architecture proposed in [30] with the help of security authorities that provide and verify pseudonyms to the users, that is, vehicles.

6. CONCLUSION

In this paper, we present a comprehensive study of the performance of routing protocols in distributed vehicular networks, and we propose a novel and efficient routing protocol for VANETs. It considers mobility and cross layer information from PHY and MAC layers, in a joint weighting function in order to make effective forwarding decisions. With the help of AHP, we optimise the relative weight assignment of the weighting function components, in order to enhance the performance of CLWPR. The performance analysis suggests that mobility related information is not the only criteria that should be considered in making forwarding decisions; link quality and utilisation related information are also important. The comparison of the proposed protocol with the greedy forwarding algorithm proposed by ETSI, an advanced greedy forwarding algorithm, and GyTAR shows that the *carry-and-forward* mechanism as well as a prediction policy can increase PDR (up to 40%) with the cost of increase in E2ED. However, the use of cross-layer information can reduce the impact of caching on delay (up to 10%) and further increase PDR. Finally, dynamic broadcast should be considered in order to cope with overhead, which can potentially be halved.

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APPENDIX A: CSI FUNCTION

The selection of channel quality function is based on the characteristics of message dissemination. Interference is relatively high in VANETs and nodes that are located close to the border of the communication range experience more adverse phenomena than those being near the centre, with the SINR value of the received messages at the border being smaller. Our approach selects nodes far enough from the source, but within a good communication range of the source node. This is achieved by selecting an appropriate SINR threshold ($SINR_{th}$) for which the weight is minimised. Nodes with lower $SINR$ than $SINR_{th}$ will have higher weight because they are closer to the border and the probability that the message will be dropped is increased. Also, nodes with higher $SINR$ value will have higher weights to give them higher forwarding priorities. We have selected the following CSI function that fulfils our requirements.

$$CSI_{i,j} = \begin{cases} ax^2, & \text{if } \mathrm{SINR}_r \leq \mathrm{SINR}_{th} \\ be^{-x}, & \text{if } \mathrm{SINR}_r \geq \mathrm{SINR}_{th} \end{cases} \tag{A.1}$$

where $a/b = e^{-x}/x^2\big|_{x=(SINR_{th}-SINR_{\min})}$ and x is the difference between the obtained SINR_r value and the lowest SINR at the border of the communication ($\mathrm{SINR}_{\min}$).

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