Time-controlled Neighborhood-driven Policy-based Network Selection Algorithm for Message Dissemination in Hybrid Vehicular Networks

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Abstract: In vehicular ad hoc networks (VANETs), successful delivery of GeoUnicast and GeoBroadcast packets depends on scenario-specific aspects like vehicle density, distribution of vehicles on the road and type of the environment (e.g., urban, rural). These aspects can significantly influence the reliability of the connection between communication parties making traditional ITS-G5 based ad hoc networks unreliable. The absence of communication partners in range, long transmission distances, non-line-of-sight (NLOS) conditions are just a few examples that could hinder ITS-G5 transmissions. In this paper, we propose a Hybrid Policy-based Network Selection Algorithm that uses LTE to strengthen and complement ITS-G5 under critical conditions in which successful transmission over the ad hoc network is highly unlikely. The main objective is to use as less LTE transmissions as possible whilst maintaining high Packet Delivery Ratio (PDR) within defined delay constraints. The results, which are derived from extensive simulation campaigns, show a clear advantage of using the hybrid scheme over solely ITS-G5 or LTE.

1 INTRODUCTION

Information timeliness and reliability are key for V2X message distribution, however catering for different Intelligent Transport System (ITS) application classes and their diverse communication requirements is not possible using a single wireless access technology. Strengths and shortcomings of the enabling technologies namely ETSI ITS-G5 and LTE for hybrid networks used in the scope of this work, were analyzed extensively in literature (5G-PPP, 2015) (Araniti et al., 2013). ITS-G5 (ETSI, 2013) which is the de facto standard for V2X communication in Europe allows low-latency communication in quickly changing network topologies, but it has some drawbacks due to its shared medium characteristics, transmission range limitations and network fragmentation issues that could arise when the penetration rate of ITS-G5 equipped vehicles is under a certain threshold (5G-PPP, 2015). LTE on the other hand provides wide coverage thanks to its high market penetration rates so it can be used to bridge communication gaps in low density scenarios or enable communication in challenging ones e.g., intersections where NLOS conditions exist however, it has some shortcomings related to message transmission latency. Necessity of all transmitted messages to pass through the infrastructure, random access procedure and mode switching from idle to connected could create considerable delays (Araniti et al., 2013). Moreover, it can suffer from packet loss due to fading for fast moving vehicles. As a result, provisioning of concepts for intelligent radio access technology selection in a multi-networking environment by combining the strengths of ad hoc and infrastructure-based networks becomes necessary in order to better fulfill application Quality of Service (QoS) requirements. Therefore for ITS stations capable of hybrid communication, it is significant to select the most appropriate technology/technologies for message dissemination.

In this work, we propose a policy-based network selection algorithm that aims to determine the optimal communication technology on a per-packet basis based on identified context indicators and predefined policies. The main design goal and philosophy behind the algorithm is to enable the cooperation of both ad hoc and cellular radio technologies with the aim of providing application transparent geolocalized message dissemination over ITS-G5 and LTE so that improved QoS will be provided to applications while keeping the LTE footprint low. Limiting LTE usage is important since in typical V2X scenarios where a large number of small packets are being exchanged with high frequencies, the excessive usage of this technology might become costly and lead to cellular network congestion (Araniti et al., 2013). We focus on geographical (position-based) networking since ETSI ITS GeoNetworking is the network layer protocol standardized for ITS in Europe. Furthermore, addressing of nodes based on their location (geo-broadcast) is beneficial for many ITS use cases (ETSI, 2010) e.g., informing the following vehicles about a sudden braking maneuver.

The algorithm operates on the network layer (corresponding to the ISO/OSI layer 3) of the ETSI ITS protocol stack. Delegating this task to the network layer enables coordinating multiple applications. Moreover, direct access to the link layer to retrieve real-time performance indicators of the underlying access networks becomes possible. The algorithm will gather requirement indicators from the applications, performance metrics from the link layer and exploit this information combining it with its view of the network conditions that are directly available in the network layer. Using such an approach abstracts applications from the network selection process and provide them an always best informed approach transparently. The downside is that the applications lose direct control over technology selection and message dissemination.

The algorithm was evaluated using a high-fidelity simulation environment comprising of multiple simulators coupled together. Orchestration of multiple simulators for realistic evaluation of vehicular communication protocols is a widely used approach (Kumar et al., 2009) (Sommer et al., 2011b). Two cardinally different scenarios (i.e., Manhattan grid and open highway) were used throughout the simulation campaigns in order to assess the algorithm's performance under different communication environment conditions from a delay restricted packet delivery perspective with an indication on LTE resources usage.

Taking into consideration the results of our work, main advantages of the proposed policy-based adaptive hybrid networking algorithm are:

- Improved QoS to applications
- An increase in path resilience and fault tolerance with low LTE footprint
- Efficient use of available resources (i.e., both intra- and inter-technology optimizations are possible, limitations imposed by a single technology are reduced)
- Higher performance without requiring any modifications at the application level (i.e. application-agnostic)
- Ease of implementation and integration into the ITS environment
- Performance improvements with respect to the identified Key Performance Indicators (KPIs) over individual technologies in all scenarios
- Facilitation in the market introduction for cooperative ITS services (intermittent connectivity due to network fragmentation in the initial deployment phase of ITS-G5 can be overcome by LTE)
- Possibility of extension with future technologies and new services

This article is structured as follows: Section 2 summarizes related work regarding hybrid communication and network selection in the context of vehicular networks. Section 3 describes the hybrid network architecture providing some background information necessary to understand the context in which the proposed algorithm operates. In section 4 we present the policy-based network selection algorithm in detail including the design considerations made, parameters used for decision-making and its control flow. Section 5 describes the simulation toolchain, selected scenarios and network configuration parameters used in performance evaluation. Section 6 presents the evaluation results. Section 7 summarizes the findings and gives an outlook.

2 RELATED WORK

Network selection in hybrid communication environments is a widely researched problem. (Charilas and Panagopoulous, 2010) provides a methodological approach to address this problem by decomposing it into four steps, namely selection of the parameters that should be considered in the process, collection of the values for the selected criteria, estimation of importance of each parameter by weight assignment and determination of the optimal choice by ranking the alternatives. Various methods that can be used in each step are also provided and analyzed in terms of their pros and cons. (Wang and Kuo, 2013) gives an overview of mathematical theories applied in the modeling of the network selection problem. A broad classification of the set of attributes that might be considered during the network selection process is given in (Charilas and Panagopoulous, 2010) (Kumaran and Shaji, 2014). It is important to stress that most of the research on network selection is based either on direct feedback or on continuous measurement of QoS parameters as in the case of multimedia streaming none of which are applicable to the vehicular networking case.

On the ITS side, one reference architecture of a standardized component responsible of coordinating multiple access technologies is the ETSI communication interface (CI) management component which aims to provide application friendly communication services to a diverse range of applications over multiple media (Bouali and Senouci, 2015). Although the specification of the component is at a block diagram level and no specific methods for network selection are mentioned, the component architecture stresses the value of collecting and combining different criteria.

In literature, several policy-based network selection mechanisms were proposed. Policy-based network selection systems are composed of identified rules and policies that are used in the technology selection process. Optimum communication medium is selected by evaluating the current network selection parameters based on the policies stored. In (Brickley et al., 2007), estimated quality of the wireless channel derived from achievable throughput and allowable load is used to determine the selection between UMTS and WLAN. In (Meneguette et al., 2012), a multi-network packet scheduling technique based on the mapping of ITS application classes to one or more channels is proposed. If two application classes compete for the same channel, the order of access is determined by the priorities associated with each application class (e.g., safety applications take priority over infotainment). In (Olivera et al., 2009), all communication is done by default over the V2V ad hoc network and complementary technologies are only utilized in cases where it is not possible to communicate via V2V (e.g., no neighbors in the communication range). Despite providing improved performance, approaches based on a few criteria/attributes often result in suboptimal decisions as they do not follow a holistic approach and therefore cannot adapt to dynamic environments.

More holistic approaches in which the selection is done by monitoring the current context of the vehicle and capturing context indicators is suggested in (Bouali and Senouci, 2015) (Gopinath et al., 2016b) (Gopinath et al., 2016a). These context indicators can be provided by in-vehicle sensors, the underlying access layer technology or the network layer. The proposed approaches are based on estimating the QoS that can be offered by the ad hoc and cellular networks subject to the context indicators and making a selection based on how well the QoS they offer matches the requirement indicators (gathered from the applications) using fuzzy inference systems (Bouali and Senouci, 2015) (Abbas and Saade, 2015) (Ndashimye et al., 2016). The drawback of using fuzzy inference systems is that they do not scale well when the number of input parameters increase.

The approach we propose strikes a delicate balance between the tradeoffs mentioned in this section i.e., it uses a holistic approach taking a multitude of parameters and most importantly application requirements (maximum tolerable latency, required reliability in terms of PDR) into account and still remains viable to be used for ITS applications that have strict latency requirements.

3 HYBRID NETWORK ARCHITECTURE

Hybrid communication systems (HCS) are systems that are able to leverage multiple communication technologies for improved QoS. Although a wide variety of technologies can be utilized in order to realize such a system, in the context of vehicular networking use of cellular networks with Dedicated short-range communications (DSRC) is regarded as a potential solution for meeting ITS application requirements (Zheng et al., 2015). Therefore we focused on enabling hybrid communications in a distributed manner using ITS-G5 and in a centralized manner via LTE since these technologies are already available. Some background information about the hybrid network architecture we utilized is given below so as to ease understanding of the network selection algorithm that will follow.

3.1 ITS-G5

The distributed approach with ITS-G5 is based on short range wireless radio and position based ad hoc networking. Using this approach, data packets can be distributed to the specified geographical position or geographical area potentially in a multi-hop fashion via direct communication among the vehicles and possibly Roadside Units (RSUs) without requiring back-end infrastructure support (Le et al., 2011). Distribution of packets in geographical areas is possible through a set of network layer functionalities also known as GeoNetworking (ETSI, 2017). GeoNetworking supports multiple addressing schemes making it possible to address an individual node by its position or multiple nodes within a geographical region. Each node maintains a location table which holds information about neighboring nodes and their locations along with other features that might become relevant for the protocol operation. Packets received by a node are locally forwarded towards their geographic destination based on the nodes view of the network topology and the geographical address contained in the packet.

3.2 LTE and GeoMessaging Server

The infrastructure assisted approach is based on LTE. The aim of this approach is to emulate the functionality of the ETSI ITS-G5 network using the cellular network i.e. to support ad hoc like communication between ITS stations equipped with LTE. In order to realize this approach, we introduced a new network component called the GeoMessaging Server (GMS). GMS manages the distribution of ETSI ITS GeoNetworking data packets over cellular networks. It operates on the network layer (ISO/OSI layer 3) of the protocol stack thus is unaware of the information and contents of messages pertaining to higher protocol layers making it application agnostic. It maintains the context of the vehicular network through periodic location updates sent from nodes which are LTE capable. Since GMS is aware of the mapping between IP addresses and geographical positions, it can distribute messages to vehicles in a geographical target area via cellular links (Le et al., 2011). Figure 1 shows the possible communication flows in a hybrid V2X network.

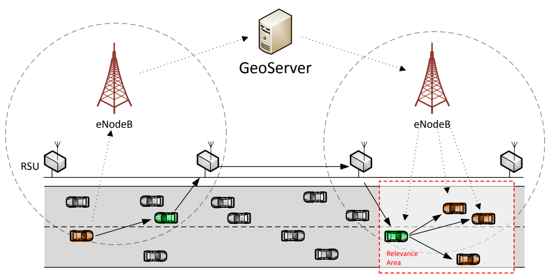

Figure 1: Possible communication flows in a hybrid V2X network.

Hybrid ITS stations were enabled to communicate with the GMS with what can be seen as a virtual access layer device. This device makes UDP/IP tunneling of GeoNetworking packets over LTE possible. Moreover, it has the added benefit of being completely coherent with the ETSI common reference architecture as no modifications to the network layer and above are necessary in order to use it. Unlike wireless ad hoc communications which relies on a shared medium with broadcast characteristics via direct communication among the ITS stations, communication is based on a client-server design with individual connections for each user and traverses the infrastructure of the cellular network. When a vehicle for instance detects an event and determines the geographical target area where this event should be disseminated, it sends this message uplink (UL) to the base station towards the GMS. The GMS then evaluates the headers of the GeoNetworking protocol associated with this message to determine the packet transport type and destination geographical area. It then distributes the message downlink (DL) accordingly over the cellular infrastructure. In order to receive messages from the GMS, at least one location update should have been sent by the ITS station (through a time-based beaconing scheme) otherwise the GMS would be unaware of the ITS station and have no means to deliver the message to it.

4 POLICY-BASED NETWORK SELECTION ALGORITHM

The design goal of the hybrid algorithm is to exploit ITS-G5 as the primary (default) technology for transmission and complement it with a limited and selective support via LTE under critical conditions in which successful transmission over the ad hoc network is highly unlikely and while doing so keeping the LTE footprint low. The algorithm takes into consideration a multitude of parameters. Selection is performed by each node i.e., both source and forwarding nodes along a packet's path towards its destination by monitoring application, mobility and QoS related context indicators. As it relies on simple policies with basic rules and parameters for network selection can be collected without additional communication overhead, it is characterized by its ease of implementation and integration into the ITS environment.

In the following design considerations and main building blocks of the algorithm will be described followed by a detailed explanation of the parameters used in the decision-making process along with their optimal thresholds derived from conducted analysis and/or literature review. After explaining its constituent components i.e. two pillars on which it rests namely the time control mechanism and classification of neighbors into reliable and unreliable ones, the overall control flow of the algorithm will be provided.

4.1 Design Considerations and Features

GeoNetworking requires forwarding of a packet towards the destination. This process is called line forwarding. GeoUnicast uses line forwarding, GeoAnycast and GeoBroadcast use it as well if the sender is not located within the destination area (Campolo et al., 2015). There are two approaches for line forwarding namely Contention-Based Forwarding (CBF) and greedy forwarding. CBF has shown to provide much better performance in terms of reliability than the greedy approach as it leverages multiple forwarding candidates (Roscher et al., 2016) and is therefore the basis of our algorithm.

Using CBF every node that is closer to the destination than the previous forwarder is considered a viable forwarding candidate and sends the packet with a delay inversely proportional to its distance progress. This means that the candidate that is closest to the destination will try to forward the packet first. A forwarding candidate refrains from transmitting the packet if it received it the second time while its CBF contention timer is running since it means the packet was already forwarded by another node (Campolo et al., 2015). This suppression mechanism is an integral part of CBF.

In light of this information, it is important to analyze what would happen if the forwarding nodes were allowed to perform network selection. In such a case, multiple forwarding candidates might prefer to transmit the packet via LTE and send the packet immediately towards the GMS. As a result, the destination would receive the same packet over LTE multiple times resulting in a very redundant usage of cellular network resources and high congestion assuming that under ideal network conditions, it is enough to use LTE only once along a transmission path. The successive forwarding over ITS-G5 only aggravates the problem. Addressing this problem necessitates having to implement a suppression mechanism for LTE message transmissions by introducing additional messages or extending standardized messages for piggybacking this information.

In order to avoid introducing proprietary mechanisms and instead utilize the existing ones, LTE transmission mechanism is integrated with CBF. This means that whenever LTE is selected, the packet is queued in the CBF buffer and is sent to the GMS only when its CBF contention timer expires. It should be noted that forwarders are not allowed to select only LTE and should use ITS-G5 in parallel whenever LTE is selected so as to make use of the CBF suppression mechanism. This ensures that when the forwarder with the most distance progress forwards the packet first, possible LTE transmissions of other forwarding candidates which overhear this transmission over ITS-G5 will be suppressed. The downside of utilizing the CBF mechanism for LTE transmissions is that the packets will incur queuing delays in the CBF buffer. Also there might be some redundant transmissions in the UL channel due to some nodes not overhearing the ITS-G5 transmissions (NLOS conditions) however, these redundant transmissions are detected by the duplicate packet detection performed by the GMS based on packet IDs and sequence numbers and do not translate into DL congestion. This logic which eliminates duplicates in the DL on the GMS side is also regarded as an integral part of the algorithm's functionality.

Another important design feature of the algorithm related to LTE transmissions is what we termed as the LTE suppression flag which influences the selection logic at the forwarding nodes. For this flag, we used the reserved field of the GeoNetworking basic header (ETSI, 2017). This flag can assume two values: 0 or 1. Whenever a forwarder receives a packet, it first inspects this flag. If the flag is set to 0 the forwarder refrains from selecting LTE, if it is set to 1 the forwarder is allowed to select LTE. This flag is set at the decision making nodes whenever LTE is selected according to one of the following 3 strategies and which strategy to use is a configuration option that applies to all nodes:

- Always set the flag to 0 i.e., indicate to other nodes that LTE should not be selected again: This option will henceforth be referred to as the "Flag 0" policy. Using this configuration results in other forwarders which will overhear this transmission via ITS-G5 to refrain from using LTE. The advantage of this approach is that it decreases traffic in the UL however, if the LTE transmission of the node that set the flag fails due to some reason (e.g., no coverage in the destination area), the possibility of using LTE at a later stage is eliminated as the flag gets propagated among the forwarders. This in turn decreases reliability.
- Always set the flag to 1 i.e. indicate to other nodes that LTE could be reselected: This option will henceforth be referred to as the "Flag 1" policy. Using this approach the forwarders in the next hop are allowed to reselect LTE. This approach increases UL channel congestion, however improves reliability. For instance if the LTE transmission of the previous node has failed, next hops along the transmission path are allowed to try again and might be successful in delivering the message.
- Set the flag dynamically: This option will henceforth be referred to as the "Flag dynamic" policy. It uses the current UL Reference Signal Received Power (RSRP) value as an indication of the network propagation conditions and determines whether to set the flag based on RSRP to delay and RSRP to PDR mappings. It constitutes a middle ground in terms of LTE footprint and reliability between "Flag 0" and "Flag 1" policies. If the estimated delay via LTE is over the remaining lifetime of the packet or the RSRP to message delivery success probability is below the threshold required by the application, the flag is set to 1

as the LTE transmission is deemed unreliable and likely to fail.

4.2 Time Control Mechanism

One of the key parameters that steers the technology selection logic is the remaining packet lifetime. This can be classified as an application-related network selection attribute. Depending on its ITS application class, each application can indicate the maximum tolerable latency for a packet. This value is set at the source and decremented at each hop as the packet is being forwarded.

Time control mechanism employed by the algorithm is similar for source and forwarders, the only difference being a minor extension for the source nodes. It should also be noted that the algorithm takes into account the CBF buffer queuing time when calculating the remaining packet lifetime at the forwarding nodes.

4.2.1 Source Node Specific Functionality

Communication sessions originate at source nodes thus the source nodes represent unique points in the decision making process. Since the originated packet has never been forwarded before and only the source is aware of its existence at the time of the technology selection process, source nodes are allowed to select only LTE unlike the forwarders. Using only LTE at the source nodes for long range transmissions can reduce ITS-G5 channel congestion and decrease the LTE footprint compared to its use in parallel with ITS-G5 when “Flag 1“ or “Flag dynamic“ policy is in effect. But sticking with the design philosophy of using ITS-G5 by default and supporting it via LTE only when it is necessary, we limited using only LTE at the source to one situation: only when the estimated optimistic delay of ITS-G5 transmission based on distance to the destination (derived using dense highway scenarios) is larger than the packet lifetime i.e., transmission via ITS-G5 is not feasible and estimated to fail.

4.2.2 Common Functionality

The main philosophy behind the time mechanisms explained in this subsection is to support the transmissions via LTE whenever it is determined or estimated that using LTE would not be possible in the next hop due to remaining packet lifetime constraints. Mechanisms described in this chapter make use of the two thresholds defined below:

- LTE Lower Delay Threshold: This is the minimum possible LTE transmission latency. If the packet lifetime drops below this value, it is not feasible to use LTE anymore. In our simulated LTE network this threshold was 35ms.
- LTE Upper Delay Threshold: This value is set such that the average LTE transmission latency is in the middle of the LTE Lower Delay Threshold and this value. In our simulated LTE network, the average LTE transmission latency was 50ms therefore this threshold was set to 65ms.

Using these two thresholds, time mechanism functions as follows:

- If the remaining packet lifetime is below the minimum LTE transmission latency, it is not possible to transmit via LTE anymore therefore select only ITS-G5. If this condition holds, LTE suppression flag is set to 0 regardless of the chosen flag policy so as to inform forwarders that selecting LTE is not feasible anymore.
- If the remaining packet lifetime is between the lower and upper thresholds i.e., it is close to the average LTE time and destination is not among forwarder’s reliable neighbors, support the transmission via LTE in parallel to ITS-G5 otherwise it might be too late to use it again.
- If the remaining packet lifetime is above the upper LTE threshold, calculate the CBF delay that would be incurred by the next forwarder (reliable neighbor with the most distance progress). If the remaining packet lifetime drops below the lower threshold by the taking into account the delay that would be incurred in the next hop and destination is not among forwarder’s reliable neighbors, support the transmission via LTE in parallel to ITS-G5 otherwise it will be too late to use it again.

4.3 Reliable Neighbors

Success of multi-hop message dissemination in VANETs depends on the presence of neighboring nodes with stable links. Therefore a major part of the algorithms selection logic is based on the current set of neighbors and their classification into reliable and unreliable ones. The algorithm classifies a communication partner as a reliable neighbor if it satisfies all of the conditions listed below:

- It is a direct neighbor (accessible via 1 hop).
- Its distance progress is positive meaning that it is closer to the destination than the current node.
- It is a fresh neighbor meaning that time since the last direct message received from it, is less than or equal 1 second. Last update time is the most informative value for neighborhood classification

and its optimal value is taken from (Roscher et al., 2017).

- Received signal strength of the last message from it, is above the configured threshold. This threshold is determined to be -80 dBm based on our simulations to eliminate the nodes that are close to the maximum transmission range.

At the end of this classification process if the number of reliable neighbors is below a certain threshold, communication is supported via LTE in parallel to ITS-G5. This threshold was determined to be 1 meaning that whenever a node does not have at least one reliable neighbor, the algorithm secures the transmission by selecting LTE in addition to ITS-G5. It should be noted that setting this threshold above 1 resulted in considerable increases in LTE footprint without significant improvements in PDR.

4.4 Algorithm Flowchart

Control flow of the algorithm is provided in a top-down fashion in figure 2 with "Time-to-live" (TTL) denoting the remaining packet lifetime.

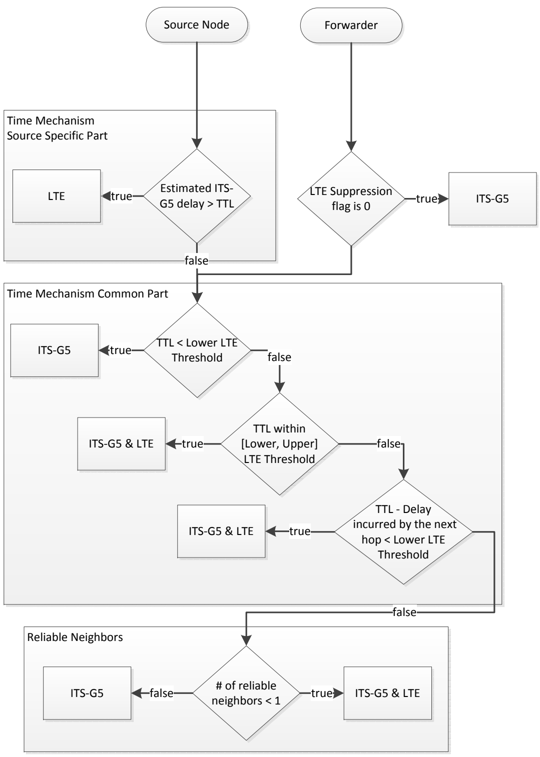

Figure 2: Algorithm flowchart

5 SIMULATION ENVIRONMENT AND SCENARIOS

In this section the constituent components of the simulation environment are described. Moreover, the scenarios used to evaluate the performance of the algorithm are detailed in terms of their road topology and network design summarizing all the relevant parameters used and design considerations/assumptions made.

5.1 Simulation Environment

Simulation environment comprises of the Network Simulator 3 (ns-3) discrete event simulator (ns-3, 2017), Simulation of Urban Mobility (SUMO) traffic simulator (D. Krajzewicz and Bieker, 2012) and ezCar2X framework - ETSI ITS-compliant communication stack with added support for hybrid communications (Roscher et al., 2014). Figure 3 illustrates the block diagram of the simulation toolchain.

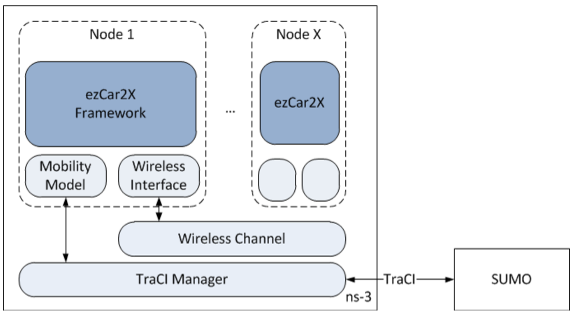

Figure 3: Block diagram of the simulation environment

ezCar2X is a modular software framework for rapid prototyping of cooperative ITS applications and novel communication protocols. It consists of an ETSI standard compliant communication stack, which was extended with an adaptive GeoNetworking layer supporting application transparent geo-localized message dissemination via ITS-G5 and LTE. ezCar2X provides basic set of protocols and abstractions, enabling implementation of new communication algorithms and concepts. Moreover, it allows using a single implementation for evaluation both within a simulation environment and on real world prototypes. The network simulator of choice is ns-3.25. It provides out of the box device models for IEEE 802.11-family as well as a variety of wireless channel models. On the LTE side, it includes the LTE/Evolved packet core (EPC) network simulator (LENA) (LENA, 2017), which was used for the LTE network design of the scenarios.

Traffic simulator of choice is SUMO. SUMO is coupled with ns-3 using its well documented Traffic Control Interface (TraCI) (Wegener et al., 2008) API with ns-3 nodes mapped to vehicles in SUMO i.e., vehicle movements in SUMO are communicated to the mobility model of the assigned ns-3 node.

5.2 Simulation Scenarios

Performance evaluation was done utilizing 2 different scenarios.

The first scenario is the Manhattan grid scenario with four blocks, one lane roads and one intersection. A relatively small grid size (720 x 200 m) was preferred to ensure straightforward results interpretation. This scenario was chosen to simulate urban-like mobility with very limited line-of-sight (LOS) conditions. Utilizing a topology with one lane roads makes it possible to create traffic congestion with lower number of vehicles particularly at the central intersection as the vehicles cannot drive with their maximum target speed as in the case of a highway scenario. Moreover, it helps create a non-uniform distribution of vehicles where inter-vehicle gaps are more pronounced allowing simulation of challenging conditions for ITS-G5, where ad hoc communication can be disrupted due to network fragmentation.

The second scenario is the highway - a 10 km long road with 3 lanes in each direction. This scenario was chosen to evaluate the algorithm with highly mobile users in LOS conditions. Contrary to the Manhattan scenario, vehicles do not face any obstacles in the form of buildings that might disrupt their communication via ITS-G5 however, due to their high mobility patterns; they experience higher frequency dispersion as a result of Doppler shift (fast fading) which reduces LTE transmission reliability.

5.2.1 Traffic Parameters

Vehicle and packet traffic can be varied using the following parameters:

- Vehicle injection rate: Determines the traffic density by controlling how many cars depart every second from each lane.
- Penetration rate: Determines the proportion of vehicles equipped with communication capabilities i.e, vehicles that are ITS-G5 and LTE capable.
- Packet generation rate: Determines the number of packets generated within a predefined time frame.

Summary of traffic related parameters for each scenario is presented in Table 1. It is worth mentioning that the values for these parameters were chosen so as to create low road traffic saturation. This allowed us to test our algorithm under unfavorable ITS-G5 conditions to gauge the benefits of using a hybrid approach, but also to better understand the influence of simulation parameters on defined KPIs.

Table 1: Summary of traffic related parameters for each scenario

Scenario	Manhattan	Highway
Vehicles saturation level	40	180
Penetration rate	0.1, 0.3, 0.6, 1	0.1, 0.3, 0.6, 1
Hybrid capable vehicles (avg.)	4, 12, 24, 40	18, 54, 108, 180
Packet generation rate [Hz]	10	10
Vehicle injection rate [Hz]	0.5	0.1
Average speed [kmph]	30	100
Simulation time [s]	400	500

5.2.2 Communication Parameters

In our simulations at every packet generation instant, the framework picks randomly the source and destination nodes and creates a corresponding communication session. These sessions are created uniformly with respect to distance and correspond to a valid range of [0,720] m for the Manhattan scenario and [0,5000] m for the Highway scenario. All created sessions are unicast ones, meaning that each packet is designated for only one receiving node. Table 2 provides a summary of ITS-G5 communication parameters.

Table 2: Summary of ETSI ITS-G5 parameters

Parameter	Value
Tx Power	23 dBm
Propagation Model	Nakagami with obstacles
Uni-cast Packet size	300 Bytes
Neighbor timeout	20 s
Default Beaconing rate	0.3 Hz

For ITS-G5 communication we used a realistic, computationally inexpensive simulation model for IEEE 802.11p radio shadowing in urban environments that allowed us to model a city scenario with obstacles. It is comprised of the Nakagami fading channel described in (Taliwal et al., 2004) with the obstacle shadowing model in (Sommer et al., 2011a).

From the LTE design point of view, the network is planned to provide good coverage conditions, without severe fading/shadowing effects that would result in intermittent connectivity. The detailed overview of LTE design parameters is presented in Table 3. The Figures 4 and 5 depict the Manhattan and the Highway scenarios under the coverage of the designed LTE network respectively.

Table 3: Summary of relevant LTE design parameters

Parameter	Manhattan	Highway
Number of sites (cells)	1 (3)	3 (6)
UL EARFCN	18100	
DL EARFCN	100	
Frequency Reuse	1	
Bandwidth per Cell	25 PRB	
Propagation Model	Log Distance	
Pathloss Exponent	3.9	3.1
Reference Loss	38.57 dB	
UE max. Tx Power	23 dBm	
eNodeB max. Tx Power	43 dBm	
Antenna Model	Cosine	
UE Antenna Gain	0 dBi	
eNodeB Antenna Gain	18 dBi	11 dBi
eNodeB Antenna HPBW	65 degrees	120 degrees
UE NF	7 dB	
eNodeB NF	2 dB	
Target Edge Throughput	0.5 Mbps	
Target min. SINR	0.2 dB	
Cell Radius	578 m	1773 m
HO type	PBGT	
HO Hysteresis	3 dB	
HO TTT	256 ms	
Average Speed for Channel Fading	30 km/h	100 km/h
Fading Model Time Resolution	1 ms	

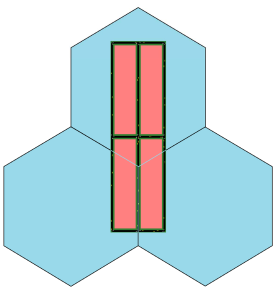

Figure 4: Schematic coverage area for the Manhattan scenario

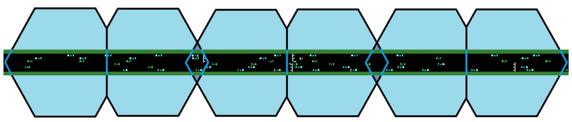

Figure 5: Schematic coverage area for the Highway scenario

6 PERFORMANCE EVALUATION

The evaluation considers different scenarios and penetration rates as well as the distance to destination and application time requirements to present important KPIs, such as PDR and LTE Packet load, in comparison to reference simulations, namely transmission using only ITS-G5, only LTE and both technologies.

6.1 Methodology

Since for the Manhattan scenario the generated sessions are in the close range of [0,720] m, the results were not fractioned into different distance bins and are presented as an average over all transmissions. In the Highway scenario the results are presented for the following ranges: close [0,500] m, medium [500,2500] m and far [2500,5000] m. Time requirement, which is termed as “Application delay requirement”, is used to assess the performance of the algorithm under two application-imposed time constraints (100ms and 500ms) defined in (Karagiannis et al., 2011) as plausible thresholds for foreseen ITS services. Additionally, the algorithm is evaluated under time-unlimited conditions to obtain an insight on the performance of its Neighborhood-driven part. The KPIs used, namely PDR and Packet load, are defined as follows:

$$PDR_u^{dest} = \frac{n_{u,r}^{dest}}{n_{u,g}^{source}}, \tag{1}$$

where PDR_u^{dest} is PDR of unique packets measured at the destination, $n_{u,r}^{dest}$ is the number of correctly received unique packets at the destination and $n_{u,g}^{source}$ is the total number of unique packets generated at the source.

$$L_u^{gms} = \frac{n_{u,r}^{gms}}{n_{u,g}^{source}}, \tag{2}$$

where L_u^{gms} is the Packet load due to the unique packets measured at the GMS, $n_{u,r}^{gms}$ is the number of uniquely received packets at the GMS and $n_{u,g}^{source}$ is the total number of unique packets generated at source nodes.

$$L_r^{gms} = \frac{n_{r,r}^{gms}}{n_{u,g}^{source}}, \tag{3}$$

where L_r^{gms} is the Packet load due to redundant packets measured at the GMS, $n_{r,r}^{gms}$ is the number of redundantly received packets at the GMS and $n_{u,g}^{source}$ is the total number of unique packets generated at source nodes.

$$L_{tot}^{gms} = L_u^{gms} + L_r^{gms}, \tag{4}$$

where L_{tot}^{gms} is the total Packet load measured at the GMS. To illustrate the gains of the algorithm over a single technology, the results were depicted for the same scenarios and configuration using a single technology at each node i.e., only ITS-G5 or only LTE. Moreover, to show the maximum achievable PDR (ceiling values) using the hybrid ITS-G5/LTE approach, the same simulations were run using both technologies simultaneously at each node, without any DL redundancy suppression techniques at the GMS/vehicle side. All results are presented with a confidence level of 95%.

6.2 Simulation Results

In the following the graphs for the Manhattan scenario are shown. Figures 6, 7 and 8 present the results for 100ms, 500ms and unlimited Application delay requirements respectively. Figure 9 shows the total Packet load when both technologies are used.

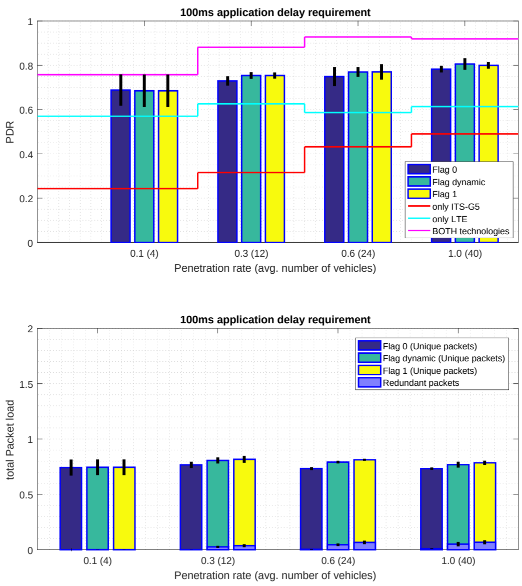

Figure 6: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 100ms (Manhattan scenario).

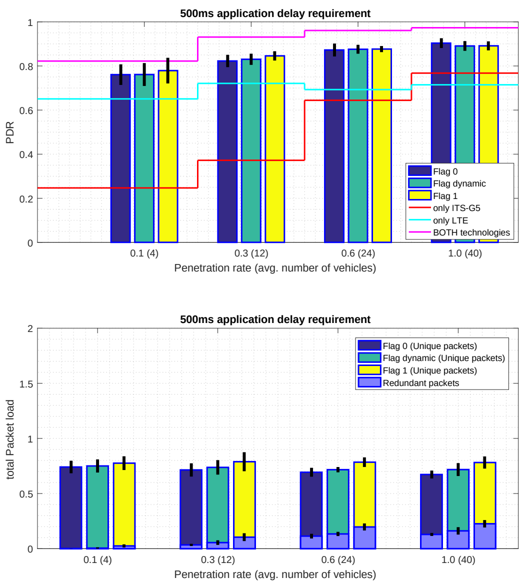

Figure 7: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 500ms (Manhattan scenario).

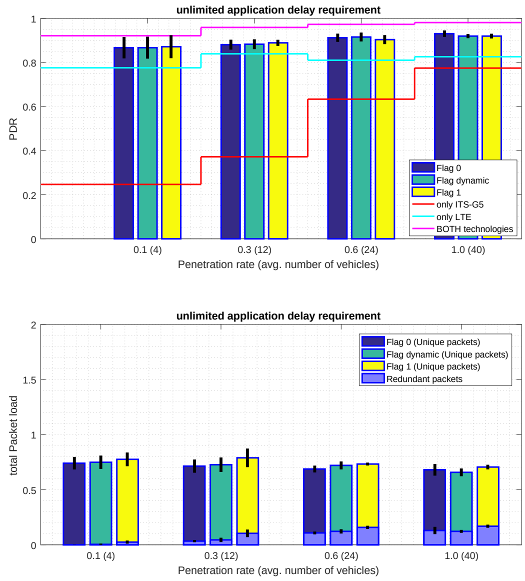

Figure 8: Upper graph: PDR; Lower graph: Total Packet load ratio for unlimited Application delay requirement (Manhattan scenario).

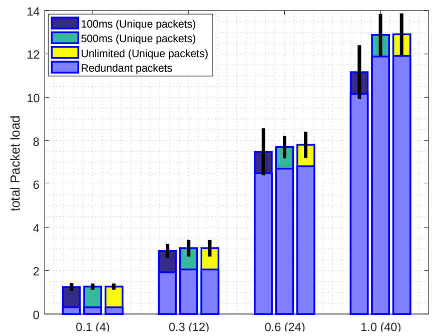

Figure 9: Total Packet load using both technologies (Manhattan scenario).

From the Manhattan scenario graphs, we observed a poor ITS-G5 performance - only up to 50% PDR for time critical transmissions (100ms) and at very low Penetration rates (0.1) - only up to 25% for any time requirement. Whereas LTE ensures average to decent communication support resulting in average at 60% to 80% PDR depending on the time requirement. In light of such results, our algorithm demonstrated very high PDR, above ITS-G5 and LTE for any configuration, resulting in average at 70% to 90% and getting very close to the value achieved using both technologies whilst keeping Packet load stable at around 75%. It is important to note that using both technologies, the Packet load is drastically higher than for the algorithm and results in up to 17-fold increase (confidence intervals are provided for the total Packet load only). Since in this scenario mostly the neighborhood-driven logic of the algorithm is triggered due to lack of re-

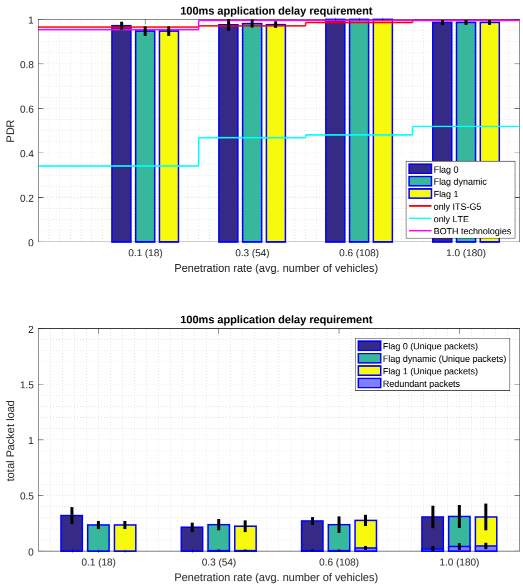

Figure 10: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 100ms (Highway scenario, close range).

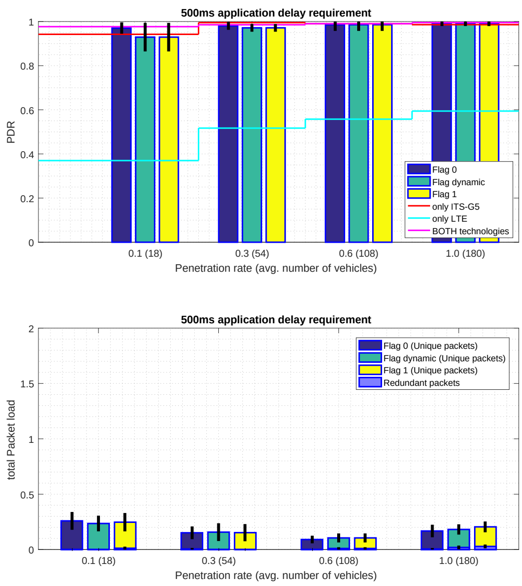

Figure 11: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 500ms (Highway scenario, close range).

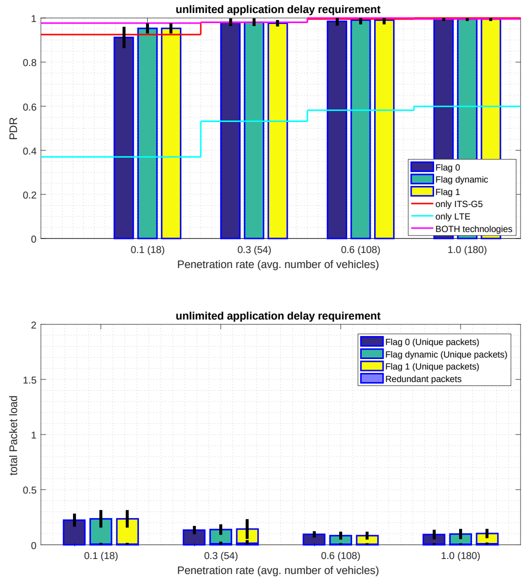

Figure 12: Upper graph: PDR; Lower graph: Total Packet load ratio for unlimited Application delay requirement (Highway scenario, close range).

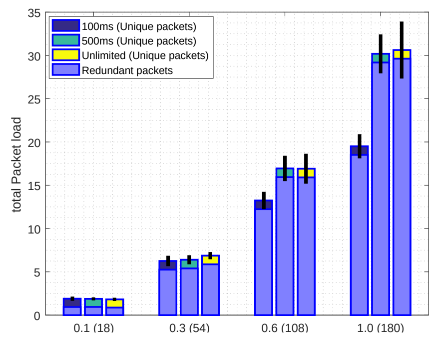

Figure 13: Total Packet load using both technologies (Highway scenario, close range).

liable neighbors, we did not observe any significant difference in using one of the three LTE suppression techniques as they get pronounced when the time control mechanism is used to trigger LTE transmission.

Next, we present the graphs for the Highway scenario. Figures 10, 11 and 12 illustrate the results for 100ms, 500ms and unlimited Application delay requirements respectively for close range transmissions up to 500m. Figures 14, 15 and 16 depict the results for medium range transmissions and Figures 18, 19 and 20 for the far range. Figure 13, 17 and 21 show the total Packet load for both technologies at close, medium and far ranges respectively.

From the Highway scenario graphs for closed range transmissions, we observed that ITS-G5 provides a very high PDR - on average 95% for all configurations, whereas LTE due to fast fading achieved at maximum 60%. In this respect, our algorithm had shown its good adaptability and achieved the same PDR as ITS-G5 while keeping the total Packet load at maximum 30% - only in time critical case of 100ms which proves the proper functioning of its time control mechanism. Usage of both technologies resulted in enormous total Packet load, especially in the time unlimited case where the number reached 3000%.

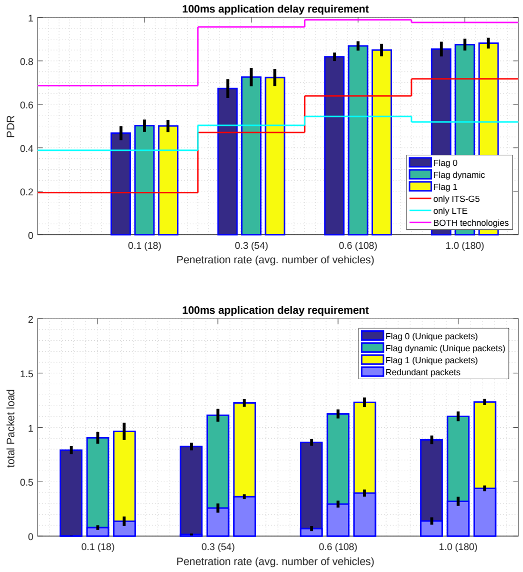

Figure 14: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 100ms (Highway scenario, medium range).

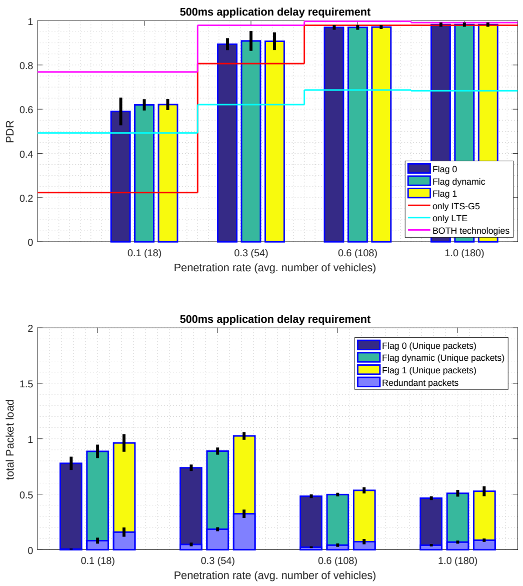

Figure 15: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 500ms (Highway scenario, medium range).

Again, we did not observe any significant difference between the three LTE suppression techniques as the transmission distance is very short.

From the Highway scenario graphs for medium range transmissions, we observed that ITS-G5 has very low PDR - 20% for the Penetration rate of 0.1 for all delay requirements and performs mediocre for

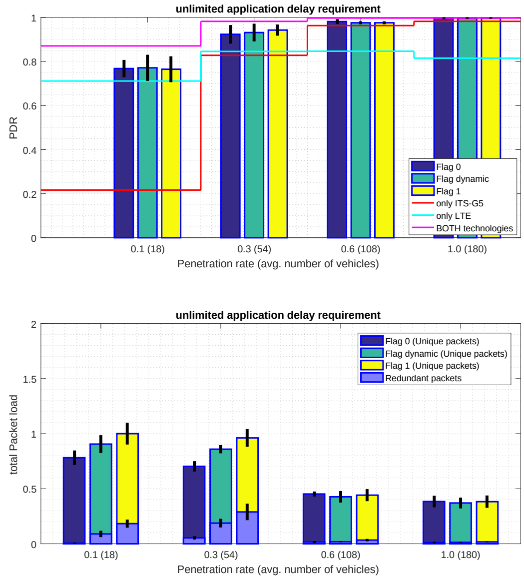

Figure 16: Upper graph: PDR; Lower graph: Total Packet load ratio for unlimited Application delay requirement (Highway scenario, medium range).

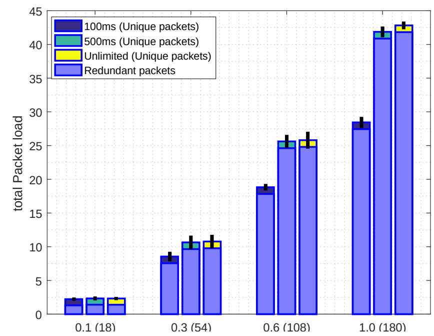

Figure 17: Total Packet load using both technologies (Highway scenario, medium range).

all other considered penetration rates in the time critical case of 100ms. LTE showed in average 50% to 80% of PDR depending on the time requirement. The selection algorithm confirmed its efficiency and overperformed all technologies in all cases for all configurations. Importantly, for the time limited scenario of 100ms, it showed a 10% to 20% increase in PDR over the best technology. Total Packet load in most of the cases was below 100%. The usage of two technologies is highly inexpedient in this scenario and resulted in up to 4500% of total Packet load providing only minor increases in terms of PDR in the 500ms and time unlimited cases. For the medium range, using the dynamic LTE suppression technique i.e., "Flag dynamic" policy can save up to 12% of total Packet load while guaranteeing the same PDR as the unrestricted "Flag 1" policy.

From the Highway scenario graphs for far range

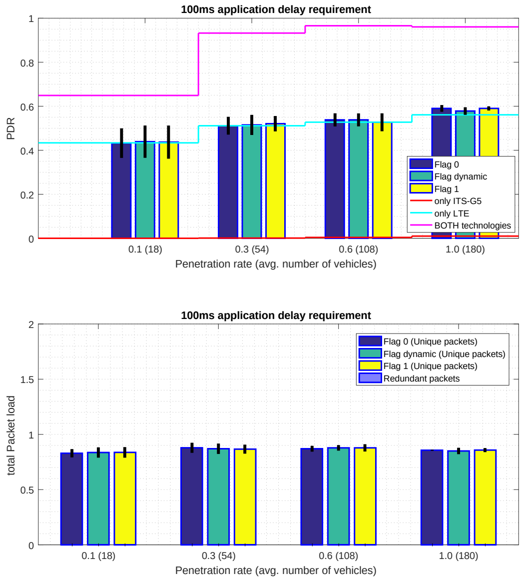

Figure 18: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 100ms (Highway scenario, far range).

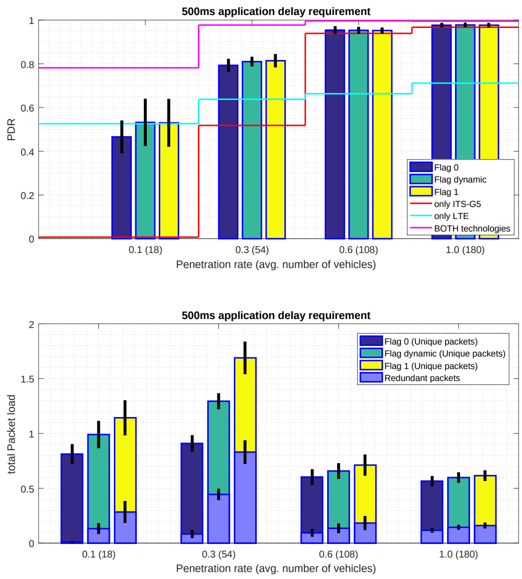

Figure 19: Upper graph: PDR; Lower graph: Total Packet load ratio for Application delay requirement 500ms (Highway scenario, far range).

transmissions, we observed that cumulative ITS-G5 delay (due to CBF buffer waiting time) excludes the possibility of successful packet transmission for the time critical case of 100ms or for the very low penetration rate of 0.1. The only technology that can be used under these circumstances is LTE, that shows on average 50% to 80% PDR which our algorithm perfectly matches in every tested case. Once ITS-G5

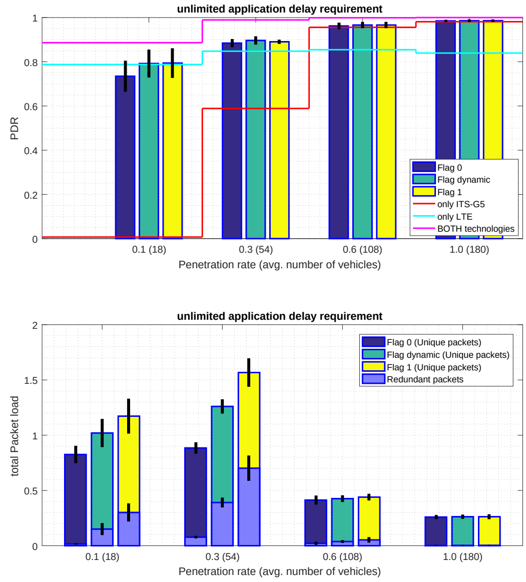

Figure 20: Upper graph: PDR; Lower graph: Total Packet load ratio for unlimited Application delay requirement (Highway scenario, far range).

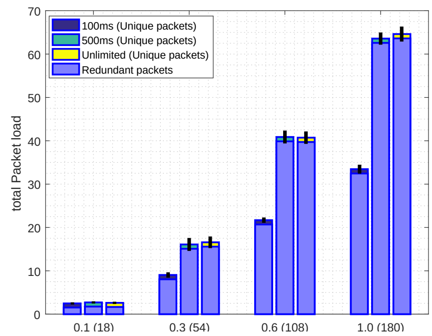

Figure 21: Total Packet load using both technologies (Highway scenario, far range).

PDR rises above zero in the 500ms delay requirement case, the selection algorithm starts to over-perform the best technology resulting in a clear improvement over a single technology approach. In general, if the time requirement is not too strict (500ms or higher) and penetration rate is above 0.1, we observed that the transmission over far distances using our algorithm is possible with decent PDR values of 80% and above. Since the communication range is long and average number of forwarders is larger in comparison to previous ranges, usage of two technologies redundantly results in extremely high total Packet load values of up to 6500%. Using the proposed algorithm and the “Flag dynamic“ policy in this scenario, one can save up to 40% of total Packet load while ensuring the same PDR as the unrestricted “Flag 1“ policy.

6.3 Evaluation Summary

Abstracting from the absolute numbers, we can conclude that the results of our experiments proved the capability of the proposed algorithm to provide substantial performance improvements (measured in tens of percent) over a single technology approach whenever using ITS-G5 and LTE is physically possible (i.e. their respective PDRs are greater than zero). When it is infeasible or risky to use ITS-G5, the hybrid algorithm will immediately switch to LTE, for instance in medium/far range transmissions in time limited cases, which confirms the effectiveness of its time control mechanism, or under the absence of forwarding vehicles in the vicinity, which confirms the effectiveness of its neighborhood assessment logic. The ultimate PDR gain of the policy-based algorithm is not only achieved by using dozens of times less LTE resources than the both technologies approach, but it also relies on the proposed GMS logic that entirely eliminates LTE DL redundancy.

7 CONCLUSION AND OUTLOOK

In this work we tried to remedy the cases when ITS-G5 is physically unable to satisfy the QoS requirements demanded by applications particularly pertaining to reliable and time critical data transfers. This occurs usually at low traffic densities with low number of forwarders, at long communication ranges or in presence of obstacles. In order to better fulfill application QoS requirements we proposed a policy-based network selection algorithm that enables combining the strengths of ad hoc and infrastructure-based networks. The algorithm was designed to take into account the most relevant parameters for ITS-G5 to address critical cases for vehicular ad hoc connectivity. It relies on a multi-parameter neighborhood estimate, being on the other hand secured with a time control mechanism that facilitates in-time delivery of messages.

Evaluation showed that the proposed algorithm significantly improved the overall reliability of vehicular data transmissions in all considered scenarios and distance ranges, over-performed traditional ITS-G5, provided a necessary support in neighborhood-constrained or time critical scenarios and demonstrated an ability to select the optimal technology to achieve PDR values always equal or higher than the best technology. LTE load rarely exceeded the number of uniquely generated packets leading to a limited LTE usage which was one of the main design goals of the algorithm. Performance improvements over approaches using a single technology is the result of proper and selective simultaneous usage of ITS-G5 and LTE. It is worth noting that the algorithm not only achieved higher PDR efficiency than the best technology, it also entirely eliminated the DL redundancy, since the duplicate packets received on the UL are not forwarded in the DL thanks to the mechanisms implemented on the GMS side.

In the future it is worth evaluating the proposed algorithm for GeoBroadcast message dissemination under diverse LTE scenario realizations. Also both GeoUnicast and GeoBroadcast cases have to be verified in real field-tests to obtain better insights on the algorithm's performance. Additionally, it is foreseen that the current GMS logic will be improved to take advantage of UL redundancy by enabling DL success estimation via incorporation of RSRP values in the location update beacons sent to the GMS. Moreover, a scheme utilizing the nodes with negative distance progress will be considered in order to increase LTE transmission success in cases exhibiting spotty coverage.

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REFERENCES

5G-PPP (2015). 5G Automotive Vision, White paper.

Abbas, N. and Saade, J. J. (2015). A fuzzy logic based approach for network selection in wlan/3g heterogeneous network. In *Consumer Communications and Networking Conference (CCNC), 2015 12th Annual IEEE*, pages 631–636. IEEE.

Araniti, G., Campolo, C., Condoluci, M., Iera, A., and Molinaro, A. (2013). Lte for vehicular networking: a survey. *IEEE Communications Magazine*, 51(5):148–157.

Bouali, T. and Senouci, S.-M. (2015). A fuzzy logic-based communication medium selection for qos preservation in vehicular networks. In *Proceedings of the 5th ACM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications*, pages 101–108. ACM.

Brickley, O., Shen, C., Klepal, M., Tabatabaei, A., and Pesch, D. (2007). A data dissemination strategy for cooperative vehicular systems. In *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pages 2501–2505. IEEE.

Campolo, C., Molinaro, A., and Scopigno, R. (2015). Vehicular ad hoc networks. *Standards, Solutions, and Research*.

Charilas, D. E. and Panagopoulous, A. D. (2010). Multiaccess radio network enviroments. *IEEE Vehicular Technology Magazine*, 5(4):40–49.

D. Krajzewicz, J. Erdmann, M. B. and Bieker, L. (2012). Recent development and applications of sumo - simulation of urban mobility.

ETSI (2010). ETSI TS 102 637-1 V1.1.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 1: Functional Requirements.

ETSI (2013). ETSI EN 302 663 V1.2.1 - Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band.

ETSI (2017). Etsi en 302 636-4-1 v1.3.1 - intelligent transport systems (its); vehicular communications; geonetworking; part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; sub-part 1: Media-independent functionality.

Gopinath, S., Wischhof, L., Jaumann, M., Ponikwar, C., and Hof, H.-J. (2016a). On context-aware communication mode selection in hybrid vehicular networks. In *Fachgespräch Inter-Vehicle Communication 2016-(inter-veh-comm-2016)*. Humboldt-Universität zu Berlin.

Gopinath, S., Wischhof, L., Ponikwar, C., and Hof, H.-J. (2016b). Hybrid solutions for data dissemination in vehicular networks. In *Wireless Days (WD), 2016*, pages 1–4. IEEE.

Karagiannis, G., Altintas, O., Ekici, E., Heijenk, G., Jarupan, B., Lin, K., and Weil, T. (2011). Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *IEEE Communications Surveys and Tutorials*, 13:584–616.

Kumar, V., Bauza, R., Filali, F., Gozalvez, J., Lin, L., and Rondinone, M. (2009). itetris-a large scale integrated simulation platform for v2x communications: Application to real-time traffic management. In *Proc. of the 9th international conference on Intelligent Transport Systems Telecommunications (ITST), Lille*.

Kumaran, U. and Shaji, R. (2014). Vertical handover in vehicular ad-hoc network using multiple parameters. In *Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 2014 International Conference on*, pages 1059–1064. IEEE.

Le, L., Festag, A., Mader, A., Baldessari, R., Sakata, M., Tsukahara, T., and Kato, M. (2011). Infrastructure-assisted communication for car-to-x communication. In *Proceedings of the ITS world congress*.

LENA (2017). Lte-epc network simulator. http://networks.cttc.es/mobile-networks/software-tools/lena/. Last accessed on 26.10.2017.

Meneguette, R. I., Madeira, E. R., and Bittencourt, L. F. (2012). Multi-network packet scheduling based on vehicular ad hoc network applications. In *Proceedings of the 8th International Conference on Network and Service Management*, pages 214–218. International Federation for Information Processing.

Ndashimye, E., Sarkar, N. I., and Ray, S. K. (2016). A novel network selection mechanism for vehicle-to-infrastructure communication. In *Dependable, Autonomic and Secure Computing, IEEE 14th Intl Conf on Pervasive Intelligence and Computing, 2016*, pages 483–488. IEEE.

ns-3 (2017). Network simulator 3. http://www.nsnam.org. Last accessed on 26.10.2017.

Olivera, J. A., Cortázar, I., Pinart, C., Los Santos, A., and Lequerica, I. (2009). Vanba: a simple handover mechanism for transparent, always-on v2v communications. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5. IEEE.

Roscher, K., Bittl, S., Gonzalez, A., Myrtus, M., and Jiru, J. (2014). ezcar2x: rapid-prototyping of communication technologies and cooperative its applications on real targets and inside simulation environments. In *11th Conference Wireless Communication and Information*, pages 51–62.

Roscher, K., Jiru, J., and Knorr, R. (2016). Low-delay forwarding with multiple candidates for vanets using multi-criteria decision making. In *Vehicular Networking Conference (VNC), 2016 IEEE*, pages 1–8. IEEE.

Roscher, K., Nitsche, T., and Knorr, R. (2017). Know thy neighbor - a data-driven approach to neighborhood estimation in vanets. *IEEE Vehicular Technology Conference*.

Sommer, C., Eckhoff, D., German, R., and Dressler, F. (2011a). A computationally inexpensive empirical model of ieee 802.11 p radio shadowing in urban environments. In *Wireless On-Demand Network Systems and Services (WONS), 2011 Eighth International Conference on*, pages 84–90. IEEE.

Sommer, C., German, R., and Dressler, F. (2011b). Bidirectionally coupled network and road traffic simulation for improved ivc analysis. *IEEE Transactions on Mobile Computing*, 10(1):3–15.

Taliwal, V., Jiang, D., Mangold, H., Chen, C., and Sengupta, R. (2004). Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*, page 88. ACM.

Wang, L. and Kuo, G.-S. G. (2013). Mathematical modeling for network selection in heterogeneous wireless networksa tutorial. *IEEE Communications Surveys & Tutorials*, 15(1):271–292.

Wegener, A., Piórkowski, M., Raya, M., Hellbrück, H., Fischer, S., and Hubaux, J.-P. (2008). Traci: an interface for coupling road traffic and network simulators. In *Proceedings of the 11th communications and networking simulation symposium*, pages 155–163. ACM.

Zheng, K., Zheng, Q., Chatzimisios, P., Xiang, W., and Zhou, Y. (2015). Heterogeneous vehicular networking: a survey on architecture, challenges, and solutions. *IEEE communications surveys & tutorials*, 17(4):2377–2396.