Context-Aware Heterogeneous V2I Communications

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***Abstract*— The automotive industry is currently focusing on the research and development of the IEEE 802.11p technology to support V2V and V2I communications. However, connected vehicles will benefit from exploiting heterogeneous communications technologies to satisfy the diverse functional and operational requirements of vehicular applications under variable context conditions. In this context, a key aspect is the adequate selection and management of the different radio access technologies that will be integrated in connected vehicles. This paper proposes a novel context-aware heterogeneous V2I communications technique that exploits context information to make intelligent decisions on the most adequate communications technology to use at each moment in order to improve both individual and system performance. The decision is directly made by each vehicle with assistance from the infrastructure. The results obtained demonstrate the benefits of the proposed technique, and its robustness to the variability and accuracy of the context information.**

***Index terms*—heterogeneous networking, connected vehicle, cooperative ITS, context, V2I, vehicle to infrastructure.**

I. INTRODUCTION

Connected vehicles will enable the wireless exchange of information between vehicles (V2V, Vehicle-to-Vehicle), and between vehicles and infrastructure nodes (V2I, Vehicle-to-Infrastructure). Connected vehicles will extend in space and time the driver's awareness of the surrounding environment, while providing Internet connectivity on the move. First generation of connected vehicles will make use of the IEEE 802.11p radio access technology operating in the 5.9GHz band, and its variant in the 760 MHz band in Japan. However, cellular technologies are also being embedded into connected vehicles. This is especially the case with the introduction of eCall in Europe. Separately, 3GPP has recently created a Work Item to study the use of LTE (Long Term Evolution) for V2X services [1]. Connected vehicles are also expected to be a relevant component of the 5G ecosystem [2] that will enable new secure, dependable, ultra-reliable, and delay-critical services to everyone and everything, including cognitive objects and cyber-physical systems. 5G networks will exploit heterogeneous radio access technologies and networking [3] to improve efficiency and aggregate capacity.

The use of heterogeneous wireless networks in the vehicular environment is motivated by the fact that a single radio access technology will not be able to ubiquitously satisfy all performance requirements (communications range, reliability, latency, etc.) or provide all possible features (security, geo-cast, group-cast, etc.) needed by all vehicular applications. Heterogeneous vehicular networking will enable solutions capable to satisfy the diverse functional and operational requirements of vehicular applications under variable context conditions (traffic density, radio propagation or networking). In this context, a key aspect will be the selection and management of the different radio access technologies [3] that will be embedded into connected vehicles. In cellular networks, the management process is centralized and the infrastructure decides the radio access technology to be used by each node according to certain algorithms, parameters and metrics. Vehicular networks should foster vehicles to participate in the selection process in order to account for their specific and stringent requirements and their dynamic context conditions. In this context, this paper proposes and evaluates a context-aware heterogeneous V2I technique where vehicles select the most adequate radio access technology with the assistance of the infrastructure. The decision is driven by the objective to satisfy the vehicular application requirements at the minimum cost in terms of radio resources to maximize the transmission efficiency. The results obtained demonstrate the benefits of introducing context-aware heterogeneous V2I policies in connected vehicles, and the robustness of the proposed technique against the variability and inaccuracy of relevant context factors.

II. STATE OF THE ART

From the standardization point of view, connected vehicles have been designed from the ground up to facilitate the introduction of heterogeneous networking. ISO standardized the ITS station reference architecture that enables the use of multiple protocols and radio access technologies in vehicular networks (ISO 21217). This architecture has been adapted to the European context by ETSI (ETSI EN 302 665). ISO and ETSI ITS station reference architectures have been designed to support all types of applications. Applications are abstracted from the radio access technologies, network and transport protocols. A transversal management layer (under development) will be in charge of aspects such as networking management, management of congestion control, management of service advertisement, a common management information base (MIB), cross-interface management, etc. Standardization bodies are defining the components needed for the dynamic selection of the radio access technology and protocols.

M. Sepulcre and J. Gozalvez would like to acknowledge the support of DGT under the grant SPIP20141414.

978-1-4673-8049-2/15/$31.00 ©2015 IEEE

The research community has dedicated significant efforts to the study and design of radio access technology selection techniques for cellular networks. The selection process consists of three phases: information gathering, decision and execution. Five types of decision schemes can be identified depending on the decision criteria and parameters: RSS (Received Signal Strength), QoS (Quality of Service), decision function, network intelligence, and context [4]. Schemes combining multiple approaches are also possible. The RSS- and QoS-based schemes are relatively simple to implement, but generally result in low performance. RSS-based schemes decide on the technology to use based on the RSS measured from the nearest base stations or access points. For example, [5] presents an adaptive technique that exploits predictive RSS patterns. QoS-based schemes generally take into account factors such as capacity, bandwidth or user preferences. The third type of schemes utilizes functions that quantify the advantages of one radio access technology over the others. These schemes are especially useful as the selection process becomes more complex due to the large number of parameters and complex trade-offs between conflicting criteria. One example is the work in [6], where the authors propose a radio access technology selection mechanism for V2I communications that seeks to minimize the probability of outage through the sensing and processing of some physical, access, and networking. [7] also proposes a decision function based scheme with a prediction engine to maximize user utility, and takes into account parameters such as power consumption, application requirements, and user preferences (quality and monetary cost). Network intelligence schemes that utilize Fuzzy Logic or Artificial Neural Networks are useful to operate with inaccurate data that feed the decision process. Finally, context schemes utilize relevant context information to could improve the decision process. Context schemes have the potential to achieve the highest performance (throughput, adaptability, reliability, packet loss, etc.) at the cost of complexity [4]. The context is a very relevant factor for vehicular networks [8], and therefore this study, and the rest of this section, focuses on context-based decision schemes.

Location-aware algorithms are a basic type of context-aware algorithms. The work in [9] presents a location-based approach that combines location information and network information in order to avoid the ping-pong effect related to performing predictions at wireless cells' boundaries. The work in [10] focuses in heterogeneous vehicular networks, and proposes a decision algorithm that jointly considers the vehicle location and networking metrics to select the best radio access technology in order to guarantee the QoS demanded by the application. More advanced context information is considered in [11] for multi-homed nomadic mobile services. In particular, the work in [11] exploits the user trip information, device services, network services, user preferences and device specifications to perform a path prediction to ensure the end-to-end QoS. Specifically designed for vehicular networks, the work in [12] proposes NAIRHA, an algorithm that takes into account user preferences to select the most suitable network that fulfils the application requirements. NAIRHA exploits location and navigation information to estimate the useful coverage time for each technology, and a Simple Additive Weighting (SAW) function to quantify the benefit of selecting each available radio access technology. The work in [13] proposes a method to select in vehicular networks the most adequate radio access technology (considering WiFi and LTE) that maximizes QoE throughout the mobility path. The proposal takes into account context information such as the service type, mobility, and the traffic dynamics over the backhaul links of the different available technologies.

III. Context-aware Heterogeneous V2I Proposal

A. Overall concept

The context-aware heterogeneous V2I technique proposed in this paper follows a distributed decision process where each vehicle dynamically decides which technology, and when, it should use based on its context conditions. Contrary to most of related studies, the distributed approach is better suited for the vehicular network architecture [14], and enables exploiting more accurate local context information. Uploading in real-time this information to the infrastructure so that the infrastructure takes centralized decisions would increase the signaling overhead and introduce additional delays in the decision process.

The proposed scheme takes its decisions using context-based performance and cost models. The performance represents the utility or satisfaction for the user or the application, whereas the cost represents aspects that should be minimized. Different performance and cost metrics can be considered. For example, the performance can be estimated in terms of the time needed to upload certain information or the experienced throughput. The bandwidth, transmission cost or communications overhead are examples of possible cost metrics. The employed models reflect the relation between the vehicular context and the performance experienced and the associated cost. Vehicles make use of these models to estimate the performance and cost that would be achieved with each available radio access technology. This study considers that the models are built by the infrastructure using context, performance and cost information uploaded by the vehicles[1]. This information is used by a central server to build the models that are then distributed to the vehicles to support the decision process (e.g. on a daily, weekly or monthly basis depending on the changes produced in the models). The number of context factors can be increased without modifying the core of the proposed technique, which represents a relevant difference between the proposed technique and existing studies.

The proposed distributed decision process avoids that greedy decisions negatively impact the system performance. To do so, the decisions taken by vehicles are not only driven

[1] The information does not need to be uploaded in real-time. Algorithms (that are out of the scope of this study) could be created to decide when it is more efficient to upload this information.

by the vehicles' individual application requirements but also the system performance and benefits. In particular, each vehicle dynamically selects the radio access technology that minimizes the cost, as long as the performance estimated is sufficient to satisfy the application requirements. This decision is periodically re-evaluated to account for changes in context conditions or inaccuracies in the context estimation.

B. Heterogeneous V2I proposal

The proposed technique has been designed for a scenario where vehicles need to download certain information within a given time window. This information could be a 2D/3D map update, a software update, or any other application that can tolerate certain delay in the download process. Each vehicle needs to download B bits in ΔT seconds, where B and ΔT represent the application requirements. To satisfy these requirements, the proposed technique makes use of context-based models that model the throughput as a function of the distance between a vehicle and an infrastructure node (e.g. base station, road side unit, access point). The context information includes: location, navigation information (trajectory) of the vehicle, location of the infrastructure nodes, and channel load.

1) *Estimation of utility and cost*. The decision process is based on the estimation of the utility and cost of using each radio access technology along the future vehicle trajectory (next ΔT seconds). To this aim, the future vehicle trajectory is sampled every Δt seconds, which results in $n=\Delta T/\Delta t$ discrete positions. Using these discrete positions, we define the road segments for which the utility and cost will be estimated. For example, road segment i is the road segment between positions i and $i+1$. For simplicity, we assume that the utility and cost of using a given technology in road segment i is constant and equal to the utility and cost of using it at position i. This simplification and the discretization of the vehicle trajectory allow reducing the complexity of the problem resolution. The utility that could be experienced at road segment i is calculated as the ratio between the amount of information that can be downloaded during Δt seconds (b_{ij}), and the remaining amount of data that needs to be downloaded (B', where initially $B'=B$). For road segment i and radio access technology j, the utility can be therefore expressed as:

$$u_{ij} = \frac{b_{ij}}{B'} = \frac{th_{ij} / \Delta t}{B'} \quad (1)$$

b_{ij} is obtained by dividing the throughput (th_{ij}) that can be achieved with technology j by Δt. The throughput level is obtained by calculating the distance between position i and the closest infrastructure node of technology j, and using the context-based models that relate throughput and distance (information on the models utilized will be presented in Section IV). The cost of using a given radio access technology has been defined as the inverse of the transmission efficiency. The transmission efficiency is the ratio between the throughput th_{ij} and the maximum throughput that can be achieved with radio access technology j (th_{max}^{j}). The maximum efficiency is therefore obtained with the highest modulation scheme and lowest coding rate, i.e. when the throughput is maximized (typically at short distances to infrastructure nodes). As a result, the cost of using technology j at road segment i is calculated by each vehicle as:

$$c_{ij} = 1 - e_{ij} = 1 - \frac{th_{ij}}{th_{\max}^{j}} \quad (2)$$

2) *Selection*. The technique selects at each road segment the technology that satisfies the application requirements with minimum cost. To this aim, each vehicle calculates for each road segment i and technology j the ratio between cost and utility:

$$r_{ij} = \frac{c_{ij}}{u_{ij}} \quad (3)$$

A lower ratio means lower cost and/or higher utility. If two technologies have the same cost, the one with higher utility will have lower ratio and will be preferred. For each road segment i the vehicle identifies the radio access technology with minimum ratio:

$$r_i = \min(r_{i1}, r_{i2}, ..., r_{ij}) \quad (4)$$

Then, all road segments are sorted in ascending order based on their ratio r_i. The vehicle selects the smallest number of road segments with minimum ratio r_i that need to be considered so that the sum of their utilities is higher or equal than one. Following eq. (1), the file is completely downloaded if the utility is higher or equal to 1. This set of road segments will be referred to as S, and do not need to be consecutive, i.e. the download process can be paused and resumed. When the vehicle reaches a road segment that belongs to S, it will make use of the technology providing the minimum ratio between cost and utility for this road segment. In the rest of road segments, the vehicle will not communicate because it will be less efficient than communicating in the identified set of road segments S. The proposed technique therefore does not require a continuous transmission, but rather exploits the considered delay tolerance to opportunistically decide not only the communications technology to use but also when to utilize it. The selection algorithm is executed every Δt seconds. This periodic execution allows reacting to changes in context conditions or errors in utility or cost levels estimations due to inaccurate identification of context conditions.

To illustrate the proposed technique, Fig. 1 represents a situation where a vehicle needs to select between Technology A and B to download certain information before reaching the end of the street. The vehicle first samples its future trajectory to obtain positions 0 to 3 (and therefore road segments 0 to 3). The vehicle then estimates the utility and cost (u_{ij}, c_{ij}) for each road segment and radio access technology. Technology B is identified as the one with minimum ratio between utility and cost for road segments 1 and 2, and Technology A for road segments 0 and 3 (dashed rectangles in Fig. 1). The vehicle has estimated that using Technology B at road segments 1 and 2 it will be sufficient to download the required information. As a result, it will only download at road segments 1 and 2 as they represent the smallest set of road segments, S, that minimizes the ratio between cost and utility and satisfies the application requirements (filled rectangles in Fig. 1).

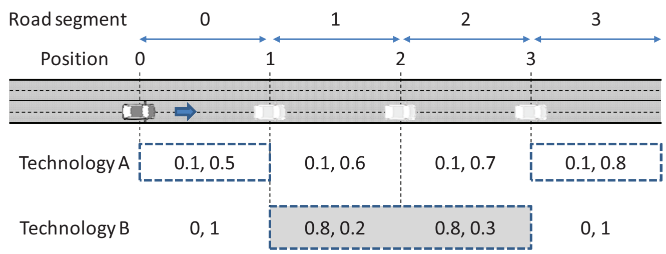


Fig. 1. Illustration of the proposed technique. The vehicle estimates the utilities and costs (u_{ij}, c_{ij}) for each technology and road segment. Dashed rectangles highlight the technologies with minimum ratio between cost and utility for each road segment. Filled rectangles highlight the technologies finally selected to satisfy the overall utility while minimizing the cost. The example results in that the vehicle will not transmit in road segments 0 and 3, since it will be sufficient to use Technology B in road segments 1 and 2 to satisfy the application requirements.

IV. Evaluation

The proposed context-aware heterogeneous V2I technique has been evaluated through simulations that model a Manhattan-like urban scenario with 15x15 blocks (3750mx3750m) with 2 lanes per driving direction. The simulated scenario is depicted in Fig. 2 with the streets represented by a dashed grid. The traffic simulator SUMO has been used to generate realistic mobility patterns. Vehicles have been generated with random origin and destination points at a rate of *R* vehicles/second. Different values of *R* result in different average traffic densities (see Table I). For each traffic density, 10 simulation runs of 500s have been conducted to ensure results with adequate statistical accuracy.

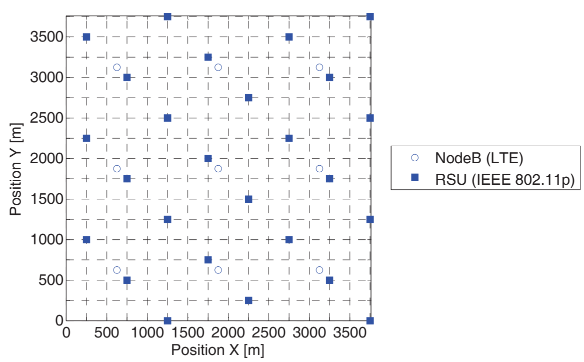


Fig. 2. Manhattan-like urban scenario with 15x15 blocks (3750mx3750m), 9 NodeBs and 26 RSUs.

TABLE I. Simulated Traffic Densities

R [vehicles/second]	*Travel time [s]*	*Vehicles in the scenario*	*Traffic density [veh/km]*
2	180	440	3.4
4	182	870	6.8
6	185	1410	11.0
8	187	2090	16.3
10	190	2950	23.0

Each vehicle triggers the data download application when it enters the scenario. Once triggered, the vehicle needs to download B=20Mb in less than ΔT=60s. The objective is to satisfy these requirements for all possible vehicles. The Δt parameter has been set to 1 second, but other values are possible. All vehicles are equipped with IEEE 802.11p and LTE interfaces, since both are being analyzed for vehicular applications [15]. The scenario includes 9 LTE base stations (NodeB) and 26 Road Side Units (RSU) uniformly distributed as illustrated in Fig. 2. We consider that the 9 LTE base stations completely cover the simulated scenario. On the other hand, the IEEE 802.11p RSUs only provide coverage under Line-of-Sight (LOS) conditions on the four adjacent streets to the intersections where they are placed.

Estimating the utility and cost (eq. (1) and (2)) requires throughput models for IEEE 802.11p and LTE (Fig. 3). The throughput is shown as a function of the distance to the serving NodeB or RSU. This study considers the LTE transmission modes (modulation and code rates) associated to the 15 CQI values defined in 3GPP TS 36.213. The LTE throughput model has been obtained considering that each cell is divided into 15 concentric QoS rings [16]. Each QoS ring is associated to a different transmission mode. The throughput for each ring has been calculated considering the number of data bits that can be transmitted per second with each transmission mode. The IEEE 802.11p throughput is obtained using the WINNER+ B1 urban propagation model and the modulation and code rate that provide the higher throughput at each distance to the serving RSU. This study assumes that radio resources are uniformly distributed among users being served by the same infrastructure node. For example, if two vehicles are simultaneously connected to the same NodeB or RSU, each vehicle will receive 50% of the radio resources and experience half the throughput shown in Fig. 3 for the corresponding distance. Without loss of generality, this work also assumes that only the vehicles in the scenario are connected to the NodeBs or RSUs.

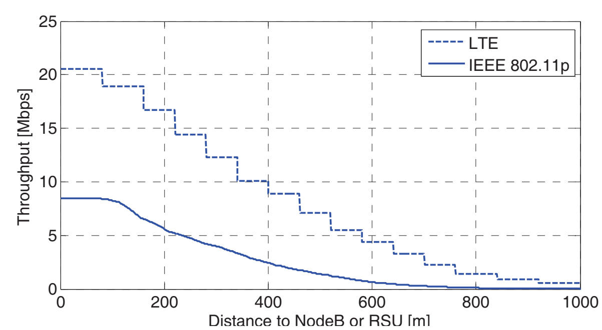
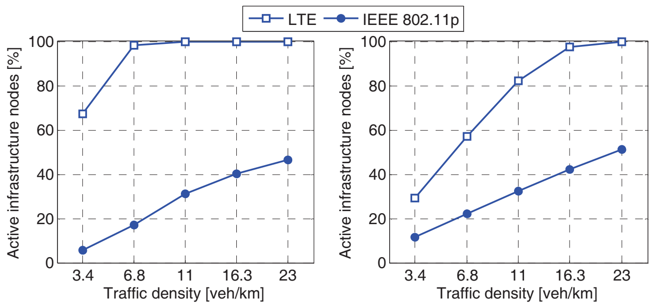


Fig. 3. Throughput models for LTE and IEEE 802.11p.

A. Results

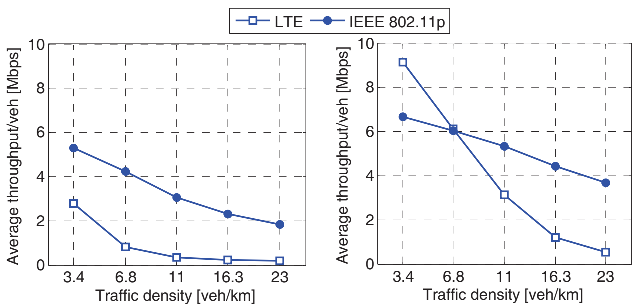
A reference scheme has also been implemented for comparison purposes. With this scheme, each vehicle selects the technology that provides the highest instantaneous throughput. This approach can be considered greedy in the sense that vehicles look at their instantaneous maximum benefit and do not take into account their impact on the network or the benefits from postponing the transmission until better conditions (lower cost) are experienced. The reference scheme also periodically reevaluates its selection decision.

Fig. 4 shows the average percentage of active infrastructure nodes per technology for the reference scheme (Fig. 4a) and our proposal (Fig. 4b). A value equal to 100% for a given technology means that all NodeBs or RSUs in the scenario have at least one active connection all the time. As it can be observed, the proposed scheme better distributes the load among infrastructure nodes compared to the reference scheme that tends to connect to LTE as it provides ubiquitous coverage across the scenario. With the proposed scheme, vehicles do not connect immediately to LTE and wait for better transmission conditions that reduce the effective transmission times. Fig. 5 shows that this operation results in that our proposed scheme increases the throughput experienced per vehicle and technology (200% for LTE and 25% for IEEE 802.11p).



(a) Reference scheme (b) Heterogeneous V2I proposal

Fig. 4. Average percentage of active infrastructure nodes.



(a) Reference scheme (b) Heterogeneous V2I proposal

Fig. 5. Average throughput obtained per vehicle.

Fig. 6 shows the percentage of vehicles that are able to download the required information within the specified period. As it can be observed, the propose scheme notably improves the user quality of experience thanks to the use of context information and the integration of opportunistic principles. This improvement is obtained at the expense of slightly increasing (by 8.4%) the handover rate between communications technologies compared to the reference scheme

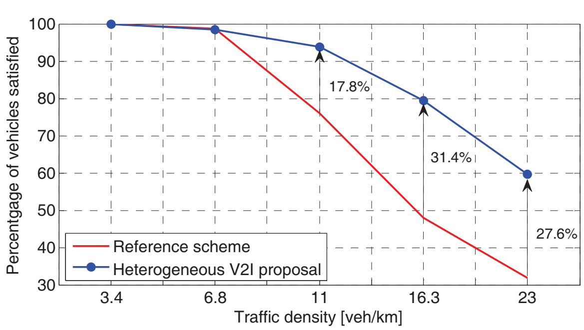


Fig. 6. Percentage of vehicles that are able to to download the required information before the deadline.

B. *Impact of context conditions*

The previous results were obtained with utility and costs models that only depended on the location of vehicles (and hence on their distance to the infrastructure nodes). The utility (throughput in our case) also depends on the number of vehicles that are simultaneously downloading information from the same NodeB or RSU. This is the case because the radio resources are shared among vehicles simultaneously connected to the same infrastructure node. To account for this effect, this section considers the case in which the infrastructure broadcasts the average percentage of bandwidth (or resources) assigned per vehicle for LTE and IEEE 802.11p during the last Δt seconds. This information is used by the vehicles to improve the throughput estimation. The results depicted in Fig. 7 show that our proposed scheme further improves its performance if we jointly exploit location and channel load information.

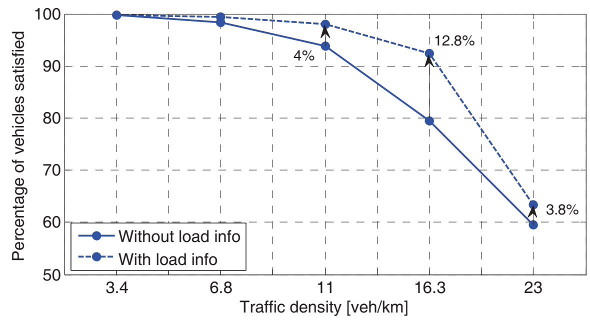
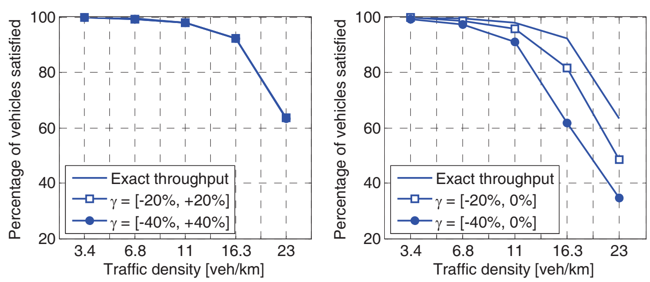


Fig. 7. Percentage of vehicles that are able to download the required information before the deadline with the proposed technique when using and not channel load information.

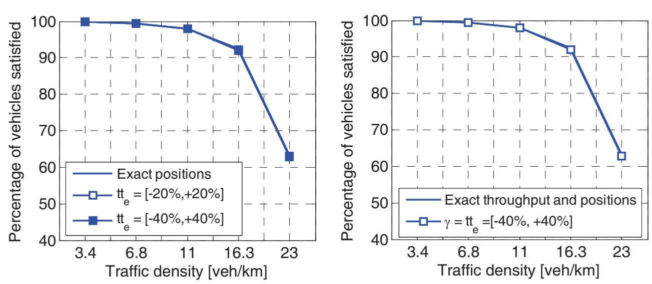
The previous results were obtained considering that the throughput experienced by the vehicles exactly matches the one indicated in the context-based models. In practice, models will be built using measurements, and the throughput experienced by vehicles will not exactly match that indicated by the model due to the probabilistic nature of propagation. To analyze how this effect could impact the obtained results, we have conducted simulations considering that the throughput experienced by vehicles is a random variable uniformly distributed within the intervals γ=[-20%, +20%] and γ=[-40%, +40%] around the throughput indicated by the models (Fig. 3) for a given distance between the vehicle and the infrastructure nodes. Fig. 8a shows that this effect does not have a significant impact on the percentage of vehicles that download the required information on time when using the proposed technique. Fig. 8b shows that the mismatch between the throughput experienced and the throughput models only has an influence on the user quality of experience if the model results in that vehicles always overestimate the throughput.

The utility and cost depend significantly on the estimation of future positions and road segments. The previous results were obtained considering exact positioning information extracted from SUMO traces. In a real network, vehicles will not be able to exactly know their future location. It is hence necessary to analyze the impact of errors in the future location estimation on our proposed scheme. To do so, we have conducted additional simulations where we consider that vehicles are able to estimate the end-to-end travel time with certain error. Intermediate positions between origin and destination are then computed considering a constant speed. This speed is a function of the origin-destination distance and the estimated travel time. Fig. 9a shows that the percentage of vehicles satisfied considering the case in which future positions can be exactly computed, and when they are computed considering a random travel time uniformly distributed around the exact one. Fig. 9a shows that this percentage is not significantly affected (the degradation is around 1%) even when the interval considers errors in the travel time estimation of 40%. This is mostly due to the fact that the proposed scheme periodically reevaluates its selection decision, which allows partially correcting estimation errors. Fig. 9b shows the results when accounting for estimation errors of the throughput and travel time (and consequently position). The results are shown for [-40%, 40%] intervals around the exact values. The results show that the degradation experienced is only 1%, which demonstrates the robustness of our proposed scheme against context estimation errors.



(a) Centered intervals (b) Throughput overestimated

Fig. 8. Percentage of vehicles that are able to download the required information before the deadline with the proposed technique (using location and channel load information) and different throughput variability levels.



(a) Exact throughput and different travel time interval errors (b) Different throughput variability levels and travel time interval errors

Fig. 9. Percentage of vehicles that are able to download the required information before the deadline with the proposed technique (using location and channel load information). The results are shown for different throughput variability levels and random travel time interval errors.

V. Conclusions

This paper proposes a context-aware heterogeneous V2I technique where vehicles dynamically select the most adequate communications technology using context information and the assistance of the infrastructure. Vehicles base their selection decisions on performance and cost estimations obtained using context-based models. The results obtained demonstrate the benefits of introducing context-aware heterogeneous V2I policies in connected vehicles, and the robustness of the proposed technique against inaccurate estimations of relevant context conditions. The proposed technique can be extended with other metrics and richer context information. For example, different models could be built for different environments (urban, suburban, highway, etc.). Other relevant context factors could also be used to build the performance and cost models. This could include context factors such as the number of lanes, the presence of trees, or the traffic density among others [17].

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