Context-Aware Heterogeneous V2X Communications for Connected Vehicles

Miguel Sepulcre and Javier Gozalvez

***Abstract* – Connected vehicles will require heterogeneous or hybrid communication technologies to implement the full range of cooperative ITS services in diverse scenarios. This paper presents an architecture for context-aware heterogeneous vehicular networks. The architecture is compatible with the current ETSI and ISO standardized ITS station reference architectures, and allows for the dynamic selection and configuration of communication profiles based on the context conditions and the application requirements. The potential of the proposed architecture is demonstrated with the implementation and evaluation of a heterogeneous V2I communications algorithm that improves the quality of service and the capacity to satisfy the vehicular application requirements, and reduces the economic cost of connected vehicle services.**

***Index Terms* – Vehicular networks, cooperative ITS, connected vehicles, heterogeneous networks, hybrid networks, context-aware, architecture, vehicle to infrastructure, V2I, V2X.**

I. Introduction

Connected vehicles and cooperative ITS (C-ITS) systems will rely on V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) communications to improve traffic safety and efficiency. C-ITS systems will have to operate under variable conditions, and efficiently satisfy the diverse functional and operational requirements of C-ITS applications. Satisfying all the requirements can be a significant challenge when relying on a single protocol stack, communication technology or frequency band. In fact, the European C-ITS platform [1] recently concluded that currently neither ETSI ITS-G5 (the European adaptation of the IEEE 802.11p/WAVE standards in the 5.9GHz band) nor cellular systems can provide the full range of necessary services for C-ITS. To address this challenge, the C-ITS platform proposes to utilize different communication technologies to take advantage of their complementarities. This is commonly referred as heterogeneous or hybrid networking. The ITS station reference architecture standardized by ISO [2], and adapted in Europe by ETSI [3], already offers the possibility to implement heterogeneous networking and use multiple protocols and communication technologies.

Heterogeneous networking has been mainly utilized to date in cellular networks with the objective to increase the user quality of service, and maximize the networks' utilization and revenue. Recent studies have suggested the use of heterogeneous networks to satisfy the various requirements of vehicular applications, including those related to autonomous vehicles [4]. The selection of the adequate network in a heterogeneous framework can be improved using context information [5]. For example, information about the presence of obstructing elements (e.g. buildings) could be used to select the most adequate frequency band or even protocol stack. Context information could also be used to select the most cost-efficient technology, which can be particularly relevant as it is expected that connected and automated vehicles will upload large amounts of data to the cloud. In fact, a car manufacturer announced in 2016 a new high-precision map generation system that will use data from on-board cameras and GPS devices installed in production vehicles [6]. The information gathered by vehicles will be sent to data centers, where it will be automatically pieced together, corrected and updated to generate high precision road maps that cover a wide area. Another example is the recent agreement between Qualcomm and TomTom to crowdsource high-definition map data for autonomous driving [7]. TomTom's HD Map for autonomous vehicles will be generated using rich vehicular data collected and transmitted by the new Qualcomm Drive Data Platform. In both examples, the information could be sent using cellular networks, but this could have a high economic cost. On the other hand, the vehicles could use the knowledge of their trajectory and the position of IEEE 802.11p-based RSUs (Road Side Units) or WiFi APs (Access Points) to upload part of this information when covered by RSUs or APs. This will reduce the economic cost to upload the data compared to always relying on cellular connectivity.

The context-awareness paradigm is already partly present in the current ETSI ITS communications architecture through the Local Dynamic Map (LDM)[1] [8]. However, the current architecture requires changes to fully implement and exploit context-aware heterogeneous vehicular networking. This paper proposes an evolution of the ITS communications architecture to facilitate the implementation of context-aware heterogeneous vehicular networking. The proposed architecture is compatible with current ETSI and ISO ITS station reference architecture, and enables the dynamic selection, coordination and configuration of communication

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[1] The LDM is a conceptual data store located at the Facilities layer of the protocol stack. It is used to store relevant vehicular information.

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profiles (CP) based on the context conditions and the application requirements. According to the ISO standard [9], a communication profile is defined as a parameterized ITS communication protocol stack. ETSI evolved this definition in [10], and defined communication profile as a consistent association of communication resources provided by the four layers of the communication stack. The CP includes the protocol stack, communication technology, communications mode (V2V or V2I), and frequency band. The potential of the proposed architecture is demonstrated with the implementation and evaluation of a heterogeneous V2I communications algorithm that improves the quality of service and the utilization of network resources, and reduces the economic cost to upload vehicular data to the cloud.

II. ITS Station Reference Architecture

This study takes as baseline the ETSI ITS station reference architecture illustrated in Figure 1. The architecture considers different protocols at the network and transport layers, as well as different communication technologies. Applications are abstracted from the communication technologies, the network and the transport protocols. A Facilities layer collects a set of common functionalities and data structures to support cooperative vehicular applications and communications. The transversal security layer is in charge of security and privacy protection.

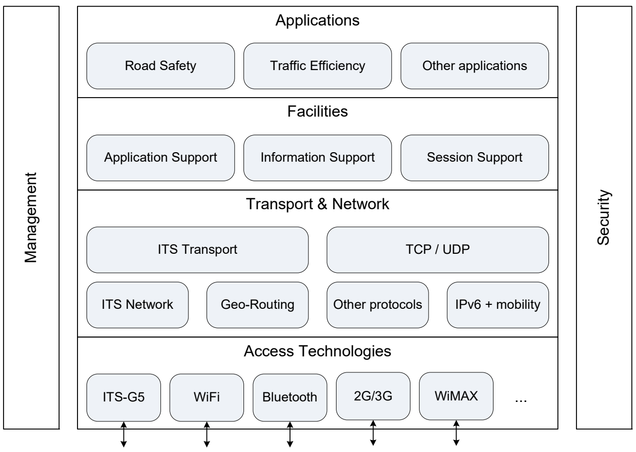

Figure 1. ETSI ITS station reference architecture.

The transversal management layer is in charge of the management of congestion control, the management of service advertisement, handling a common management information base (MIB), and cross-interface management. The transversal management layer also manages the different networks, and selects the communication profiles (CP). The CP includes the protocol stack, communication technology, communications mode (V2V or V2I) and frequency band. ISO has defined the main components of the management layer for the dynamic selection of CPs [9]. The standard identifies as input to the CP selection, the application requirements, the status of communication and networking protocols, and decision rules (regulations and policies). The current CP selection component does not fully exploit external context information.

III. Architecture

The architecture here proposed is aimed at exploiting context information for heterogeneous vehicular networking. Context is formally defined as any information that can be used to characterize the situation of an entity (person, place, or object) [11]. We extend here this definition to define the context of a vehicle as follows: "*Context is a collection of measured, exchanged and inferred knowledge that characterizes the vehicular environment and the communication needs and conditions of a vehicular node*". This definition considers that the context information can be directly measured by a vehicle, obtained from other vehicles or infrastructure nodes, or inferred. The context influences the requirements of vehicular applications (needs) and the status of vehicular networks (conditions). Examples of context factors include weather conditions, traffic density, communications channel load, vehicle characteristics, or presence of nearby V2I infrastructure units. All these context factors can have a direct or indirect influence on the requirements of vehicular applications [12] and on the performance of vehicular communications [13].

A. System architecture

This paper considers a system architecture that can embed the functions required by context-aware systems [14]: (1) collecting raw context data; (2) reasoning/processing such data to synthesize higher-level context information; (3) storing the context information in a retrievable and indexed format; and (4) managing the context information between different components of the system. Three different types of architectures can be identified for context-aware systems [14]: server-based, peer-to-peer, and server-based with distributed components. In server-based architectures, a central server performs the functions of acquisition and reasoning. Clients access the server remotely to retrieve context or raw data to process locally. In a peer-to-peer architecture, the functional context-awareness tasks are carried out by peer components, with each peer acting as both a server and a client. The server-based architecture with distributed components allows each function to be hosted on different nodes in a network, and a central server coordinates the flow of information and controls the different components.

This study considers a server-based architecture with most of its components distributed across the vehicular network. Vehicular nodes (vehicles and RSUs) are in charge of acquiring the context information they need. This information can be exploited to select and configure the most adequate CP at each point in time. The CP selection process can be supported by a central server that provides the necessary information to the vehicular nodes so that they can autonomously identify their most convenient CP under their specific context conditions.

The two main phases of the CP selection process are information gathering and decision [15]. The information gathered typically includes communication metrics (e.g. throughput, packet loss ratio, received signal strength, etc.), mobile device state (e.g. available battery and computing

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resources) and user preferences (e.g. budget and services required). The decision phase is probably the most critical one, and optimization- or heuristics-based algorithms can be used. The establishment of a vehicular communication session first requires acquiring the context information. Vehicular nodes can then run a reasoning process to estimate what utility and cost could be achieved with each available CP under the experienced context conditions. Different types of utility and cost metrics could be considered. Examples of utility metrics are throughput and reliability. Examples of cost metrics are channel load, interference or economic cost (price).

To reflect the relationship between context factors and utility/cost metrics this study considers the use of context-based models. Context-based models can be used to estimate what communication utility/cost should be expected under certain context conditions. For example, a context-based model should reflect the fact that the communications range in an urban street with trees can be significantly lower than in streets without obstructions [5]. This study foresees the possibility to build these models using data from different vehicles. The models could be located at a central server, and be periodically distributed to vehicular nodes. The decision process identifies and selects the most adequate CP using the estimated utility and cost metrics. During the session, the utility and cost are continuously monitored in case the selected CP needs to be changed or reconfigured to satisfy the application requirements. The proposed distributed decision approach allows each node to take its own CP decisions based on the available context information.

Figure 2 depicts the key entities of the system architecture. The network heterogeneity is represented by the different BSs (cellular Base Stations), RSUs (IEEE 802.11p/ITS-G5) and APs (WiFi Access Points). The vehicles can acquire context information from their onboard sensors, other vehicles or RSUs, or context information servers. Context information servers can be of different types, and can be operated by different entities. Examples of context information servers include traffic management servers (provide traffic density statics), servers providing weather forecasts, or open data servers in smart cities providing sensor data. The central server builds, stores and distributes the context-based models.

B. *Vehicular node*

The vehicular node (vehicle or RSU) is in charge of: context acquisition, context reasoning, decision, evaluation, context exchange, and model update. Figure 3 represents the components at the vehicular node in the proposed context-aware architecture. The figure also maps these components to the layers of the standardized ETSI ITS station reference architecture. The components for context acquisition and for the exchange of context information and model update are located at the Facilities layer. This study proposes to locate the components for context reasoning and evaluation at the management layer. The decision component is distributed between the management and the applications layers.

Decision component

Context-based adaptation of application requirements. The application requirements (especially those related to safety) depend on context factors such as the vehicle's speed, the driver's reaction time or the position of nearby vehicles [12]. An example is the distance at which vehicles should be able to detect and communicate with other vehicles. This distance should be adapted to the context conditions since the time to decelerate when a risk is detected depends, for example, on the vehicle's speed, the type of vehicles and the weather conditions among other context factors. A context-based adaptation of the application requirements is therefore necessary to ensure the safety levels expected in C-ITS. Each application should define the periodicity at which its requirements should be evaluated and adapted if necessary. The adaptation does not need to be executed by the Management layer. In fact, the proposed architecture considers the option for each application to have its own context-based

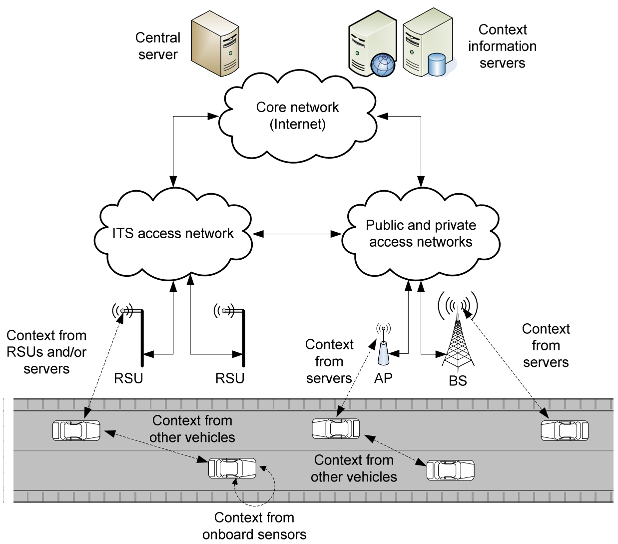

Figure 2. System architecture.

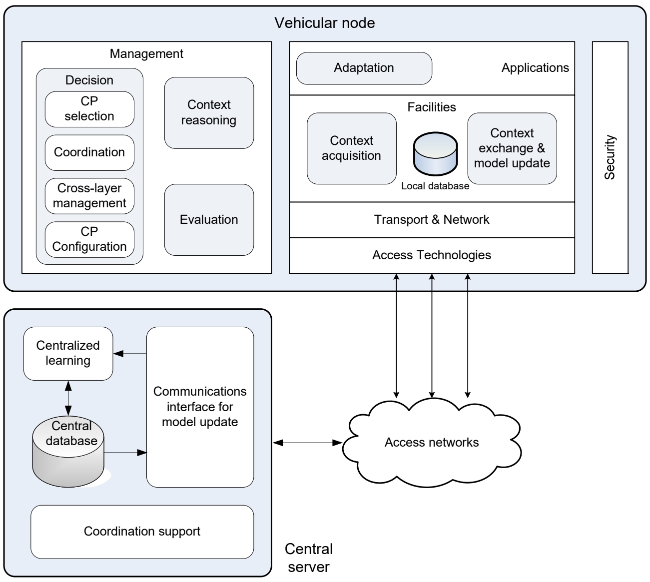

Figure 3. Components of the architecture.

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adaptation module ('Adaptation' module at the applications layer in Fig 3). In this case, the applications layer requires access to context information. This is possible with the proposed architecture since applications have direct access to the Facilities layer, where the context information is stored.

Context-based CP selection. Every time a vehicular node needs to transmit, or establish a communication session, it needs to take a decision on what is the most appropriate CP to efficiently satisfy the application requirements. The same process should be followed when context conditions, utility or cost change. The CP selection component is located at the transversal management layer in order to be able to access the different layers of the protocol stack. The selection process should be permanently active in case a change of CP is necessary. However, changes in the CP should also be minimized to avoid excessive signaling and delays. To this aim, the CP could be selected not only based on the current context conditions, but also on possible variations of the context conditions that could influence the utility and cost[2]. The selected CP should try first to support such variations (by reconfiguring its parameters) in order to avoid frequent changes of CP.

Coordination. A dynamic CP selection requires coordination mechanisms so that nodes that want to communicate with each other coordinate their decisions in the CP selection process. The coordination process will avoid for example, that the source node selects a CP that is not supported or available at the destination node. The information to be exchanged for the coordination process will have to use a known reference CP. The coordination process should be driven by the node that wants to initiate the transmission. However, the central or context servers could also support the coordination process by providing relevant information (e.g. channel usage policies, channel/band load levels, etc). We propose to locate the coordination module at the management layer so that it can have access to the context information and the CP selection component. Alternatively, it could also be located at the Facilities layer.

Context-based CP configuration. Once a CP is selected, its protocols should be dynamically configured based on the context conditions and the application requirements. Parameters such as the transmission power or frequency of 1-hop broadcast messages, the transport layer TCP congestion window, or the IEEE 802.11 contention window are examples of parameters to be adapted. CP configuration decisions can be taken more frequently than CP selection ones since their (implementation) cost is lower. The proposed CP configuration component is located at the management layer, and it has interfaces with the communication protocols operating at different layers of the protocol stack.

Context-based cross-layer management. The CP selection and configuration modules can interact with multiple protocols at different layers. A cross-layer management module is then proposed to coordinate the operation of these protocols. If the protocols operate independently, negative interactions or conflicts can arise. This situation can occur for example if a congestion control protocol requires the reduction of the transmission power to reduce the channel load, and such reduction negatively influences the operation of an awareness control protocol that requires a higher transmission power to ensure a given communications range. The cross-layer management module should exploit the synergies and interactions among layers of the protocol stack taking into account context information.

[2] For example, let's consider that a vehicle needs to download an updated road map, and at the start of the download process the most adequate CP is IEEE 802.11p because there is a nearby RSU. Let's then consider that during the download process the vehicle soon loses RSU coverage (e.g. because it turns around an intersection). This will require a CP change that could have been avoided if the time the vehicle was going to remain under RSU coverage was estimated (e.g. using its trajectory or GPS guidance).

Context reasoning component

The reasoning component acts as an interface between the context acquisition component and the decision component. The reasoning component implements the necessary methods to transform the context data into information that can be directly understood and processed by the decision component. The decision component can then operate independently of the context sources or acquisition methods. In the proposed architecture, the reasoning component is part of the management layer, but it could also be part of the Facilities layer with an interface to the management layer. Different reasoning methods could be utilized for the various decision processes identified.

Context acquisition component

The context acquisition component receives queries from the reasoning component. It provides the context data in an adequate format to the components (e.g. the reasoning component) and protocols that need it. The context acquisition component is in charge of: (1) controlling the acquisition process to minimize unnecessary acquisition costs, (2) processing raw context data, and (3) combining processed context information from different sources. Acquiring large amounts of context data could help achieve a more accurate estimation of CP utility and costs. However, it could also increase the acquisition cost (equipment resources needed, computing power and possibly communications overhead). The acquisition process should hence be controlled to extract only the more relevant context data. The definition of a model to represent the context data (e.g. using ontologies) will facilitate the exchange of context data, and make the functionalities of the context acquisition component independent from other modules. The context acquisition component is part of the Facilities layer. It has an interface to the local database where the context information is stored.

Evaluation component

The evaluation component continuously measures the utility and cost experienced with the selected CP and configuration. The specific metrics to be evaluated depend on the application that is executed and its requirements. The utility and cost is evaluated by the source and/or destination nodes. In the case of multi-hop transmissions, intermediate nodes can also

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participate in the evaluation process. The evaluation component is located in the management layer.

Context exchange and model update

This component is in charge of sharing context information with other nodes. Sharing information reduces the cost of acquiring context data, and improves its accuracy. This component also serves as an interface with the central server to upload context information, and utility and cost metrics measured by the vehicular node. This information will be used by the central server to build context-based models that could be distributed to other nodes. This component is part of the Facilities layer.

Local database

The local database contains all acquired and processed context information, as well as the measured utility and cost metrics. This local database could extend or complement the LDM standardized by ETSI at the Facilities layer. The context factors considered in the LDM are only the ones that are relevant to the applications. However, the proposed architecture considers that context factors relevant to V2X communications should also be stored at the local database.

C. Central server

The central server builds and distributes the context-based models. The models are built using the utility and cost measurements (and their associated context conditions) that are sent by the vehicular nodes. The authors propose in [5] to build the models using Bayesian or artificial neural networks, but other approaches are certainly possible. The central server can also support the CP coordination process. To this aim, it could for example, periodically distribute geo-localized channel usage policies, i.e. indicate which channels and communication technologies should be used at each location [16]. The central server could also arbitrate the coordination process to solve conflicting situations, actively participate in it, or even manage it given its knowledge about the complete network.

IV. INTERACTIONS BETWEEN COMPONENTS

Figure 4 represents the interactions between the components of the proposed architecture. The following steps are executed when a vehicular node (vehicle or RSU) wants to launch an application:

1. The application is launched automatically or by the driver.
2. The application queries the context acquisition component, and establishes its requirements using the provided context information.
3. The application requirements are reported to the CP selection component, and the CP selection process is triggered.
4. The CP selection component identifies the available CPs that could satisfy the application requirements. The component requests the reasoning component to estimate the utility and costs metrics for the identified CPs.
5. The reasoning component queries the context acquisition module for the context information necessary to perform the required estimations.
6. The context acquisition component acquires, processes and combines the context information. It then sends the result to the reasoning component.
7. The reasoning component estimates the utility and cost metrics that would be obtained with the identified CPs under the current context conditions.
8. The CP selection component uses the computed metrics to elaborate a prioritized list of the CPs capable to satisfy the application requirements. This list is passed to the coordination module.
9. The coordination module can request additional context information to support the CP selection process.
10. Similarly, the coordination module could require the exchange of information between vehicular nodes and/or the central server.
11. The CP is selected taking into account the indications of the coordination process, and the objective to satisfy the application requirements and minimize the costs.

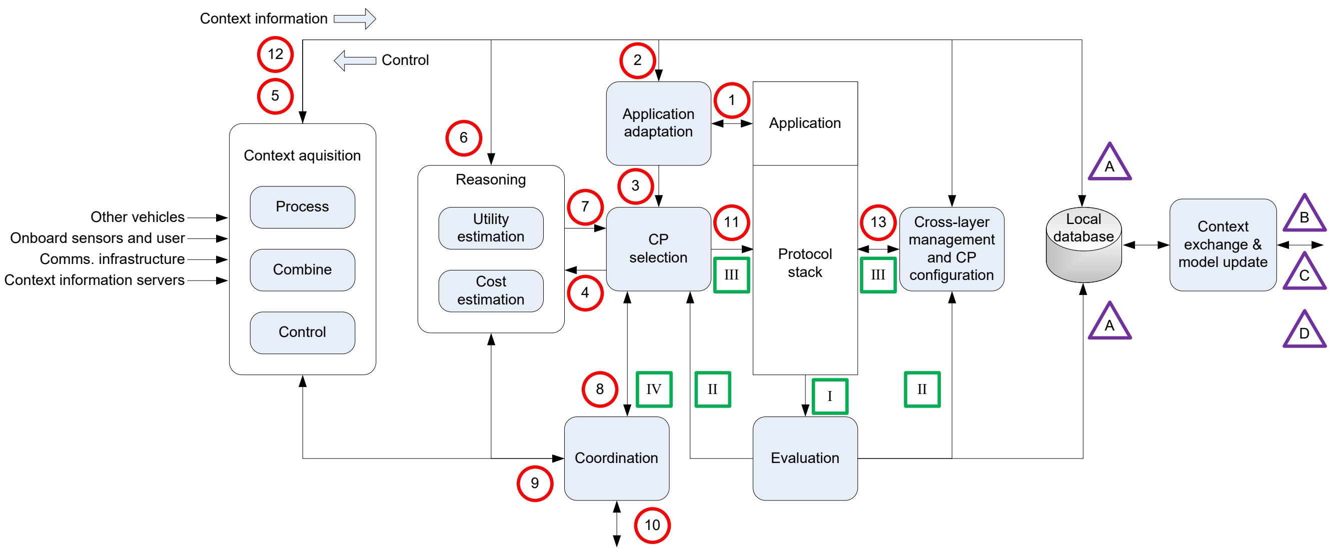

Figure 4. Interactions between components in the architecture for context-aware heterogeneous vehicular networks.

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12. The cross-layer management and CP configuration processes solicit the context information they need.
13. The selected CP is configured and interacting cross-layer protocols are coordinated.

The following steps are necessary to maintain an active communication:

I. The evaluation component continuously monitors the communications utility and cost of the current CP.
II. The utility and cost values are used to control the selected CP and its configuration.
III. The CP is reconfigured (first option), or a new CP is selected if the utility decreases or the cost increases (second option).
IV. A new CP can also be selected if the coordination component requires so following a change of the context conditions for the communicating nodes.

The management of the context information involves the following steps:

A. The context conditions are stored together with the estimated utility and cost values in the local database.
B. The stored context information can be shared with neighboring nodes.
C. The stored context, utility and cost data are uploaded to the central server. This can be done regularly or when an adequate connection is found.
D. Context-aware models are downloaded from the central server when updated.

V. CONTEXT-AWARE HETEROGENEOUS V2I COMMUNICATIONS

The potential of the proposed architecture is here demonstrated with the implementation and evaluation of a context-aware heterogeneous V2I communications algorithm. In particular, the original algorithm presented in [17] has been first implemented using the proposed architecture. The algorithm is then modified to take into account the economic cost of using each communication technology in the decision process. The 5.9GHz frequency band is currently reserved for ITS transmissions using ETSI ITS-G5 or IEEE 802.11p/WAVE. Despite being a dedicated band, transmissions at 5.9GHz are free of charge. On the other hand, connected vehicles using cellular technologies to upload and download information generally require a data plan with a cellular operator. It would hence be most convenient if the heterogeneous V2I algorithm dynamically selects the communication technologies that can satisfy the application requirements while reducing the economic cost to do so.

A. Heterogeneous V2I algorithm

We consider a scenario where vehicles need to download or upload certain information (B bits) within a given time window (T seconds). This information could be a 2D/3D map update (downlink), an over-the-air software update (downlink), or images gathered by vehicles that are uploaded to data centers to generate high precision road maps for automated vehicles (uplink). Each vehicle dynamically decides using the implemented heterogeneous V2I algorithm which communication technology it should use to upload or download the information. The decision is based on its context conditions. The algorithm mainly interacts with the CP selection, reasoning, context acquisition, and evaluation components that have been here implemented in detail[3].

Following the proposed architecture, when an application wants to download or upload some information, the implemented algorithm needs to decide which communication technology should be used for the transmission. The decision is based on the utility and cost that could be achieved with each communication technology available on the vehicle. The utility and cost are estimated per road segment. The utility is calculated as the ratio between the amount of information that could be downloaded/uploaded while driving through a road segment, and the data that still needs to be downloaded/uploaded before T when reaching the end of the road segment. The cost of a communication technology is defined as one minus the ratio between the throughput expected in the road segment and the maximum throughput that could be achieved. The minimum cost is therefore obtained typically at short distances to infrastructure nodes where the highest-order modulation scheme and lowest coding rate can be utilized.

The utility and cost are estimated considering the context conditions of the vehicle. In particular, the reasoning component requests the following context information to the acquisition module: the current location of the vehicle, its future trajectory during the next T seconds, the location of nearby communication infrastructure nodes (e.g. base stations, access points and road side units), and the channel load experienced by each communication technology. The reasoning component uses this information together with pre-computed context-based models to estimate the utility and cost of each communication technology in all the road segments of the upcoming vehicle's trajectory. The models relate the throughput as a function of the distance between a vehicle and an infrastructure node, and of the channel load. We assume that the infrastructure can periodically broadcast the channel load information for all available communication technologies per area.

The CP selection component uses the estimates of utility and cost to decide which communication technology should be used at each road segment in order to satisfy the application requirements (uploading/downloading the information before T seconds) and minimize the channel occupancy of the communication technologies. Vehicles have T seconds to upload or download the information, so they do not need to upload or download data in every road segment if the available communication technologies do not achieve a satisfactory utility or have a high cost. When the transmission starts, the evaluation component continuously measures the experienced utility and cost, and reports these values to the CP

[3] In the current implementation, the algorithm does not modify the protocol stack the communication technologies.

selection component. This component re-evaluates its CP selection decision every Δ*t* seconds to account for possible changes in context conditions, or even errors in the estimation of the utility or cost. The measurements obtained by the evaluation component can be uploaded to the central server to update the context-based models.

The heterogeneous V2I algorithm presented in [17] is modified in this paper to also take into account in the CP selection process the economic cost of each communication technology. To this aim, we categorize the technologies according to their economic cost. The first category includes the technologies that can be used at no cost to the user, e.g. IEEE 802.11p since vehicles can use for free the licensed 5.9GHz spectrum band to transmit ITS-related data. The last category includes the most expensive technologies. To reduce the economic cost of uploading/downloading the *B* bits, each vehicle first executes the original heterogeneous V2I algorithm considering only the technologies belonging to the first category. If the vehicle estimates that these technologies are not sufficient to download/upload the required information before *T*, the algorithm is executed again including the technologies of the first and second categories. A technology belonging to the second category will only be considered in those road segments where the transmission efficiency of the technologies belonging to the first category is below certain threshold E_{min}. If the technologies of the first and second categories are not sufficient to satisfy the requirements, the algorithm is executed again considering also the technologies belonging to the third category. The algorithm stops when it estimates that the requirements can be satisfied, or after the last category has been included.

B. *Impact of the infrastructure deployment*

The context-aware heterogeneous V2I algorithm has been evaluated first in a Manhattan-like urban scenario with 15x15 blocks (3750mx3750m), bi-directional streets and 2 lanes per driving direction. This generic urban scenario has been chosen to analyze the effectiveness of the algorithm with different deployments of infrastructure nodes and average traffic densities. Traffic densities between 3.4 and 23 vehicles/km have been generated using the traffic simulator SUMO. Each vehicle runs an over-the-air software update application or a 2D/3D map update application that needs to download *B*=20Mb in less than *T*=60s. Δ*t* has been set equal to 1s. All vehicles are equipped with LTE, WiFi (IEEE 802.11g) and IEEE 802.11p interfaces. The scenario includes 9 LTE base stations (NodeB) that cover the complete simulated scenario. The IEEE 802.11g Access Points (APs) and IEEE 802.11p RSUs are uniformly distributed at random intersections.

Figure 5 compares the average throughput per vehicle when 20 RSUs and 20 APs are deployed in the scenario. The figure shows the throughput experienced with a reference scheme that selects for each vehicle the communication technology that provides the highest instantaneous throughput. It also depicts the performance achieved with the original heterogeneous V2I algorithm (HetV2I), and with the modified algorithm that takes into account the economic cost of using each communication technology (HetV2I-$). HetV2I-$ is executed considering that IEEE 802.11p and WiFi belong to the first category and LTE to the second one. The results obtained show that the use of context information can notably increase the throughput . Vehicles are always covered by at least one technology (LTE) in the implemented scenario. In this case, the reference scheme results in that vehicles are continuously transmitting (until all the information is downloaded or uploaded) even if the utility is low. On the other hand, the context-aware heterogeneous V2I algorithm results in that vehicles transmit when a high utility can be achieved, for example, close to the infrastructure nodes where better channel quality conditions are experienced. The higher throughput obtained with HetV2I reduces the time to transmit the B bits. This reduces the number of vehicles simultaneously connected to each infrastructure node, which results in even higher throughput levels. HetV2I-$ increases the usage of the IEEE 802.11p and WiFi, which augments their channel load and reduces their throughput. However, HetV2I-$ still achieves a significantly higher throughput than the reference scheme.

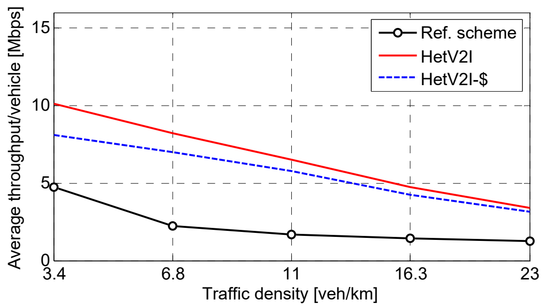

Figure 5. Average throughput per vehicle for *N*=20 RSUs and *N*=20 APs.

The benefits derived from the use of context information result in a higher percentage of vehicles able to download the required information within the specified time period (Figure 6). This trend is observed for different deployments of RSUs and APs. The use of context information is particularly positive for medium and high traffic densities. In these scenarios, the communication resources available at the infrastructure nodes are not sufficient to satisfy the requirements of all vehicles unless they transmit when the conditions are optimum to maximize the transmission efficiency. Figure 6 also shows that the performance of the heterogeneous V2I algorithm is not degraded when introducing the economic cost in the decision process. This result is independent of the number of RSUs and APs. Context-aware heterogeneous V2I communications improve the efficiency of the wireless transmissions, and this has also an economic impact. For example, Figure 6 shows that the reference scheme needs 30 RSUs and 30 APs to satisfy the requirements of 80% of vehicles when the traffic density is 16.3vehicles/km. The context-aware heterogeneous V2I algorithm can obtain higher satisfaction levels with only 20 RSUs and 20 APs.

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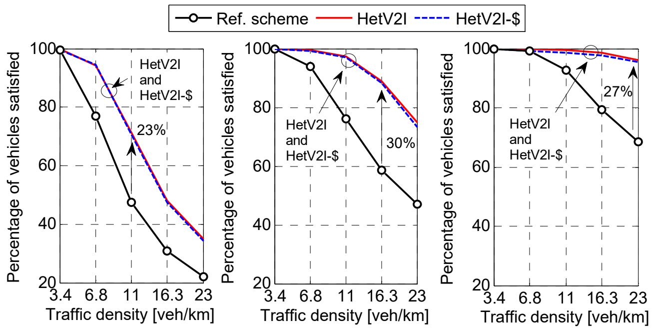
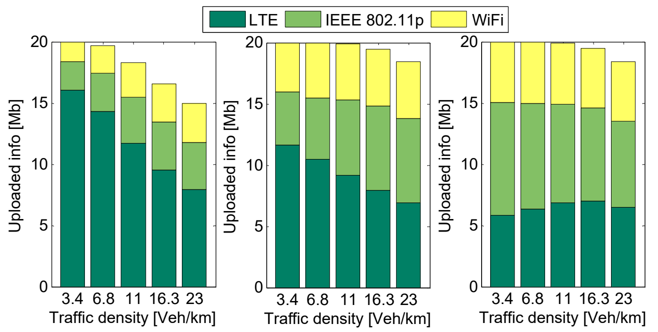


(a) N=10 (b) N=20 (c) N=30

Figure 6. Percentage of vehicles that can download the required information before the deadline. Scenario with N RSUs and N APs.

Figure 7 shows the average amount of data that each vehicle uploads using each of the available technologies (LTE, IEEE 802.11p and WiFi). The figure corresponds to a scenario with 20 RSUs and 20 APs. Figure 7 shows that the reference scheme results in that vehicles mainly utilize the LTE network to upload their data since it provides ubiquitous coverage across the scenario. On the other hand, the heterogeneous V2I algorithm reduces the amount of data uploaded using LTE, and increases the usage of IEEE 802.11p and WiFi. These technologies are utilized whenever they offer higher utility values. HetV2I-$ reduces the usage of LTE even further. Additional simulations have shown that the reduction levels increase with the number of RSUs and APs.



(a) Ref. scheme (b) HetV2I (c) HetV2I-$

Figure 7. Uploaded info for N=20 RSUs and N=20 APs.

C. *Real scenario*

The proposed architecture and the benefits of heterogeneous V2I communications are now evaluated under real deployment conditions. In particular, we have simulated 9km of the Metropolitan Expressway No. 5 in Ikebukuro (Tokyo, Japan). This expressway has two driving directions and two lanes per driving direction, and the maximum speed is 80km/h. Twelve RSUs have been deployed in this expressway according the Japanese Ministry of Land Infrastructure Transport and Tourism (Figure 8); we locate one AP next to each RSU. LTE base stations are located every 600m, and provide full coverage to the scenario. If we consider a 200m communication range per direction for each RSU, vehicles are under RSU range in around 53% of the expressway. All vehicles are again equipped with LTE, WiFi and IEEE 802.11p interfaces. The mobility of vehicles has been simulated using SUMO. Each vehicle runs an application that collects road images using an onboard camera and vehicle positioning information. The information is sent to data centers where it is pieced together, corrected and updated to generate high precision maps [6]. We consider that each vehicle is equipped with a standard VGA camera (640x480 pixels) and collects 10 images per second (10Hz). The size of each compressed image is assumed to be 50Kb, and the information collected every T seconds needs to be uploaded during the next T seconds.

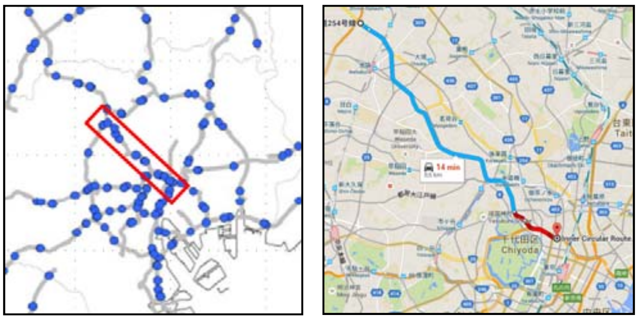


Figure 8. RSUs or ITS Spots in the 9km of the Metropolitan Expressway No. 5 in Ikebukuro (Tokyo, Japan). Online: http://www.mlit.go.jp/road/ITS/j-html/spot_dsrc/files/dsrc_tokyo.pdf

Vehicles can travel the 9km of expressway in 415s under free flow conditions. Each vehicle will need to upload 207Mb of data during this time. Figure 9a depicts the average amount of data uploaded per vehicle using LTE. The reference scheme tends to upload most of the required information using LTE. This is not the case of the heterogeneous V2I algorithm that also exploits the IEEE 802.11p and WiFi connectivity without actually degrading the percentage of vehicles that can upload the collected data before T (Figure 9b[4]). HetV2I-$ further reduces the usage of LTE compared to HetV2I (in particular under low traffic densities) without significantly reducing the capacity of vehicles to upload the information before the established deadline.

Without loss of generality, we assume that each vehicle drives 60 minutes per day through the expressway and 30 days per month. Table I reports the economic cost of the minimum LTE monthly data plan needed per vehicle to upload all the information gathered by the onboard cameras. The economic cost is shown per algorithm, and for different average traffic densities and values of T. The economic cost is shown considering the current AT&T cellular data plans[5]. Table I shows that heterogeneous V2I communications can help reduce the economic cost of connected vehicle services. It also shows that the larger savings are achieved when the selection

[4] The expressway scenario has a higher density of communication infrastructure nodes per kilometer than the urban scenario. This explains the higher percentages reported in Figure 9b compared to Figure 6a. In any case, the results in Figure 9b confirm again that the use of context information improves the capacity to satisfy the application requirements.

[5] The cellular data plans can be found online [last access on March 2017] https://www.att.com/shop/wireless/connected-car.html: 10$ for 1GB, 20$ for 4GB, or 40$ for 10GB.

process takes into the economic cost resulting from the use of each communication technology.

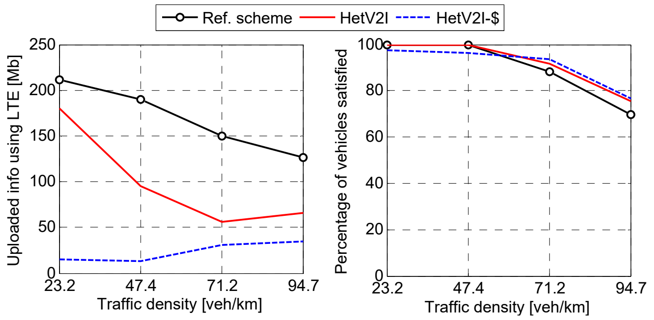


Figure 9. (a) Amount of information uploaded per vehicle and per trip using LTE. *T*=60s. (b) Percentage of vehicles that can upload the required information before the deadline.

TABLE I. ECONOMIC COST OF THE MINIMUM LTE MONTHLY DATA PLAN NEEDED PER VEHICLE

T	Algorithm	Traffic density [veh/km]			
		23.2	**47.4**	**71.2**	**94.7**
60s	Ref. scheme	40$	40$	40$	40$
	HetV2I	40$	20$	20$	20$
	HetV2I-$	10$	10$	10$	20$
120s	Ref. scheme	40$	40$	40$	20$
	HetV2I	40$	40$	40$	20$
	HetV2I-$	10$	20$	20$	20$

VI. CONCLUSIONS

This paper has presented an architecture for context-aware heterogeneous vehicular networks. The architecture is an evolution compatible with the current ETSI and ISO standardized ITS station reference architectures. The proposed architecture enables the dynamic selection and configuration of communication profiles based on the context conditions and the application requirements. This is particularly relevant as connected vehicles will require the use of different communication technologies to satisfy the vehicular requirements in diverse scenarios. The potential of the proposed architecture has been demonstrated with the implementation and evaluation of a heterogeneous V2I communications algorithm. The architecture and algorithm have been used to demonstrate how context-aware heterogeneous vehicular communication can improve the quality of service, scalability and the utilization of the communications infrastructure, which can in turn result in a positive economic impact. Open research issues include the exploitation of the proposed architecture for heterogeneous V2V communications, or the analysis of multi-application scenarios.

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