Collaborative and Distributed QoS Monitoring and Prediction: A Heterogeneous Link Layer Concept towards always Resilient V2X Communication

Daniel Hincapie, Ahmad Saad and Josef Jiru
Fraunhofer Institute for Embedded Systems and Communication Technologies, Munich, Germany

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Abstract: Vehicle-To-Everything (V2X) communication is a fundamental pillar of autonomous driving. It enables the exchange of safety-critical data between vehicles, infrastructure and pedestrians to enhance the awareness of the surrounding environment and coordinate the execution of collective functionalities vital to achieve full automation. Due to the safety-critical nature of the interchanged information, V2X communication must be resilient, so that it provides reliable connectivity despite of the very dynamic characteristics of both its environment and network topology. In this position paper, we propose a novel concept that aims at achieving resilient V2X communication. We introduce the Quality of Service Manager (QoSM), a collaborative and distributed implementation concept for the Heterogeneous Link Layer (HLL) that operates on the top of the Medium Access Control (MAC). The QoSM first monitors and predicts QoS indicators of Radio Access Technologies (RAT) in Heterogeneous Vehicular Networks (HetVNET). Then, it determines, under the principle of Always Resiliently Connected (ARC), and sets timely the configuration settings of RAT that meet performance and reliability requirements of autonomous driving applications. Should it not be possible to fulfill applications demands, the QoSM can instruct applications in advance to lower the requirements or run in a safe mode. Like in many autonomous driving applications, the concept of our proposed QoSM is distributed and collaborative to enhance accuracy, self-awareness and safety. QoSMs shall be grouped hierarchically according to correlation of applications demands, conditions of communication links and mobility information. Group's members share monitored and predicted indicators, as well as configuration settings. This information is used to determine collectively the configuration of the HetVNET. On the one hand, sharing information among QoSMs increases the amount of correlated data used by prediction algorithms, which improves prediction accuracy. On the other hand, hierarchical groups allow to extend the proposed methodology to other hierarchical elements of the access and core network. With this position paper, we intend to open the discussion on the importance of implementing protocols for sharing parameters that allow distributed and collaborative QoS management for resilient V2X communication.

1 INTRODUCTION

Autonomous driving systems rely on collective and safety-critical applications that must meet stringent performance and reliability requirements. Thanks to the rapid development of wireless communication technologies, Vehicle-To-Everything (V2X) communication is expected to boost the development of autonomous driving by enhancing the detection of surrounding conditions and allowing coordinating the execution of collective functionalities (Zheng et al., 2015b; Zheng et al., 2015a). However, provisioning satisfactory performance in V2X communication is a difficult task for wireless access networks due to the mobility of involved entities, i.e., vehicles, infrastructure and pedestrians, and dynamic change of network topology (Zheng et al., 2015b). To counteract this issue, entities are equipped with Heterogeneous Vehicular NETworks (HetVNET) that integrate different Radio Access Technologies (RAT) such as Long Term Evolution (LTE) and Dedicated Short Range Communication (DSRC). Communicating entities must then select the interface that best suits running applications needs in a decision process known as Access Network Selection (ANS).

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1.1 HetVNET

Having technology diversity, i.e., different RAT, aims to provide communicating entities with complementary technologies. Mobile cellular networks such as LTE can provide wide geographical coverage, but cannot efficiently support real-time information exchange for local areas. Conversely, DSRC is designed for short-range communications and supports well real-time safety messages distribution in a very limited service area (Zheng et al., 2015a). Technology diversity also offers alternative connectivity paths when the degradation of a technology threatens applications functionalities.

Selecting effectively the access technology that fulfills the performance of running applications accessing the HetVNET is not trivial. From the technological point of view, RAT performance depends on numerous radio and network resources, so the universe of variables that have to be taken into account by ANS algorithms is large and tends to increase in amount and complexity for the coming 5G technologies. Regarding the applications accessing the HetVNET, they must remain agnostic of the heterogeneity of the underlying infrastructure driven by vertical handover procedures that offer service continuity, robustness/availability, and consistency maintained transparently (Gustafsson and Jonsson, 2003; Louta and Bellavista, 2013).

Whereas handover procedures have received special attention in fourth Generation (4G)-related research and several standardization efforts provide a framework for seamless vertical handover, decision-making methods have not been standardized (Louta and Bellavista, 2013). Nevertheless, ANS solutions can be broadly divided into two categories: user- and network-initiated algorithms. In user-initiated schemes, no cooperation between technologies of the Heterogeneous Networks (HetNet) is considered, so entities individually take selfish RAT selection decisions to maximize individual utility functions, which may not provide a globally optimum solution. Conversely, network-initiated (also called network-centralized) ANS algorithms seek to optimize global network performance parameters, since decisions are taken by a centralized controller that has an overall view of the network (Roy et al., 2018). However, there are downsides to centralized network-controlled HetNet derived from the fact that information gathering and decision tasks are not distributed. Chief among these and very critical for V2X communication are the issues of timeliness of switching, scalability of the system to multiple clients with multiple interfaces, and the issue of how to obtain global control of client-RAT association (Wang et al., 2016). Representative vertical handover schemes with emphasis on both user- and network-initiated decision process for ANS are presented and analyzed in (Louta et al., 2011; Wang et al., 2016; Mohamed et al., 2012; Lahby et al., 2015; Trestian et al., 2012; Wang et al., 2016).

Independently of the scheme chosen to select the access technology, decision-making methods must define criteria to quantify and evaluate RAT performance. We now take a look at the Always Best Connected (ABC) concept, a decision criterion commonly employed in ANS algorithms for HetVNET.

1.2 Selection Criteria

The ABC concept suggests that entities shall be not only always connected, but also connected through the best available technology at all times (Gustafsson and Jonsson, 2003). In line with the ABC principle, but also lack of unity regarding the characteristics and parameters used as decision criteria, selection algorithms rely on performance indicators of RAT that they monitor periodically (Louta and Bellavista, 2013). Performance indicators can be, but not limited to: Link quality measurements such as Signal-to-Noise Ratio (SNR), Received Signal Strength (RSS), and Carrier-to-Interference-Ratio (CIR); network-related indicators considering coverage, bandwidth availability and load; and Quality of Service (QoS) aspects such as throughput, latency, jitter and Packet Delivery Rate (PDR). They all or a sub-set of them are retrieved from available RAT and analyzed to select the access that outperforms and offers the best connectivity (Louta and Bellavista, 2013; Zheng et al., 2015a). After deciding which interface should be used to transmit data and when it should be activated, handover involving seamless transition to the new network point of attachment has to take place (Louta and Bellavista, 2013).

Resilience describes an autonomous system that continues to function reliably despite of the occurrence of expected or unexpected changes (Fraunhofer ESK Institute, 2018). Wireless technologies play a crucial role in autonomous driving (Zheng et al., 2015b), particularly, because its safety-critical applications require ultra-reliable V2X connectivity able to at least ensure minimum performance requirements for their functionalities. In case those requirements cannot be met under extreme degradation of RAT conditions, a mechanism should alert safety-critical applications in advance, so that they start failure procedures and modes that guarantee basic functionalities. Hence, ANS in HetNets for V2X communication should not only aim to obtain high performance in terms of link, network and QoS indicators, but also to achieve resilient connectivity. To the best of our knowledge, there does not exist any ANS algorithm that takes account of resilience as decision criterion.

1.3 Contribution of this Position Paper

Towards the goal of supporting the dynamic and instant composition of HetVNET, the work in (Zheng et al., 2015a) introduced the Heterogeneous Link Layer (HLL). The HLL operates on the top of Medium Access Control (MAC) layer and enables global management of network resources to meet QoS requirements of safety/non-safety services. However, a unified approach to enable cooperation among multiple systems is difficult to achieve due to the huge amount of radio resources and unique characteristics of RAT. In this position paper, we propose a novel HLL concept that aims to achieve resilient applications: the Quality of Service Manager (QoSM). Since our purposed QoSM is oriented to achieve resilience, we introduce the concept Always Resiliently Connected (ARC) (an adaptation of the ABC vision (Gustafsson and Jonsson, 2003)) according to which applications accessing RAT of HetVNET must always be connected to the access technology that provides the most resilient *configuration profile*. A configuration profile is the object containing all general technological resources offered by RAT and target QoS indicators. Resources may include features such as carrier aggregation, dual-connectivity, or methodologies such as traffic steering, packet duplication, among others; target QoS indicators on the other hand, indicate the values that are intended to be achieved by configuring the corresponding features. This approach allows the QoSM to address the problem of unified management by grouping the particularities of RAT in a more abstract concept: the configuration profile. Consequently, according to our approach, the problem of selecting an access technology under the ABC principle turns into the problem of selecting the most resilient configuration profile. In regards of evaluation, we define, conceptually based on link quality, network status and QoS indicators, three quantifiers of configuration profiles resilience: Predictability, stability, and flexibility. To achieve ARC applications, the proposed approach is both collaborative and distributed. This enables functional grouping to counteract the scalability and timeless problems of centralized solutions, as well as the lack of global overview of entity-based approaches.

This paper is organized as follows. Section 2 defines the indicators used to qualify and quantify resilience. Section 3 describes the concept, characteristics and tasks of the QoSM. Section 4 presents our distributed and collaborative monitoring and prediction approach, and how it can be scaled to improve the QoS performance of higher hierarchical elements of the access network. Concluding remarks and future work are given in Section 5.

2 RESILIENCE INDICATORS

In order to determine the characteristics that shall rule Configuration Profile Selection (CPS) for ARC safety-critical application, it is necessary to define the resilience indicators to be evaluated by the decision algorithm. Resilience of systems is determined by numerous components: memory, robustness, redundancy, resourcefulness, and the capacity to recover quickly from failures and adapt to them (Connelly et al., 2017; Linkov, 2018). However, resilience features can not be straightforwardly used as decision criteria for CPS, because they are abstract concepts on which there is not general consensus to quantify them.

Based on the aforementioned characteristics and with the purpose of quantifying them, we define (for the moment conceptually) three resilience indicators: Predictability, Stability and Flexibility.

2.1 Predictability

Predictability quantifies, for prediction horizon, the prediction accuracy of the QoS indicators that result from selecting a given configuration profile. This feature allows to rank configuration profiles according to the certainty about their future performance. A predictability quantifier could be, for example, the Mean Squared Prediction Error (MSPE) of throughput or latency. For some latency-sensitive applications, it would be important to choose the configuration profile that lasts the longest in order to avoid latency caused by hardware reconfiguration and overheads accessing the network. In that case, an approach to quantify this resilience indicator would be to fix a maximum MSPE for a the set of QoS indicators (those of interest for the application), and then evaluate the maximum prediction horizon that can be achieved by the configuration profiles without exceeding the maximum MSPE value.

2.2 Stability

This concept intends to represent the capacity of a configuration profile to keep QoS indicators in a steady state or regime. A configuration profile shall be able to absorb changes in conditions to a certain extent (Connelly et al., 2017). If a disruptive condition, e.g., an interferer, perpetuates changes in conditions that exceed some intrinsic tolerance threshold of the configuration profile, e.g., minimum SNR, the profile must adopt a regime where the resources of the profile are fundamentally different. Some quantifiers of this indicator could be: jitter, gradient of throughput or latency with respect to SNR, and covariance between QoS and link quality indicators.

2.3 Flexibility

Stability may not be sufficient to keep functionality of a system. A configuration profile may be very stable and sustain its regime against one type of disturber, but it may fail when the nature of the disturbance changes (Connelly et al., 2017). For example, using a configuration profile that implements interleaving is effective to preserve the PDR in environments exposed to impulsive noise. The same profile can vary the interleaving depth according to the impulse width to sustain the targeted PDR, i.e., it is a stable configuration profile for PDR (but maybe not for latency). However, if the noise source is not impulsive but constant, such configuration profile may experiment low PDR, i.e., it is considered as poorly flexible. In contrast with stability, in which the nature of agents is invariant and only their characteristics (e.g., magnitude or duration) vary, flexibility measures the profile capacity to maintain the value of QoS indicators when the environment conditions change fundamentally. Indicators of flexibility can be derived from the same stability quantifiers when they are obtained under well known different scenarios, e.g., noise sources interfering different frequency bands.

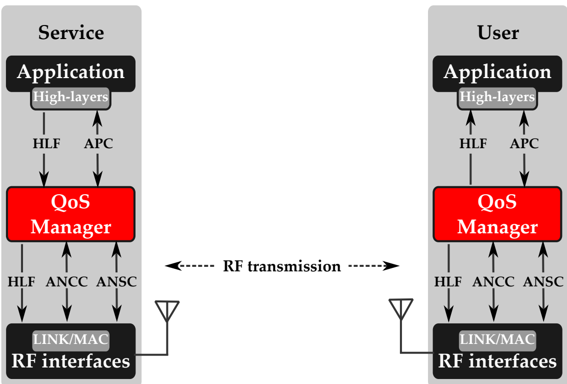

Figure 1: Role of the Quality of Service Manager (QoSM) in the protocol.stack. The QoSM interacts with both applications and MAC layers of RAT via Application Profile Commands (APC) and Interface Profile and Status Commands (IPSC), respectively.

All three resilience indicators may be strongly correlated: QoS indicators of unstable profiles tend to be difficult to predict; very flexible profiles should exhibit stable QoS indicators that can be accurately predicted; flexible profiles should also be stable, but stable profiles may not be flexible. However, estimating the inter-dependencies between them is complex due to the huge cardinality of resources that can define configuration profiles. Additionally, applications may differ regarding their resilience necessities. For example, some applications may need a very stable link with low throughput requirements; in this case stability and predictability have priority over flexibility to select an access technology. Conversely, other applications may require high data rate in all possible scenarios, so flexibility must have a higher weight to select the link to be established. Therefore, resilience indicators are required to be weighted according to applications needs when the selection process takes place.

Adaptive Management, the spacial and temporal feature of resilient systems that allows them to dynamically adapt to emergent conditions, reduce uncertainty, and enhance learning in safe-to-fail manner (Connelly et al., 2017) is the key to pursue our goal: ARC applications. The QoSM is in essence the concept of an adaptive management system for proactive CPS and corresponding configuration of resources in the available RAT. The following section details the functionalities and components of the QoSM.

3 QoS MANAGER FUNCTIONALITIES AND INTERNAL COMPONENTS

The HLL has been defined to enable unified processing, offer a unified interface to the higher layers, and adapt to the underlying RAT (Zheng et al., 2015a). A QoS-oriented implementation of this layer can be described as a continuous control functionality: receive QoS requests from upper layers, gather and monitor QoS performance indicators of available RAT, select network resources that meet QoS requirements, and instruct both application and RAT to function coherently with each other. The QoSM proposed in this position paper is a HLL concept oriented to achieve ARC safety-critical applications. Details on its tasks, internal blocks and flow of information are given as follows.

3.1 Functionalities

Figure 1 shows the role of the QoSM in an exemplary service-user connection. High-Layer Frame (HLF)s are generated by applications at the service side and go through the QoSM, which determines their requested/specified QoS, hereinafter referred to as Target Quality of Service (TQoS), before forwarding them to low level layers, i.e., LINK, MAC and physical (PHY). Applications can indicate QoS performance requirements, for example, marking Layer-3 header with a code in its Differentiated Services Code Point (DSCP) field as it is done in LTE and 5G architectures (3rd Generation Partnership Project, 2018). The QoSM shall be able to read this marking system and determine QoS requirements in terms of indicators, i.e., throughput, latency, jitter. The QoSM interact with applications via Application Profile Commands (APC). APCs inform applications about the the achievable QoS, so that they select coherent functional modes matching QoS conditions, e.g., report the communication throughput to a video streaming service which shall set video resolution accordingly; or warn applications of coming degradation of connection quality, so that they can activate safety modes or mechanisms. Via APC, applications can also specify QoS requirements (in case they do not use an explicit marking system in their HLFs), and request status of QoS indicators to the QoSM.

Whereas APC enable communication with upper layers, Access Network Configuration Commands (ANCC) and Access Network Status Commands (ANSC) are used for the interaction between the QoSM and MAC layers of RAT. On the one hand ANSC retrieve link quality, network-related and QoS indicators directly from each MAC layer of RAT. On the other hand , ANCC contain the configuration profile, to be set at each RAT.

As a HLL concept implementation towards ARC applications for autonomous driving, our proposed collaborative and distributed QoSM shall:

- Determine the TQoS of applications accessing to RAT. This is done either by extracting it from marks in HLFs or directly via APC.
- Receive HLFs from RAT MAC layers and forward them to upper layers.
- Retrieve indicators of link quality, network condition and QoS from all available RAT via ANSC.
- Quantify and analyze resilience indicators based on gathered indicators.
- Predict QoS indicators with a given prediction horizon. The cardinality and complexity of the variables that determine QoS indicators is expected to be high: increasing number of RAT and resources in 5G, numerous interdependent and parallel applications, highly dynamic environment and network topology, among others. This suggests the use of machine learning algorithms for this purpose.
- Share collected and predicted QoS indicators with QoSMs at other entities.
- Share the Profile Quality of Experience (PQoE). This resembles the resilience feature of memory (Connelly et al., 2017), and indicates the performance obtained by setting a given interface profile under specific conditions, e.g., relative position and velocity, SNR, noise floor, current throughput demand, etc.
- Evaluate the overhead costs of configuration profiles in terms of hardware reconfiguration and synchronization times, random network access and any aspect that may increase communication latency.
- Determine the configuration profile that shall ensure the target QoS of running applications with a very high probability.
- Set configuration profiles of available RAT using ANCC.
- If it is allowed by the application, communicate with applications via APC to inform QoS conditions.

3.1.1 Functional Components and Interface Management for V2X Communication

Until now, only generic functionalities of the QoSM have been described. We now focus on its internal

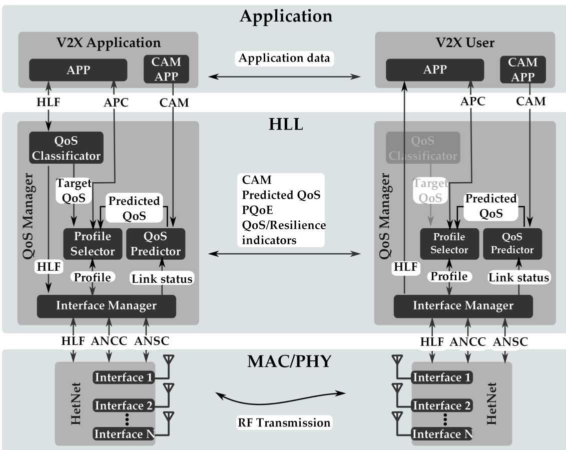

Figure 2: Functional blocks of the Quality of Service Manager (QoSM) .

components and their functionalities to achieve ARC applications in the V2X communication context. Figure 2 details the functional blocks of the QoSM and their interactions with both applications and interfaces of a HetNet used to transmit V2X data. HLFs generated at the V2X application side are analyzed by a *QoS classifier* in the QoSM to extract the TQoS. After obtaining the TQoS, the classifier forwards the analyzed HLFs to the *Interface Manager* to transmit them over the physical interfaces of the HetNet. Concurrently, an application is running at every entity generating and receiving periodically Cooperative Awareness Message (CAM)s, which provide information of presence, positions as well as basic status of communicating Intelligent Transport System (ITS) stations to neighboring ITS stations that are located within a single hop distance (European Telecommunications Standards Institute (ETSI), 2019). Using the information contained in this messages (position, velocity, acceleration and steer angle) and records of QoS indicators, the *QoS Predictor* estimates the performance parameters of the interfaces, i.e., Predicted QoS, for a given time horizon. Both target and Predicted QoS are sent to the *Profile Selector*, which is the functional block in charge of selecting the configuration profiles of RAT.

Figure 3 depicts the concept of configuration profiles, which not only specify technological resources specific for each RAT, but also application-specific and technology-independent description of target performance. Profile parameters may be grouped according to specific requirements of an application. Table 1 exemplifies the definition of profiles. Applications requiring high performance are mapped to one of four profiles that aim at obtaining high data rate rather than very high PDR and low latency. On the other hand, reliability and safety profiles aim to ensure low PDR at cost of data rate and latency. The task of the Profile Selector is to use the predicted QoS to select the profile that ensure the Target QoS with very high probability, and inform the application via APC whether the required performance can or cannot be met to adjust its requirements accordingly.

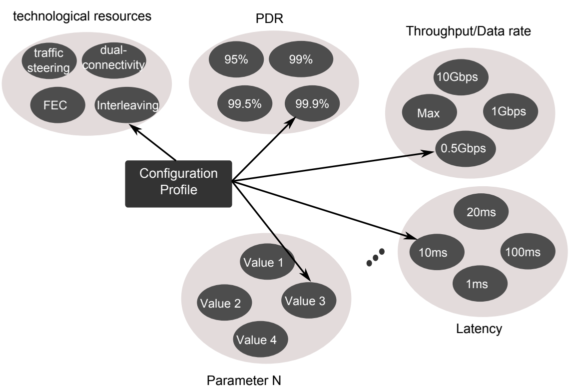

Figure 3: Concept of Configuration Profile. Target QoS indicators and technological resources are grouped to define a more abstract representation.

Configuration profiles are agnostic descriptions, i.e., technology-independent. However, RAT of the HetVNET have to be configured using their own set of specific commands. The task of the *Interface Manager* is to translate the high-level description and parameters of profiles into interface-specific settings and corresponding configuration commands. Then, agnostic commands coming from the profile selector, e.g., ”SetPerformanceProfile”, must be mapped to specific technology commands such as ”SetWiFiChannel(5gHz), SetWiFiOFDM(), SetWiFiTransmitPower(13.5dBm)”. The tasks of the Interface Manager include routing HLFs via the selected interface(s) and retrieving measurements, link status and current configuration settings of the RAT.

QoS Predictor and Profile Selector are the core elements of the QoSM. The capacity of the QoS Predictor to accurately estimate QoS indicators, determines the timely selection of suitable configuration profiles performed by the Profile Selector. On the other hand, the Profile Selector must choose ”wisely” among a set of configuration profiles, and shall be able to modify them and add new entries to the profile table. To achieve these goals, we propose a collaborative and distributed scheme for QoSM functionalities. In this approach, predicted QoS, PQoE and link status measurements are multi-casted along a group of QoSMs. This provides prediction and profile selection functions with more data to accomplish their tasks. The following session explains how such scheme shall be developed and how it would contribute to achieve resilient V2X communication.

Table 1: Profile definition. Example of performance parameters that are combined to define high-level descriptions based on application requirements such as high performance, reliability and safety.

Application Requirement	**Data Rate**	**PDR**	**latency (ms)**
High Performance	Maximize	95	5
	8 Gbps	95	10
	6 Gbps	95	10
	4 Gbps	95	10
Reliability	2 Gbps	99	20
	1 Gbps	99	20
	100 Mbps	99.5	50
Safety	10 Mbps	99.9	50
	1 Mbps	99.99	100

4 COLLABORATIVE AND DISTRIBUTED MONITORING, PREDICTION AND PROFILE SELECTION

Figure 4 illustrates a group of 5 vehicles that can communicate with each other via two links: over Vehicle-To-Vehicle (V2V) communication, e.g., WiFi 802.11p, and the infrastructure using mobile technology, e.g., acLTE. Red and blue arrows indicate active links. Now, let us assume the following hypothetical scenario:

- Car B is located at 10 m and 45° from car A.
- Car C is located at 13 m and 57° from car D.
- Car B is located at 16 m and 72° from car E. They are currently experiencing very good performance while implementing the first configuration profile in Table 1.

According to current positions, velocities and accelerations of vehicles informed via CAMs, communicating pairs (A,B) and (D,C) are expected to be located in 100 ms at the same current relative position of pair (E,B), i.e., 16 m and 72° from each other. If cars A, B, C and D are experiencing increment of the performance demanded by their applications, it would be very useful for their QoSMs to receive the current PQoE of pairs (E,B), so that their profile selectors can configure timely their RAT to fulfill the potential future conditions. The same reasoning can be used for the Vehicle-To-Infrastructure (V2I) communication of vehicles A and C, and also in the prediction of QoS performance at the QoS predictor. The general reasoning is that increasing the amount of useful data should derive in a more accurate predictions and resilient communication.

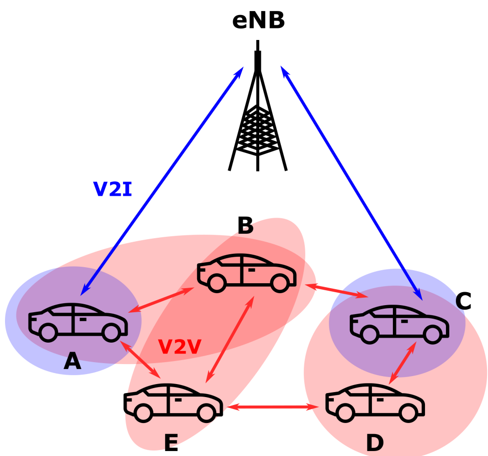

Figure 4: Collaborative and distributed scheme for monitoring, prediction and profile selection. Enabling task distribution and data sharing of data useful for QoS prediction and profile selection, help to obtain resilient V2X communication.

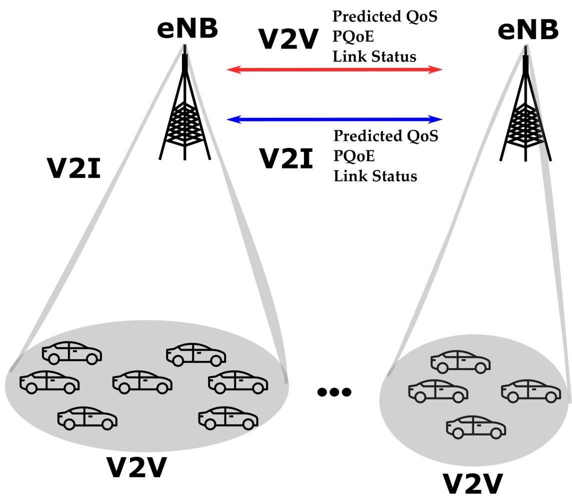

Figure 5: Scaling collaborative and distributed scheme. Shared data of V2X and V2I communication can be transmitted beyond local coverage. Access network entities such enhanced Node B (eNB) can benefit from shared data to perform resource allocation and reserve resources for groups of cars approaching to its coverage range.

The problem of grouping entities can be addressed by analyzing the correlation of conditions, predictions and profiles: entities with similar QoS indicators, configured profiles, performance demand and mobility should be encourage to collaborate. Additionally, some entities may be able to produce more accurate predictions due to their relative positions, number of links or time of membership within the group. Then, each group could select the best entity to rule group's profile configurations and be representative to share group's PQoE, QoS prediction and link status measurements with other groups. This would reduce the traffic of shared data and add features of self-organization to HetVNETs. Cooperative and non-cooperative game theory algorithms could be considered for the selection of groups' members.

4.1 Scaling the Collaborative and Distributed Scheme beyond Local Coverage

Whereas the information contained in CAMs is limited to be received by a geographically-defined group of entities (European Telecommunications Standards Institute (ETSI), 2019), data such PQoE, link status measurements and predicted QoS may be useful for groups of entities located out of the vicinity. In mobile networks such as LTE, an evolved Node B (eNB) providing mobile service to a group of vehicles can share equivalent information with other nodes regarding individual or global resource allocation. This is, the current radio resources being demanded by the served group and a prediction of the potential future demand could be reported to other eNBs on the rode. Hence, eNBs that will soon serve the same group could reserve the same or equivalent resources in advance, providing lower hand-over times or the possibility to instruct vehicles to start safety modes in case resources cannot be allocated. Figure 5 shows two groups of communicating cars whose V2I communication is being served by two different eNBs. The backhaul network communicating them can be used to transmit collaborative data between nodes or for QoSM at vehicles. Such potential implementation shows how scalable our collaborative and distributed scheme can be.

5 CONCLUSIONS AND FUTURE WORK

In this position paper, we propose a concept for a HLL implementation. The proposed scheme, called Quality of Service Manager (QoSM), aims at obtaining resilient applications for V2X communication. We argue that using QoS indicators to quantify and evaluate resilience, and adopting the concept of Always Resiliently Connected will lead to resilient safety-critical applications. To achieve this, our approach proposes a collaborative and distributed solution that seeks to increase and diversify the sources of information for prediction of QoS parameters and selection of configuration settings of HetVNETs. Our approach is highly scalable since it enables QoSMs to group hierarchically, as well as the definition of technology-independent profiles, which results in agnostic management of HetVNET.

Future work includes the implementation and results analysis of the proposed scheme to ensure the communication performance for collective functionalities of autonomous driving such as sensor-data sharing and see-through application.

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