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A Spatial QoS Requirements Specification for V2V Applications

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***Abstract*— Vehicle-to-vehicle wireless communication is a key component of tomorrow's cooperative safety applications. However, the wireless link is susceptible to effects such as shadowing which can cause communication failures. Such failures may in turn lead to hazardous traffic situations when safety applications cease to function. By monitoring communication QoS and adapting to changes, effects of link failure may be mitigated, however this requires a specification of the application QoS requirements. In this paper we combine the T-Window reliability QoS metric with a spatial component, allowing us to capture the dependencies between VANET QoS requirements and road geometry. The proposed representation can be used both at design-time, to characterize applications, and at run-time for QoS monitoring and adaptation purposes.**

I. Introduction

A vehicular ad-hoc network (VANET) running traffic safety applications depends on the wireless channel for the safety of its users and requirements on timely delivery of information between vehicles are strict. In wired networks guaranteed usage of the communication channel, and guaranteed properties of the same, are typically referred to as quality-of-service (QoS) guarantees. Guaranteeing QoS in wired networks is mainly a question of how to share a relatively fixed resource in overload situations, for example through admission control and scheduling strategies. However, in a mobile wireless network the shared communication resource varies significantly due to various factors affecting radio wave propagation. Guaranteeing QoS using wired network strategies is difficult, since in the wireless setting controlling network load does not guarantee QoS. Instead, a strategy of monitoring and adapting to changes in the shared communication resource must be employed. Adaptation can take place in many layers of the communication stack but can also successfully be delegated to higher layers, e.g. middleware and application, making them *QoS-aware*.

A well-known example of application-level adaptation to QoS changes is data scaling, often employed in multimedia applications where compression parameters are tuned based on available bandwidth [1]. In VANET applications based on periodically transmitted beacon messages, the advantages of data scaling as a means to react to QoS changes are diminished since the messages contain very little redundant information to begin with. Instead, adaptation to decreases in QoS can be made by exploiting the connection between the physical state and communication requirements that exists for many VANET applications. A collision avoidance application, for example, has a clear connection between its range requirement and vehicle speed; lowering the speed lowers the range requirement. In this paper we explore abstractions for expressing such dependencies between communication QoS requirements and the state of participating vehicles as well as the spatial context.

We propose that the application developer explicitly specifies QoS requirements associated to an application and how the application should behave if the requirements are not met. This allows for so-called graceful degradation of system functionality, for example altering recommendations to the driver so that the degraded communication performance can be taken into account. In the remainder of this section we give an overview of what characterizes a VANET from a communication viewpoint and in section II we introduce VANET-specific QoS metrics and argue that communication properties must also be defined in a spatial context.

A. VANET characteristics

Inter-vehicle communication promises many advantages when it comes to improving safety, reducing traffic congestion and increasing driver comfort. Cooperative systems not only extend the perceptive range beyond the typical line-of-sight of traditional in-vehicle sensors, they also allow for higher level information to be communicated such as driver intentions. The wireless carriers available for transmitting and receiving this information are manyfold, some of them will be familiar technologies such as cellular 2G and 3G networks for which large scale deployments and performance studies have been made. However, for some parts of the information flow, mainly traffic safety applications, cellular networks are often considered insufficient. Examples of centralized networks drawbacks are the end-to-end latency associated with sending a message through the network infrastructure, as well as scalability problems in dense traffic conditions. When the information to be transmitted is of interest mainly to those in the vicinity of a vehicle, direct communication with those vehicles is an intuitive approach. By doing away with base stations a decentralized and scalable ad-hoc network can be temporarily created by vehicles that happen to be in the same area at the same time. Since there is no "master" entity controlling the flow of information, the participating nodes have to do this themselves, waiting for the medium to become free before accessing it in a suitably fair manner.

To limit the number of nodes attempting to access the channel simultaneously a key strategy is to limit how far the wireless signal can propagate, for example by choosing

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a suitable transmission power. Additionally, the frequencies available for allocation to inter-vehicle communication services affect wireless signal propagation.

For example, The IEEE draft standard 802.11p specifies carrier frequencies around 5.9 GHz where the influence of obstacles, such as buildings in a city, to a large degree impacts radio wave propagation. While limited transmission range enables spatial reuse it also negatively affects traffic safety applications that impose strict requirements on reliable message transmission and reception. For example, an intersection collision warning application that helps drivers avoid potentially lethal collisions requires continuous updates of the locations of all vehicles approaching an intersection. For a 5.9 GHz carrier frequency whether the requirements can be met or not will depend to a large extent on the characteristics of that particular intersection and its surroundings. Thus, maintaining knowledge about the state of the communication channel is an important part of safety critical wireless systems.

Information about experienced communication quality can be used at various levels of the wireless networking stack to adapt to changing conditions. Link state is often used to decide how to route information through an ad-hoc network, for example by updating routing tables to maximize the probability of succesfully sending a message from one node in the network to another. However, in highly mobile networks, such as VANETs, topology and link states change rapidly making such proactive routing approaches difficult. Additionally, the need for multi-hop communication in vehicular networks is not completely clear, for example in situations where long-range message dissemination is required (in contrast to local safety applications) it has been shown that the use of cellular infrastructure is a highly competitive alternative when it comes to reliability, latency and throughput [2].

Instead, single-hop communication plays an important role for traffic safety applications that rely on information about the immediate vicinity of a vehicle. Periodic broadcasts of vehicle position and kinematic properties, so called Cooperative Awareness Messages (CAMs), can be used to build a highly dynamic picture of the surroundings. In this situation the locality of the information transmitted favors direct vehicle-to-vehicle communication, i.e. even with a transmission range of less than 1000 m a vehicle should be able to provide information via direct communication to those for who it is of importance.

Another characteristic of cooperative safety applications is that they produce as output recommendations to the driver or even control signals to actuators within the vehicle. As such they have the ability not only to observe the world state but also to influence its future evolution. We wish to emphasize this characteristic as the system not only influences driver behavior when it is generating warnings or providing recommendations but also to a large degree affects this behavior when it is not. In other words, a driver is likely to assume that if the warning system does not produce output then there is no risk present. This assumption requires the system to always have a perfect knowledge of the world state, and as we have seen, this will often not be the case, for example due to communication failures.

II. VANET QoS REQUIREMENTS

For the type of applications considered in this paper (i.e. those based on CAMs) the ability for a transmitting node to deliver enough messages per time unit to nodes within its vicinity is a naturally recurring metric. Since CAMs are used for periodically informing other traffic participants about a vehicle's current properties, acknowledgement and retransmission strategies are typically not used in CAM transmission. Instead, newly generated CAMs are sent with up-to-date state information. This is based on the fact that the contents of missing CAMs, which relates to properties of moving physical objects, in most cases can be accurately derived from previous messages and physics models up to an application-dependent time horizon. Metrics that relate specifically to this characteristic of CAM exchange have been proposed in literature.

Bai and Krishnan [3] propose *T-Window reliability* (TWR) which is related to the packet delivery ratio, or CAM delivery ratio in our terminology if we assume that CAM data will fit into a single packet. TWR is defined as the probability p_T of receiving at least one CAM within a time window of size T. The authors then measure TWR as a function of distance between vehicles in freeway and open field conditions. It is also shown that, assuming independence between packet drops, the CAM broadcast interval greatly affects the reliability of the application. However the assumption of packet drop independence can be questioned for other traffic scenarios than those explored. Still, the TWR metric is useful in that it gives application developers a way of expressing the QoS requirements of the application without having to consider lower level parameters such as CAM transmission intervals.

Xu et al. [4] define and use the *probability of reception failure* (PRF) to study the exchange of safety messages between vehicles. PRF is defined as the probability that a transmission between two randomly chosen nodes at a certain distance and for a certain message delay fails. This metric thus includes the notion of message lifetime, and the authors also investigate various repetition strategies.

In addition to requirements on the inter-arrival times of CAMs the transmission range is another widely investigated parameter within VANET research, for example the characterization by Bai et. al of the range of interest (ROI) of several VANET applications into one of three qualitative levels; long, medium and short [5].

In previous work, specifications of communication ranges for safety services in VANETs have been given assuming equal requirements in all directions within the communication range. Although an omni-directional, "disk-like", specification of communication requirements is easily mapped onto the capabilities of a more or less omni-directionally transmitting radio such a specification of communication requirements is too coarse-grained for many envisioned applications. For example, an intersection collision-avoidance application requires reliable communication mainly with vehicles approaching the same road intersection, an area which seldom corresponds to a perfect disk centered on the vehicle running the application. Range is in many cases an over-specification of application QoS requirements which is a convenient abstraction to make during design time, however with more intelligent QoS monitoring and prediction schemes such over-specifications will lead to unnecessarily pessimistic adaptations. Therefore, a more fine-grained coverage model than simply range should be used to specify VANET QoS requirements.

However, in defense of the use of simple range requirements, they are easier to define and evaluate using existing models and tools, e.g. many radio-propagation models used in VANET simulators are statistical descriptions that depend only on parameters such as distance between transmitter and receiver, antenna heights and terrain type.

A. Requirements format

Requirements on the ability to send CAMs to other nodes is tightly coupled both with node properties such as kinematics and relative positions but also with properties of the environment such as road geometry, in other words communication requirements are “context dependent”.

This context dependence is common across several applications and should be factored out to avoid duplication of functionality. In particular the need to define and reason about quality requirements using spatial concepts is one such commonality to be factored out. We exploit the application dependence on road geometry and the fact that intelligent vehicles will have access to highly detailed road maps to construct the spatial component of our QoS specification. The ability to specify QoS parameters is intentionally restricted to the road areas of the digital on-board map in order to create a compact yet expressive representation. This limitation is in line with the fact that, in the general case, vehicles are only able to travel on road surfaces.

B. Spatial coverage specification

The digital map is assumed to consist of a graph of connected links that represent driveable segments of the road network. The endpoints of each link are associated to real-world coordinates which implies that each link also has a length associated to it, more complex road shapes are approximated by connecting several such linear link segments. The set of all links available in the digital map is denoted U, the universal set. The spatial component of the QoS specification is then defined as a subset of U using the common set-theoretic operators union ($\cup$), intersection ($\cap$), and complement ($\setminus$) as well as two functions $Flood$ and $Trajectory$. In the following we denote the link that the vehicle is currently travelling on as l_{curr}.

The first function, $Flood(d, L, U)$, specifies all links in U that have a reachable endpoint within a distance d meters from any of the endpoints of the links belonging to the set L, where d is specified as the distance along connected links and $L \subset U$ (see Fig.1).

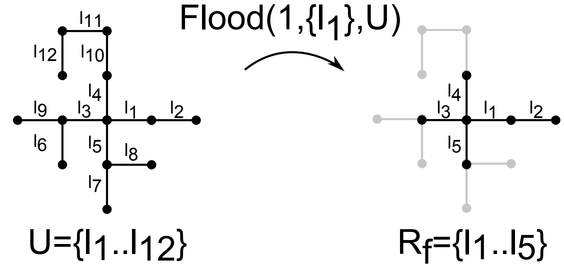

Fig. 1. $Flood$ applied to a set $\{l_1\} \subset U$ producing the subset R_f. All links are of unit length.

More formally the function $Flood : U \rightarrow R_f$ produces a subset $R_f = \{l_1 \in U : distance(l_1, l_2) < d$ for any $l_2 \in L\}$ where $distance(l_1, l_2)$ is the distance of the shortest path through the graph consisting of links in U from any endpoint of l_1 to any endpoint of l_2 or infinity if l_1 is not reachable from l_2.

The second function, $Trajectory(t, U)$, specifies a set containing all links in U that the vehicle is predicted to travel on t seconds into the future. The function $Trajectory : U \rightarrow R_t$ produces a subset $R_t = \{l \in U : predict(l, t)\}$ where $predict(l, t)$ is a predicate that is true if link l is predicted to be travelled by the vehicle within the next t seconds, otherwise it is false.

The $Trajectory$ function relies on the availability of a trajectory prediction mechanism, for which the $predict$ predicate is an abstraction, without specifying how this mechanism is implemented. The set of links specified by such a mechanism may for example include multiple hypothesis about future locations or may be as simple as including all links reachable within a certain distance and direction from l_{curr}. The fundamental idea is that instead of including the trajectory prediction model in the application specification we see it as a separate, interchangeable, component. We argue that for the application programmer it is sufficient to reason about spatial QoS relative the abstract concept of the future vehicle trajectory, something that will be highly dynamic depending on the current situation and context.

More complex sets of links can be composed by combining the two functions, e.g. by nesting them or by using the previously mentioned set theoretic operators. For example, in an emergency vehicle response scenario it may be important to send information to all vehicles close to the emergency vehicle route. The spatial component of such a specification could then be expressed as: $Flood(500, Trajectory(60, U), U)$ which would select all reachable links in a map U within 500 meters from the predicted emergency vehicle route one minute into the future.

Similarly, $Flood(1000, l_{curr}, U) \setminus Flood(500, l_{curr}, U)$, could be used to specify links that are between 500 and 1000 meters away from the vehicle location.

It is assumed that links are of suitably short lengths so as to allow sufficient granularity in defining an area by a set of such links. It is evident that including links with very large length in relation to the lengths given to *Flood* and *Trajectory* functions may lead to sets that span an area much larger than that intended by the application designer. However, in practice a simple mechanism could be employed that, using a standard digital map, produces a new map consisting of links of sufficient size. Another, more complex, method would be to split links on the fly using the original map.

A set of links defined using the described notation is called a *spatial coverage set* (SCS) and additionally has QoS parameters associated to it as described in the following section.

C. QoS specification

We have adopted the *T-Window reliability* (TWR) metric to define message inter-arrival time requirements. This metric expresses QoS at an application level for the large class of applications that rely on periodic transmission of CAMs. By combining TWR with a specification of required coverage in the form of a SCS a spatial application-level QoS specification is created.

To a spatial coverage set S a time window value T is assigned together with a probability value p_T. The value p_T is the minimum acceptable probability of successfully communicating at least one CAM between link l_{curr} and any link in S within a time window of length T seconds. Here we make no distinction between receiving or transmitting messages, i.e. the specification is of symmetric requirements.

The minimum QoS specification for an application consists of at least one SCS/TWR pair. However, multiple such pairs may be defined for applications that have different QoS requirements for different areas of coverage. In the case of multiple SCS in an application QoS specification there may be links that are part of several sets, i.e. not all SCS may be disjoint. In such cases the order in which the SCS/TWR pairs were specified (where 1 is the highest priority) is used to decide which TWR specification that is to be applied to the common links.

D. Example requirements specifications

To exemplify how the proposed QoS specification can be applied we have chosen to apply it to two safety applications based on CAM transmission, *intersection collision avoidance* (ICA) and *emergency brake lights* (EBL). The ICA application monitors the risk of colliding with other vehicles at intersections, a common and often serious type of traffic accident. The QoS requirements of the ICA application can informally be stated as: "the vehicle must be able to receive CAMs from all vehicles that may cross the vehicle's future route within the next t seconds, assuming that no other vehicle's average speed is above v m/s for the next t seconds".

The reason for assuming an upper bound on the average speed of other vehicles is to limit the coverage area. Bounds on the properties of other vehicles must be made since the actual values of such properties cannot be assumed to available, i.e. one cannot formulate a requirements specification of communication quality that itself requires that a communication link already exists.

TABLE I
QoS Specification for ICA Application

Appl.	Order	SCS	T	p_T
ICA	1	$Flood(50, l_{curr}, U)$	0.2	0.9
	2	$Flood(250, Trajectory(10, U), U)$	0.5	0.9
EBL	1	$Trajectory(5, U)$	0.5	0.9
	2	$Trajectory(10, U)$	2	0.9

We set t to 10 seconds in the informal specification above since our hypothetical ICA application requires a few seconds of observations to detect if another driver is behaving erratically and the own vehicle driver also has a reaction time. The bound on other vehicles maximum average speed is set to 25 m/s which implies that the maximum range relative the vehicle's future trajectory is $10s * 25m/s = 250m$.

The EBL application requires communication with vehicles on the predicted future trajectory. If any such vehicle is observed to be braking heavily a warning is generated. EBL is useful for example to avoid rear-end collisions due to unexpected freeway traffic jams.

The formalization of these requirements using our proposed QoS specification can be seen in Table I.

For both ICA and EBL each specification includes two pairs of QoS specifications that impose varying values of T to reflect that the requirement on inter-message arrival time is stricter for vehicles closer to the own vehicle. The ICA application, for example, requires a T value of 0.2s and that this can be achieved 90% of the time for CAMs sent from vehicles within a distance of 50m while for vehicles further away the T value is increased to 0.5s.

E. Requirements monitoring

Although the focus of this paper is on the QoS requirements format we will briefly discuss possible implementations making use of such a specification. The requirements specification as discussed above is a key component in enabling adaptive VANET applications, however it is one piece of a larger architecture.

When an application with a requirements specification, similar to the example applications EBL and ICA in the previous section, is loaded on the vehicle platform its specification is registered with a *QoS monitoring service* in the platform middleware (Fig. 2). The monitoring service is responsible for evaluating the requirements specification for one or more applications in relation to a model of the available communication resources. Such resource models can be based on e.g. measured data, statistical propagation models or site-specific propagation models. In previous work we have investigated the measurement approach [6].

If the requirements of an application are violated, adaptation is required to gracefully handle the situation. A *fault handler* component receives alerts from the QoS monitor when there is a risk that application requirements may be violated and then decides if it is possible to handle the problem below the application layer (i.e. to mask it) or if the application needs to be notified for application-specific adaptation. Possible ways to mask an error is to employ various routing mechanisms to achieve coverage by switching carriers (e.g. to cellular infrastructure) or to shorten the CAM transmission interval in order to decrease the drop rate.

As a last resort the fault handler signals the application which is then responsible for handling the error, this means that all applications must contain adaptation logic that can be invoked in such situations. Strategies for application level adaptation are numerous but can include data scaling, degraded functionality and controlled shutdown. For the ICA and EBL applications a controlled shutdown could mean that the driver is given more conservative recommendations on maximum speed and minimum inter-vehicle distance to reflect that the applications are no longer running. The application also has the option of re-defining its QoS specification, for example to reflect new requirements as a consequence of entering into a degraded mode.

III. Related work

A. Context aware communication

In the field of ubiquitous computing and communication the vision of transparently providing services to users depending on their location, current activity, personal preferences and other contextual information has been the goal. Although much work has focused on using location-awareness as a means of choosing which information to present to the user, reliability aspects have also been proposed. Schilit et.al give an overview of context-aware communication and exemplify how location awareness can be utilized to select between various communication carriers, depending on previously experienced communication quality [7]. Location awareness has also been explored as a basis for routing messages between nodes in mobile networks [8].

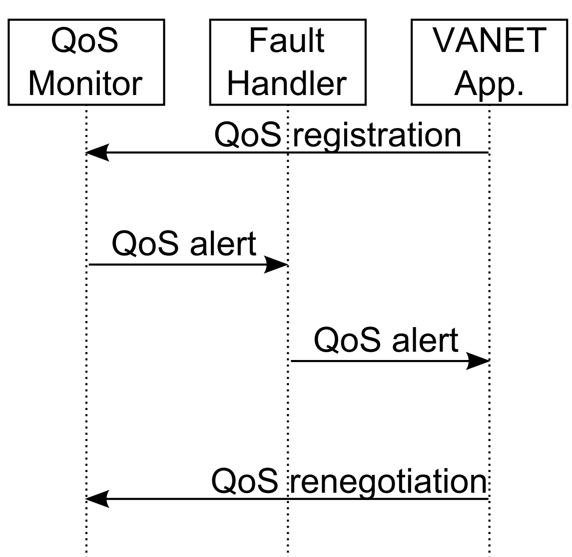

Fig. 2. Sequence diagram illustrating a situation where the fault handler is unable to mask a situation where QoS requirements cannot be met.

B. Adaptive applications

Allowing the application programmer to consider QoS parameters in order to create "adaptive applications" has been previously studied. Much in line with our work in this paper, the focus has been on providing abstractions of QoS terms that are relevant to the application domain, either in the form of library APIs or QoS-aware middleware.

Srivastava and Mishra advocate increased application intelligence in order to provide QoS awareness in mobile wireless networks [9] and state that QoS guarantees in a mobile wireless setting is an oxymoron, instead adaptive applications that make use of QoS renegotiation are preferable. In our framework renegotiation is yet one adaptation strategy that can be implemented in the application error handler.

Much the same view on mobile QoS is taken by Blair et.al [10] who propose a Tuple-space based QoS framework, Limbo, for mobile networks which supports both monitoring and adaptation.

Min and Chandrakasan proposed a small API that allows the application developer to specify requirements on range, reliability, latency and energy to the lower layers of the wireless communication stack. [11]. The main purpose of the proposed API is to save energy when the maximum performance of the communication platform is not required and to isolate the developer from parameters directly relating to the communication hardware.

In a cellular network setting Levine et.al. utilize "shadow clusters", spatial boundaries about the mobile node that depend on its kinematic properties, to predict where in the network resources should be allocated [12].

Many authors have proposed QoS mechanisms that attempt to reduce the network load when using multihop communication, often by introducing various routing and broadcast-limiting protocols. Wiegel et.al. proposed a mechanism intended to reduce redundant message broadcasts in VANETs [13]. Redundant messages can originate when vehicles transmit identical observations about the physical world that they sense with on-board sensors, or when relaying messages from other nodes.

The RT-STEAM middleware proposed by Meier et al. includes the concept of *event channels* to which a spatial description is associated [14]. The RT-STEAM approach is perhaps the most similar to ours. However the link between road geometry and proximity, i.e. the ability to specify proximity in terms of road geometry, is not identified. One of the strengths of our work is the definition of a formal spatial description specifically for VANET QoS that can be applied across application types.

C. Vehicular Sensor Networks

Since vehicular networks are envisioned to consist of many mobile nodes and since the vehicular platform effectively removes the restrictions on available energy and computational power they have become a promising platform for collecting information about the environment. The use of vehicles as sensor nodes is typically referred to as vehicular sensor networks (VSNs) and is a subclass of more general class of wireless sensor networks (WSNs). VSNs can be explicitly created to monitor some real world phenomena, such as air pollution in a city, but they can also be piggy-backed onto already existing networks created for other purposes, e.g. networks intended to enhance traffic safety [15].

Wireless communication quality is one environmental characteristic that a VSN could be deployed to monitor. Research work in this direction often focuses on measuring quality parameters between the vehicular sensor node and a fixed base station over multiple locations. Test-drives to measure signal reception and call quality is for example a widely used method when tuning cellular telephony network parameters.

In a VANET based on vehicle-to-vehicle communication similar methods could be employed to detect communication "black spots", i.e. certain locations where direct communication breaks down or is severely degraded. Since both receiver and transmitter are mobile the amount locations between which measurements are collected would substantially increase compared to the cellular scenario. However, the fact that vehicles travel mainly on roads as well as their limited transmission range suggests that there is a feasible upper limit to the amount of data that would need to be collected. Another advantage is that since CAMs are periodically exchanged, these messages could be used to measure channel quality without the need for introducing the overhead associated with sending dedicated QoS measuring packets.

IV. Conclusions

In this paper we propose that QoS requirements for VANET applications should be composed of not only channel properties but also a more detailed spatial definition of where those channel properties apply. The reason is that VANET applications exhibit high variation in requirements depending on the context. The static and omni-directional range requirements often seen in literature are thus a poor approximation to the actually required range. With context we specifically mean the vehicle kinematic state as well as the road geometry about the vehicle location. The ability to specify QoS requirements is fundamental in order to monitor and adapt to changes in the communication resource. We exploit the fact that the spatial coverage required by VANET applications is highly dependent on the road geometry to create a representation that is compact and expressive for the intended class of applications.

Using set theoretic notation we define two functions for selecting subsets of road links from a digital map, *Flood* and *Trajectory*. These subsets can be further composed using set theoretic concepts in order to create definitions of coverage that are context-dependent.

The spatial definition is combined with an application level QoS measure proposed in the literature, *T-Window reliability*, tailored toward VANET applications. We exemplify how the QoS requirements format can be used with two applications, intersection collision-avoidance and emergency brake light.

In future work we will investigate in more detail the other parts of our VANET QoS architecture, the *QoS monitor* and the *fault handler*. Our initial hypothesis is that by using the VANET as a sensor network, QoS measurements can be made and aggregated to form a knowledge-base for the QoS monitor.

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