Towards characterising and classifying communication-based automotive applications from a wireless networking perspective

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Abstract: Together, the Dedicated Short Range Communication (DSRC) and Vehicular Ad Hoc Network (VANET) technologies provide a unique opportunity to develop and introduce various types of communication-based automotive technologies to the marketplace. To date, many applications have been identified by the automotive community. Given the large number and diverse nature of these applications, it is advantageous to develop a systematic classification methodology to facilitate future DSRC and VANET research. Toward this objective, in this paper, we present a study that goes through two major steps: characterisation and classification. First, we focus on a set of representative applications and characterise them with respect to plausible application- and networking-related attributes. The characterisation process not only strengthens our understanding of the applications but also sets the stage for the classification step since it reveals numerous application commonalities. Thus, we have categorised the given applications into seven *generic* classes, with the consideration of balancing the trade-off between exploiting as many application similarities as possible while preserving their salient differences. This is of paramount importance to facilitate performance analysis of newly designed protocols. Finally, we have identified key performance metrics for each class of applications, which, we hope, could bridge the gap between the automotive and wireless networking communities. Accordingly, the proposed classes are envisioned to play a dual-role: facilitate application simulation and performance evaluation and guide DSRC and VANET protocol research and development.

Keywords: VANET; DSRC.

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1 Introduction

Traffic crashes and highway congestion are serious problems world-wide (Chen and Cai, 2005; Reumerman et al., 2005). To address these challenges, expensive sensors, radars, cameras and other state-of-the-art technologies are currently integrated into vehicles to improve safety and convenience. Recently, however, communication-based safety applications have attracted more attention from industry and governments in the United States, Europe and Japan because of their potential to lower manufacturing costs (Misener et al., 2005; Vehicle Safety Communications Project, 2006). In addition to safety applications, wireless communication can also be shared by commercial and vehicular "infotainment" applications to, for instance, enhance the occupants' driving experience. Thus, wireless communication can be used not only to enhance transportation safety (Yin et al., 2004; Torrent-Moreno et al., 2004; Xu et al., 2004; ElBatt et al., 2006) and traffic efficiency (Anda et al., 2005), but also to create commercial value to vehicle owners and automotive Original Equipment Manufacturers (OEMs) by providing infotainment applications (Das et al., 2004; Nandan et al., 2005).

The US federal government has recognised the importance of having a dedicated wireless spectrum for improving traffic safety and highway efficiency. Hence, the Federal Communications Commission (FCC) has allocated 75 MHz of licensed spectrum at 5.9 GHz as the Dedicated Short Range Communication (DSRC) band for Intelligent Transportation Systems (ITS) (Federal Communications Commission, 2003). The deployment of ITS, with its Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) constituents, is supported under major United States Department of Transportation (USDOT) initiatives (Vehicle Infrastructure Integration; Cooperative Intersection Collision Avoidance Systems). The physical layer (PHY) and Medium Access Control (MAC) portions of the DSRC standard are currently being addressed by the IEEE 802.11p Task Group (IEEE 802.11 WG, 1999; DSRC, 2003), which is widely considered as the leading technology for communication-based automotive applications. Major automotive OEMs, wireless device manufacturers, research institutions, public agencies, and private enterprises are conducting research on various topics pertaining to vehicle-to-vehicle and vehicle-to-infrastructure communications, such as, wireless channel modelling (Taliwal et al., 2004; Yin et al., 2006), mobility modelling (Lin et al., 2004; Bai et al., 2003), routing protocols (Lochert et al., 2005; Korkmaz et al., 2004; LeBrun et al., 2005; Chennikara-Varghese et al., 2006), security (Picconi et al., 2006; Raya et al., 2006), and market penetration mitigation strategies (Kosch, 2005; Shladover and Tan). On the other hand, very limited attention, if any, has been dedicated to better understanding, modelling and analysing communication-based automotive applications as the major driving force for VANET-focused technologies, as opposed to MANET technologies at large.

1.1 Motivation

This research challenging paper is motivated by the need for a systematic and thorough analysis of communication-based automotive applications from a networking point of view. As a preliminary study, we attempt not only to raise awareness about the performance requirements of the automotive community, but also to attract sufficient attention from the networking research community.

The Vehicle Safety Communication Project (Vehicle Safety Communications Project, 2006) has identified a number of applications for potential deployment along with projected user benefits (Vehicle Safety Communications Project). The applications of interest vary significantly in terms of their characteristics, requirements and constraints ranging from safety/warning applications to content download/streaming applications (for entertainment) and free-flow payment applications (for improving highway traffic efficiency and driver convenience). Analyzing and developing wireless networking solutions tailored to such large number of diverse applications, in an exhaustive manner, is a cumbersome and inefficient task. Obviously, there is a gap between developing communication-based automotive applications (the focus of the automotive community) and developing VANET protocols (the focus of the wireless networking community). To bridge this void, we aim at categorising communication-based automotive applications, not only from application characteristics perspective, but more importantly from a wireless networking perspective.

1.2 Contributions

To the best of our knowledge, this paper is the first study of classifying communication-based automotive applications from the perspective of wireless networking design. Towards this objective, we are interested in answering the following questions throughout this study:

- What are the key application characteristics and networking attributes in the design space of automotive application development?
- How should these applications be categorised into generic classes, from the viewpoint of network designers?
- What are the relevant performance metrics essential to adequately evaluate the behaviour of network protocols and applications, for each class of

applications? What is the mapping, if any, between application-level metrics and network-level metrics?

Part of the challenge in our study is to create a rich set of application characteristics and network attributes which capture the major dimensions of the design space of V2V/V2I applications, in a systematic and thorough manner. With deep insight into the application design space, we have categorised a set of applications into several *generic* classes based on their identified commonalities. In addition, we have identified relevant performance metrics for each generic application class, at both the network-level and the application-level, to be used, among other things, for evaluating whether the performance of a given application meets the application class requirement. We have also developed two simple analytical models to bridge the discrepancy between network-level metrics and application-level metrics, for reliability and latency. In this paper, we focus primarily on three major aspects:

- investigating the application characteristics and network attributes
- classifying the applications into generic classes
- defining relevant performance metrics for each class of applications.

1.3 Benefits of the paper

Our aim for this study is not only to simplify large-scale simulation efforts, which play important role in understanding the performance limits of VANETs in realistic scenarios, but also to shed light on designing network protocol stack(s) and system integration for different applications. For instance, using our research findings, network designers may focus on just a few abstract classes of V2V/V2I applications, rather than designing for individual applications in an exhaustive manner. Also, evaluating the performance trends of generic classes of applications with the same mechanisms/tools simplifies the task and reveals valuable insights at a reasonable cost. If needed, individual applications can be further studied and analysed as simple extensions of the proposed generic classes. Finally, it should be noted that the proposed classes are not meant to be comprehensive, yet, they constitute an essential first step that could be refined and extended in the future as automotive applications emerge, dominate or subside.

This classification serves as a potential road-map for developing the VANET technology needed to support different applications. A generic class of applications is more likely to have a similar set of protocols and mechanisms in the network stack because similar application characteristics and performance requirements tend to implicitly mandate the same technical solution. Thus, network designers should be able to maximise the re-usability of common mechanistic “building blocks” (or modules) for a specific class of applications with similar application characteristics and performance requirements. In summary, the benefits of characterising and classifying V2V/V2I applications include:

- Development of a few types of application models to represent a large number of applications with similar properties belonging to the same class, for application simulation and validation.

- Identification of key performance metrics relevant to each identified application class, as benchmarks for evaluating whether the designed application mechanisms can meet common requirements mandated by application classes.
- Creation of networking protocol stacks for each class of applications, with the consideration of improving re-usability of common mechanistic modules or networking protocols.

1.4 Paper organisation

This paper is organised as follows. In Section 2, we introduce a set of V2V/V2I applications as a representative of the *connected vehicle* vision. Afterwards, we introduce the attributes used for characterising those applications in Section 3. In Section 4, we characterise each application according to the introduced attributes, which constitutes a fundamental step towards identifying few *generic* application classes. Next, we introduce the application-level and network-layer performance metrics and QoS requirements for each application class in Section 5. Finally, we conclude the paper and lay out potential directions for future research in Section 6.

2 Background: a set of V2V/V2I applications from the perspective of user benefits

Research on Vehicular Ad Hoc Networks (VANET) technology has been driven mainly by the demand of providing network support for application development. So far, the DSRC research community has developed a large number of potential V2V/V2I applications for future deployment, ranging from safety/warning applications, highway traffic management to commercial applications. Since it is difficult to analyse a large number of applications, we chose 16 representative applications based on criteria such as customer value, near-term feasibility of deployment, technical novelty, and diversity of enabling technologies. The chosen applications (shown in Table 1) constitute the basis for our study.

From a value or customer benefit perspective, these applications can be roughly organised into three major categories: *safety-oriented*, *convenience-oriented*, and *commercial-oriented*.

- *Safety applications* actively monitor the nearby environment (the state of other vehicles or road conditions) via message exchanges between vehicles, so that applications are able to assist drivers in handling the upcoming events or potential danger. Some applications may automatically take appropriate actions (such as automatic braking) to avoid potential crashes, while others provide only advisory information to drivers as they choose. The latter category of applications is very similar to the former, even though the system requirements (such as reliability, latency, etc.) are less stringent. However, both types of applications aim to improve the level of vehicle safety.
- *Convenience (Traffic Management) applications* share traffic information among roadway infrastructure, vehicles on the road, and centralised traffic

Table 1 V2V/V2I applications of interest

Acro.	*Name*	*Description*	*Benefits*
SVA	Stopped or Slow Vehicle Advisor	A slow or stopped vehicle broadcasts slow/stopped vehicle warning messages to approaching vehicles in its neighbourhood	Safety
EEBL	Emergency Electronic Brake Light	A vehicle braking hard broadcasts a warning message to approaching vehicles in its neighbourhood for the duration of the event	Safety
PCN	V2V Post Crash Notification	A vehicle involved in an crash broadcasts a warning message to vehicles in its neighbourhood until the crash site is cleared	Safety
RHCN	Road Hazard Condition Notification	A vehicle detecting a road hazard (e.g., fluid, ice) notifies vehicles within the potentially affected region	Safety
RFN	Road Feature Notification	A vehicle detecting a road feature (e.g., road curve, hill, road grade) notifies approaching vehicles in its neighbourhood	Safety
CCW	Cooperative Collision Warning	A vehicle actively monitors kinematics status messages from vehicles in its neighbourhood to warn of potential collisions	Safety
CVW	Cooperative Violation Warning	A road-site unit actively transmits signal phase, timing and related information to approaching vehicles. The vehicles use this information to warn drivers of potential violation of traffic signal	Safety
CRN	Congested Road Notification	A vehicle reports road congestion to vehicles or road-side units in other regions for the purposes of route and trip planning	Convenience
TP	Traffic Probe	Vehicles aggregate traffic probe information and transmit to road-side units for traffic management	Convenience
TOLL	Free Flow Tolling	Vehicle toll collection at highway toll booths (non-stop)	Convenience
PAN	Parking Availability Notification	A vehicle receives the availability of parking lots in a certain geographical region	Convenience
PSL	Parking Spot Locator	A vehicle receives a list of open parking spots upon entering a parking lot	Convenience
RVP/D	Remote Vehicle Personalisation/ Diagnostics	Downloading of personalised vehicle settings or uploading of vehicle diagnostics from/to infrastructure	Commercial
SA	Service Announcements	Road-side businesses (e.g., MacDonald's) announce services to vehicles as they pass by or come within range	Commercial
CMDD	Content, Map or Database Download	A vehicle downloads content (e.g., maps, multimedia, webpages) from home stations or from mobile "hot-spots"	Commercial
RTVR	Real-Time Video Relay	Transmission and relay of streaming real-time video from a vehicle to other vehicles or road-side units	Commercial

control systems, to enable more efficient traffic flow control and maximise vehicle throughput on the road. Ultimately, these applications not only enhance traffic efficiency, but also boost the degree of convenience for drivers.

- *Commercial applications* provide drivers with various types of communication services to improve driver productivity, entertainment, and satisfaction, such as web access and streaming audio and video.

From the description of the applications in Table 1, it is easy to see that SVA, EEBL, PCN, RHCN, RFN, CCW and CVW can all be considered *safety-oriented* applications, whereas CRN, TP, TOLL, PAN and PSL can be considered *convenience-oriented* applications. Likewise, RVP/D, SA, CMDD and RTVR (and other Internet access applications) can be considered *commercial-oriented* applications. These categories are derived from the characteristics and customer benefits of the applications. Note that, among those listed, safety-oriented applications are of special interest because they are expected to reduce the fatalities and economic losses caused by traffic crashes.

3 Criteria of classification: application characteristics and network attributes

In this section, we define the application and networking criteria used in our classification. Careful selection of these criteria is critical to adequately capture the subtle, yet, important differences between various applications and their diverse networking requirements. Thus, our approach was to first enumerate the characteristics of the applications in Table 1 in a systematic and thorough manner so we could gain important insight into the applications, use this insight to explore the demands these applications place on network design and enumerate their common network-related attributes. Thus, we group these criteria into two major divisions, application-related characteristics and network-related attributes, which are shown in Table 2 and Table 3, respectively. In the remainder of this section, we discuss the contents of these tables in further details.

3.1 Application characteristics

In this section, we introduce the application-related characteristics that we identified and used as the basis for our proposed classification. These characteristics, summarised in Table 2, describe properties directly related to the applications themselves, such as user benefit and affected geographical region. As mentioned previously, the goal is to develop key characteristics that cover the various design aspects of the set of applications that we explored. While we attempted to be as general and as thorough as possible, we acknowledge that future analysis of a broader set of applications may uncover other important characteristics. Indeed, it is our hope that the work presented here will inspire others to research and expand the list as future applications are explored and developed. However, as we will show, this list covers a sufficiently broad range of applications to be a useful reference tool for application and network designers. In the remainder of this section, we discuss these characteristics in more detail.

Table 2 Candidate criteria to characterise and classify applications (application characteristics)

Application Characteristics	*Description*	*Choices*
User Benefit of Application	What benefit does the application bring to users?	Safety, Convenience, Commercial
Participants of Application	What entities participate in the application?	V2V, V2I
Application Region of Interest (ROI)	What is the size of the affected geographical region of the application?	Large, Medium, Small
Application Trigger Condition	When and how is the application triggered?	Periodic, Event-Driven, User-Initiated
Recipient Pattern of Application Message	What is the pattern of recipients for the application messages?	One-to-One, One-to-Many, One-to-a-Zone, Many-to-One
Event Lifetime	How long does the event last?	Long, Short
Event Correlation	What is the degree of event correlation in the ROI?	Strong, Weak, None
Event Detector	How many hosts can detect/ generate the event?	Single Host, Multiple Hosts

- *User Benefit*: This describes the type of benefit or value the application provides to the end customer, as defined in a number of studies (Vehicle Safety Communications Project) (and discussed in Section 2). Overall, there are three widely accepted application types: *safety-oriented* applications, *convenience-oriented* applications, and *commercial-oriented* applications.
- *Application Participants*: This specifies the entities that may be potentially involved in the application. Some applications only require communication

Table 3 Candidate criteria to characterise and classify applications (network attributes)

Network attributes	*Description*	*Choices*
Channel Frequency	What channel does the application use?	DSRC-CCH, DSRC-SCH, WiFi
Infrastructure	Is infrastructure required?	Yes, No
Message Time-To-Live	How far do messages propagate?	Single-hop, Multi-hop
Packet Format	What type of packet is used?	WSMP, IP
Routing Protocol	How are messages distributed?	Unicast, Broadcast, Geocast, Aggregation
Network Protocol Initiation Mode	How is a network protocol initiated?	Beacon, Event-triggered, On-Demand
Transport Protocol	What form of end-to-end communication?	Connectionless, Connection-oriented
Security	What kind of security is needed?	V2V security, V2I security, Internet Security

among vehicles, while other applications require the coordination between vehicles and road-side infrastructure. Hence, communication-based automotive applications can be categorised as either *vehicle-to-vehicle* (*V2V*) applications or *vehicle-to-infrastructure* (*V2I*) applications.

- *Application Region of Interest* (*ROI*): The ROI is the size of the geographical region covered by those entities participating in an application. Different kinds of applications have different ROI sizes. For example, in some safety applications, vehicles need to be aware of the kinematics status of other vehicles in their direct neighbourhood (i.e., a few hundred meters), whereas in other safety applications vehicles need to know the hazard situation of a stretch of road that lies ahead (i.e., up to 1 kilometer). Likewise, for some convenience applications, vehicle occupants may want to know the status of road congestion far ahead (i.e., several kilometers) for trip planning. Qualitatively, the application ROI can be classified into three major types: *small*-, *medium*-, and *large-range*. Quantitative characterisation of the shape and dimensions of the ROI, for various applications, is an important topic that requires interdisciplinary research in system reliability, driver behaviour, and traffic/road dynamics to name a few.
- *Application Trigger Condition*: This specifies how applications are triggered, which is generally either *periodic*, *event-driven*, or *user-initiated*. Implicitly, it also specifies the kind of communication methods used by the application. For example, the vehicular kinematics status messages used for collision detection are normally broadcasted periodically, whereas warning messages for events such as panic braking are usually event-driven and request messages for on-demand convenience services from vehicle occupants are generally user-initiated.
- *Recipient Pattern of Application Message*: This specifies the pattern of potential message recipients for an event, which varies across applications. For instance, for safety applications like CCW and CVW, it is critical for all neighbouring vehicles to hear broadcasted safety alert messages to avoid potential collisions (a *one-to-many* pattern), whereas for safety applications such as EEBL, SVA and PCN, only vehicles in the region being affected (vehicles behind the event originator) need to hear the safety alert message (a *one-to-a-zone* pattern). Likewise, a *point-to-point* communication pattern is often used in many convenience and commercial applications and a *many-to-one* pattern is also sometimes used. Thus, the pattern of event message recipients can be grouped into four categories: *one-to-many*, *one-to-a-zone*, *one-to-one* and *many-to-one*.
- *Event Lifetime*: This illustrates how long an application event (e.g., traffic crash or road congestion) persists over time. Among the criteria discussed so far, event duration is one application characteristic that may directly affect network system design. Among all applications, event lifetime may differ significantly. For example, some events have relatively short durations (e.g., EEBL events may last only a few seconds on average), while others may have relatively long durations (e.g. a PCN event may take hours before the crashed vehicles are cleared from the roadway). Among the applications we studied,

most fell into one of two general categories: either a *short* event lifetime (O(seconds)) or a *long* event lifetime (O(minutes to hours)).

- *Event Correlation*: This specifies the degree to which events generated by entities within a geographical region of interest are correlated with each other. For example, the occurrence of an EEBL event in a vehicle may be highly correlated to EEBL events generated by other vehicles in front of it. Another example is the RHCN application, where RHCN events in nearby vehicles may be highly correlated since they are caused by the same road hazard condition. Qualitatively, applications can be grouped into three categories: those with *strong* event correlation, *weak* event correlation and *no* event correlation.
- *Event Detector*: This specifies how many vehicles generate event messages in response to the same event. For instance, for applications such as SVA or PCN, where a vehicle reports its kinematics status, the vehicle is the sole event detector (i.e. of its kinematics state) and event message host (originator), whereas for applications such as RHCN and RFN, where a vehicle reports road hazards, many vehicles may detect the same event (i.e. the same road hazard) and serve as event message hosts. Therefore, we classify application event detection as either *single* host or *multiple* hosts.

As mentioned previously, we believe these are the key defining characteristics, among the 16 applications that we studied, that are of most relevance to network design. However, we acknowledge that further application analysis may reveal other characteristics to add to the list and we hope that it inspires others to do so. For the purposes of this study, however, these are the basis for the application characteristics portion of our classification effort. In the next section, we present our group of key network-related attributes and their relation to the application characteristics above.

3.2 Network attributes

In this section, we introduce the key network-related attributes that we used in our classification to characterise the fundamental aspects of network design for communication-based automotive applications. These attributes, summarised in Table 3 are somewhat related to the application characteristics discussed in the previous section, as we will show. In the remaining part of this section, we discuss these network attributes, and their relationship with the corresponding application characteristics, in detail.

- *Channel Frequency*: This attribute specifies the type of physical-layer channels that may be used to support communication-based automotive applications. Following FCC regulations, safety-oriented applications are normally assumed to use a single DSRC control channel (CCH), whereas convenience-oriented applications use one of six DSRC service channels (SCH). On the other-hand, commercial-oriented applications can either occupy DSRC SCH channels, or any other channel frequency in the unlicensed Industrial, Scientific and Medical (ISM) bands (e.g. WiFi 2.4 and 5.8 GHz). In other words, the choice of channel is largely determined by the value of the *user benefit* characteristic of the application. While there are many other channels that can be used (such as cellular telephony or WiMAX), in practice the choice of channel is generally one of either *DSRC CCH*, *DSRC SCH*, or *WiFi*.

- *Infrastructure*: This attribute specifies whether the application needs infrastructure (i.e. a road-side unit) for its operation. Obviously, infrastructure is needed if the *participants of the application* characteristic involves a road-side unit. Otherwise, infrastructure may not be required.
- *Message Time-To-Live* (*TTL*): This attribute specifies how far a message is propagated by the network and what type of packet forwarding/routing functionality is needed (i.e., single-hop or multi-hop) by the network layer. This attribute is partly determined by the *application region of interest* characteristic. Single-hop communication is sufficient for short-range applications, while medium- or long-range applications require multi-hop packet forwarding/routing functionality for extended reachability. Thus, design choices include either *single-hop* or *multi-hop* routing.
- *Message Packet Format*: This attribute describes the format of the network packets that are used to encapsulate the application messages. This attribute is partly influenced by the *user benefit* characteristic of the application. In general, the automotive industry (Vehicle Safety Communications Project) and the IEEE standard community (IEEE 802.11 WG, 1999) have promoted the idea that safety and convenience applications are more likely to use relatively constant and small-sized packets, whereas commercial applications are more likely to use variable and large-sized packets. In the DSRC standard, the Wave Short Message Protocol (WSMP) is proposed for safety and convenience use. It is essentially a simplified version of the IP protocol, with a smaller packet header to reduce per-packet overhead for improved network efficiency. For commercial applications, it is assumed that the traditional IP packet format will be used. Thus, we classify packet formats into to types: either *WSMP* format or *IP* format.
- *Routing Protocol*: This design choice illustrates what kind of network routing protocols are used for the various applications. Obviously, this network attribute is closely related to the *recipient pattern of application message* characteristic. For instance, most safety applications use *broadcast* routing (one-to-many) or *geocast* routing (one-to-a-zone), while convenience and commercial applications normally use *unicast* routing (one-to-one) or *aggregation* routing (many-to-one).
- *Network Protocol Initiation Mode*: This attribute describes how the network protocol is triggered. Some safety applications mandate periodic broadcast "beaconing" of status messages, like CCW and CVW (i.e., *beacon* mode), whereas other safety applications, like EEBL and PCN, send messages only when a critical event is detected (i.e., *event-triggered* mode). For a portion of convenience and commercial applications, it is the vehicle occupants that initiate message announcements and service request (i.e., user-initiated *on-demand* mode).

- *Transport Protocol*: This design choice indicates whether or not a reliable end-to-end connection is needed to support the application. As we discovered, safety and convenience applications generally follow the *connection-less* paradigm (e.g. WSMP, UDP), while commercial applications often use the traditional *connection-oriented* paradigm (e.g. TCP).
- *Security*: This network attribute considers what kind of security solution is needed for the application. The choices include *V2V security*, *V2I security* and *Internet security*. Safety applications require high-level V2V security preventing vehicles from malicious attacks, convenience applications also mandate the stringent V2I security solution because financial transactions could be involved at road-side infrastructure and most commercial application require the efficient collaboration between V2V/V2I security solutions and existing security solutions for the Internet.

As indicated earlier, many of these network attributes are closely related to specific application characteristics. Intuitively, a given application characteristic or performance requirement normally requires a given networking mechanism or capability. In the next section, we show how sets of applications with similar characteristics and requirements lead to the same network solutions, resulting in a very useful and intuitive general classification.

4 Application characterisation and classification

In this section, we present the results of characterising and classifying the set of 16 applications shown in Table 1. We then compare and contrast these applications first with respect to the application characteristics presented in Table 2 and then with respect to the network attributes presented in Table 3. Afterwards, we show how, by combining the applications with similar characteristics and network functionalities, we can group these applications into 7 generic classes (from the perspective of network design).

4.1 Characterisation based on application characteristics

The process of application characterisation is divided into two steps: *characterisation of application attributes* and *characterisation of network attributes* (i.e., network design), as shown in Tables 4 and 5 respectively. By first exploring all the relevant application characteristics for each application, we gain a more complete understanding towards the fundamental properties and functionality requirements of these applications. Later, we show how this effort gives rise to application characterisation from the network design point of view.

Table 4 lays out the main characteristics of each application based on the selected application-related attributes summarised in Section 3.1. Given the limited space, we are unable to discuss the characteristics for all 16 applications. Instead, we only highlight a few important application characteristics, illustrating how these criteria help to differentiate the often subtle difference between various applications:

- Notice that most of the safety applications have a medium-sized effective application range (i.e., a few hundred metres to 1 km), since safety messages,

Table 4 Application characterisation based on application characteristics

Acro.	*User Benefit*	*Application Participants*	*Trigger ROI*	*Application Recipient Condition*	*Event Pattern*	*Event Lifetime*	*Event Correlation*	*Detector*
SVA	Safety	V2V	Medium	Event	One-to-a-zone	Long	None	One
EEBL	Safety	V2V	Medium	Event	One-to-a-zone	Short	Weak	Many
PCN	Safety	V2V	Medium	Event	One-to-a-zone	Long	None	One
RHCN	Safety	V2V	Medium	Event	One-to-a-zone	Long	Strong	Many
RFN	Safety	V2V	Medium	Event	One-to-a-zone	Long	Strong	Many
CCW	Safety	V2V	Small	Periodic	One-to-Many	N.A.	N.A.	N.A.
CVW	Safety	V2I	Small	Periodic	One-to-Many	N.A.	N.A.	N.A.
CRN	Convenience	V2V	Large	Event	One-to-zone	Long	Strong	Many
TP	Convenience	V2I	Large	Event	One-to-one	Short	None	Many
TOLL	Convenience	V2I	Small	Event	One-to-one	Short	None	One
PAN	Convenience	V2I	Large	User-Initiated	One-to-one	N.A.	N.A.	N.A.
PSL	Convenience	V2I	Small	User-Initiated	One-to-one	N.A.	N.A.	N.A.
RVP/D	Commercial	V2I	Small	User-Initiated	One-to one	N.A.	N.A.	N.A.
SA	Commercial	V2I	Large	User-Initiated	One-to-a-zone	N.A.	N.A.	N.A.
CMDD	Commercial	V2I	Large	User-Initiated	One-to one	N.A.	N.A.	N.A.
RTVR	Commercial	V2I	Large	User-Initiated	One-to-one	N.A.	N.A.	N.A.

Table 5 Application characterisation based on network attributes

Acro.	*Channel Frequency*	*Infra-structure*	*Message TTL*	*Packet Format*	*Routing Protocol*	*Network Trigger*	*Transport Protocol*	*Security Solution*
SVA	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
EEBL	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
PCN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
RHCN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
RFN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
CCW	DSRC CCH	No	Single-hop	WSMP	Broadcast	Beacon	Connection-less	V2V security
CVW	DSRC CCH	Yes	Single-hop	WSMP	Broadcast	Beacon	Connection-less	V2I security
CRN	DSRC SCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
TP	DSRC SCH	Yes	Multi-hop	WSMP	Unicast	Event-triggered	Connection-oriented	V2I security
TOLL	DSRC SCH	Yes	Single-hop	WSMP	Unicast	Event-triggered	Connection-oriented	Internet security
PAN	DSRC SCH	Yes	Multi-hop	WSMP	Unicast	On-demand	Connection-oriented	V2I security
PSL	DSRC SCH	Yes	Single-hop	WSMP	Unicast	On-demand	Connection-oriented	V2I security
RVP/D	DSRC SCH WiFi	Yes	Single-hop	IP	Unicast	On-demand	Connection-oriented	V2I security
SA	DSRC SCH WiFi	Yes	Multi-hop	IP	Geocast	On-demand	Connection-less	Internet security
CMDD	DSRC SCH WiFi	Yes	Single-hop	IP	Unicast	On-demand	Connection-oriented	Internet security
RTVR	DSRC SCH WiFi	Yes	Multi-hop	IP	Unicast	On-demand	Connection-oriented	Internet security

such as vehicular kinematics status or road conditions, are only relevant to other vehicles within a moderate geographical region. Exceptions are the CCW and CVW applications, which have a small application effective range because they require closer monitoring of vehicles in their direct neighbourhood (i.e., within 200 m). Conversely, convenience applications generally require a medium to large effective range (i.e., up to a few kilometers), because it is vital for drivers to know the congestion situation or traffic condition at this range for effective detour or trip planning decision making. Similarly, commercial applications tend to have a large effective range in order to access remote commercial service providers.[1]

- Most safety applications (e.g., EEBL, RHCN and SVA) and few convenience applications (e.g., CRN, TP and TOLL) are initiated by the events happening on the road, such as vehicle collisions, detection of road hazards (e.g. ice, oil), sudden braking, or detection of traffic congestion. If no such events happen, these applications will not be called upon. Among safety applications, CCW and CVW are unusual because they rely on the periodical message updates to monitor the neighbouring vehicles' driving status, regardless of safety events. On the other hand, most convenience applications and commercial applications are triggered on-demand by vehicle occupants, rather than by any safety event on the road or the vehicle itself.
- The potential recipients of application messages, in most safety applications (e.g., SVA and EEBL), are vehicles within a specific zone (i.e., behind the vehicle which detects the event and originates the safety message). Thus, safety applications can be summarised as *one-to-a-zone* recipient patterns.[2] At the same time, convenience and commercial applications vary from application to application: some convenience applications (e.g. TOLL) and commercial applications (e.g., RVP/D, CMDD and RTVR) belong to the point-to-point (*one-to-one*) communication paradigm, while other convenience (e.g., CRN) and commercial applications (e.g., SA) are fundamentally *one-to-a-zone* in nature.
- "Event" is an important concept in safety applications and a few convenience applications, because it is an event that initiates the application operations. In our study, we also characterise safety events via several properties, including event duration, event correlation and event detectors. Consistent with our conjecture, we find that safety events drastically vary from application to application. For example, sudden braking (EEBL) is a one-shot event, while road hazard/feature events (RHCN or RFN) are persistent events. Also, different instances of RHCN or RFN events caused by the same road hazard/feature are more likely to be correlated with each other, in contrast to the totally independent PCN events. Even though the study of event characteristics is not directly used in the network design conducted in Section 4.2, we believe that such an analysis can assist future network designers better capture the data traffic patterns induced by event-driven safety applications.

From an application benefits point of view, different applications have different functionalities, providing different usages for customers. Interestingly enough, we realise that many applications exhibit highly similar application characteristics, with the exception of a few minor differences. To validate whether such an observation is valid from a network design perspective, we conduct an application characterisation based on the relevant network attributes listed in Section 4.2.

4.2 Characterisation based on network attributes

As mentioned in Section 3.2, for each application we discovered that its characteristics tend to mandate a certain design in the network protocol stack. For example, applications with one-to-many recipient patterns are more likely to use broadcast routing protocols, while unicast routing protocols are suitable for applications with one-to-one recipient patterns. Similarly, a single-hop packet dissemination mechanism is adequate to support applications with small application Region Of Interests (ROI) (i.e. a few hundred meters). In contrast, multi-hop routing protocols are needed for applications with medium or large application ROI. Accordingly, we are capable of determining the potential design choices for various components in the network stack by referring to their corresponding application characteristics and requirements.[3]

Table 5 lays out the main network attributes of each application based on the selected network attributes summarised in Section 3.2, starting from the lower physical layer to the upper transport layer. These network attributes cover design issues such as the physical layer channel frequency, the usage of infrastructure, message TTL (Time-To-Live), routing protocol and network protocol triggers at the network layer, transport layer design, and security solutions. Again, we only emphasise a few important network attributes, discussing the potential impact of application characteristics on these network design issues.

- The message packet format is determined by the type of application (from the perspective of user benefit). Normally, safety and convenience applications use light-weight short messages in the WSMP format, to improve network resource efficiency. Commercial applications, on the other-hand, generally prefer the traditional heavy-weighted IP format to be compatible with existing Internet commercial services.
- The network-layer routing protocol is one essential component in a network stack, differentiating the reachability and recipient patterns of various applications. Most safety applications utilise multi-hop geocast routing protocols,[4] because of the one-to-many communication nature in safety applications. CCW and CVW applications, instead, use the single-hop broadcast scheme to announce the periodic update in their direct neighbourhood. Convenience and commercial applications either use geocast/broadcast protocols to announce messages in a region (for advertisement service like SA, or traffic congestion notification like CRN), or exploit unicast protocols to forward packets to a given destination (for financial transactions like TOLL, or data download from infrastructure like CMDD).
- How the network routing protocol is triggered is another interesting design choice to be examined in our study. Event-driven safety applications

(e.g., SVA, EEBL and CRN) require the event-triggered mechanism in network protocols, periodic-based safety applications (e.g., CCW and CVW) mandate the periodic beacon (or hello message) mechanism and user-initiated convenience and commercial applications (e.g., SA, RVP/D and PSL) are triggered in an on-demand fashion.

- The involvement of infrastructure in network design and application development is another key issue for consideration.[5] Both infrastructure-oriented approaches and non-infrastructure approaches (or, even a combination of both approaches) are used to achieve the objective of supporting the applications or services discussed above. Deployment of infrastructure-oriented services depends on considerations such as availability of infrastructure, costs and technology deployment. Infrastructure can facilitate the design of convenience applications as well as enable commercial applications by providing the gateway to the existing Internet infrastructure. As a side note, the involvement of infrastructure also complicates the design of security solution. We believe that security solutions for V2V applications are different from that for V2I applications. However, the gateway to the Internet requires the compatibility of V2V/V2I security solutions with the existing Internet security solutions.

Throughout our study, we found that Tables 4 and 5 reveal a number of interesting observations. Generally speaking, many applications exhibit highly similar application characteristics, resulting in similar protocol design across various layers in the network stack. For instance

- RHCN and RFN are nearly the same, except that the type of safety warning messages are different: RHCH is about road hazards, while RFN is about road features.
- PCN and RHCN are also similar except for the number of event originators: PCN has a sole message host, while RHCN has multiple message hosts. Even though this difference gives rise to different levels of data traffic burstiness from event generation, the network protocol stacks for these two applications are still similar to each other.
- Also, CCW and CVW applications can be categorised into the same type, although the former is a V2V application whereas the latter is a V2I application.

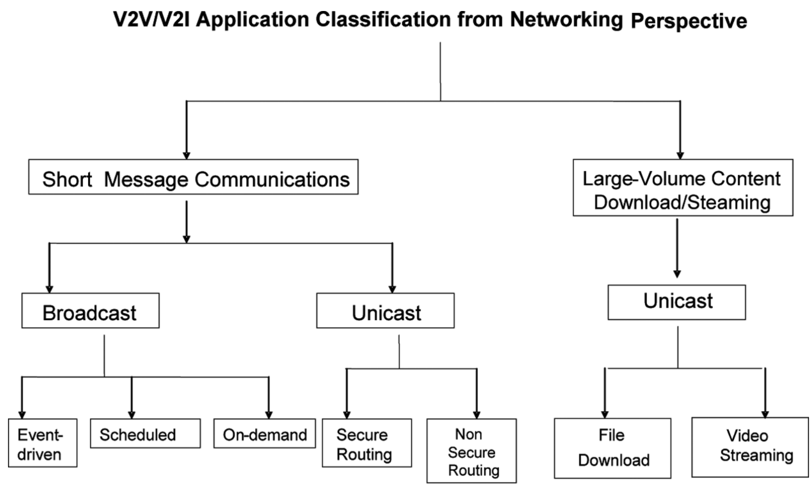
In summary, the first seven safety applications (SVA, EEBL, PCN, RHCN, RFN, CCW and CVW) all utilise broadcast/geocast routing protocols to distribute safety/warning messages in the WSMP format. On the other hand, some convenience applications mostly rely on user-initiated unicast routing protocols to deliver non-safety messages in the WSMP format, while commercial applications may exploit IP protocols to enable enhanced functionality such as QoS routing. This, in turn, suggests that the studied applications naturally lend themselves to fewer numbers of *generic/abstract* classes, which is the subject matter of the next section.

4.3 Application classification

With a deep understanding of application characteristics and network attributes applied to all studied applications, we are able to classify them into a number of *generic* classes. Notice that application classification can be conducted at different levels, depending on the design granularities. For example, simple classification and few abstract classes are adequate for high-level concept design of automotive communication applications. On the contrary, empirical design of prototype systems normally mandates an exhaustive effort, resulting in a sophisticated multi-level application categories.

At the initial stage of this emergent research field, we believe that a high-level classification is sufficient to serve the purpose of distilling the major concepts and identifying the synergy among various applications, without unnecessarily complicating the problem formulation. Later on, the empirical prototype system can be designed and implemented based on the refined and enriched version of this study. Here, we present such a way to classify the aforementioned applications from the perspective of network design (as shown in Figure 1), among other alternatives. Generally speaking, V2V/V2I applications can be classified into two broad generic classes, namely *Short Message Communications* and *Large-Volume Content Download/Streaming*. Most safety and convenience applications belong to the first class, since the messages in these applications are light-weight WSMP messages. Considering that the IP message format is appropriate for large-volume data (such as Internet web access or video/audio streaming), most commercial applications fall under the second category.

Figure 1 Classification from perspective of network design



4.3.1 Short message communication

First, we discuss the class of short message communication which uses light-weight WSMP packets. This can be classified, depending on the recipient pattern and routing protocol, as either Broadcast/Geocast or Unicast applications.

Clearly, most safety applications require message announcements be sent to a large number of nodes (one-to-many or one-to-a-zone), hence, they would fall under the Broadcast/Geocast-oriented type. On the other hand, many convenience applications (including payment-type applications) would fall under the Unicast-oriented type.

According to the network protocol triggering condition, *Broadcast/Geocast*-oriented applications can be further classified as event-driven, scheduled (periodic) and on-demand approaches. The event-driven class is used to model safety applications focusing on life-threatening events and the scheduled class is suitable for safety applications requiring periodic message updates, whereas the on-demand class is appropriate for convenience applications such as parking spot locator. As a side note, high-level V2V security solutions are required to protect safety applications from malicious hackers. These three sub-classes of Broadcast/Geocast-oriented applications are:

- *Event-driven Broadcast/Geocast Class*: SVA, EEBL, PCN, RHCN and RFN applications, as well as CRN application, belong to this category. (class 1)
- *Scheduled (periodic) Broadcast/Geocast Class*: CCW and CVW applications fall into this category. (class 2)
- *On-demand Broadcast/Geocast Class*: Some convenience or commercial applications, like SA, belong to this category. (class 3)

The secure routing of financial transactions in convenience applications also plays an important role in *Unicast*-oriented applications. Thus, these Unicast-oriented applications can be classified as either involving stringent secure routing for financial transactions, or those which do not involve secure routing. Thus, we list these two sub-classes of Unicast-oriented applications:

- *Secure Unicast Class*: One example of this approach are TOLL applications (e.g., Drive-thru payment, Free-flow Tolling). RVP/D also falls into this category since it is potentially related with the control components of vehicles. (class 4)
- *Unsecured Unicast Class*: TP, PAN and PSL applications fall into this category. Also, some of commercial applications (e.g., vehicle-to-vehicle online chatting or social networking application) belong to this category. (class 5)

4.3.2 Large-volume content download/streaming

Next, we focus on the second major class of applications, namely Large-Volume Content Download/Streaming, which is normally implemented in the IP format for compatibility. These applications often utilise unicast protocols because of their one-to-one communication nature. This class is further classified depending on the content type: either file download or media streaming. The former type allows short-term disruption in network service, so it is inherently latency-tolerant. The latter type requires a relatively smooth streaming transfer, so it is fundamentally latency-sensitive. It is straightforward to notice the following memberships in large-volume content download/streaming applications:

- *File Download*: CMDD application (e.g., map database download or web access/browsing) is one example of this approach. (class 6)
- *Video Continuous Streaming*: RTVR application (e.g., video/MP3 streaming among vehicles or from road-side infrastructure for entertainment) falls into this category. (class 7)

These seven types of V2V/V2I applications and their key considerations in network design are summarised in Table 6. From the above discussion, we conclude that the given set of applications can be classified into seven generic classes. Since these applications are carefully chosen to represent many other applications, we believe that our classification methodology and classification results can also apply to a large number of V2V/V2I applications.

The potential benefits of application classification include:

- Such a classification effort not only contributes to capturing the common features and technical requirements of applications, but also helps to develop common networking stacks for the identified generic classes. In the near future, with the deeper understanding of these *generic* and *abstract* classes, we are able to increase the module re-usability of wireless networking solutions for the given set of applications with similar characteristics.
- At the same time, such a classification effort helps to identify common requirements and performance metrics relevant to each application class. It also eases application modelling in simulation studies targeted at the performance evaluation of a large number of applications. By appropriately, isolating generic network design from different application instantiations, we argue that it is much more efficient to model these seven generic classes than it is to model all 16 applications in an exhaustive manner without exploiting their noticeable commonality. Thus, a generic model should suffice for gathering statistics for the performance metrics defined for a specific class. Gathering performance results for a particular application, for the purposes of detailed analysis, could be achieved by deriving the application of interest as a simple extension from its generic model.

5 Performance metrics and QoS requirements

Defining and gathering the “right” performance metric is crucial to efficiently guiding the development of networking algorithms and protocols, towards guaranteeing satisfactory performance of the applications, under a wide variety of realistic operating environments. Performance metrics can be generally classified to *network-level* (or packet-level) metrics and *application-level* metrics. In traditional Internet and Mobile Ad hoc Networking (MANET) communities, the network-level metrics have received wide interest. This is primarily because of the strong need to analyse and understand, at a microscopic packet-level, how protocols/algorithms behave under different environments and user dynamics. Examples of these packet-level metrics include: packet delivery ratio (PDR) and average per-packet latency, etc. On the other hand, the application-level metrics also constitute the driving force for protocol development, when applications play an important role

Table 6 Network design considerations for 7 types of applications

Application Type	*Channel Frequency*	*Packet Format*	*Routing Protocol*	*Connection to Internet*	*Transportation Protocol*	*Security*
Event-driven Broadcast/Geocast	DSRC CCH	WSMP	*Event-driven* multi-hop broadcast/geocast	No	Connection -less	V2V Security
Scheduled Broadcast/Geocast	DSRC CCH	WSMP	*Scheduled* multi-hop broadcast/geocast	No	Connection -less	V2V/V2I Security
On-demand Broadcast/Geocast	DSRC SCH, or WiFi	WSMP, or IP	User-initiated *on-demand* multi-hop broadcast/geocast	No	Connection -less	V2V/V2I Security
Secure Unicast	DSRC SCH	WSMP	multi-hop unicast with *secure routing*	No	Connection -oriented	Stringent V2V/V2I Security
Normal Unicast	DSRC SCH	WSMP	multi-hop unicast	No	Connection -oriented	V2V/V2I Security
File Download	DSRC SCH, or WiFi	*IP*	multi-hop unicast	Yes	Connection -oriented	V2V/V2I /Internet Security
Media Streaming	DSRC SCH, or WiFi	*IP*	single-hop unicast with *QoS routing*	Yes	Connection -oriented	V2V/V2I /Internet Security

in pushing the development of technical solutions. For example, QoS performance requirements are clearly defined for voice over IP (VoIP) and video streaming applications in the traditional telephony industry and on-line video rendering business (e.g., VoIP E2E latency is about 50–100 msec). Notice that the mapping between packet-level metrics and application-level metrics is generally non-trivial.

Based on the classification proposed in Section 4.3, our objective is to introduce performance metrics for these classes of application, which quantitatively capture their key characteristics. Referring to the seven generic classes, it can be easily noticed that the first two classes (event-driven and scheduled broadcast/geocast approaches used to accommodate safety applications) significantly differ from traditional applications, because of their safety nature. One of our major challenges is to define the application-level metrics relevant to safety applications. For safety-oriented applications, we introduce both network-level metrics and application-level metrics as well as discuss their relation to each other through simple mappings, which are our focus of this section. We believe that such an understanding helps the networking research society and the automotive society to bridge the gaps between them. For the remaining types of applications, we are able to borrow the well-defined metrics from existing literature. Accordingly, we begin with performance metrics for broadcast-oriented safety applications and follow with unicast-oriented applications. Finally, we discuss the QoS performance metrics for content download/streaming applications.

5.1 Performance metrics for broadcast-based safety and non-safety applications (class 1, 2 and 3)

For broadcast (geocast)-based safety applications, network-level and application-level metrics are important to capture the performance of network protocols and performance of applications, respectively.

5.1.1 Network-level metrics

Two major network-level metrics are defined to capture the performance of network protocols: (a) *Packet Delivery Ratio* (PDR) $P_{net}(d)$ and (b) *Average Per-packet Latency* (APL) $\Delta\tau$. PDR $P_{net}(d)$ is defined as the probability of successfully receiving packets at distance d from broadcasting vehicle, illustrating the reliability of packet transmission over wireless medium. Average per-packet latency $\Delta\tau$ is defined as the duration between the time of generating a packet at sender vehicle and the time of successfully receiving that packet at receiver vehicle. Only successfully received packets are counted to calculate average per-packet latency.

These two network-level metrics serve an important role for network designers in verifying and debugging protocols and answering fundamental questions of the form: What dominates the performance of average per-packet latency $\Delta\tau$? What is the maximum back-off time experienced by the MAC for a given network density? How does $P_{net}(d)$ vary with distance under extreme network densities? However, these metrics are of limited utility from an application perspective, because performance requirements are typically given in terms of application-level metrics as opposed to packet-level metrics. For example, application reliability of SVA could be required to be above 99% for warning messages to be received within

1 second. An effort of examining the application performance, from application point of view, is lack in the current VANET community. Accordingly, the mapping function between safety application requirements and packet-level metrics is also lack in previous studies. This, in turn, suggests the need for a set of application-level metrics that can bridge the gap between network performance and application performance, directly relating to the aforementioned application requirements from automotive safety engineers' perspective. Next, we define two candidates of application-level metrics.

5.1.2 Application-level reliability metric

In event-driven safety applications, same safety messages are broadcasted several times when the safety event occurs; Similarly, different safety messages in the scheduled safety applications (containing the GPS and kinematics information of vehicles) are more likely to be correlated with each other. Thus, the safety applications are claimed as "reliable" as long as more than one of several safety messages are successfully received in a given duration. To capture this comprehension, we also introduce the concept of application-level reliability. *Application-level T-Window Reliability* (TWR) $P_{app}(d)$ is defined as the probability of successfully receiving at least one packet out of multiple packets from a broadcasting vehicle at distance d, within a given time interval T (we call this time interval T as application tolerance window) (Bai and Krishnan, 2006). This metric describes the application-level reliability for safety application, rather than reliability of wireless communication at packet level.

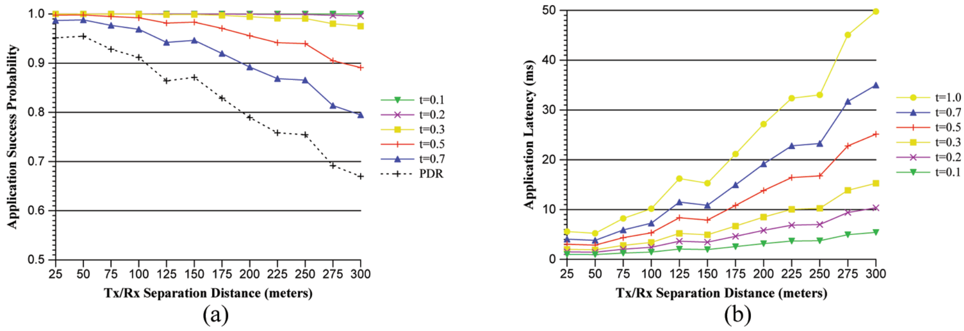
Using scheduled broadcast protocols as an example, we propose a simple model relating the application-level reliability with packet-level reliability. According to definition, application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet during tolerance time window T, at distance d. Since safety application periodically broadcasts its information with given fixed broadcast interval t, we know that application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet among M (here, $M = \frac{T}{t}$) consecutive packets. This, in turn, is equal to $1 - Pr$ (receiving no packet among M consecutive packet). Given the assumption that packet drops are independent, we know that Pr (receiving no packet among M consecutive packets) follows a binomial distribution with probability $P_{net}(d)$ and $n = 0$. Therefore, Pr (receiving no packet among M consecutive packets) $= (1 - P_{net}(d))^M$. By putting all the steps together, we obtain an analytical model linking application-level reliability to network-level reliability, as follow

$$P_{app}(d) = 1 - (1 - P_{net}(d))^M \quad (1)$$

$$= 1 - (1 - P_{net}(d))^{\frac{T}{t}} \quad (2)$$

Based on equation (2), safety application reliability $P_{app}(d)$ at distance d is a function of both wireless communication reliability $P_{net}(d)$ at distance d and the safety application re-broadcast interval t. Equation (2) can be readily used to map packet-level reliability to application-level reliability, providing us the freedom to use either metric in the application performance specification. As an intuitive example, both the network-level reliability[6] and the resultant application-level reliability, are presented in Figure 2(a) as a function of distance d between the transmitter and receiver. Shown are the results for varying broadcast interval t (seconds) for a constant application tolerance interval of $T = 1$ (seconds). Notice that the application reliability can be high even if the PDR is low as long as t is small compared to T. In this instance, $T/t \approx 3$ results in an application reliability of 97% for a 67% PDR. Also notice that network-level reliability, which is typically used by wireless networking designers, says nothing about whether the application performance is met or not. The simple mapping we have enables network research community to accurately account for application requirements and also allows automotive research community to evaluate the impact that wireless network reliability has on communication-based automotive applications.

Figure 2 Analytical results for the application-level reliability (a) and time-to-successful reception (b) metrics for broadcast-based applications, where the baseline packet delivery ratio P_{net} (shown in (a) as PDR) is empirically measured from real-world experiments: (a) Application reliability P_{app} for varying broadcast intervals t (sec) and tolerance interval $T = 1$ (sec) and (b) Application-perceived mean packet latency ΔT for varying broadcast intervals t (sec) and per-packet latency $\Delta\tau = 5$ (ms) (see online version for colours)



5.1.3 Application-level latency metric

Time-to-Successful Reception (TSR) ΔT is defined as the duration between the time when a broadcast packet is generated at application layer of transmitting vehicle and the time at which the first successful packet is received by the application layer of receiving vehicle (ElBatt et al., 2005). Notice that this measure becomes equal to the average per-packet latency $\Delta\tau$ discussed earlier if and only if there are no packet losses. In case of packet losses, this measure becomes larger due to the direct impact of successive packet collisions on this measure. This measure is directly related to safety application requirements through the following constraint

$$P(\Delta T \geq t_0) \leq \epsilon, \tag{3}$$

where t_0 is the maximal allowed value of time-to-successful reception for the given application and ϵ is arbitrarily small value (e.g., at the order of 10^{-3}).

Again, using scheduled broadcast protocols as an example, we are able to relate the network-level average per-packet latency $\Delta\tau$ and the application-level latency ΔT. For a given sequence of packet broadcasts P_i $(i = 1, 2, 3, \dots)$, with assumptions of independent packet losses, packet transmissions can be modelled as independent Bernoulli trials with probability of success P_{net} and probability of failure as $(1 - P_{net})$. Thus, the probability mass function (PMF) of Time-to-Successful Reception ΔT would be given as

$$f_{TSR}(\Delta T) = \begin{cases} \Delta\tau(P_1) & \text{w}/p = P_{net} \\ t + \Delta\tau(P_2) & \text{w}/p = P_{net}(1 - P_{net}) \\ 2t + \Delta\tau(P_3) & \text{w}/p = P_{net}(1 - P_{net})^2 \\ 3t + \Delta\tau(P_2) & \text{w}/p = P_{net}(1 - P_{net})^3 \\ . & . \\ . & . \\ (n-1)t + \Delta\tau(P_n) & \text{w}/p = P_{net}(1 - P_{net})^{(n-1)} \\ . & . \\ . & . \end{cases}$$

Assuming per-packet latency for different packets is the same (i.e., $\Delta\tau(P_1) = \Delta\tau(P_2) = \dots = \Delta\tau$), the above equation can be simplified as

$$f_{TSR}(\Delta T) = \begin{cases} \Delta\tau & \text{w}/p = P_{net} \\ t + \Delta\tau & \text{w}/p = P_{net}(1 - P_{net}) \\ 2t + \Delta\tau & \text{w}/p = P_{net}(1 - P_{net})^2 \\ 3t + \Delta\tau & \text{w}/p = P_{net}(1 - P_{net})^3 \\ . & . \\ . & . \\ (n-1)t + \Delta\tau & \text{w}/p = P_{net}(1 - P_{net})^{(n-1)} \\ . & . \\ . & . \end{cases}$$

Thus, the expected value of Time-to-Successful Reception can be calculated based on its PMF, as follow

$$E[\Delta T] = \sum_{i=1}^{\infty} (\Delta T(P_i) \times p(P_i)) \tag{4}$$

$$= \Delta\tau + t\left(\frac{1}{p_{net}} - 1\right) \tag{5}$$

Equation (5) reveals that application-level latency ΔT is a function of per-packet latency $\Delta\tau$, re-broadcast interval t and wireless communication reliability P_{net}. This way, we are also able to map the packet-level latency to the application-level latency, so that we can specify the latency requirement in either of them.

As another intuitive example, the application-perceived latency for varying broadcast intervals t (seconds) is presented in Figure 2(b) as a function of distance d between the transmitter and receiver. Here, $\Delta\tau = 5\,ms$. Again, we observed that application-level latency experienced by users is not solely determined by the network-level latency.

Interestingly, from Equations (2) and (5), we find that both application-level reliability and application-level latency are not only affected by wireless communication behaviour (e.g., network-level reliability P_{net} and network-level latency $\Delta\tau$), but also significantly affected by the communication-based automotive application parameter (i.e., broadcast interval t). Thus, by appropriately adjusting the automotive communication system parameters (such as broadcast interval t), we are still able to achieve the required application performance even under the scenarios where the wireless communication behaviour is not satisfactory.

In summary, we find out that reliability and latency (at both network-level and application-level) are the major metrics to capture the performance trends of broadcast-oriented safety applications (class 1 and 2). At the same time, we also realise that only packet-level reliability and latency metrics are relevant to user-initiated on-demand applications (class 3).

5.2 Performance metrics for on-demand message unicast-based applications (classes 4 and 5)

Different than safety applications where broadcasted messages are somehow correlated with each other, messages in convenience applications normally bear important pieces of information which are independent from each other. This is similar to many traditional Internet applications. Therefore, we believe that network-level metrics, such as packet delivery ratio and per-packet latency, are the most relevant metrics to capture the performance for these applications.

5.2.1 Network-level reliability metric

In most convenience applications, messages are uncorrelated with each other. Given this consideration, the packet-level reliability metric PDR not only captures the network-level reliability, but also accurately describes the application-level reliability. Hence, the network design should strive to deliver all transmitted packets successfully. Thus, we expect that the network-level reliability requirements of convenience applications are roughly at the same level as those of safety applications.

5.2.2 Network-level per-packet latency

With the same argument, we believe that network-level APL is the relevant metric for convenience applications, as compared to the application-level latency metric. For applications requiring secure routing (class 4) such as free-flow TOLL collection, the challenging part is that the entire process of the financial transaction (including handshaking, authentication and transaction) has to be completed over a short time period when the OBU, moving at, say, 70 mph, lies within the communication range of the RSU. This situation implicitly requires a very small network-level latency (e.g., a few hundred milliseconds) to successfully complete the financial transaction. Such a latency requirement is even more stringent than broadcast-based safety applications. Unsecured routing applications (class 5) do not enforce such strict latency requirements because the cumbersome handshaking mechanism for security is unnecessary.

From the above discussion, we realise that the packet-level latency and the network-level packet delivery ratio seem to capture the most important characteristics of convenience applications (class 4 and class 5).

5.3 Performance metrics for content download and streaming applications (classes 6 and 7)

Unlike the first five classes of applications, which rely highly on short message communication, content downloading and streaming applications provide efficient downloading and streaming of large data files. As a result, performance measures of these applications are focused on network-level metrics (such as packet-level packet delivery ratio and end-to-end latency) and application-level QoS metrics (such as end-to-end throughput and jitter).

5.3.1 Packet-level metric

Performance measures of Internet web-access applications also apply to file download applications (class 6, e.g. FTP or map database download). Generally speaking, this type of applications is delay-tolerant since it does not involve real-time communications. Hence, latency requirements are not considered for these applications. On the other hand, these applications are typically loss-sensitive, since packet loss may hinder the successful data transfer and thus damage the reconstructed data file. Therefore, we argue that packet-level metric such as PDR is the most important performance metric for file download applications.

On the contrary, media (video or VoIP) streaming applications are normally latency-sensitive but loss-tolerant. Thus, we argue that *End-to-End Latency* metric is the most important packet-level metric for such type of applications. End-to-end delay, in the traditional Internet literatures, captures the latency that VoIP or video streaming applications experience. Many factors, such as wireless propagation/transmission delay, encryption delay, filtering and other processing delay, contribute to application-level end-to-end delay. In fact, this metric is the APL metric defined in Section 5.1.

5.3.2 Application-level QoS metrics

Besides packet-level metrics like packet delivery ratio and end-to-end latency, application-level QoS metrics also play an important role in defining application performance trends for streaming applications (class 7). For example, media streaming applications use similar application-level performance measures developed for real-time media streaming over the Internet, including end-to-end throughput and end-to-end jitter. *End-to-End Jitter* (E2EJ) refers to the variance of delays for several consecutive packets arriving at the destination. For example, successive packets might suffer different delays, resulting in a choppy voice quality directly affecting quality of service. *End-to-End Throughput* (E2ET) illustrates the bandwidth that streaming applications enjoy, which also directly determines the quality of service for end users.

To summarise, PDR is the most important performance metric to capture the performance trend of delay-tolerant loss-sensitive contend downloading applications (class 6). However, for delay-sensitive loss-tolerant streaming applications (class 7), end-to-end delay, jitter and end-to-end throughput are the major three performance metrics to illustrate quality of service, among other metrics.

5.4 Summary

Based on the above discussion, we summarise the key performance metrics of our interests in Table 7. Clearly, both network- and application-level performance metrics play important roles in accurately capturing the performance of automotive communication applications: *Network-level metrics help to evaluate the performance of the wireless network. Application-level metrics, on the other hand, are used to evaluate the performance of the targeted applications which the end users would directly experience in their daily usage.*

Safety-oriented applications (class 1, 2 and 3) is of our special interests, because they have a great potential to provide real-time safety alerts and benefit the drivers. Here, we find that the network-level metrics include PDR and APL, while other metrics like T-Window Reliability (TWR) and Time-to-Successful Reception (TSR) fall into the category of application-level metrics. In addition, we also establish the relationship between network-level metrics and application- level metrics for safety-oriented applicatgions. Via such a linkage, we are able to translate the needs of the specific applications into the application-independent wireless networking performance measures.

6 Conclusion and future work

In this paper, we analyse the characteristics of various communication-based automotive applications in a systematic manner and classify them into several major *generic* classes. Such an application characterisation and classification effort facilitates the design and implementation of network protocol stack for these applications. In this study, we first propose a rich set of attributes of the applications, including both application characteristics and networking attributes, to better capture the properties of various applications. We then carefully investigate and analyse the attributes of 16 Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) applications. We realise that these applications can be categorised into three major classes: Short Message Broadcast type (for safety applications), On-demand Short Message Unicast type (for convenience applications) and Large-Volume Content Download/Streaming (for commercial applications). Finally, we present a list of performance metrics and QoS requirements for each type of applications, which are used to evaluate the performance trend of applications and network protocols.

The analysis of application characteristics and networking attributes, the classification of various vehicular communication applications and the identification of key performance metrics for each category of applications presented in this paper, shed some light on our future task of developing network protocol stack for various communication-based automotive applications. As the next step, we aim to continue our current effort of investigating the potential network solutions for these seven generic types of vehicle-related communication applications, with the consideration of re-usability of network protocol modules (or building blocks). To be specific, we would like to decompose the network protocol stack into a set of mechanistic building blocks for different types of applications, so that we are able to maximise the re-usability of common building blocks for various applications.

Table 7 Summary of performance metrics and QoS requirements

Metric Level	*Metric Name*	*Definition*	*Applied Classes*
Network	Packet Delivery Ratio (PDR)	The probability of succesfully receiving packets at a given distance from broadcasting vehicle.	1, 2, 3, 4, 5, 6
Network	Average Per-packet Latency (APL)	The duration between the time of sending a packet at sender vehicle and the time of receiving that packet at receiver vehicle, if that packet is successfully received.	1, 2, 3 4, 5, 7
Application	T-Window Reliability (TWR)	The probability of successfully receiving at least one packet out of multiple packets from a broadcasting vehicle at a given distance, within a given time interval T (T is tolerance window).	1, 2, 3
Application	Time-to-Successful Reception (TSR)	The duration between the time when a packet is generated at transmitting vehicle and the time when the first successful packet is received at receiving vehicle.	1, 2, 3
Application QoS	End-to-End Jitter (E2EJ)	The variance of per-packet latency for several consecutive packets arriving at the destination from the same source.	7
Application QoS	End-to-End Through-put (E2ET)	The maximal bandwidth of streaming applications can occupy over wireless channel.	7

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