ARTICLE IN PRESS

Computer Communications xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Reliability and energy-efficiency analysis of safety message broadcast in VANETs

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ARTICLE INFO

Keywords:
Vehicular ad hoc networks
Reliability
Flooding
Wireless networks
Routing
Energy-efficiency

ABSTRACT

Safety applications in vehicular ad hoc networks (VANETs) rely heavily on broadcast schemes for the exchange of status messages. Reliable and on-time delivery of safety messages is critical in VANETs that requires extremely efficient broadcast models. In this paper, we model the reliability of flooding used as the underlying data dissemination protocol for time-critical safety messages. We consider a multi-hop VANET and model end-to-end reliability provided by the network layer. The analytical results unleash important insights about the flooding mechanism. For instance, the reliability drops exponentially beyond a certain threshold value of packet loss probability. Secondly, the impact of hop length on reliability can be catastrophic if not handled appropriately. Keeping in view of the fact that energy-efficient protocols is a key requirement in the upcoming Internet of Vehicles (IoV), we also show that restrictive flooding is more energy-efficient than plain flooding under the same reliability constraint. We validate our theoretical findings through simulations and propose modifications to plain flooding to make it more reliable.

1. Introduction

With the increase in the demand of transportation mechanisms all over the world (railways, roads & air), the modern world is experiencing high density of vehicles on roads, more traffic jams and fatal road accidents. According to the official website of World Health Organization (WHO), approximately 1.2 million people die yearly as a result of road accidents, which is also the leading cause of death among young people, i.e., aged between 15 and 29 [1]. To this end, Intelligent Transportation Systems (ITS) is a viable option with the potential of providing novel services including traffic management, well-informed users/drivers, more coordinated and efficient use of transport networks. Although ITS generally refers to all modes of transport, according to EU Directive 2010/40/EU, it refers to the application of modern information & communication technologies to engineer road transport. Vehicular Ad hoc Networks (VANETs) is a critical component to realize the concept of such a modern ITS.

VANET is a special and possibly the largest class of Mobile Ad hoc Networks (MANETs). The movement of vehicles in a VANET is confined within the boundaries of traffic lanes/highways. Wireless Access for Vehicular Environment (WAVE) is a set of standards specifically developed for VANETs keeping in view of their unique requirements e.g., long range communications, high speed support etc. WAVE devices, On-Board Units (OBU) housed inside a vehicle and Road Side Units (RSU), contain a processor, read/write memory for information storage and retrieval, a user interface and a wireless device based on 802.11p standard [2]. In addition to this, OBUs are also linked to sensors for collecting, processing and sharing the information with other vehicles and RSUs. Furthermore, in addition to the normal 802.11p interface, RSUs usually have other types of communication interfaces connecting them to bigger networks e.g., Internet. This makes a range of services available to drivers, travelers and other components of ITS.

One critical service is the dissemination of safety/emergency messages e.g., vehicles collision/pre-crash warnings, hazardous location warnings, accident notifications. Most safety related applications require fast and reliable delivery of messages. Furthermore, the communication pattern in such cases is usually broadcast for two main reasons. First and foremost is the quick dissemination of warning/safety messages as stated earlier. The normal table lookup routing schemes for MANETs do not fit here [3]. Once an emergency situation happens, it is

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https://doi.org/10.1016/j.comcom.2018.01.006
Received 26 June 2017; Received in revised form 10 December 2017; Accepted 10 January 2018
0140-3664/

Please cite this article as: Sattar, S., Computer Communications (2018), https://doi.org/10.1016/j.comcom.2018.01.006

mandatory to disseminate the information as quickly as possible. The lifetime of a safety message should be less than 500 ms as drivers response time usually falls in the range of 700-800 ms. If the communication service fails to deliver a safety message within its lifetime, it is useless if drivers are expected to respond to the emergency situation. Second reason is the fact that the safety messages are of common interest to all the network nodes (vehicles and RSUs) [4]. It is also important to note that the reliability of a safety message delivery should not be less than 0.99. The broadcast of safety messages spans multiple hops and the analysis of such a multi-hop broadcast scheme is the focus of our work.

The reliability problem in VANETs has also been investigated previously [5,6]. However, all these models are based on Media Access Control (MAC) layer and analyze single hop reliability. On the contrary, we argue that a safety message broadcast is almost always expected to travel to destinations that are multi-hop apart before its lifetime expiry. To this end, we assume flooding as a possible routing mechanism to disseminate time-critical safety messages and model end-to-end reliability provided by the network layer. More specifically, we model V2V network as a set of nodes (vehicles) connected through WAVE links forming a backbone for message delivery. A vehicle, on the detection of an emergency situation, broadcasts an emergency message to its neighbors, which is subsequently flooded into the network in a multi-hop fashion. We model the probability that this message is successfully delivered, before the expiry of its lifetime, to all points in the network, the so-called *reliability* of message delivery. We evaluate the reliability of flooding a safety message against two important metrics; hop count (exhibits the network size) and packet loss probability (exhibiting the dynamic nature of the network).

Our analytical results show that, with an increase in the packet loss probability, which is a function of channel error rate, collision probability and the willingness of a node to participate in the message broadcast, the reliability decreases slowly in the initial stages. However, after a certain threshold value of loss probability, it decreases exponentially. This threshold is a function of average node degree i.e., the number of directly connected neighbors of a node. Higher node degree results in a lower value of threshold. However, as the network gets sparse, the threshold gets significantly higher. Our model also shows that this is caused by enhanced number of collisions and channel errors in the dense networks. We also observe that, for a given set of paths, the flooding reliability decreases rapidly as the hop count rises. This drop in reliability can be countered by increasing the number of paths connecting a source-destination pair. However, as argued earlier, its a tricky business as it can lead to more collisions.

Energy-efficiency is not much of a concern in current VANETs. The primary reason is the fact that 99% of the vehicles are gasoline cars with a built-in recharging mechanism. However, it is predicted that, within a decade or so, electric cars shall be in more widespread use [7]. This will make such a modern car a critical component of the next generation networks e.g., 5G/Internet of Things (IoT). The researchers have already started working on efficient algorithms to find a nearby charging station for electric cars [8]. Therefore, energy-efficient operation of the modern VANET/Internet of Vehicles (IoV) will become mandatory. Based on this forecast, in this paper, we investigate the impact of flooding a safety message on the energy consumption of the network. To be more specific, we compare the energy consumption of restricted flooding and the plain flooding keeping an eye on their attained level of reliability. Based on this and the aforementioned reliability analysis, we propose modifications to the flooding, applicable to both plain and restrictive versions, to improve their reliability.

We also perform simulations to validate our reliability models. We adapt two different techniques for this purpose. First, we simulate a simple VANET and investigate the impact of two metrics namely *packet delivery ratio* and the *vehicles speed* to compare them with the theoretical results. We notice that, as the number of vehicles in the area increases, the packet loss probability rises due to channel errors and collisions. We observe a similar trend in the analytical results. In the next phase, we compute the packet loss probability through experiments and feed it to our reliability model. The comparison shows that both empirical and theoretical values of packet delivery reliability have identical trends proving the validity of the model.

The rest of the paper is organized in the following manner. Section 2 briefly discusses background, the related work and the contribution of this article. Section 3 introduces the modeling assumptions and the key definitions along with the channel error and collision modeling. The reliability model is introduced in Section 4. Section 5 contains the empirical validation of the proposed models and discussion on analytical results to gain insights. Changes to conventional flooding process are proposed in Section 6. Section 7 concludes the paper with an outlook to our future work.

2. Background and related work

VANET, due to its tremendous potential to improve vehicle and road safety, has been investigated extensively in academia, industry and international standardization bodies e.g., IEEE, ASTM etc [9,10]. In this section, we first summarize all these efforts and discuss important concepts relevant to VANETs. In the next subsection, we describe the related work and explain the novelty of our work.

2.1. History & background

The history of Dedicated Short Range Communication (DSRC) dates back to early 1990s when US Federal Communication Commission (FCC), in the band of 5.9 GHz, allocated 75 MHz bandwidth for vehicular communications fueling the DSRC standardization process. In 2003, American Society for Testing & Material (ASTM) approved the first draft of ASTM-DSRC standard, published as ASTM E2213-03, which was based on two other existing standards; IEEE 802.11a for the physical layer and IEEE 802.11 for the MAC layer.

Apart from the fact that DSRC has regional versions, it was never enough to counter the challenges of VANETs e.g., high speed of vehicles, long range communication, reliability requirements of safety messages etc. Therefore, ASTM 2313 working group was merged with the IEEE 802.11 group in order to expedite the work on a more universally expected standard. Consequently, the efforts of IEEE 802.11 standard group resulted in IEEE 802.11p and other WAVE P1609.x series of standards in 2006 [11]. Since then, WAVE trial-use standards are under constant evolution process and the latest series was released in 2016. With reference to the standard TCP/IP protocol suite, WAVE devices use IEEE 802.11 & 802.11p physical layer and WAVE 1609.x MAC layer. While enhancements have also been made to the higher layers in 1609.x standards, for the standard functionality of networking and transport layers, WAVE makes use of the well-known protocols like IPv6, TCP/UDP (see Fig. 1). It is also worth mentioning here that WAVE/DSRC MAC layer is built on top of IEEE 802.11 and hence follow the same CSMA/CA scheme for channel access.

The WAVE 5.9 GHz spectrum is divided into a Control Channel (CCH) and multiple Service Channels (SCH). CCH is used for exchanging management, safety & emergency messages while SCH is used for commercial applications. One of the major enhancements made to the MAC layer in IEEE 1609.x standards is the multi-channel operation of WAVE devices. In this perspective, WAVE/DSRC devices, OBUs & RSUs, may be single channel or multi-channel. Single channel devices listen to one channel at a time that may be CCH or a SCH [11]. Synchronization issues between single & multi-channel devices is achieved through monitoring of CCH at regular intervals.

2.2. Related work

2.2.1. Safety message dissemination

Safety message dissemination in VANETs has been addressed in