Information Freshness for Vehicles Communications of Safety-critical Vulnerable Road Users

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Abstract. Information freshness is an indicator of the timing of a status update which is of utmost significance for many real-time applications, such as connected vehicles, autonomous vehicles, and sensor networks. The age of information (AoI) metric is useful for quantifying the information freshness for messages delivered to the entities concerned. In this paper, we averaged the peak AoI (PAoI) over time for each vulnerable road user (VRU) in the network with a proposed algorithm namely, priority-based push-out last-generated first-served (PPLGFS) strategy, for safety-critical usage cases to address the issue of maintaining timely VRU status updates across all nearby connected vehicles. A multi-VRU system that supports the cellular network is assumed in which status updates arrive and should be transmitted over the network to the intended vehicle. We model the worst-case information freshness (i.e., PAoI) for VRU-destination vehicle links, using a queuing model with the proposed algorithm to manage the packets on arrival. It gives priority messages which have arrived recently, and blocks stale packets to avoid wasting network resources for the transmission of old information. Results show that the proposed algorithm used with PAoI gradually achieves a better performance than other queuing models as the packets arrival rate increases. Besides, it also enhances the maintenance of timely VRU status updates in the intended vehicle.

1. Introduction

The emerging vehicular networks can establish cooperative safety communications between various entities on the road, which provides access to vehicles on the roads, and bring numerous benefits such as driving safety, driving intelligence, and road efficiency [1]. It can guarantee the safe interaction between the vehicles and vulnerable road users (VRUs) such as motorbikes, pedestrians and cyclists, through the exchange of periodic cooperative awareness message (CAM) [2]. CAM is a kind of periodically shared message in the intelligent transportation system and in general, the information found in this type of message is related to the status (e.g., location, speed, time, etc.) and to the characteristics (e.g., type of the vehicle, dimensions, etc.) of a vehicle [3]. This includes continuous updates of information about the real-time state of a given VRU and its intended vehicle cluster [4]. To identify the timeliness of the updates, a metric, i.e., the age of the information (AoI) at time t is defined as \( \Delta(t) = t - U(t) \) [5], where \( U(t) \) is the time when the freshest status update was generated at the destination. A number of recent studies concentrate on characterizing the average age of different strategies and decreasing the AoI in single-hop networks [5]–[8]. In [5], [7], the first-come first-served (FCFS) information-update strategy was proposed, and the update generation rate was optimized to increase data freshness. These studies can reduce the update generation rate to optimize the AoI and it can reduce the effect of queuing delay for improving data freshness. When the timely updates is not negligible, controlling the packets in a network can achieve a lower AoI than other strategies, starting from the last-come-first-served (LCFS) strategy in [9], to more generally the
AoI of multihop networks have been studied recently, using the last-generated first-served (LGFS) strategy in which the last update packet is served first and it has been shown (nearly) optimal for minimizing the AoI [10]. In [11], the authors proposed an analytical model in order to evaluate the AoI of a vehicular ad hoc network (VANET) where the results showed that the model estimate how the average AoI changes with the transmitting frequency of the beacon, which is related to the density of the vehicles. In [12], the authors minimized the latency in the end-to-end (E2E) scenario by multi-access edge computing (MEC). MEC can eliminate the round-trip propagation delay, which is another essential component that contributes to reducing the latency, but also not enough for timely services [13]. In particular, the vehicular network needs to manage congestion and information updates. Inspired by these gaps, this paper proposes an algorithm, namely, priority-based push-out last-generated first-served (PPLGFS) strategy, which depends on the scenario that the last update message is received first in the intended vehicle and does not necessarily arrive in the same order according to their generation times. Besides, it also enhances timely updates by pushing out the stale information and gives priority messages which have recently arrived. The objectives of this work are summarized as follows:

a) We estimate the AoI for the VRU related to a system which consists of numbers of VRU, vehicles, road side unit (RSU) and MEC aggregated to the radio access network (RAN).

b) We model the worst-case information freshness i.e., PAoI, and proposed a priority-based push-out last-generated first-served (PPLGFS) strategy, taking VRU as an example for safety-critical usage cases and focusing on a specific road segment under the coverage of the RSU.

c) We analyze and investigate the effect of increasing the VRU packets (CAM messages) in relation to the PAoI of inter-arrival time information.

![Figure 1. Freeway scenario of vehicles communication for VRUs](image)

### 2. System Model

Under the coverage of the RSU collocated with a MEC host which provides processing capabilities, we assume a freeway road environment with one lane per direction, as shown in Figure 1. Each of the existing VRUs sends out messages periodically to inform about its type, position, direction of movement, speed, and other information. In the periodically transmitted VRU messages, the VRU notification information is intended to alert the drivers of approaching distance between vehicles and the VRUs on the road. The inter-arrival time of generated VRU messages can significantly affect the overall system timeliness by changing the AoI. The timeliness of VRU messages received by nearby vehicles need to be controlled and improved to guarantee a real time VRU awareness across the vehicles. The critical challenge is how to maintain timely VRU status updates across all nearby connected vehicles [14]. Let $P_k(t)$ denote the message generation time for the number of VRU; then, the AoI at the $(t + 1)$, denoted by $\Delta_k(t + 1)$, is defined recursively as follows:

$$
\Delta_k(t + 1) = \begin{cases} 
\Delta_k(t) + 1; & \text{if status update is not received} \\
 t - P_k(t) + 1; & \text{otherwise.}
\end{cases}
$$

(1)
Here, we study the transmission of status update messages using a queuing system that can block some old information that have been generated, as shown in Figure 2. For this system model, we assume Poisson packet arrivals with rate $\lambda$ and exponentially distributed service times with rate $\mu$. The supported queuing model contains a single server. We are interested in characterizing the timeliness of the information available about the $P_k(t)$ process in the vehicle destination. We represent the random process of interest $P_k(t)$, which is observed in various time instants $t_k, k = 1, 2, \ldots$, as a packet containing $\{P_k(t), t_k\}$. Each observation becomes available immediately to the VRU source node.

Depending on the need for information to be fresh in the intended vehicle for safety-critical usage cases, it is necessary to distinguish the maximum value of the AoI, immediately before receiving the update. Here we explicitly express the peak age of information (PAoI) as a function of the update rate $\lambda$. The PAoI metric was first considered in [8] for the M/M/1/2 queue:

$$PAoI_{M/M/1/2} = \frac{3}{\mu} + \frac{1}{\lambda} - \frac{2}{\lambda + \mu}$$

(2)

where $\mu$ is the service time and $\lambda$ is the arrival rate of the transmitted packet. Figure 3 shows how the AoI evolves linearly over time until a new VRU message is successfully received by the intended vehicle. In this work, we focus on a specific VRU, thus we consider PAoI, which is defined as the AoI that is observed on the target vehicle achieved immediately before this vehicle receives a new VRU message [7]. Since the PAoI can provide guaranteed system performance, we consider that as an important metric for the VRU scenario investigated. Mathematically, when PAoI is averaged over time, the PAoI of the number of VRU can be written as follows:

$$\Delta^P_k = E_{t} \{T_{k-1} + D_k\}$$

(3)

where $D_k$ is the inter-arrival time between consecutive VRU messages and $T_{k-1}$ is the transmission time of a given VRU message which is successfully transmitted to the vehicle. Finally, according to
the periodic messages of the VRU identified in eq. (3), the PAoI, averaged over all $K$ VRUs in the network is evaluated as:

$$\bar{\Delta}_k^P = E\{\Delta_k^P\} = \frac{1}{K} \sum_{i=1}^{K} (T_{k-1} + D_k)$$  (4)

3. Optimizing Timely Update Via Priority Based Push-Out Last-Generated First-Served Strategy

We use a LGFS strategy that the CAM messages generate the freshest among all the CAM messages in the queue and use a priority in the case of updating the information. Which means the server is always running the message that arrived recently. Besides, it also uses a push-out strategy to avoid the transmission of old information as shown in Figure 4. The implementation details of a priority-based push-out LGFS strategy is explained in Algorithm 1.

4. Simulation Results

In this section, we illustrate the results of the numerically evaluated PAoI for each VRU in the network with the proposed algorithm and compare the algorithm with other queuing models. We provide a simulation scenario whereby a main system parameter is varying, namely the VRU packet rates. Because of the periodic nature of generating VRU CAM messages, each VRU user equipment is set to send its packet, on average every $8$ millisecond. In this simulation, we consider a LTE cellular network with a bandwidth of 10 MHz, where the total number of available physical resource blocks...
(PRBs) is shared equally among the VRUs transmitted at the same time index, so in this scenario, the number of PRBs is equal to 50 and the service time is one millisecond. Table 1 shows the values of all parameters involved, and the number of packets arrivals for VRU with server utilization is presented in Table 2.

Table 1. Simulation Parameters

| Parameter    | Value  |
|--------------|--------|
| Bandwidth    | 10 MHz |
| Number of PRBs | 50    |
| Service time | 1 ms   |
| Tx power     | 46 dBm |
| Frequency    | 5.9 MHz|
| Inter-vehicle distance | 10 m |
| Vehicle/meter | 0.01  |
| Tx power for VRU | 23 dBm|
| Number of lanes | 2     |

Table 2. An Illustration of Change of Packets Arrivals (For VRUs) With Server Utilization

| Number of Packets for VRUs | Server Utilization $p = \lambda / \mu$ |
|----------------------------|--------------------------------------|
| 10                         | 0.2                                  |
| 20                         | 0.4                                  |
| 30                         | 0.6                                  |
| 40                         | 0.8                                  |
| 50                         | 1.0                                  |

Figure 6 shows the network-wide PAoI performance for the number of VRUs by using queuing model with the proposed algorithm, which is compared to the FCFS queuing models with M/M/1/1, M/M/1/2, and the M/M/1/2 with packet replacement analyzed in [8]. We observe that the PAoI for the number of VRUs in the network is gradually decreasing for all queuing models. For a small arrival rate i.e., number of VRUs < 20 the other queuing models perform better than the proposed algorithm. This is due to keeping the old packet in a buffer is preferable in the case of small packets arrival rates. The proposed algorithm achieves the better PAoI than the other queuing models, especially for the number of VRUs > 20.

Figure 6. PAoI with increasing number of VRUs in the network comparing the results of the proposed algorithm with other FCFS queuing models.
Figure 7. PAoI with increasing number of VRUs in the network comparing the results of the proposed algorithm with FCFS, LCFS queuing models, and the preemptive LGFS

Figure 7 shows a comparison of the PAoI with respect to the number of VRUs by comparing the proposed algorithm with $M/M/1$ LCFS queuing model, $M/M/1$ FCFS queuing model, and the preemptive LGFS. The PAoI for the FCFS queuing model with $M/M/1$, where all packets arrivals find the server busy are saved in the queue for later transmission. This queuing model was calculated theoretically in [7], then presented and analyzed in [15]. For a small arrival rate i.e., number of VRUs < 20, the $M/M/1$ LCFS queuing model and $M/M/1$ FCFS queuing model perform better than preemptive LGFS and the proposed algorithm because they do not work for a large part of the time. As the number of VRUs increases, the PAoI of the FCFS queuing model approaches infinity as a result of the increase in arrival rate. This is a result of network congestion, which leads to the delivery of old packets while the proposed algorithm with queuing model greatly enhances the PAoI, especially for the number of VRUs > 20. The preemptive LGFS and the proposed algorithm have nearly identical behaviors and the proposed algorithm achieves the better PAoI for the number of VRUs ≥ 45. This is due to the continues pushing out the stale packets in the queue which enhances the PAoI for large arrival rates.

5. Conclusion

In this paper, we consider the issue of maintaining the status updated generated by VRU as fresh as possible at the intended vehicle. With the goal of managing the packets on arrival to avoid stale information which wastes network resources and reduces the impact of queuing delay on information freshness, we averaged the PAoI over time for the number of VRU with the proposed algorithm that helps to enhance the system abstracted in the queue model, where the packets of VRU arrives following a Poisson process. By means of simulation results, compared with other queuing models, it can be observed that the proposed algorithm provides improvements to the PAoI metric with guarantees that the information available at the intended vehicle remains fresh at any time.

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