Dynamic Priority Scheduling Mechanism Based on Spatio-Temporal Correlation for VANETs

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***Abstract*—A dynamic priority scheduling scheme is conceived for the safety messages of vehicular ad-hoc networks (VANETs). The priority of a message is dynamically adjusted for satisfying the specific VANETs safety requirements. A spatio-temporal correlation function based on the message-priority is developed, which monotonically decreases as the transmission range and the transmission duration increasing. Additionally, the spreading of a message is limited to the dynamic life-span and spatial area. Our simulations demonstrate that the proposed scheduling scheme is capable of significantly reducing the network's duplicated tele-traffic when the vehicular density is high, whilst improving the achievable transmission range in the low vehicular density.**

***Keywords*: VANETs, spatio-temporal correlation, dynamic priority scheduling.**

I. Introduction

In vehicular ad-hoc networks (VANETs), safety-related applications such as congestion avoidance and accident warning have recently attracted the attention of both researchers as well as the automotive industries and governments owing to their potential of improving the driver's awareness of the surrounding environment [1]. The scheduling of safety-related messages is a challenge owing to the rapid dynamic variations in the VANETs' topology, as well as the spatio-temporal sensitivity of safety-related messages [2][3]. A practical scheduling mechanism not only meets the actual security needs of vehicle users, but also must adapt to the dynamic network topology under different traffic density to reduce the network load.

The priority-based scheduling of VANETs was addressed in [4][5][6], relying on service differentiation, where the message priority was fixed throughout the entire message dissemination despite the fact that the urgency of a message drops as the distance from the source or the time from its origination increases. A cross-layer based message priority-reliant scheduling scheme was conceived in [7], where several measures were conceived for the priority-based handling of different types of messages. Since higher-priority messages are always transmitted before the lower-priority ones, the above schemes are not suitable for the scheduling of safety messages, since the urgency of the same safety-message is different for vehicles at different locations and time instants. A jamming-based media access control (MAC) protocol relying on dynamic priority adjustments was proposed in [8] for supporting multimedia services in ad-hoc networks, but it did not consider the specific safety aspects of a vehicle.

Furthermore, the spreading of messages across the VANETs only slowly adapts to the network's dynamic topology changes [9][10][11]. Due to the sparsity of vehicles in low vehicular density scenarios, the messages may have to be stored for a long time before finding the next hop. If the message-expiry delay threshold is set excessively low, the messages cannot be spread sufficiently widely before its validity expires. By contrast, if it is set too high in high vehicular density scenarios, the messages will spread so widely that they exceed the useful scope of influence for safety-critical events, thus unnecessarily delay-urgent messages destined for less distant vehicles.

Given the paucity of solutions, we propose a new dynamic priority scheduling scheme for transmission of safety-critical messages in VANETs, which is both delay-sensitive as well as distance-sensitive. The main contributions of this paper are outlined as follows:

- A spatio-temporal correlation function is designed for characterizing the message-urgency. The priority of safety-critical messages is adjusted, which decreases as the transmission range and the transmission duration increasing.
- Besides, the spreading of each safety message is limited to the dynamic life-span and spatial area.

When multiple messages are stored in a vehicle's buffer for transmission, their priorities are computed and the vehicle transmits the most urgent one subject to its own metric, thus matching the requirements of safety-critical applications. We limit both the message-spreading life-span and the spreading range by adapting to different vehicular densities, which taking into account the prevalent requirements.

The remainder of this paper is organized as follows. The system model is given in Section II. The new dynamic-priority based scheme is outlined in Section III, followed by its performance characterization in Section IV. Our conclusions are provided in Section V.

II. System Model

Safety-critical messages are characterized by their spatio-temporal relevance [12]. In this contribution, the following spatio-temporal correlation function is invoked for dynamically characterizing the relevant message priorities as

$$\left\{ \begin{array}{l} f = \alpha f_1(\Delta t) + \beta f_2(d) + \phi, (\alpha \leq 0, \beta \leq 0), \\ \Delta t = t_r - t_s, \\ d = \sqrt{(x_r - x_s)^2 + (y_r - y_s)^2}, \end{array} \right. \tag{1}$$

where $f_1(\Delta t)$ and $f_2(d)$ are monotonically increasing functions of Δt and d, respectively, with Δt and d being the time-elapse and the distance from the source of the message to the receiving vehicle, (x_s, y_s) denotes the position of the source, t_s is the time-instant of the source-message generation. Furthermore, (x_r, y_r) is the position of the receiving vehicle, t_r is the instant of receiving the message, α and β are non-positive constants that represent the decay factors of time and distance respectively, and finally ϕ is the initial priority of a message, which is determined by the significance of the event itself.

Different safety-critical messages have different sensitivity to the factors of time and distance. For example, we may set $f_1(\Delta t) = \Delta t^2$ or $2\Delta t$+1, and $f_2(d) = \sqrt{d}$ or d, respectively. In this contribution, we let $f_1(\Delta t) = \Delta t$ and $f_2(d) = d$. Note that the function f is commensurate with the transmission duration and distance, thus it may also be used for characterizing the dynamic priority of the messages. The design of both ϕ and the ratio α/β will be considered in the following subsection.

III. Dynamic Priority-Reliant Scheduling

A. Spreading Boundary

Each message has its own range of influence and useful life-span. For example, no vehicle cares whether the vehicles 10 km away are accelerating, braking or changing lane. Even though these messages are safety-critical in their immediate vicinity. In order to avoid wasting communication resources, it is natural to limit the spreading of messages within the actual scope of influence of the event. Even if its useful life-span has not as yet expired, and vice versa.

The topology of VANETs is dynamic and asymmetric in different regions and time slots, such as in urban or suburban scenarios and during the day or night. The message delay imposed by a single hop is defined as

$$b = b_{1h} + b_w, \tag{2}$$

where b_{1h} includes both the transmission and the queueing delay. b_w represents the delay imposed by seeking the next hop when there are no other vehicles within its range of communication. When the vehicular density is high, it may be easy to find the next hop, hence b_w may become negligible. By contrast, when the vehicular density is low, b_w may be high, since the relay node may require a long time to find the next hop.

If the message-expiry delay threshold is set excessively low, the message cannot be spread sufficiently far. Especially, when the vehicular density is low, the tight delay budget may become exhausted within a few hops. By contrast, if the message-expiry delay threshold is set too high for the high vehicular density encountered, the message will be spread too widely, which goes beyond the actual scope of influence for the event and hence wastes the limited communication resources available.

We denote the initial bounded life-span and spreading range by Δt_{th} and d_{th}, respectively. Then, the initial priority ϕ may be defined as

$$\phi \triangleq -\alpha \Delta t_{th} - \beta d_{th}. \tag{3}$$

By substituting (3) into (1), we arrive at

$$f = \alpha \Delta t + \beta d - \alpha \Delta t_{th} - \beta d_{th}. \tag{4}$$

When the priority function f satisfies $f \leq 0$, the message forwarding is curtailed. We note that the life-span of a message denotes the resultant time-duration of its continuous spreading before satisfying $f \leq 0$.

For further analysis, we set $f = 0$ and thus obtain the dynamic bounds of the tolerable transmission delay and distance $(\mathcal{T}, \mathcal{D})$, respectively as

$$\mathcal{T} \triangleq \Delta t_{th} + \frac{\beta}{\alpha}(d_{th} - d), \tag{5}$$

$$\mathcal{D} \triangleq d_{th} + \frac{\alpha}{\beta}(\Delta t_{th} - \Delta t). \tag{6}$$

Since a message usually cannot be spread all the way to the spatial bound d_{th} in the low vehicular density scenarios, typically we have $d < d_{th}$. By substituting $d < d_{th}$ into (5), we arrive at

$$\mathcal{T} \geq \Delta t_{th}. \tag{7}$$

This implies that the adoption of our scheme will result in an extended useful life-span for message dissemination in the low vehicular density scenarios. The worst situation associated with $d = 0$ leads to the maximum delay of $\mathcal{T}_{max} \triangleq \Delta t_{th} + \frac{\beta}{\alpha} d_{th}$. Hence, we have to set $\mathcal{T} \leq \mathcal{T}_{max}$.

In the same way, since a message may spread beyond its useful scope influence d_{th} in the high vehicular density scenario, we may have $d > d_{th}$. By substituting $d > d_{th}$ into (5), we obtain

$$\mathcal{T} \leq \Delta t_{th}, \tag{8}$$

which implies that the excessive spatial spread of messages may be prevented by reducing their useful life-span for $d > d_{th}$.

In the extreme case of substituting $\Delta t = 0$ into (6), the maximum transmission distance becomes

$$\mathcal{D}_{max} = d_{th} + \frac{\alpha}{\beta} \Delta t_{th}, \tag{9}$$

there is a discrepancy of $\frac{\alpha}{\beta} \Delta t_{th}$ between $\mathcal{D}_{max}$ and d_{th}, which may be narrowed by adjusting the ratio of α/β.

The frame size of safety-critical messages is typically small, hence b_{1h} in (2) is typically expressed in milliseconds or microseconds. Additionally, b_w is typically in seconds in the low vehicular density scenarios. Hence, Δt_{th} should be set in terms of seconds. However, when the vehicular density becomes high, b_w may be ignored and then b is on the order of milliseconds or microseconds. Now, if the above-mentioned Δt_{th} value is fixed, having too many hops during the message dissemination leads to excessive spatial spreading. Hence, for the conventional fixed-priority based scheme using Δt_{th}, the maximum transmission distance is likely to exceed $\mathcal{D}_{max}$.

B. Validity of Dynamic Priority-Reliant Scheduling

According to (5), when the message fails to propagate to its actual influence range $d<d_{th}$, the delay $\mathcal{T}$ is $\frac{\beta}{\alpha}(d_{th}-d)$ greater than Δt_{th}. Compared with the mechanism of fixed delay, the increase of propagation distance is at the cost of increasing delay. On the contrary, when the propagation distance exceeds the influence range $d>d_{th}$, the delay $\mathcal{T}$ is $\frac{\beta}{\alpha}(d_{th}-d)$ smaller than Δt_{th}. By substituting it into (6), it can be seen that the propagation range of the mechanism proposed in this paper is smaller than that of the mechanism with fixed delay. In other words, the propagation distance is limited by reducing the delay.

Therefore, we set up a function to evaluate the effectiveness of the transformation between $\mathcal{T}$ and $\mathcal{D}$.

$$\mathcal{F} = \log_2 |\mathcal{D} - d_{th}| \times \mathcal{T}. \tag{10}$$

As shown in (10), the smaller $\mathcal{F}$ is, the higher the effectiveness is. That is to say, the closer the propagation distance $\mathcal{D}$ is to d_{th}, as well as the smaller the time $\mathcal{T}$ is, the higher the effectiveness is.

C. Safety-critical Message Scheduling

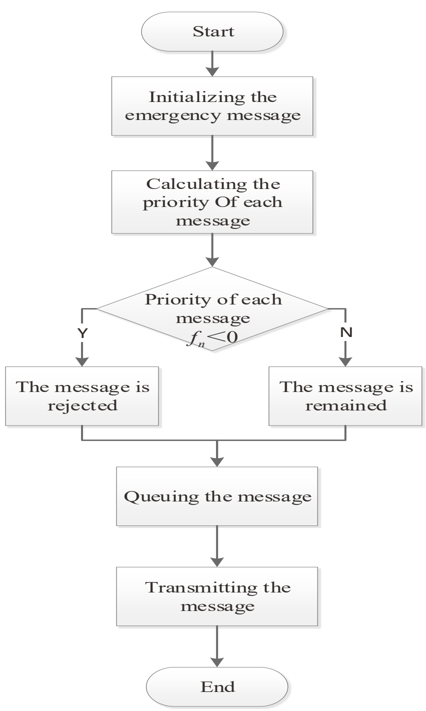

Fig. 1. The dynamic priority scheduling mechanism.

If the message priority function obeys the inequality $f \leq 0$, the message becomes useless and will be dropped. Otherwise, it will be queued up for transmission. Let us assume that there are N emergency messages $\{m_1, \cdots, m_N\}$ waiting for transmission in a vehicle's buffer, with each being defined as $m_n = \{\alpha_n, \beta_n, \phi_n, x_{s(n)}, y_{s(n)}, t_{s(n)}\}$. The vehicle will compute the message-priorities and queue them in a descending order. Then it schedules the most urgent one for transmission. Fig. 1 shows the dynamic priority scheduling mechanism based on spatio-temporal correlation for VANETs. The exact details of the dynamic priority based scheduling algorithm are outlined in **Algorithm 1**.

Algorithm 1: Dynamic Priority Based Scheduling

$\forall m_n \in \{m_1, \cdots, m_N\}$
for ($n = 1$ to N):
    $f_n = \alpha_n (t_r - t_{s(n)}) + \beta_n \sqrt{(x_r - x_{s(n)})^2 + (y_r - y_{s(n)})^2} + \phi_n$
    if ($f_n \leq 0$)
        drop the message n
    else
        queue f_n in descending order
    end if
end for
transmit messages from queue

The specific steps are given as follows.

Step 1: Initializing the emergency messages $\{m_1, \cdots, m_N\}$, and $m_n = \{\alpha_n, \beta_n, \phi_n, x_{s(n)}, y_{s(n)}, t_{s(n)}\}$.

Step 2: The receiving vehicle calculates the priority of each message f_n based on its basic properties.

Step 3: If the priority function of the message is less than zero, the message is rejected;If not, proceed to Step 4.

Step 4: Queuing messages in order of priority from largest to smallest.

Step 5: All vehicles transmit messages in turn.

IV. Performance Results

We considered three different types of security messages: braking warning (BW), traffic violation (TV) and traffic accident (TA). We set the maximum communicating distance between any two hops as 300 m, the transmission rate as 2 MB/s and the frame size of each message as 10 KB. The vehicles run on a 12 km long and 30 m wide highway at the same speed, which has two running directions with two parallel routes in each direction. When the vehicular densities is $10-100$, $100-200$, $200-300$, and $300-500$ vehicles/km^2, the vehicular speed is corresponding to 30, 20, 10 and 5 m/s respectively. At $t = 0$, all vehicles start moving and randomly generate a safety message from the three types of messages in Table I. No new messages are generated until the end of a message's lifetime.

TABLE I
Message Parameters

VANET Application	d_{th}	Δt_{th}	α	β	ϕ
Braking Warning (BW)	300m	3s	-150	-2.5	1200
Traffic Violation (TV)	1km	6s	-60	-0.6	960
Traffic Accident (TA)	3km	12s	-10	-0.1	420

The averaged life-span versus the vehicular density is shown in Fig. 2. For each type of messages, the life-span of the proposed scheme monotonically decreases with the vehicular density. In contrast to the fixed life-span Δt_{th} of the fixed-priority based scheme, as expected, the life-span of the proposed scheme is higher in low vehicular density, while it becomes lower in high vehicular density. It implies that the adoption of our scheme will relax the delay constraints of the message spread in low vehicular density, while tightening the constraints for shortening the life-span in high vehicular density.

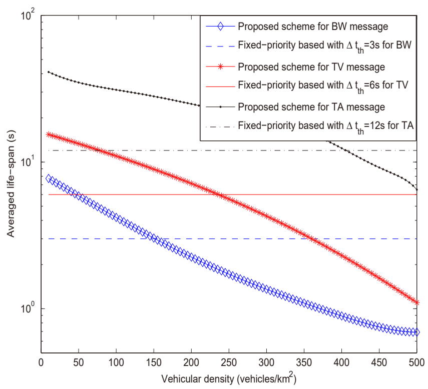

Fig. 2. Delay vs. vehicular density

Fig. 3 depicts the averaged spreading range versus the vehicular density. For each type of messages, the proposed scheme has the higher spreading range than the fixed-priority based scheme in low vehicular density. As the vehicular density increases, the spreading range of the proposed scheme merely approaches to the bound $\mathcal{D}_{max}$, whereas the spreading range of fixed-priority based scheme greatly exceeds $\mathcal{D}_{max}$.

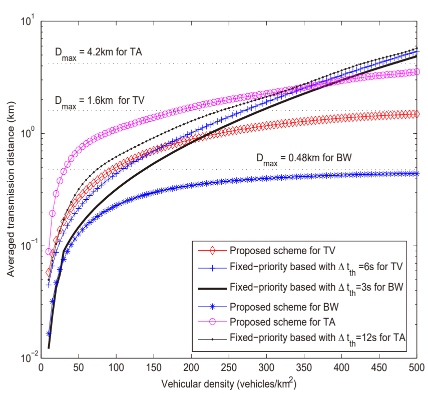

Fig. 3. Transmission distance vs. vehicular density

During the message spread, the process of the vehicle's store-and-forward duplicates the messages and thus generates a great of network traffic. The averaged generated-traffic versus the vehicular-density is illustrated in Fig. 4, where all types of messages are considered and are randomly generated. As expected, the averaged generated-traffic increases monotonically with the vehicular density, simply because more vehicles lead to more opportunities of the message-duplication regardless of the scheduling scheme used. The network traffic generated in the proposed scheme is more than that of the fixed-priority based scheme in low vehicular-density scenarios, whereas the situation is reversed for high vehicular-density regions. This phenomena may be explained by observing in Fig. 3 that the proposed scheme extends the message spreading range in low vehicular-density scenarios, given more life-spans as observed in Fig. 2, whereas in high vehicular-density scenarios the spreading range is constrained by shortening the life-spans.

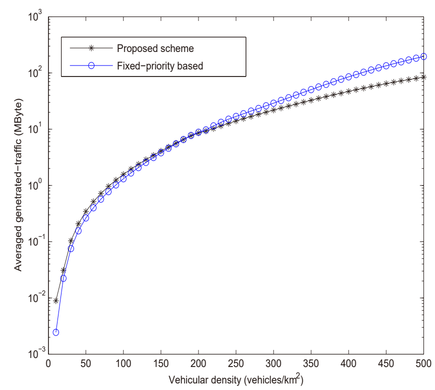

Fig. 4. Network load vs. vehicular density

V. Conclusions

A spatio-temporal correlated dynamic-priority based scheduling scheme is proposed for the safety messages of VANETs. We develope the spatio-temporal correlation function for characterizing the dynamic of the message-urgency and we also limit the spreading of a message to a dynamic life-span and spreading range. It demonstrates that the dynamic-priority based scheduling is more suitable for safety-critical messages than the fixed-priority based scheme, thus meeting the users' actual safety requirements better.

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