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Age of Information Modeling and Optimization for Fast Information Dissemination in Vehicular Social Networks

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***Abstract*—Autonomous vehicles (AVs) with advanced communication, computing, and control capabilities will provide not only a convenient means of transportation but also an emerging platform for real-time social communications and networking. Thereby, it is crucial to enable timely exchange of information over the dynamic cyber-physical-social system enabled by the AVs. In this paper, we consider age of information (AoI)-centric real-time information dissemination over vehicular social networks (VSNs), where the AoI captures the *freshness* of received data packets. We first propose a mathematical framework based on the mean-field theory (MFT) to analyze the network AoI (NAoI) of VSNs, namely AoI for the AV that lastly receives the information update in the network. The proposed analytical framework considers both the social features of vehicular networks, which are characterized using the scale-free network theory, and the underlying wireless communication process to evaluate the NAoI. Then, we further consider joint optimization of the information update rate at the source node and the transmit probabilities at the AVs for minimization of the average peak NAoI (PNAoI), i.e., the time average of peak values occurred in the evolution of the NAoI, which is solved via a novel parametric optimization scheme. Both analytical and simulation results show that compared with several baseline schemes, the proposed scheme can exploit the scale-free feature of the VSNs to significantly lower the average PNAoI by up to 96$\%$.**

***Index Terms*—Age of information (AoI), vehicular social networks (VSNs), scale-free network theory, autonomous vehicles (AVs), information dissemination, mean-field theory (MFT).**

I. Introduction

Thanks to advances in mobile communications, mobile sensing, and autonomous driving technologies, the vehicular networks are evolving towards a smart cyber-physical-social system [1], [2]. It is expected that future autonomous vehicles (AVs) will enable not only reliable connected driving control [3], [4], but also versatile social communications such as information and content sharing among passengers and human drivers [5]. For the latter communication paradigm, social relations/ties among onboard humans can significantly impact the information dissemination process in vehicular networks. For example, AVs may prefer to communicate and exchange information with other AVs that share close social connections [6]. However, how to exploit existing social relations to improve the performance of vehicular networks has been a new research challenge.

Recently, vehicular social networks (VSNs) have been proposed to study the interplay between social connections and vehicular communications. In VSNs, infotainment (such as news and weather conditions) and on-road context information about e.g. the status of road traffic and traffic lights are shared with drivers and passengers for enhanced travel experience. Meanwhile, such information exchange among AVs can also be exploited to satisfy the social and communication needs of humans onboard the AVs. However, as the contents of the aforementioned services vary constantly over time, timely updating and dissemination of these contents are crucial to ensure that information received at the AVs is always fresh. Otherwise, staleness in information update will diminish the value of the information, particularly when the vehicular network topology dynamically varies and the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links become intermittent. To improve the timeliness of information dissemination in VSNs, in this paper, we consider i) characterizing the impact of social relations on real-time dissemination of information updates in VSNs and ii) designing efficient information update and communication schemes that can exploit existing social relations to achieve real-time information dissemination.

To evaluate the timeliness of information dissemination in VSNs, we consider a new performance metric, namely *age of information (AoI)*, or simply *age*, which is defined as the time elapsed since the freshest received packet was generated till the current time [7], [8]. Appealingly, AoI captures not only the latency/delay of information transmission but also the inter-delivery time of information updates. Meanwhile, AoI has been widely adopted for real-time applications in vehicular networks [9]–[12], other than in VSNs. In [9], Ni *et al.* investigated the AoI of vehicular beacon broadcasting, where a low-complexity greedy algorithm was proposed to minimize the expected sum AoI while mitigating collisions during beacon broadcasting. To facilitate ultra-reliable low-latency V2V communications, the authors of [10] formulated a transmit power minimization problem subject to probabilistic AoI constraints, which is built on the extreme value theory and further solved using Lyapunov optimization. In [11],

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TABLE I
SUMMARY OF THE STATE-OF-THE-ART SCHEMES IN THE LITERATURE

Reference	Research problem	Methodology	Advantages	Limitations
[9]	Vehicular beacon broadcast scheduling optimization subject to communication resource and vehicle mobility constraints	Greedy heuristic	User fairness considered for scheduling and low complexity	Social features of vehicular networks are ignored.
[10]	Vehicle transmit power minimization subject to probabilistic AoI constraints	Extreme value theory and Lyapunov optimization	Likelihood of extreme AoI events reduced	
[11]	AoI-aware vehicular network resource management for expected long-term performance optimization	Long short-term memory and deep reinforcement learning	Applicable for local partial network state observations	
[12]	Vehicle driving route planning for AoI optimization	Deep Q-learning	Applicable to systems with large state and action spaces	
[13]	Optimal cache placement for maximization of network throughput	Multi-armed bandit learning	Commuters' social degree distribution exploited	Neither the impact of social features on AoI of vehicular networks nor the scale-free characteristics of vehicular social relations are considered.
[14]	Mitigation of false alarms triggered by malicious users during message dissemination	Reputation and social importance based forwarding	Low false alarms and high message delivery ratio	
[15]	Enhanced data delivery considering dynamic topology and intermittent connectivity in vehicular networks	Social acquaintance based routing	High packet delivery ratio and low end-to-end delay	
[16]	Improved message forwarding for protecting the personal interests of vehicle users	Vehicular social proximity based forwarding	Privacy-preserving and high message delivery ratio	

AoI-aware radio resource management was investigated for optimizing the expected long-term quality of experience in vehicular networks with Manhattan grid road topology. The authors of [11] proposed a proactive algorithm based on the long short-term memory and deep reinforcement learning techniques to solve the formulated problem without requiring *a priori* knowledge about network dynamics. In [12], the impact of information generation frequency, processing delay and selection of fog/cloud servers on the AoI in a multi-vehicular campus shuttle system was investigated, where the empirical probability density function (PDF) of AoI was shown to exhibit strong spatial correlations. Moreover, the authors of [12] proposed a deep Q-learning algorithm to optimize the driving route of each vehicle for improving the average AoI performance.

On the other hand, the impact of social features on performance of vehicular networks, particularly VSNs, has not been investigated in the literature until recently [13]–[16]. Considering the average degree centrality of socially-tied commuters in cache-enabled VSNs, a multi-armed bandit learning based cache placement scheme was proposed in [13] for maximization of the network throughput. Simulation results in [13] revealed that the proposed placement scheme can significantly increase the network throughput. By estimating a trust score for each vehicle according to its reputation and social importance, the authors of [14] proposed a novel trust based message dissemination scheme to reduce false alarms triggered by malicious users in VSNs. In [15], a social acquaintance based routing protocol was proposed for packet forwarding in VSNs, which can improve both the packet delivery ratio and the end-to-end delay. In [16], a privacy-preserving forwarding scheme was proposed to improve the forwarding performance without leaking personal interest information of vehicle users.

The aforementioned works [9]–[12] have analyzed the AoI of vehicular networks from the cyber-physical perspective, while ignoring the impact of social characteristics on information dissemination in vehicular networks. In practical VSNs, AVs may prefer to contact and share information with the AVs that have close social relations, which can significantly impact the AoI. Therefore, the AoI of VSNs needs to be re-examined from a comprehensive cyber-physical-social perspective. On the other hand, the research works [13]–[16] have mainly evaluated the impact of social attributes of vehicles, including interests, preferences, affiliations and social relations, on performance metrics other than AoI. To our knowledge, extending the evaluations to the AoI of VSNs has not been reported yet. Moreover, recent measurement data of VSNs have shown that the social relations among vehicles exhibit strong scale-free characteristics [17]–[20], i.e., most of the vehicles only contact with few vehicles whereas a small number of vehicles may contact with many vehicles in practical VSNs. However, this scale-free characteristics were ignored in [13]–[16], which may lead to inaccurate performance analysis and inefficient communication designs for VSNs. Table I further compares the state-of-the-art schemes in [9]–[16] from the aspects of research problems, solution methodologies, advantages and limitations.

To bridge the knowledge gap, in this paper, we propose a new mathematical framework for analyzing and optimizing the age of information updates received by AVs to facilitate real-time information dissemination over VSNs. Our model captures the characteristics of social relations among AVs using the scale-free network theory [21]. Moreover, the network AoI (NAoI), defined as the AoI for the AV that lastly receives the information update originally sent from base stations (BSs) in the VSN, is analyzed using the mean-field theory (MFT), taking into account the features of both social relations and wireless communications. Based on the derived results, we further consider joint optimization of the BS information update rate and AV transmit probabilities for minimizing the NAoI of the VSN. Our contributions are as follows:

1) We propose a novel probabilistic social communication

TABLE II
LIST OF KEY NOTATIONS

Symbol	**Description**	**Symbol**	**Description**
$\mathscr{V}$, N	Set and number of AVs within the VSN, respectively	λ	Information update rate at the BSs
B_B, B_V	Bandwidths occupied by the I2V communication and V2V communications, respectively	$\mathcal{X}$, $\mathcal{Y}$	Index sets for data packets generated at the BSs and successfully received by all AVs in the VSN, respectively
α, Λ	Path loss exponent and propagation constant, respectively	γ	Degree exponent of the scale-free VSN
L_0, L	Distance between adjacent AVs and AV communication range, respectively	ϑ_1, ϑ_2	Willingness to communicate between the acquaintance AVs and the stranger AVs within the VSN, respectively
V_i, $V_{(w)}$	The ith AV indexed from the left- to right-hand side and an AV having degree w in the platoon, respectively	Γ_i, ϕ_i	Sets of neighboring AVs located within the sensing range and the communication range of AV V_i, respectively
Φ_i	Set of contending AVs for AV V_i	w_i	Degree of AV V_i
P_B, P_V	BS and AV transmit powers, respectively	$T_{\rm bk}$	Backoff time period
N_0	Noise power spectral density	Ξ	Minimum size of the contending window
d_0, v	BS-to-road distance and AV speed, respectively	R	Radius of the area covered by a BS
τ_B, τ_V	Transmission delays of a data packet over the I2V link and each V2V link, respectively	β, $\beta_{(w)}$	Probabilities that an AV in the VSN and AV $V_{(w)}$ can successfully receive from other AVs within time τ_V, respectively
$T_y^{\rm all}$	Time required for successfully disseminating the yth effective data packet from the subscriber AV to all other AVs within the VSN	$\Delta_{V_i}(t)$, $\Delta(t)$, Δ_{Py}	AoI for AV V_i, NAoI and the yth local maximum value of NAoI, respectively
$\xi_y(t_y)$	Proportion of AVs having successfully received the yth effective data packet by time slot t_y	g_x, u_y	Generation times of the xth data packet and the yth effective data packet, respectively
$A_l(j,L)$, $A_r(j,L)$	Numbers of AVs located within the communication range of AV V_j on the left- and right-hand sides of V_j, respectively	a_y, G_y	Time when the last AV within the VSN successfully receives the yth effective data packet and time when the BSs generate the first data packet after time a_{y-1}, respectively
$p_{i,{\rm b0}}$, $p_{i,{\rm c1}}$, $p_{i,t}$	Probability that the backoff timer of AV V_i decreases to zero, probability of collision when AV V_i starts transmission, and transmit probability of AV V_i, respectively	S_y, Z_y, H_y	Service time of the yth effective data packet, time elapsed from the moment a_{y-1} till the moment G_y, and time elapsed from the moment G_y till the moment a_y, respectively
$p_{j,{\rm f1}}$	Probability that there is at least one receiving AV that AV V_j would like to send information to within its communication range	$h_{i,j}^V$, $d_{i,j}^V$, $\varepsilon_{i,j}^V$	Channel fading, distance, and SER of the single-hop V2V link from AV V_i to AV V_j, respectively
$p_{i,j}^{\rm tie}$, $p_{i,j}^{\rm cw}$	Probability of a social tie and willingness to communicate between AV V_i and AV V_j, respectively	h_x^B, d_x^B, θ_x^B, ε_x^B	Channel fading, distance, SNR, and SER of the BS-to-subscriber AV link for transmitting the xth data packet, respectively
$\boldsymbol{p}_t$	Vector of transmit probabilities for AVs within the VSN	P_R	Receiver sensitivity of the I2V link
m, $m_{\max}$	Number of collisions and “maximum backoff stage”, respectively	Ψ, M	Size and blocklength of data packet, respectively

model for evaluating the AoI of VSNs, where both the scale-free characteristics of the social relations and the underlying wireless communications are taken into account. Using this model, we analyze the probability that an AV can successfully receive data packets from the other AVs within VSNs.

2) Using the MFT, we then analyze the time evolution of the proportion of AVs having successfully received given data packet, which is formulated as a nonlinear first-order differential equation and solved analytically. The derived results further facilitates a convenient analysis of the NAoI for information dissemination over VSNs.
3) Finally, a novel scheme is proposed for joint optimization of the BS information update rate and AV transmit probabilities to facilitate fast information dissemination over VSNs. Both analytical and simulation results indicate that compared with several baseline schemes, the proposed scheme can reduce the average peak NAoI (PNAoI) of VSNs by 96%.

The remainder of this paper is organized as follows. The system model of VSNs and the definition of NAoI in VSNs are presented in Section II. The information dissemination process and the average PNAoI of VSNs are analyzed in Section III. The optimization algorithm for minimizing the average PNAoI of VSNs is provided in Section IV. Section V presents both the analytical and simulation results. Finally, Section VI concludes this paper. The key notations used in this paper are summarized in Table II.

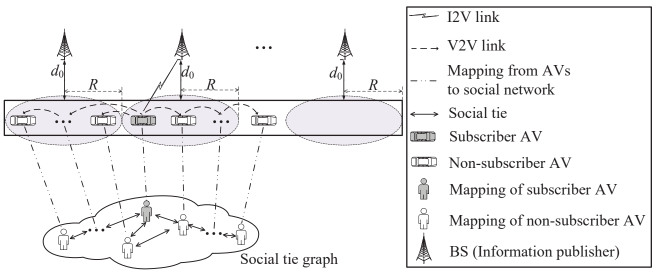

Fig. 1. System model of a VSN, where communications between AVs have to respect both communication channel conditions and social ties.

II. SYSTEM MODEL

A. Network Model

As in [22], we consider a typical VSN composed by a fleet of N AVs, which form a platoon while driving towards a common destination. The AVs move at a constant speed of v in a one-dimensional unidirectional road and each AV maintains a constant tracking distance of L_0 from its neighboring AVs, cf. Fig. 1. Over the VSN, the AVs can communicate with each other and share information about e.g. traffic information and weather news for improved fuel efficiency, driving safety and travel experience of onboard passengers and drivers.

The VSN is covered by multiple BSs located at a distance of d_0 off the road, where each BS covers an area of radius R. The BSs are connected via high-capacity backhaul links to an information publisher on the Internet, whereby the latter disseminates via e.g. a Twitter account or a Facebook page real-time information about the traffic, road condition, etc., to the BSs. The BSs then forward the information to subscriber AVs within their coverage range, who have subscribed to such information. In this paper, we ignore the communication overhead from the information publisher to the BSs, but treat the BSs as a virtual information publisher. The resulting information transmission in the VSN consists of two stages: in the first stage, the BSs send the data packets containing the information update over I2V communication links to the subscriber AVs. In the second stage, the subscriber AVs further forward the successfully received data packets to the remaining AVs using V2V communications. To speed up information dissemination, all AVs having successfully received the data packets can also assist the subscriber AVs in the second stage[1].

The two-stage transmission protocol is reminiscent of epidemic virus spreading to enable timely information dissemination [23], where the AVs having successfully received and having not successfully received data packets are compared to infectious and susceptible individuals, respectively. And similar to virus spreading, the information transmission depends on both physical (communication) and social (networking) conditions. To simplify the discussion, in the following, we consider only one typical subscriber AV, which is usually referred to as the seed AV, within the VSN. Thus, in the first stage, only the BS covering the subscriber AV will disseminate information in the VSN.

As the data packets arrived at the BSs keep updating, the BSs should ensure the data packets received at AVs to be *fresh* during information dissemination, i.e., the time stamps of the data packets received at AVs within the network, which specify the generation times of these data packets, are up-to-date. To this end, the BSs employ preemption based scheduling for data packet transmission. In particular, whenever a new data packet arrives at the BSs, any ongoing transmission of other data packet(s) within the VSN becomes outdated and will be preempted. Then, all BSs will simultaneously broadcast synchronization signalings over control channels, which are used to notify the AVs to discard outdated data packet(s) and prepare for reception of the new data packet. Hence, we consider a data packet transmission to be *successful* only if it is successfully received by all AVs in the VSN without being preempted nor discarded.

B. Probabilistic Graph based Social Communications

Unlike conventional vehicular networks, social communications among AVs are initiated in a probabilistic manner. Thereby, a pair of AVs are willing to communicate with each other only in certain probability, where the probability value depends on the AV users' selfishness/altruism and the trustworthiness of social relations between them. In general, acquaintance AVs may share information with high likelihood, whereas stranger AVs with low likelihood. Let ϑ_1 and ϑ_2 be the willingness to communicate between the acquaintance AVs and the stranger AVs within the VSN, respectively, where $\vartheta_1 > \vartheta_2$. Note that in the considered VSN, V2V transmission between a pair of AVs is *feasible* with high likelihood provided that the pair of AVs have close social relations and are in good channel conditions, where the latter is discussed in Sec. II-D.

To characterize the social relations/ties of AVs within the VSN, we define an undirected graph $\mathscr{G}(\mathscr{V},\mathscr{E})$, where $\mathscr{V} = \{V_1,\cdots,V_k,\cdots,V_N\}$ is the set of N AV nodes within the platoon, V_k is the kth AV indexed from the left- to right-hand side in the platoon, and $\mathscr{E}$ is the set of edges for specifying the social ties among AV nodes. Each pair of acquaintance AVs are connected by an edge on graph $\mathscr{G}(\mathscr{V},\mathscr{E})$, whereas stranger AVs are not directly connected. To capture the scale-free feature of VSNs, we model the degree of an AV node, i.e., the number of acquaintance AV nodes directly connected to the AV node on graph $\mathscr{G}$, to be independently and identically distributed (*i.i.d.*) according to the power law [21, Ch. 1.5]. Particularly, the node degree is a random variable W with probability mass function given as

$$p(w) = \Pr(W = w) = Cw^{-\gamma}, \tag{1}$$

for $1 \leqslant w \leqslant N-1$ and $w \in \mathbb{N}$, where C is a normalization factor such that $\sum_{w=1}^{N-1} p(w) = C\sum_{w=1}^{N-1} w^{-\gamma} = 1$. γ is the degree exponent and usually satisfies $2 < \gamma \leqslant 3$ [21, Ch. 1.5]. According to (1), an AV node in scale-free VSNs can have a small degree with high likelihood, whereas only few AV nodes may have large degrees. As γ increases, the probability mass distribution $p(w)$ will become more centered around small degrees, and the number of AVs having large degrees decreases. Moreover, let w_k denote the degree of AV node V_k, where $V_k \in \mathscr{V}$. For given w_k, the acquaintance AV node(s) directly connected to AV node V_k is(are) assumed to be randomly and uniformly selected from the other AV nodes.

C. I2V Communication based BS-to-Subscriber AV Information Dissemination

The data packets generated or updated at the BSs follow a Poisson process of intensity λ, referred to as the information update rate hereinafter. Each data packet has a size of Ψ and is encoded into M symbols before being sent to the subscriber AV. The I2V transmission occupies a bandwidth of B_B. In this paper, we consider one-shot transmission of each data packet during I2V communication, while ignoring the retransmissions of unsuccessful data packets. Then, the transmission delay of each data packet incurred on the I2V link is $\tau_B = \frac{M}{B_B}$ [24]. We note that the modeling framework and analysis approach can also be extended to scenarios with retransmissions at the cost of extra notations.

Let $\mathcal{X} = \{1,2,\cdots\}$ and $\mathcal{Y} = \{1,2,\cdots\}$ be the index sets of data packets arrived/generated at the BSs and successfully received by all AVs in the VSN, respectively. The data packets indexed by $\mathcal{Y}$ are considered to be *effective*. Note that the size of a data packet in the VSN, Ψ, is usually small and, at the

[1]Since each AV maintains a constant tracking distance of L_0 from its neighboring AVs, the relative positions of all AVs remain unchanged. As a result, the movements of AVs would rarely impact the performance of second-stage transmission.

same time, each data packet transmission is subject to stringent delay constraint. As such, the positions of the AVs are assumed to remain unchanged during the I2V transmission of a data packet [25]. Let d_x^B be the distance between the subscriber AV and its associated BS during the I2V transmission of data packet $x \in \mathcal{X}$. Then, the signal-to-noise ratio (SNR) of the I2V link for transmitting data packet x is given by

$$\theta_x^B = \frac{h_x^B P_B \Lambda \left(d_x^B\right)^{-\alpha}}{N_0 B_B} = \frac{h_x^B P_B \Lambda \left(R_x^2 + d_0^2\right)^{-\frac{\alpha}{2}}}{N_0 B_B}, \quad (2)$$

where $h_x^B \sim \mathrm{Exp}(1)$ is the small-scale Rayleigh fading, P_B is the BS transmit power, Λ is a constant capturing antenna gains and reference distance for measuring the propagation path loss, α is the path loss exponent, and N_0 is the power spectral density of the received additive white Gaussian noise. Moreover, R_x is the horizontal distance between the subscriber AV and its associated BS during the I2V transmission of data packet x and is given as

$$R_x = \left| vT_x - R\left(2\left\lceil \frac{vT_x}{2R} \right\rceil - 1\right) \right|. \quad (3)$$

In (3), the first and second terms give the horizontal coordinates of the subscriber AV and its associated BS, relative to the starting point of the road, respectively, where $\lceil \bullet \rceil$ denotes the ceiling function and T_x is the time elapsed since the subscriber AV starts moving on the road till the generation of data packet x. To mitigate the near-far problem caused by the movements of AVs during I2V communications [26], transmit power control is performed at the BSs. Assume that the instantaneous position of the subscriber AV is known at the BSs. Under transmit power control, $P_B \Lambda \left(R_x^2 + d_0^2\right)^{-\frac{\alpha}{2}}$ in (2) is maintained at a constant value, denoted as P_R, which is referred to as the receiver sensitivity [27]–[29].

Moreover, finite blocklength codes with blocklength $M \ll \infty$ are employed to meet the delay constraint. However, this may cause erroneous transmission of data packet x over the BS-to-subscriber AV link. The resulting symbol error rate (SER) ε_x^B is approximated by [30]

$$\varepsilon_x^B \approx Q\left\{ \frac{\sqrt{M}\left[\ln\left(1 + \frac{h_x^B P_R}{N_0 B_B}\right) - \frac{\Psi \ln 2}{M}\right]}{\sqrt{1 - \left(1 + \frac{h_x^B P_R}{N_0 B_B}\right)^{-2}}} \right\}, \quad (3)$$

where $Q\{r\} = \int_r^\infty \mathrm{e}^{-\rho^2/2} \Big/ \sqrt{2\pi} \mathrm{d}\rho$ is the Q-function. Note that with transmit power control, the receiver sensitivity P_R in (4) becomes a constant. Hence, the SER for the I2V transmission is independent of the AV speed v.

D. V2V Communication based Information Dissemination within the Platoon

The V2V communications within the considered VSN occupy a spectrum of bandwidth B_V, which is non-overlapping with the spectrum used for I2V communication. To mitigate interference during multi-hop V2V communications, we employ the carrier sense multiple access/collision avoidance (CSMA/CA) protocol for distributed spectrum access [25], [31].

However, an exact analysis of the V2V information dissemination within the platoon is prohibitive due to the possibly large population of AVs and their complicated competition for spectrum access, as well as the dynamic evolution of multi-hop senders and receivers over time. To address this challenge, we propose an approximate analysis framework based on the MFT. For convenience of presentation, in the following, we first introduce the modeling of single-hop V2V communications before discussing the modeling of multi-hop communications within the platoon. Throughout this paper, we assume that each AV employs a transmit power of P_V and has a communication range of L.

1) Modeling of Single-hop V2V Communications: With distributed spectrum access, collision occurs when multiple AVs compete for data packet transmission over the allocated V2V communication spectrum. To mitigate potential collisions caused by the resource competition from uncoordinated AVs, the CSMA/CA protocol introduces the random backoff mechanism. Thereby, each AV waits for a time period T_{bk} before starting transmission. Within T_{bk}, the AV keeps sensing the channel. Recall that AVs have a communication range of L. By setting the sensing range as $2L$, collisions within the communication range of AV can be mitigated, as $4L$ defines the maximum possible distance between two competitive transmitting AVs that locate within the communication range of a given receiving AV. If the channel is sensed to be idle, T_{bk} is reduced by one; otherwise, it remains unchanged. The AV is allowed to transmit when T_{bk} reduces to zero. In this case, if collision recurs, another round of backoff is initiated and the same process continues. In this paper, we consider an exponential backoff, which randomly selects T_{bk} from the contending time window $[0, 2^m \Xi - 1]$, provided $m \leqslant m_{\max}$. Herein, m and Ξ denote the number of collisions and the minimum size of the contending window, respectively. Moreover, $m_{\max}$ is the "maximum backoff stage" as defined in [32], where the size of the contending window remains to be $2^{m_{\max}} \Xi$ when $m > m_{\max}$.

To reduce collisions and the delay incurred in spectrum access, the AVs contend for data transmission only in a probabilistic manner. In particular, if AV V_i has a data packet to transmit and at least one receiving AV to which it will forward this data packet within its communication range, it would start transmitting with probability $p_{i,t}$ when T_{bk} reduces to zero. Then, the probability that T_{bk} reduces to zero for AV V_i, denoted as $p_{i,\mathrm{b0}}$, is given by [32]

$$p_{i,\mathrm{b0}} = \frac{2\left(1 - 2p_{i,\mathrm{c1}}\right)}{\left(1 - 2p_{i,\mathrm{c1}}\right)\left(\Xi + 1\right) + p_{i,\mathrm{c1}} \Xi \left[1 - \left(2p_{i,\mathrm{c1}}\right)^{m_{\max}}\right]}. \quad (5)$$

In (5), $p_{i,\mathrm{c1}}$ is the probability that collision occurs when AV V_i starts transmission. By considering the CSMA/CA protocol, $p_{i,\mathrm{c1}}$ is given by [33]

$$p_{i,\mathrm{c1}} = \frac{2\Xi \left|\Phi_i\right|}{\left(\Xi + 1\right)^2 + 2\Xi \left|\Phi_i\right|}, \quad (6)$$

where Φ_i denotes the set of contending AVs for AV V_i and $|\Phi_i|$ is the cardinality of set Φ_i.

Similar to the I2V communication, during V2V communication, the data packet is encoded into M symbols for transmission over bandwidth B_V. Hence, each V2V communication hop incurs a transmission delay of $\tau_V = \frac{M}{B_V}$. Moreover, the SER for transmission from AV V_i to AV V_j is approximated as [30]

$$\varepsilon_{i,j}^V \approx Q\left\{\frac{\sqrt{M}\left[\ln\left(1+\frac{P_V h_{i,j}^V \Lambda\left(d_{i,j}^V\right)^{-\alpha}}{N_0 B_V}\right)-\frac{\Psi \ln 2}{M}\right]}{\sqrt{1-\left(1+\frac{P_V h_{i,j}^V \Lambda\left(d_{i,j}^V\right)^{-\alpha}}{N_0 B_V}\right)^{-2}}}\right\}, \tag{7}$$

where $h_{i,j}^V \sim \text{Exp}(1)$ and $d_{i,j}^V$ capture the small-scale Rayleigh fading and the distance for V2V communication between AV V_i and AV V_j, respectively.

Let τ_V be the length of time slot for packet transmission within the platoon. When AV V_j is located within the communication range of AV V_i, the probability that V_j can successfully receive the data packet from V_i within time τ_V is given by

$$p_{i,j}^V = p_{i,j}^{\text{cw}} p_{i,t} f_1\left(|\Phi_i|\right)\left(1-\varepsilon_{i,j}^V\right), \tag{8}$$

where

$$f_1\left(|\Phi_i|\right) = p_{i,\text{b0}}\left(1-p_{i,\text{c1}}\right), \tag{9}$$

and $p_{i,j}^{\text{cw}}$ is the willingness to communicate between AV V_i and AV V_j. Let $p_{i,j}^{\text{tie}}$ and $1-p_{i,j}^{\text{tie}}$ be the probability that AV V_i and AV V_j are acquaintance AVs and stranger AVs, respectively. Then, we can derive $p_{i,j}^{\text{cw}}$ as

$$p_{i,j}^{\text{cw}} = p_{i,j}^{\text{tie}}\vartheta_1 + \left(1-p_{i,j}^{\text{tie}}\right)\vartheta_2. \tag{10}$$

2) Modeling of Multi-hop V2V Communications: Rather than evaluating the individual impact of each local single-hop V2V communication, which is prohibitive, we now exploit the MFT to estimate their aggregate impact on information dissemination within the platoon. Let t_y be the time slot for the dissemination of the yth effective data packet within the platoon, where $y \in \mathcal{Y}$. Moreover, denote by $\xi_y\left(t_y\right)$ the proportion of AVs having successfully received the yth effective data packet by time slot t_y. Based on the MFT, the evolution of $\xi_y\left(t_y\right)$ over time is captured by a nonlinear first-order differential equation given as follows

$$\frac{\mathrm{d}\xi_y\left(t_y\right)}{\mathrm{d}t_y} = \left[1-\xi_y\left(t_y\right)\right]\beta\xi_y\left(t_y\right), \tag{11}$$

where β is the probability that an AV can successfully receive from other AVs within time τ_V. According to (11), the instantaneous growth rate of $\xi_y\left(t_y\right)$ is a product of three terms, the proportion of AVs having not received the yth effective data packet, $1-\xi_y\left(t_y\right)$, the successful receiving probability of an AV, β, as well as the proportion of AVs having received the yth effective data packet, $\xi_y\left(t_y\right)$. The last terms are included because similar to the susceptible-infectious model in epidemiology [23], AVs having received the yth effective data packet may further facilitate the forwarding of this packet to the AVs having not received it (similar to the spreading of virus from infectious individuals to susceptible individuals), whose proportion is given by $1-\xi_y\left(t_y\right)$.

At the beginning of V2V information dissemination within the platoon, i.e., when $t_y = 0$, only the subscriber AV receives

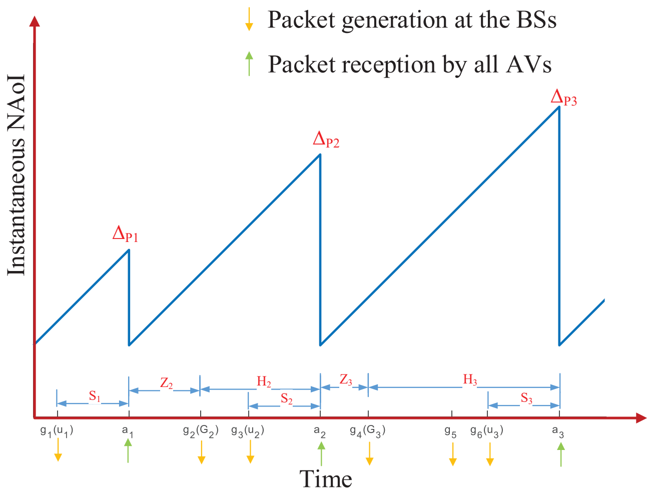

Fig. 2. Illustration of the evolving trajectories of NAoI over time.

the yth effective data packet. Then, we have $\xi_y(0) = \frac{1}{N}$, which defines a boundary condition for solving the differential equation (11), cf. Sec. III-A. Moreover, let t_y^{all} be the number of time slots spent for transmitting the yth effective data packet to all AVs other than the subscriber AV in the platoon. We have another boundary condition given as

$$\xi_y\left(t_y^{\text{all}}\right) > \frac{N-1}{N}. \tag{12}$$

E. AoI of the Considered VSN

AoI is considered to characterize the timeliness of data packets received at the AVs. Let t be the current time. Moreover, assume that the data packet most recently received at AV V_i is generated at the BSs at time $t_{V_i}^g(t)$. Then, the AoI for AV V_i is given as $\Delta_{V_i}(t) = t - t_{V_i}^g(t)$.

Since an effective data packet needs to be successfully received by all AVs, we define the AoI of the VSN, referred to as NAoI, as follows

$$\Delta(t) = \max_{V_i \in \mathcal{V}} \Delta_{V_i}(t) = \max_{V_i \in \mathcal{V}} t - t_{V_i}^g(t). \tag{13}$$

According to (13), the NAoI captures the AoI for the AV that lastly receives the information update originally sent by the BSs. Fig. 2 illustrates the evolution of the NAoI over time. As shown in Fig. 2, the value of NAoI keeps increasing over time, until a data packet is successfully received by all AVs in the VSN. In the latter case, the value of $t_{V_i}^g(t)$ with V_i being the AV having lastly received the new data packet, is updated in (13) to the generation time of this data packet, which decreases the NAoI. Consequently, the evolution of the NAoI is bounded by a series of local maximum values, $\{\Delta_{P1}, \Delta_{P2}, \Delta_{P3}, \cdots\}$ as shown in Fig. 2, which are also referred to as the PNAoI.

Let g_x and u_y be the generation times of data packets $x \in \mathcal{X}$ and $y \in \mathcal{Y}$, respectively. For data packet $y \in \mathcal{Y}$ being successfully received by all AVs, we denote by a_y the time when the last AV within the VSN successfully receives packet y. Moreover, let S_{y-1} be the service time of the $(y-1)$th effective data packet. From Fig. 2, we have $S_{y-1} = a_{y-1} - u_{y-1}$.

Now, let Z_y be the time elapsed since the successful reception of the $(y-1)$th effective data packet by all AVs till the generation of the first new data packet at the BSs. We have $Z_y = G_y - a_{y-1}$, where G_y specifies the time when the BSs generate the first data packet after time a_{y-1}, i.e., $G_y = \min\{g_x | g_x > a_{y-1}\}$. Then, the time elapsed from the moment G_y till the yth effective data packet being successfully received by all AVs, denoted by H_y, can be given as $H_y = a_y - G_y$.

As shown in Fig. 2, the yth local maximum value of the NAoI, i.e., the yth PNAoI, is given by $\Delta_{Py} = S_{y-1}+Z_y+H_y$. Moreover, Ω_t as the number of successfully received effective data packets till time t, which is given by $\Omega_t = \max\{y|a_y \leqslant t\}$. Then, the average PNAoI of the considered VSN is defined as

$$\overline{\Delta_P} = \lim_{t\to\infty} \frac{1}{\Omega_t}\sum_{i=1}^{\Omega_t} \Delta_{Pi} \overset{(a)}{=} \mathbb{E}\left(S_{y-1}\right)+\mathbb{E}\left(Z_y\right)+\mathbb{E}\left(H_y\right), \quad (14)$$

where $\mathbb{E}(\bullet)$ is the expectation operator. In (a), the time average of PNAoI converges to its expected value when time t and Ω_t are sufficiently large. This is due to the ergodicity of the AoI, as has been commonly assumed in the literature [34], [35].

III. Analysis of Average PNAoI

In this section, we analyze the average PNAoI of the considered VSN for a sufficiently long time period, assuming that the AVs within the VSN may employ any probabilistic transmission scheme. The results derived in this section provide a basis for further optimizing the average PNAoI in Sec. IV.

A. Analysis of Single-Packet Dissemination within the VSN

Assume that a given effective data packet has been successfully received at the subscriber AV. We then analyze the time required for (successfully) disseminating the effective data packet from the subscriber AV to the remaining AVs within the VSN. This requires analyzing the time spent for packet transmission by employing the CSMA/CA based multi-hop V2V communications.

Let j be an integer being randomly and uniformly selected from the interval $[1,N]$. Moreover, let Γ_j and ϕ_j be the sets of neighboring AVs located within the sensing and communication range of AV V_j, respectively. The cardinality of set ϕ_j averaged over the random index j, denoted by $\overline{|\phi_j|}$, is then given as

$$\overline{|\phi_j|} = \sum_{j=1}^{N} \frac{1}{N}\left[A_l\left(j,L\right)+A_r\left(j,L\right)\right], \quad (15)$$

where $A_l(j,L)$ and $A_r(j,L)$ are the numbers of AVs located within the communication range of AV V_j on the left- and right-hand sides of V_j, respectively, and

$$A_l\left(j,L\right) = \left\lfloor (j-1) - \frac{\max\left[(j-1)L_0 - L, 0\right]}{L_0}\right\rfloor, \quad (16)$$

$$A_r\left(j,L\right) = \left\lfloor \frac{\min\left[(j-1)L_0 + L, (N-1)L_0\right]}{L_0} - (j-1)\right\rfloor. \quad (17)$$

In (16) and (17), $\lfloor \bullet \rfloor$ denotes the floor function.

Recall that the degree of an AV within the VSN is a random variable. Hence, the AV having degree w, denoted by $V_{(w)}$, is also a random variable. Let $\phi_{(w)}$ denote the set of neighboring AVs located within the coverage of AV $V_{(w)}$. Based on (7), for AV $V_i \in \phi_{(w)}$, the expected SER of the V2V link from AV V_i to AV $V_{(w)}$ when averaged over the small-scale Rayleigh fading is approximated by (18), shown at the top of the next page, where the distance between AVs V_i and $V_{(w)}$, denoted by $d_{i,(w)}^{V}$, satisfies $d_{i,(w)}^{V} = \kappa L_0$ for some $\kappa \in \mathbb{N}$. We then have the following lemma.

Lemma 1: Let $\beta_{(w)}$ be the probability that AV $V_{(w)}$ successfully receives within time τ_V the packets from the other AVs in the platoon. Then, $\beta_{(w)}$ is lower-bounded by (19), shown at the top of the next page, with

$$f_2\left(w\right) = 1 - \vartheta_2 - \frac{w\left(\vartheta_1 - \vartheta_2\right)}{N-1}, \quad (20)$$

and $f_3\left(d_{i,(w)}^{V}\right)$ given in (18).

Proof: Please refer to Appendix A. ■

Moreover, the probability that an AV in the platoon successfully receives within time τ_V the data packets from other AVs, β, can be calculated by averaging over $\beta_{(w)}$, which is given as

$$\beta = \sum_{w=1}^{N-1} p\left(w\right)\beta_{(w)} = \frac{\sum\limits_{w=1}^{N-1} w^{-\gamma}\beta_{(w)}}{\sum\limits_{w=1}^{N-1} w^{-\gamma}}. \quad (21)$$

Substituting (21) into (11), the proportion of AVs in the platoon that have successfully received the yth effective data packet by time slot t_y can be obtained by solving the logistic differential equation in (11) and the solution is given as [36]

$$\xi_y\left(t_y\right) = \frac{\xi_y\left(0\right)\mathrm{e}^{\beta t_y}}{1-\xi_y\left(0\right)+\xi_y\left(0\right)\mathrm{e}^{\beta t_y}} = \frac{\mathrm{e}^{\beta t_y}}{N-1+\mathrm{e}^{\beta t_y}}. \quad (22)$$

By employing the boundary condition in (12), we then have $t_y^{\text{all}} > \frac{2\ln(N-1)}{\beta}$. Therefore, the time required for successfully disseminating the yth effective data packet to all AVs within the considered VSN since it has been successfully received at the subscriber AV is given by

$$T_y^{\text{all}} = \frac{2\ln\left(N-1\right)}{\beta}\tau_V = \frac{2\tau_V\sum\limits_{w=1}^{N-1} w^{-\gamma}\ln\left(N-1\right)}{\sum\limits_{w=1}^{N-1} w^{-\gamma}\beta_{(w)}}. \quad (23)$$

Remark 1: Recall that in (11), T_y^{all} is approximated as the average time required for successfully disseminating an effective data packet from the subscriber AV to all other AVs within the considered VSN. Hence, (23) holds for any effective data packet y. Moreover, since $V_{(w)}$ is randomly located in the platoon and $\beta_{(w)}$ is a function of transmit probability $p_{i,t}$ for AV $V_i \in \phi_{(w)}$, cf. (19) and (46), T_y^{all} also depends on the transmit probabilities of AVs, $\boldsymbol{p}_t \triangleq [p_{1,t}, \cdots, p_{i,t}, \cdots, p_{N,t}]$, in the considered VSN.

$$\mathbb{E}\left(\varepsilon_{i,(w)}^{V}\right) \approx f_3\left(d_{i,(w)}^{V}\right) = \int_0^{\infty} \mathrm{e}^{-h} Q \left\{ \frac{\sqrt{M}\left[\ln\left(1+\frac{P_V h \Lambda\left(d_{i,(w)}^{V}\right)^{-\alpha}}{N_0 B_V}\right) - \frac{\Psi \ln 2}{M}\right]}{\sqrt{1-\left[1+\frac{P_V h \Lambda\left(d_{i,(w)}^{V}\right)^{-\alpha}}{N_0 B_V}\right]^{-2}}} \right\} \mathrm{d}h, \tag{18}$$

$$\beta_{(w)} \geqslant \left[1-f_2(w)\right] \sum_{V_i \in \phi_{(w)}} p_{i,t} f_1 \left(\sum_{V_j \in \Gamma_i} p_{j,t} \left\{1 - \left[f_2(w_j)\right]^{\overline{|\phi_j|}}\right\} \right) \left[1 - f_3\left(d_{i,(w)}^{V}\right)\right], \tag{19}$$

B. Derivation of Average PNAoI

Based on the results of Sec. III-A, we can derive the average PNAoI of the VSN, cf. (14). Different from Sec. III-A, we consider consecutive transmissions of a train of data packets. In the following, we present the derivation results in three parts.

1) Derivation of $\mathbb{E}(S_{y-1})$*:* $\mathbb{E}(S_{y-1})$ composes the time required for successfully transmitting the $(y-1)$th effective data packet over the I2V link, which is given by τ_B, and from the subscriber AV to the other AVs within the VSN, which is given by T_{y-1}^{all}. We have

$$\mathbb{E}(S_{y-1}) = \tau_B + T_{y-1}^{\text{all}} = \tau_B + T_y^{\text{all}}. \tag{24}$$

2) Derivation of $\mathbb{E}(Z_y)$*:* According to the definition of Z_y in Sec. II-E, no new data packet would be generated at the BSs within time period $[a_{y-1}, a_{y-1}+Z_y)$. Hence, Z_y gives the waiting time for packet generation and the probability of event $Z_y > t_0$ can be calculated as

$$\Pr(Z_y > t_0) = \Pr\left[\mathfrak{N}(t_0) = 0\right] = \mathrm{e}^{-\lambda t_0}, \tag{25}$$

where $\mathfrak{N}(t_0)$ denotes the number of data packets generated within a time period of length t_0, and the last equality holds since data packet generation at the BSs follows the Poisson process with intensity λ. Hence, Z_y is an exponential random variable with expectation given as

$$\mathbb{E}(Z_y) = \frac{1}{\lambda}. \tag{26}$$

3) Derivation of $\mathbb{E}(H_y)$*:* Taking the preemption based packet transmission into account, we have to discuss four possible cases below for deriving $\mathbb{E}(H_y)$. For convenience of presentation, let P_{G_y} be the data packet generated at time G_y.

- *Case 1*: P_{G_y} is not preempted but successfully received by all AVs in the VSN.
- *Case 2*: P_{G_y} is preempted by a new update packet in the first-stage I2V communication and thus discarded by all BSs. Then the BS covering the subscriber AV sends the new update packet, which may be further preempted or not.
- *Case 3*: P_{G_y} is preempted by a new update packet in the second-stage V2V communications and thus discarded by all BSs, after being successfully received by the subscriber AV in the first-stage I2V communication. Then the BS covering the subscriber AV sends the new update packet, where further preemption is also possible.
- *Case 4*: P_{G_y} is not successfully received by the subscriber AV. Then all BSs discard P_{G_y} and wait to send a new update packet, with the possibility of being further preempted.

By evaluating each of these cases, the derivation result is given in the following lemma.

Lemma 2: The expression of $\mathbb{E}(H_y)$ is given as

$$\mathbb{E}(H_y) = \frac{\mathrm{e}^{\lambda\left(\tau_B + T_y^{\text{all}}\right)}}{\lambda\left[1-\mathbb{E}\left(\varepsilon_y^B\right)\right]} - \frac{1}{\lambda}, \tag{27}$$

where $\mathbb{E}\left(\varepsilon_y^B\right)$ is the expected SER for the I2V transmission of the yth effective data packet when averaged over the small-scale Rayleigh fading and is given as

$$\mathbb{E}\left(\varepsilon_y^B\right) \approx \int_0^{\infty} \mathrm{e}^{-h} Q \left\{ \frac{\sqrt{M}\left[\ln\left(1+\frac{hP_R}{N_0 B_B}\right) - \frac{\Psi \ln 2}{M}\right]}{\sqrt{1-\left(1+\frac{hP_R}{N_0 B_B}\right)^{-2}}} \right\} \mathrm{d}h. \tag{28}$$

Proof: Please refer to Appendix B.

Finally, substituting (24), (26) and (27) into (14), the average PNAoI of the considered VSN is given by

$$\overline{\Delta_P} = \tau_B + T_y^{\text{all}} + \frac{\mathrm{e}^{\lambda\left(\tau_B + T_y^{\text{all}}\right)}}{\lambda\left[1-\mathbb{E}\left(\varepsilon_y^B\right)\right]}. \tag{29}$$

Remark 2: We observe from (29) that $\overline{\Delta_P}$ monotonically increases with T_y^{all}, the time required for successfully disseminating an effective data packet within the platoon. Since T_y^{all} is a function of AV transmit probabilities in the VSN, $\boldsymbol{p}_t$, cf. *Remark 1*, the value of $\overline{\Delta_P}$ depends on both $\boldsymbol{p}_t$ and the BS information update rate λ. Therefore, in order to reduce the average PNAoI, joint optimization of the AV transmit probabilities and the BS information update rate is needed.

IV. Optimization of Average PNAoI

In this section, we investigate the joint optimization of BS information update rate and AV transmit probabilities for minimizing the average PNAoI of the considered VSN. This is desired to facilitate timely packet reception at the AVs within the considered VSN. In the following, we present the optimization problem formulation in Sec. IV-A. Then, a heuristic suboptimal scheme for minimizing the average PNAoI is provided in Sec. IV-B.

A. Optimization Problem Formulation

We consider centralized optimization performed at the BSs, which are assumed to know the number and degree distribution of AVs within the VSN. The goal is to minimize the average PNAoI $\overline{\Delta_P}$ by optimizing the BS information update rate λ and AV transmit probabilities $\boldsymbol{p}_t$ in the VSN. The resulting optimization problem is formulated as

$$\begin{aligned} \text{P1:} \quad & \min_{\lambda, \boldsymbol{p}_t} \quad \overline{\Delta_P} \\ & \text{s.t.} \quad \text{C1} : 0 \leqslant p_{i,t} \leqslant 1, \forall V_i \in \mathscr{V}, \\ & \qquad \text{C2} : \lambda \geqslant 0, \end{aligned} \tag{30}$$

where constraints C1 and C2 guarantee that the values of AV transmit probabilities lie in the interval $[0, 1]$ and that the BS information update rate is nonnegative, respectively.

Note that, in the objective function of problem P1, $\overline{\Delta_P}$, only the term T_y^{all} depends on $\boldsymbol{p}_t$, as $\beta_{(w)}$ in T_y^{all} is a function of $\boldsymbol{p}_t$, cf. *Remark 1*. Exploiting the special structure of the objective function, problem P1 can be solved in two stages. In the first stage, we derive the optimal λ^* which minimizes $\overline{\Delta_P}$ for any given T_y^{all}. In the second stage, we minimize $\overline{\Delta_P}$ by optimizing the transmit probabilities of AVs, by substituting $\lambda = \lambda^*$ into $\overline{\Delta_P}$.

1) Optimization of λ: According to (29), the second-order partial derivative of the objective function of problem P1, $\overline{\Delta_P}$, with respect to λ is given as

$$\frac{\partial^2 \overline{\Delta_P}}{\partial \lambda^2} = \frac{\mathrm{e}^{\lambda\left(\tau_B + T_y^{\text{all}}\right)} \left\{ \left[\lambda \left(\tau_B + T_y^{\text{all}} \right) - 1 \right]^2 + 1 \right\}}{\lambda^3 \left[1 - \mathbb{E}\left(\varepsilon_y^B \right) \right]} > 0. \tag{31}$$

Hence, $\overline{\Delta_P}$ is a convex function with respect to λ. Then, given T_y^{all}, the optimal BS information update rate λ^* for solving problem P1 is the solution of the following equation

$$\frac{\partial \overline{\Delta_P}}{\partial \lambda} = \frac{\mathrm{e}^{\lambda\left(\tau_B + T_y^{\text{all}}\right)} \left[\lambda \left(\tau_B + T_y^{\text{all}} \right) - 1 \right]}{\lambda^2 \left[1 - \mathbb{E}\left(\varepsilon_y^B \right) \right]} = 0. \tag{32}$$

Finally, by solving (32), the optimal BS information update rate admits a closed-form expression given as

$$\lambda^* = \frac{1}{\tau_B + T_y^{\text{all}}}. \tag{33}$$

2) Optimization of $\boldsymbol{p}_t$: Substituting (33) into (29), problem P1 can be reformulated as

$$\begin{aligned} \text{P2 :} \quad & \min_{\boldsymbol{p}_t} \quad \left(\tau_B + T_y^{\text{all}} \right) \left[1 + \frac{\mathrm{e}}{1 - \mathbb{E}\left(\varepsilon_y^B \right)} \right] \\ & \text{s.t.} \quad \text{C1, C2.} \end{aligned} \tag{34}$$

Note that problems P1 and P2 are equivalent since $\min\limits_{x \in \mathbb{X}, y \in \mathbb{Y}} f(x, y) = \min\limits_{x \in \mathbb{X}} \left[\min\limits_{y \in \mathbb{Y}} f(x, y) \right]$ holds for any $f(\bullet, \bullet)$, $\mathbb{X}$ and $\mathbb{Y}$ [37, Ch. 4.1]. However, problem P2 is still non-convex due to the non-convex objective function, which is generally NP-hard. To strike a balance between performance and computational complexity, in the following, we propose a suboptimal scheme tailored to the characteristics of the considered VSN for solving problem P2.

B. Proposed Suboptimal Scheme

Due to the scale-free feature of the considered VSN, a large population of AVs usually have social ties with only few AVs, i.e., these AVs have relatively small degrees, whereas a small population of AVs can have social ties with many AVs, i.e., these AVs have very large degrees. AVs having large degrees are also referred to as hub AVs. Despite of their small population, hub AVs are crucial for improving the data packet dissemination within the VSN. This is because compared with AVs having small degrees, hub AVs are more likely to forward data packets to other AVs, which enables fast information dissemination among AVs. Moreover, due to the adoption of the CSMA/CA protocol for V2V communications within the VSN, prioritizing channel access for the hub AVs by e.g. increasing the transmit probabilities of hub AVs and/or reducing those of AVs having small degrees can mitigate collisions, to further accelerate the dissemination of data packets in the VSN. Hence, for fast information dissemination among AVs, it is desired to design the transmit probabilities of AVs to be positively correlated with their degrees of social ties.

Motivated by the above characteristics of scale-free VSNs, we propose a novel degree-based transmission (DBT) scheme of AVs to solve problem P2. In particular, the transmit probability for an AV with degree w is given in a parametric form as

$$p_{(w),t}^{\text{dg}} = \eta w^{\sigma}, \tag{35}$$

where $\sigma \geqslant 0$ captures the dependency of the transmit probability on the degree of an AV. $\eta \geqslant 0$ ensures $\eta(N-1)^{\sigma} \leqslant 1$ for satisfying the constraint in (34). Note that the proposed AV transmission scheme in (35) reduces to i) degree-independent transmission with equal transmit probabilities when $\sigma = 0$, i.e., $p_{(w),t}^{\text{dg}} = \eta$, and ii) degree-proportional transmission when $\sigma = 1$, i.e., $p_{(w),t}^{\text{dg}} = \eta w$, respectively.

Consequently, with the proposed scheme, the average probability that an arbitrary AV in the VSN would start transmitting at the end of backoff period is derived as

$$\begin{aligned} p_t^{\text{dg}} &= \sum_{w=1}^{N-1} p(w)\, p_{(w),t}^{\text{dg}} \\ &= \frac{\eta \sum\limits_{w=1}^{N-1} w^{\sigma - \gamma}}{\sum\limits_{w=1}^{N-1} w^{-\gamma}}. \end{aligned} \tag{36}$$

Meanwhile, under the proposed scheme, the probability that an AV with degree w successfully receives within time τ_V the data packets from the other AVs in the VSN can be lower-bounded based on (19) by (37), shown at the top of the next page, with

$$\overline{|\Gamma_i|} = \sum_{i=1}^{N} \frac{1}{N} \left[A_l(i, 2L) + A_r(i, 2L) \right], \tag{38}$$

$$\begin{aligned}\beta_{(w)}^{\mathrm{dg}} &\geqslant \mathbb{E}\left\{[1-f_2(w)]\sum_{V_i\in\phi_{(w)}} p_{i,t} f_1\left(\sum_{V_j\in\Gamma_i} p_{j,t}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}\right)\left[1-f_3\left(d_{i,(w)}^V\right)\right]\right\} \\ &= [1-f_2(w)]\, p_t^{\mathrm{dg}} f_1\left(\overline{|\Gamma_i|}\,\mathbb{E}\left[p_{j,t}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}\right]\right)\mathbb{E}\left\{\sum_{V_i\in\phi_{(w)}}\left[1-f_3\left(d_{i,(w)}^V\right)\right]\right\},\end{aligned} \tag{37}$$

$$\begin{aligned}&\mathbb{E}\left[p_{j,t}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}\right] \\ &= \frac{\sum\limits_{w_j=1}^{N-1} p(w_j)\, p_{j,t}^{\mathrm{dg}}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}}{\sum\limits_{w_j=1}^{N-1} p(w_j)} \\ &= \frac{\eta\sum\limits_{w_j=1}^{N-1} w_j^{\sigma-\gamma}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}}{\sum\limits_{w_j=1}^{N-1} w_j^{-\gamma}},\end{aligned} \tag{39}$$

$$\begin{aligned}&\mathbb{E}\left\{\sum_{V_i\in\phi_{(w)}}\left[1-f_3\left(d_{i,(w)}^V\right)\right]\right\} \\ &= \sum_{n=1}^{N}\frac{1}{N}\sum_{V_i\in\phi_n}\left[1-f_3\left(d_{i,n}^V\right)\right] \\ &= \sum_{n=1}^{N}\frac{\sum\limits_{\kappa=1}^{A_l(n,L)}[1-f_3(\kappa L_0)]+\sum\limits_{\kappa=1}^{A_r(n,L)}[1-f_3(\kappa L_0)]}{N}.\end{aligned} \tag{40}$$

In (38), $\overline{|\Gamma_i|}$ is the cardinality of set Γ_i averaged over index i which determines the position of AV V_i in the platoon. $A_l(i,2L)$ and $A_r(i,2L)$ give the numbers of AVs located within the sensing range of AV V_i on the left- and right-hand sides of V_i, respectively, where $A_l(j,L)$ and $A_r(j,L)$ are given in (16) and (17), respectively. In (39), the expectation is taken over the degree of AV V_j, and $\overline{|\phi_j|}$ is given in (15). Finally, the expectation in (40) is taken over the position of AV $V_{(w)}$ in the platoon, since AV $V_{(w)}$ can be located anywhere in the platoon with equal probability. Particularly, we have $\sum_{\kappa=1}^{A_l(n,L)}[1-f_3(\kappa L_0)]=0$ if $A_l(n,L)=0$, and $\sum_{\kappa=1}^{A_r(n,L)}[1-f_3(\kappa L_0)]=0$ if $A_r(n,L)=0$.

By substituting (37) into (23), T_y^{all} under the proposed scheme can be upper-bounded by (41), shown at the top of the next page, which is a nonlinear function of variables η and σ. Based on the optimal BS information update rate in Sec. IV-A and proposed DBT scheme of AVs in Sec. IV-B, we now optimize parameters η and σ in (41) for minimizing the average PNAoI, which can be achieved using a grid search as given in Algorithm 1. Note that Algorithm 1 requires $\mathcal{O}(\mathscr{C}_1)$ iterations, where $\mathcal{O}(\bullet)$ denotes the big-O notation and $\mathscr{C}_1=\sum_{i=0}^{(\sigma_{\max}-\sigma_{\min})/\sigma_0}\frac{(N-1)^{-\sigma_{\min}-i\sigma_0}-\eta_{\min}+\eta_0}{\eta_0}$. Moreover, the computation of $T_y^{\mathrm{all,dg}}(\eta,\sigma)$ in step 4 defines the most expensive step in terms of computational complexity within Algorithm 1 and has a complexity $\mathcal{O}(\mathscr{C}_2)$, where $\mathscr{C}_2=7N-6+\sum_{n=1}^{N}[A_l(n,L)+A_r(n,L)]$ according to (38)-(41).

Algorithm 1 Minimization of Average PNAoI

1: Initialize degree exponent γ of the scale-free VSN, number of AVs, N, within the VSN, blocklength M, bandwidth B_B and B_V for the I2V communication and V2V communications, respectively, searching steps σ_0 and η_0, minimum and maximum searching values $\sigma_{\min}$ and $\sigma_{\max}$, minimum searching value $\eta_{\min}$, and set $T_y^{\mathrm{all}*}=\infty$;
2: **for** $\sigma=\sigma_{\min}:\sigma_0:\sigma_{\max}$ **do**
3:   **for** $\eta=\eta_{\min}:\eta_0:(N-1)^{-\sigma}$ **do**
4:     Compute $T_y^{\mathrm{all,dg}}(\eta,\sigma)$ based on the upper-bound given in (41);
5:     **if** $T_y^{\mathrm{all,dg}}(\eta,\sigma)<T_y^{\mathrm{all}*}$ **then**
6:       $T_y^{\mathrm{all}*}=T_y^{\mathrm{all,dg}}(\eta,\sigma)$;
7:       $\eta^*=\eta$, $\sigma^*=\sigma$;
8:     **end if**
9:   **end for**
10: **end for**
11: η^* and σ^* are the optimal parameters of η and σ for minimizing the average PNAoI, respectively. Substituting $\eta=\eta^*$ and $\sigma=\sigma^*$ into (35), the transmit probabilities of AVs are obtained.

Hence, the overall computational complexity of Algorithm 1 is $\mathcal{O}(\mathscr{C}_1\mathscr{C}_2)$, which is proportional to $\mathcal{O}\left((N-1)^{1-\sigma_{\min}}\right)$.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed scheme via both numerical and Monte Carlo (MC) simulations, which are implemented in MATLAB and run on a 64-bit Windows server. The server is equipped with an Intel Xeon E5-2680 v4 processor @2.4 GHz and 128 GB RAM memory. As the data packet generation is assumed to follow a Poisson process, in MC simulations, we use an exponential distribution generator to simulate the arrival time intervals of adjacent data packets and determine the generation time of each packet. Moreover, 10^4 data packets are generated at the BSs for each simulation setup, where the transmission of each data packet experiences *i.i.d.* Rayleigh fading. The other simulation parameters are set according to Table III. Moreover, the searching steps σ_0 and η_0 in Algorithm 1 are set as $\sigma_0=0.1$ and $\eta_0=1/[100(N-1)^{\sigma}]$, respectively. By tracing the generation and dissemination of each data packet as well as the resulting evolution of the NAoI over time, the final results of MC simulation are averaged over all 10^4 data packets.

A. Performance Analysis of the Proposed Scheme

Fig. 3 shows the average SER of the I2V link as a function of the receiver sensitivity for different I2V communication bandwidths. From Fig. 3 we observe that, for a given bandwidth, the average SER of the I2V link decreases with receiver sensitivity, due to improvement in the SNR of the I2V link. However, for a given receiver sensitivity, the average SER of the I2V link increases with the I2V communication bandwidth.

$$T_y^{\mathrm{all,dg}}(\eta,\sigma) \leqslant \frac{2\tau_V \ln(N-1)\left\{f_1\left(\overline{|\Gamma_i|}\mathbb{E}\left[p_{j,t}\left\{1-[f_2(w_j)]^{\overline{|\phi_j|}}\right\}\right]\right)\right\}^{-1}\left(\sum_{w=1}^{N-1} w^{-\gamma}\right)^2}{\eta\mathbb{E}\left\{\sum_{V_i\in\phi_{(w)}}\left[1-f_3\left(d^V_{i,(w)}\right)\right]\right\}\sum_{w'=1}^{N-1}(w')^{\sigma-\gamma}\sum_{w=1}^{N-1}w^{-\gamma}[1-f_2(w)]}, \tag{41}$$

TABLE III
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Number of AVs	$N = 200$ [22]	Data packet size	$\Psi = 160$ bits
AV speed	$v = 70$ km/h [38]	Radius of the area covered by a BS	$R = 500$ m
Distance between adjacent AVs	$L_0 = 1$ m [22]	AV communication range	$L = 75$ m [31]
I2V communication bandwidth	$B_B = 10$ MHz [39]	V2V communication bandwidth	$B_V = 10$ MHz [39]
Path loss exponent	$\alpha = 3.6$	AV transmit power	$P_V = 30$ dBm [40]
Propagation constant	$\Lambda = -30$ dB	Receiver sensitivity of the I2V link	$P_R = -108$ dBm [27]
Noise power spectral density	$N_0 = -174$ dBm/Hz [31]	Degree exponent of the scale-free VSN	$\gamma = 2.6$
BS-to-road distance	$d_0 = 2000$ m	Willingness to communicate between acquaintance AVs	$\vartheta_1 = 1$
Backoff parameters	$\Xi = 32$, $m_{\max} = 5$ [33]	Willingness to communicate between stranger AVs	$\vartheta_2 = 0.5$

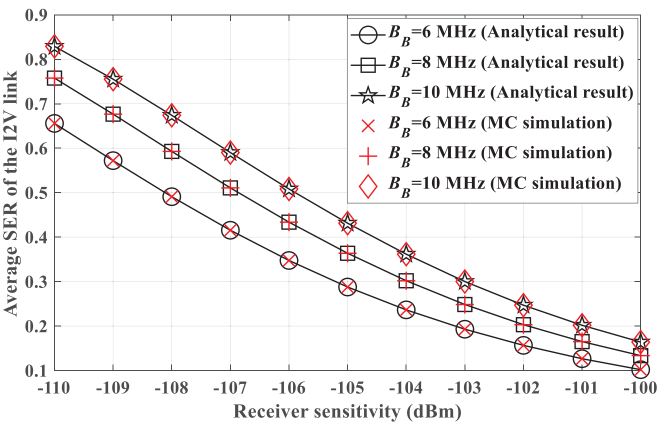

Fig. 3. Average SER of the I2V link versus receiver sensitivity for different I2V communication bandwidths ($M = 300$).

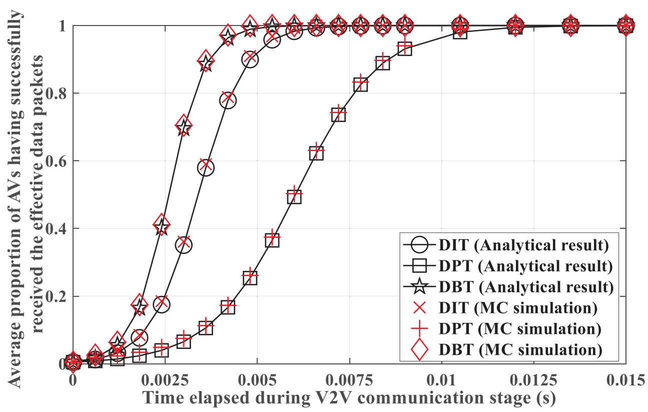

Fig. 4. Average proportion of AVs having successfully received the effective data packets versus time elapsed during V2V communication stage for the considered AV transmission schemes ($M = 300$).

This is because the noise power increases with the I2V communication bandwidth, which decreases the achievable SNR and reliability of I2V communication.

B. Comparison with Baseline Schemes

For performance comparison, we further consider the following baseline schemes:

- *Baseline Scheme 1* (Degree-independent transmission (DIT) scheme): All AVs employ the same transmit probability, i.e., $p^{\mathrm{dg}}_{(w),t} = \eta$, independent of degrees of AVs, where parameter η is optimized by employing Algorithm 1 and setting $\sigma = 0$;
- *Baseline Scheme 2* (Degree-proportional transmission (DPT) scheme): Each AV employs a transmit probability that is proportional to its degree, i.e., $p^{\mathrm{dg}}_{(w),t} = \eta w$. Moreover, the parameter η is optimized by employing Algorithm 1 and setting $\sigma = 1$;
- *Baseline Scheme 3* (Fixed-rate information update at the BSs): The BS information update rate is fixed as $\lambda = \lambda_0$.

Fig. 4 shows the average proportion of AVs having successfully received the effective data packets as a function of the time elapsed during V2V communication stage for the considered AV transmission schemes. From Fig. 4 we observe that, as the time increases, the average proportion of AVs having successfully received the effective data packets increases following "S"-shaped curve for all considered AV transmission schemes. In particular, the data packets are disseminated among the population of AVs relatively slowly when the time is small and large, as only a small number of AVs serve as the source and the destination nodes, respectively. However, when a large number of sending and receiving AVs are present after a certain amount of time, the proposed DBT scheme can significantly accelerate the dissemination process, which largely outperforms DIT and DPT schemes. This is because the DBT scheme can exploit

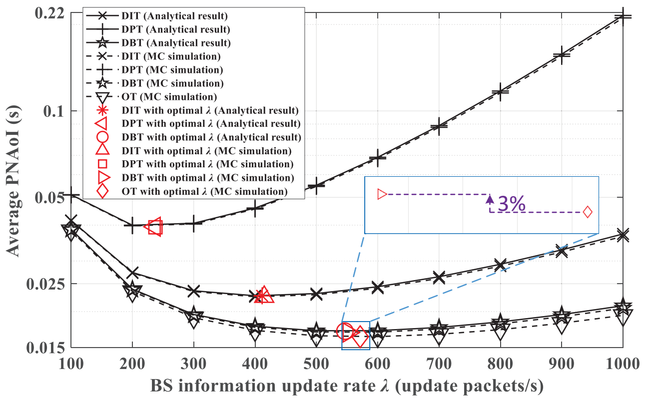

Fig. 5. Average PNAoI (in logarithmic scale) versus BS information update rate λ for the considered schemes ($N = 20$, $M = 300$).

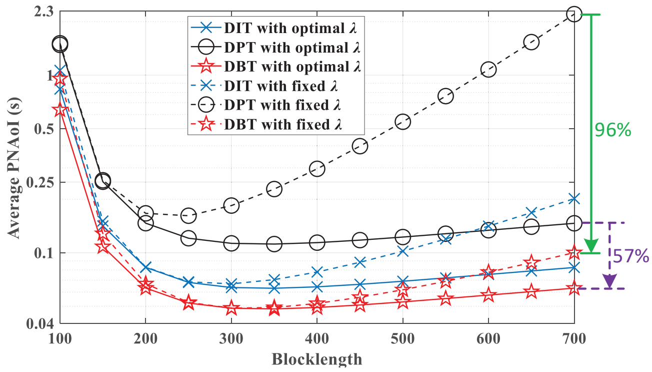

Fig. 6. Average PNAoI (in logarithmic scale) versus blocklength for the considered schemes ($\lambda_0 = 200$).

the scale-free feature of the considered VSN to improve social communication opportunities and at the same time, mitigate collisions of multi-hop V2V communications. From Fig. 4 we also observe that interestingly, the DIT scheme outperforms the DPT scheme. This is because although the DPT scheme can mitigate collisions of multi-hop V2V communications by prioritizing transmissions for hub AVs, the large proportion of AVs, which having small degrees, are usually prohibited from transmissions, as their transmit probabilities are close to 0. In contrast, the DIT scheme assigns all AVs with the same but non-negligible transmit probabilities. This result indicates that for fast information dissemination, it is necessary to balance between increasing the transmit probabilities of hub AVs (reducing the transmit probabilities of AVs having small degrees) and ensuring non-negligible transmit probabilities for the large proportion of AVs having small degrees. Figs. 3 and 4 also show that the MC simulation results coincide well with the analytical results for all the considered cases, and thus validates our theoretical derivations.

Fig. 5 shows the average PNAoI as a function of BS information update rate λ for the considered schemes. Here, we also evaluate the performance of the optimal transmission (OT) scheme, which computes the optimal AV transmit probabilities based on global exhaustive search. From Fig. 5, for each AV transmission scheme, the average PNAoI decreases with λ when λ is small. However, when λ is large, the average PNAoI increases with λ. Therefore, there exists a minimal value for the average PNAoI for each considered AV transmission scheme. This is because, when λ is small, the packet update at the BSs is slow and the packets received by AVs tend to be outdated, which penalizes the average PNAoI. In this case, increasing λ is beneficial for lowering the average PNAoI. However, when λ is large, due to frequent packet updating at the BSs, the transmission of update packets in the VSN will be preempted with a high likelihood. Hence, most of update packets will be discarded before being received by all AVs, which increases the average PNAoI. From Fig. 5 we observe that, for the considered simulation setup, the minimal average PNAoI values for DBT, DIT, DPT and OT schemes are 0.0171 s, 0.0225 s, 0.0398 s and 0.0164 s, corresponding to λs of 500, 400, 200 and 600, respectively. Moreover, through joint optimization of BS information update rate and AV transmit probabilities, the DBT scheme outperforms all baseline schemes. Also, compared with the OT scheme with optimal λ, the average PNAoI under the DBT scheme with optimal λ is increased by only 3%.

Fig. 6 shows the average PNAoI as a function of the blocklength for the considered schemes. From Fig. 6, for each considered scheme, the average PNAoI decreases with the blocklength when the blocklength is small, but increases when the blocklength is large. Therefore, there exists a minimal value for the average PNAoI for each considered scheme. This is because, when the blocklength is small, the SERs and the reliabilities of both the I2V and V2V links improve with the blocklength, cf. (4) and (7), which reduces the average PNAoI. However, when the blocklength becomes large, the packet transmission latencies in both the I2V and V2V links increase significantly, which increases the average PNAoI. Therefore, an interesting trade-off between reliability and latency/average PNAoI needs to be considered for choosing the optimal blocklength. From Fig. 6 we observe that, for the considered simulation setup, the minimal average PNAoI values for DBT scheme with optimal λ, DBT scheme with fixed λ, DIT scheme with optimal λ, DIT scheme with fixed λ, DPT scheme with optimal λ, and DPT scheme with fixed λ are 0.0483 s, 0.0488 s, 0.0631 s, 0.0668 s, 0.1119 s and 0.1616 s, corresponding to blocklengths of 350, 300, 350, 300, 350 and 250, respectively. Moreover, the DBT scheme with optimal λ outperforms all baseline schemes. In particular, compared with the DPT scheme, the DBT scheme can reduce the average PNAoI by up to 57% and 96%, when the optimal λ and a fixed λ are employed, respectively.

Fig. 7 shows the average PNAoI as a function of the willingness to communicate ϑ_2 between stranger AVs for the considered schemes. From Fig. 7 we observe that the average PNAoI decreases with ϑ_2 for all considered schemes. This is because communication opportunities between stranger AVs, i.e., AVs having no direct social ties, increase with ϑ_2, which facilitates the information dissemination among AVs and thus reduces the average PNAoI. Moreover, for given ϑ_2, the DBT scheme with optimal λ outperforms all baseline schemes.

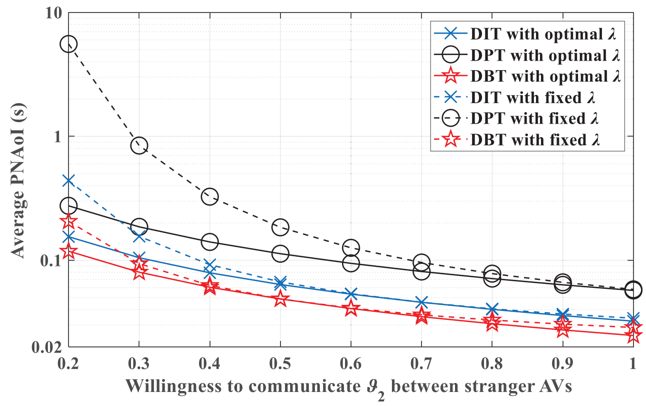

Fig. 7. Average PNAoI (in logarithmic scale) versus willingness to communicate ϑ_2 between stranger AVs for the considered schemes ($\lambda_0 = 200$, $M = 300$).

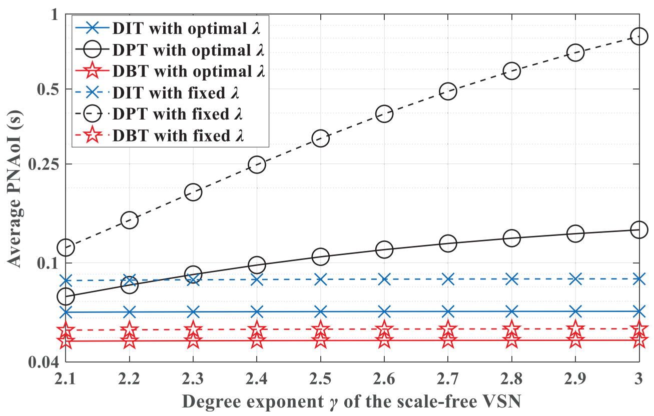

Fig. 8. Average PNAoI (in logarithmic scale) versus degree exponent γ of the scale-free VSN for the considered schemes ($\lambda_0 = 300$, $M = 300$).

Finally, Fig. 8 shows the average PNAoI as a function of the degree exponent γ of the scale-free VSN for the considered schemes. From Fig. 8 we observe that, for adopting both optimal and fixed λs, the average PNAoI remains almost unchanged with γ under the DIT scheme, but it deteriorates significantly as γ increases under the DPT scheme. This is because for DPT scheme with both optimal and fixed λs, the transmit probabilities of AVs having small degrees are much smaller than that of hub AVs, whereby information dissemination relies more on hub AVs. In this case, as the number of hub AVs decreases with γ, more time is needed for information dissemination among AVs, which increases the average PNAoI. However, with the DIT scheme, all AVs employ the same transmit probability for both optimal and fixed λs. Consequently, as γ increases, the average PNAoI remains almost unchanged, although the number of hub AVs decreases. Moreover, with the DBT scheme, the average PNAoI also almost remains unchanged with γ but always outperforms other considered schemes for both optimal and fixed λs. This result shows that the DBT scheme can fully exploit the scale-free feature of the VSN to reduce the average PNAoI.

VI. Conclusion

Based on the scale-free network theory, the social relations among AVs are considered in this paper to model the information dissemination in VSNs. Thereby, the NAoI is proposed to analyze the impact of both vehicular social relations and wireless communications on the timeliness of real-time vehicular information dissemination. Moreover, utilizing a novel framework based on the MFT, analytical results for information dissemination in VSNs and the incurred average PNAoI are derived. Furthermore, considering characteristics of wireless transmission links and social relations in VSNs, a novel scheme for joint optimization of the BS information update rate and AV transmit probabilities is proposed to reduce the average PNAoI of VSNs. Both analytical and simulation results show that compared with several baseline schemes, the proposed DBT scheme can reduce the average PNAoI of VSNs by up to 96%. In this paper, we have assumed perfect knowledge about the instantaneous position of the subscriber AV for transmit power control at the BSs. In this case, AV mobility has only negligible impact on the AoI. However, AV mobility may come into play when the position of the subscriber AV is unknown or imperfectly known to the BSs. Extending our work to such scenarios, together with packet retransmissions, multiple platoons and subscriber AVs is an interesting topic for future consideration.

Appendix A

Proof of Lemma 1

According to (10), for AV $V_i \in \phi_{(w)}$, where $\phi_{(w)}$ is the set of AVs located in the neighborhood but within the coverage of AV $V_{(w)}$, the willingness to communicate between AV V_i and AV $V_{(w)}$ is derived as

$$\begin{aligned} p_{i,(w)}^{\mathrm{cw}} &= p_{i,(w)}^{\mathrm{tie}} \vartheta_1 + \left(1 - p_{i,(w)}^{\mathrm{tie}}\right) \vartheta_2 \\ &= \left(\frac{w}{N-1}\right) \vartheta_1 + \left(1 - \frac{w}{N-1}\right) \vartheta_2, \end{aligned} \tag{42}$$

where $p_{i,(w)}^{\mathrm{tie}} = \frac{w}{N-1}$ gives the probability that AV V_i has a social tie with AV $V_{(w)}$.

Moreover, recall that Γ_i is the set of neighboring AVs located within the sensing range of AV V_i. The set of contending AVs for AV V_i, Φ_i, actually defines the set of AVs that intend for transmitting and also belong to set Γ_i. Hence, the expectation of $|\Phi_i|$ is upper-bounded by

$$\mathbb{E}\left(|\Phi_i|\right) = \sum_{V_j \in \Gamma_i} p_{j,t} p_{j,\mathrm{d1}} \overline{p_{j,\mathrm{f1}}} \leqslant \sum_{V_j \in \Gamma_i} p_{j,t} \overline{p_{j,\mathrm{f1}}}, \tag{43}$$

where $p_{j,\mathrm{d1}}$ is the probability that AV V_j has a data packet to transmit. $p_{j,\mathrm{f1}}$ is the probability that there is at least one receiving AV that AV V_j would like to send information to within its communication range. $\overline{p_{j,\mathrm{f1}}}$ is the average value of $p_{j,\mathrm{f1}}$ over index j which determines the position of AV V_j in the platoon, and $\overline{p_{j,\mathrm{f1}}}$ is given by

$$\begin{aligned}\overline{p_{j,\mathrm{f1}}} &= 1-\prod_{V_k\in\phi_j}\left(1-p_{j,k}^{\mathrm{cw}}\right)\\ &= 1-\left\{1-\left[p_{j,k}^{\mathrm{tie}}\vartheta_1+\left(1-p_{j,k}^{\mathrm{tie}}\right)\vartheta_2\right]\right\}^{\overline{|\phi_j|}}\\ &= 1-\left[1-\left(\frac{w_j}{N-1}\right)\vartheta_1-\left(1-\frac{w_j}{N-1}\right)\vartheta_2\right]^{\overline{|\phi_j|}}.\end{aligned} \tag{44}$$

In (44), w_j is the degree of AV V_j, $p_{j,k}^{\mathrm{tie}}=\frac{w_j}{N-1}$ gives the probability that AV V_j has a social tie with AV V_k, ϕ_j is the set of neighboring AVs located within the coverage of AV V_j, and $\overline{|\phi_j|}$ is the cardinality of set ϕ_j averaged over index j, which is given in (15).

Since $f_1(|\Phi_i|)$ given in (9) is a convex and monotone decreasing function with respect to $|\Phi_i|$, we have

$$\mathbb{E}\left[f_1\left(|\Phi_i|\right)\right] \overset{(\mathrm{b})}{\geqslant} f_1\left(\mathbb{E}\left[|\Phi_i|\right]\right) \geqslant f_1\left(\sum_{V_j\in\Gamma_i} p_{j,t}\overline{p_{j,\mathrm{f1}}}\right), \tag{45}$$

where (b) is due to Jensen's inequality.

Moreover, based on (8), the probability that AV $V_{(w)}$ successfully receives within time τ_V the packets from the other AVs in the platoon is given by

$$\beta_{(w)}=\sum_{V_i\in\phi_{(w)}} p_{i,(w)}^{\mathrm{cw}} p_{i,t}\mathbb{E}\left[f_1\left(|\Phi_i|\right)\right]\left[1-\mathbb{E}\left(\varepsilon_{i,(w)}^{V}\right)\right], \tag{46}$$

where $\mathbb{E}\left(\varepsilon_{i,(w)}^{V}\right)$ is the expectation of the SER in the V2V link from AV V_i to AV $V_{(w)}$ taken over the small-scale Rayleigh fading, which is given in (18).

Finally, by substituting (42) and (45) into (46), $\beta_{(w)}$ is thus lower-bounded by (19).

APPENDIX B
Proof of Lemma 2

$\mathbb{E}(H_y)$ will be derived by evaluating Cases 1-4 in Sec. III-B.

For Case 1, since packet P_{G_y} is not preempted but successfully received by all AVs in the VSN, packet P_{G_y} gives the yth effective data packet. Thus, $\mathbb{E}(H_y)$ in Case 1 is given by the service time of the yth effective data packet, i.e., $\mathbb{E}(H_y|\,\text{Case 1 takes place}) = \tau_B + T_y^{\mathrm{all}}$. On the other hand, the probability that Case 1 takes place is given as

$$\Pr(\text{Case 1 takes place}) = \mathrm{e}^{-\lambda\left(\tau_B+T_y^{\mathrm{all}}\right)}\left[1-\mathbb{E}\left(\varepsilon_y^B\right)\right], \tag{47}$$

where $\mathrm{e}^{-\lambda\left(\tau_B+T_y^{\mathrm{all}}\right)}$ denotes the probability that no update packet is generated since the generation of the yth effective data packet till its successful reception by all AVs. $\mathbb{E}\left(\varepsilon_y^B\right)$ is the expected SER for the I2V transmission of the yth effective data packet when averaged over the small-scale Rayleigh fading and is given in (28).

Moreover, for Cases 2-4, the update packet P_{G_y} generated at time G_y cannot be received by all AVs and will be discarded in the VSN, since packet P_{G_y} may either be preempted by a new update packet during the transmission or not be successfully received by the subscriber AV. Hence, H_y contains the process from the generation of a new update packet after the discard of P_{G_y} till time a_y, which is denoted as H_y' in the following.

For Case 2, since packet P_{G_y} is preempted in the first-stage I2V communication, the conditional expectation of H_y is given as

$$\mathbb{E}(H_y|\,\text{Case 2 takes place}) = \mathbb{E}(t'|\,t'<\tau_B)+\mathbb{E}\left(H_y'\right), \tag{48}$$

where $\mathbb{E}(t'|\,t'<\tau_B)$ is the expected length of the time interval from G_y until packet P_{G_y} is preempted by a newly generate packet. Hence, t' is the generation interval under the condition that packet P_{G_y} is preempted, which follows an exponential distribution with rate parameter λ, such that

$$\mathbb{E}(t'|\,t'<\tau_B) = \frac{\int_0^{\tau_B} t'\lambda\mathrm{e}^{-\lambda t'}\mathrm{d}t'}{1-\mathrm{e}^{-\lambda\tau_B}} = \frac{1}{\lambda}-\frac{\tau_B}{\mathrm{e}^{\lambda\tau_B}-1}. \tag{49}$$

Substituting (49) into (48), the conditional expectation of H_y is given as

$$\mathbb{E}(H_y|\,\text{Case 2 takes place}) = \frac{1}{\lambda}-\frac{\tau_B}{\mathrm{e}^{\lambda\tau_B}-1}+\mathbb{E}\left(H_y'\right). \tag{50}$$

Moreover, the probability that Case 2 takes place is given as $\Pr(\text{Case 2 takes place}) = 1-\mathrm{e}^{-\lambda\tau_B}$.

For Case 3, packet P_{G_y} is preempted in the second-stage V2V communications, though being successfully received by the subscriber AV in the first-stage I2V communication. Similar to the derivations in Case 2, the conditional expectation of H_y and the probability that Case 3 takes place are given as follows

$$\mathbb{E}(H_y|\,\text{Case 3 takes place}) = \frac{1}{\lambda}+\tau_B-\frac{T_y^{\mathrm{all}}}{\mathrm{e}^{\lambda T_y^{\mathrm{all}}}-1}+\mathbb{E}\left(H_y'\right), \tag{51}$$

$$\begin{aligned}&\Pr(\text{Case 3 takes place})\\ &= \mathrm{e}^{-\lambda\tau_B}\left(1-\mathrm{e}^{-\lambda T_y^{\mathrm{all}}}\right)\left[1-\mathbb{E}\left(\varepsilon_y^B\right)\right].\end{aligned} \tag{52}$$

For Case 4, since packet P_{G_y} is not successfully received by the subscriber AV, the conditional expectation of H_y is given as

$$\mathbb{E}(H_y|\,\text{Case 4 takes place}) = \tau_B+\mathbb{E}(Z)+\mathbb{E}\left(H_y'\right), \tag{53}$$

where $\mathbb{E}(Z)=\frac{1}{\lambda}$ is the expected length of the interval from the time that packet P_{G_y} is not decoded correctly by the subscriber AV until a new update packet is generated at the BSs. Moreover, the probability that Case 4 takes place is given as

$$\Pr(\text{Case 4 takes place}) = \mathrm{e}^{-\lambda\tau_B}\mathbb{E}\left(\varepsilon_y^B\right). \tag{54}$$

Finally, based on the above analyses of Cases 1-4, $\mathbb{E}(H_y)$ can be evaluated by the following expression

$$\begin{aligned}&\mathbb{E}(H_y)\\ &= \sum_{i=1}^{4}\mathbb{E}(H_y|\,\text{Case } i \text{ takes place})\times\Pr(\text{Case } i \text{ takes place}).\end{aligned} \tag{55}$$

Note that, according to the definition of H_y in Sec. II-E, the evolution of H_y' is the same as its counterpart H_y [41]. Thus, we have $\mathbb{E}\left(H_y'\right)=\mathbb{E}(H_y)$. By substituting $\mathbb{E}\left(H_y'\right)=\mathbb{E}(H_y)$ into (55), $\mathbb{E}(H_y)$ given in (27) can be obtained.

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