Optimal Sensing Time Design in ISAC-Enabled Vehicular Networks

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***Abstract*—Integrated sensing and communication (ISAC) technology is critical to the realization of Vehicle-to-Everything (V2X) intelligent interactivity. However, there is limited research conducted regarding the optimal time design within a specific frame structure. To this end, we propose a time optimization scheme that maximizes the utility of Age of Information (AoI) to improve the timeliness and effectiveness of the system, under the premise of ensuring the completion of bit information intra-sharing of every vehicle pair with mutual information as metric and meeting the quality requirement for sensing. Due to the non-convex nature of the formulated problem, we employ some transformations to convert it into an equivalent convex problem, enabling us to obtain the optimal solution. Simulation results demonstrate the superiority of our proposed method and optimal design compared with an existing method. In specific, our proposed method can significantly improve the AoI-based utility and provide a faster update of the sensing information by highly reducing AoI. With the sensing SINR requirement of 200, our proposed method can improve the AoI-based utility by 312% while reducing AoI by 48%, respectively, compared to the counterpart.**

***Index Terms*—Integrated sensing and communication, vehicular network, age of information**

I. Introduction

With the booming development of communication technology and the explosive access of various sensing and communication devices, the spectrum resources where communication and sensing co-exist are more and more congested, and the concept of integrated sensing and communication (ISAC) has come into fruition [1]. It serves as a key technology to enable seamless communication between devices and systems, providing a ubiquitous and aware mobile network. Typically, there are three ISAC systems under consideration for applications: radar-centric design, communication-centric design, and joint design. At the current research level, it is tough to make significant modifications to the hardware and software architectures or to embed communication information into the radar signal, so communication-centric integrated designs using Orthogonal Frequency Division Multiplexing (OFDM) signals are pursued in many literatures [2]–[4]. Furthermore, a key issue of ISAC research is how to avoid self-interference between those two systems, which means that the sensing echoes may interfere with the transmitting communication signals. In contrast to the guiding interval described in [2], we achieve easier and more effective elimination of signal self-interference through passive source available sensing.

A crucial area of application for ISAC is the intelligent transportation system, which necessitates real-time communication and sensing among vehicles, to achieve the objectives of enhancing driving safety, alleviating traffic congestion, and saving energy. Therefore, the investigation of V2X-related technologies is nowadays a trendy topic. Especially, 3GPP Release 16 has developed the 5G New Radio (NR)-based vehicle sidelink standard, which allows direct communication among vehicles, guaranteeing the research of Vehicle-to-Vehicle (V2V)-related technologies [5]. Du et al. in [6] propose a two-stage dynamic beamwidth design for sensing-assisted beamforming in ISAC-enabled V2I networks, aiming to achieve highly reliable communication transmission. Kumari et al. in [3] investigate the performance trade-off between radar and communication in an adaptive IEEE 802.11ad waveform design for joint automotive radar and communication systems. Nevertheless, the research on the time scheduling for each frame in V2V scenarios under the ISAC framework is yet to be further explored.

Nowadays, there are several hot research topics in ISAC systems. For example, the incorporation of Reconfigurable Intelligence Surface (RIS) to control the transmission path and phase of wireless signals, thus reducing signal transmission losses and interference [7]; the capacity of sensing recognition and communication of the system is strengthened by reinforcement learning and other pattern analysis methods [8], [9], etc. However, there are relatively fewer studies related to the time scheduling of frame structure at the Medium Access Control (MAC) layer. In specific, fewer people mention the full utilization of metrics that enable more efficient time scheduling, such as Age of Information (AoI), which is a tightly customized metric for measuring the timeliness of sensing information, urgently demanded by the ISAC-enabled V2V system. Although some closed-form solutions of the average AoI have been obtained with M/M/1 or M/G/1 models in queuing theory [4], [10], such analysis is not applicable to many ISAC-V2V scenarios.

In this work, we propose an optimal sensing time design in an ISAC-enable V2V network. Compared with previous works, we focus on the AoI of sensing information in ISAC scenario, which is critical for certain applications of intelligent transportation system. We introduce the concept of AoI-based utility function and formulate the optimal time arrangement problem to maximize the AoI-based system utility while satisfying the sensing quality requirements. Then, we solve the non-convex problem and demonstrate the significant improvement of the proposed method.

The remainder of this paper is organized as follows. Section II presents the system model and performance metrics of the system. Sections III and IV carry out the problem formulation and propose an algorithm for solving the joint optimization problem. Simulation results are shown in Section V. Section VI closes this paper with a conclusion.

II. System Model

We consider the ISAC scenario in a vehicle network, where V2V communication is facilitated by utilizing 5G NR technology. As shown in Fig. 1, different pairs are formed between vehicles, where each pair consists of a capturing vehicle (CV) and a signaling vehicle (SV). Let $\mathcal{N} = \{1, 2, \ldots, n\}$ denotes the set of vehicle pairs. At each time slot, the SV will actively send the ISAC signal to the CV for sensing purposes. Then, CV will transmit the current sensing information to SV to achieve the sensing information sharing and a win-win situation. Meanwhile, CV and SV can also share additional information via the bi-directional communication link. However, how to arrange the sensing time duration to guarantee the sensing requirement, achieve a fast response, and update of the sensing information for both SV and CV is very critical and significant in the vehicle network. In this paper, under the flexible frame structure of 5G NR, we focus on achieving better AoI performance while satisfying the sensing requirements in the ISAC scenario through the optimal design of sensing time duration at each time slot. The detailed explanation of the frame structure, signal model, sensing mutual information, communication mutual information and AoI will be elaborated as follows.

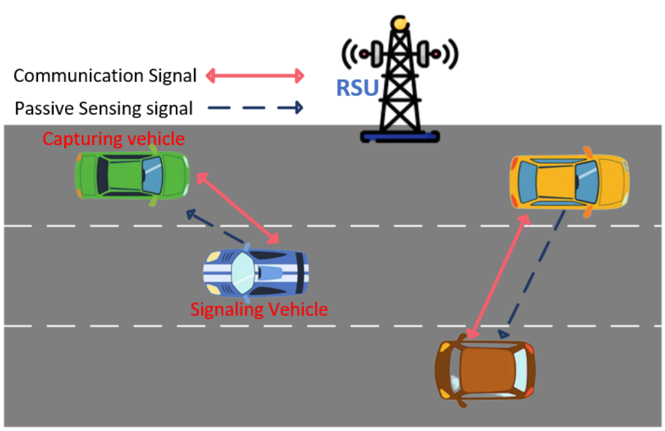

Fig. 1. ISAC-enabled V2V network.

A. Dynamic Frame Structure

Compared to the fixed frame structure of 4G LTE, the number of time slots within a frame can be adjusted. Hence, we can leverage multiple preamble parts for sensing, facilitating subframe-level analysis. The subframe structure is shown in Fig. 2, where each subframe is composed of 4 time slots, adhering to the specification of 5G NR.

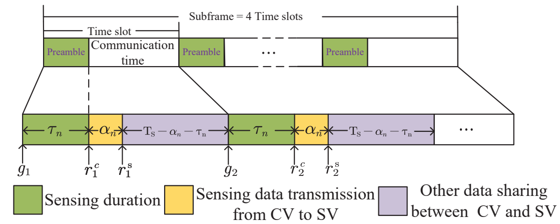

Fig. 2. Subframe structure.

At the beginning of each time slot (i.e., g_1, g_2, etc.), the signaling vehicle (SV) starts to transmit the sensing signal to the capturing vehicle (CV). After the duration of τ_n, the CV receives the sensing information at the time instants denoted as r_1^c, r_2^c, etc, respectively. Then, the sensing information received by CV will be transmitted back to SV. After the time duration α_n, SV will receive the sensing information at the time instants denoted as r_1^s, r_2^s, etc, respectively. With this process, sensing information will be shared with both SV and CV. The remaining time of each time slot is for the communication of other information between CV and SV. In this paper, we focus on the AoI for sensing information. That is, our objective is to optimize the time variables τ_n and α_n for all $n \in \mathcal{N}$ to maximize the AoI-based utility. (The AoI and AoI-based utility function will be defined in the next subsection).

Fig. 2 also shows that the service time of both vehicles is different for the same piece of sensing information. The value of τ_n depends on the requirement of the system for sensing, while α_n depends on the amount of information sensed and communication achievable rate.

B. Signal Model

In our ISAC system, adopting the integrated OFDM signal, the received baseband signal can be formulated as

$$y_n = \sqrt{P_n} h_n s_n + \eta_n, \tag{1}$$

where y_n denotes the received signal of vehicle pair n, s_n is the baseband transmission OFDM symbol, P_n is the transmission power, h_n is the channel gain of the vehicle pair n, and η_n represents the interference, composed of two parts, internal thermal noise and interference caused by signals from other pairs of vehicles.

Since the sensing signals and communication signals are processed differently, the channel gain and noise from other vehicle pairs in the model are specifically modeled as follows.

- For communication, we denote the communication channel gain as h_n^c, which is simulated by the 3GPP-3D channel model. It takes 3-D spatial distance variation into account and is an evolution of the winner+ channel model for 6Ghz+ communication scenarios [11]. Similarly, $h^c_{n,n'}$ represents the noise from other vehicles during communication.

- For sensing, we denote the sensing channel gain as h^s_n, which is related to the parameters in the radar distance equation such as transmission distance, radar cross section and receiving antenna gain, etc. Meanwhile, $h^s_{n,n'}$ represents the sensing interference.

C. Performance Metrics

1) Mutual Information: Sensing mutual information and communication mutual information are a pair of concepts with similar physical meanings that are drawn by Shannon's formula and both describe the amount of information [12]. They can both be measured in bits and serve as performance metrics to evaluate the achieved quality of service in sensing and communication, respectively.

Sensing Mutual Information (SMI): The purpose of sensing is to extract environmental information from the received signal. The performance metric SMI is the mutual information between the received signal and the propagation channel, which can be expressed as [13]

$$I\left(h^s_n, y_n | s_n\right). \tag{2}$$

Since the sensing receiver processes the OFDM signal by coherent accumulation, SMI is defined as

$$MI_n = \frac{\tau_n B}{2}\log_2\left(1+\mathit{\Gamma}^{sen}_n\right), \tag{3}$$

where τ_n denotes the duration of the sensing process, and $\mathit{\Gamma}^{sen}_n$ denotes the SINR of the sensing process, which correlates with the sensing time duration and can be expressed as [14]

$$\mathit{\Gamma}^{sen}_n = \frac{\tau_n P_n\left(h^s_n\right)^2}{\sigma^2+\sum_{n'\epsilon\mathcal{N}\backslash n}\varrho_n\tau_n P_{n'}\left(h^s_{n,n'}\right)^2}, \tag{4}$$

where ϱ_n is the attenuation factor of interference from other vehicles. The interference accumulates at the receiver of vehicle pair n and therefore the duration of the interference is also τ_n.

Communication Mutual Information (CMI) : The purpose of the communication is to pass the information from the transmitter to the receiver. Therefore, CMI is the mutual information between the received signal and the transmitted signal, which is used to evaluate the communication capacity and expressed as [15]

$$I\left(s_n, y_n | h^c_n\right). \tag{5}$$

CMI is also known as the communication achievable rate, and the instantaneous expression is given as

$$R_n = B\log_2\left(1+\mathit{\Gamma}^{com}_n\right), \tag{6}$$

where B is bandwidth. In this paper, we take the same value for all vehicle pairs since the bandwidth allocation is not our focus. $\mathit{\Gamma}^{com}_n$ is the SINR of communication and can be expressed as

$$\mathit{\Gamma}^{com}_n = \frac{P_n\left(h^c_n\right)^2}{\sigma^2+\sum_{n'\epsilon\mathcal{N}\backslash n}\varrho_n P_{n'}\left(h^c_{n,n'}\right)^2}. \tag{7}$$

2) Age of Information (AoI): It is the performance metric characterizing the timeliness of message transmission by denoting the difference between the generation time of the last successfully received message and the current time. As such, it takes not only the transmission delay of the message into consideration, but also reflects the degradation of information over time. In the ISAC-enabled V2V system, AoI can be used to evaluate the rapid response capability of vehicle system to various events such as safety warnings, traffic congestion, etc. In particular, AoI is one of the most significant performance metrics in intelligent vehicular systems since it is critical in achieving millisecond-level emergency braking without human intervention and undertaking emergency avoidance in challenging driving conditions.

AoI is a decision criterion influenced by both communication and sensing processes. Due to the different time instants to receive the sensing information, the AoI evolution for SV and CV exists a little difference, which is described in detail as follows.

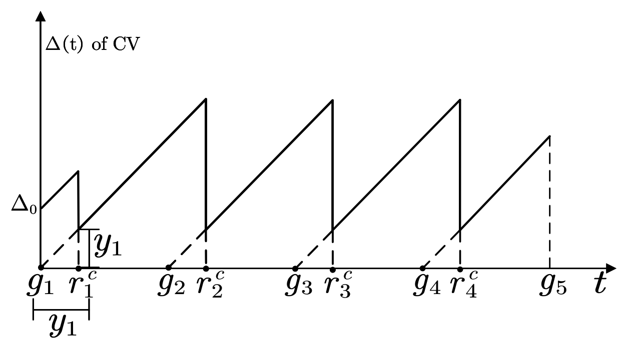

Fig. 3. Evolution of AoI for CV.

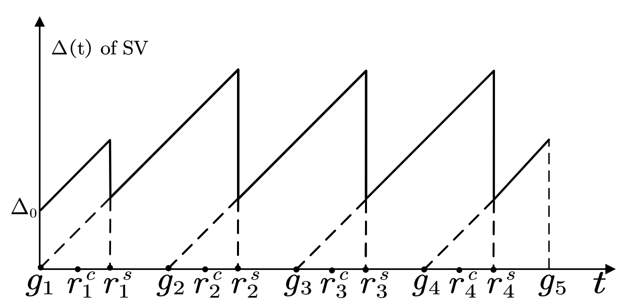

Fig. 4. Evolution of AoI for SV.

AoI for CV: Each CV receives the sensing information at r^c_1, r^c_2, etc (refer to Fig. 2). Therefore, the evolution of instantaneous AoI of CV is illustrated in Fig. 3, where g_i and r^c_i, $(i=1,2,\dots)$ denote the time instant of generating and receiving the sensing information, respectively. Let $g(t)$ represent the generation time of the most recently received information until time instant t, which can be expressed as

$$\mathrm{g}(t) = \max\{g_i : r_{\mathrm{i}}^{\mathrm{c}} \leqslant t\}. \tag{8}$$

Thus, AoI at the instantaneous moment t can be given as

$$\Delta(t) = t - \mathrm{g}(t). \tag{9}$$

For example, when $t = r_1^{\mathrm{c}}$, the message generated at the time g_1 is received, and the AoI is updated to $r_1^{\mathrm{c}} - g_1 = y_1$ as shown in Fig. 3.

AoI for SV: Each SV receives the sensing information transmitted from CV at the time instants r_1^s, r_2^s, etc. Therefore, the evolution of AoI for SV is shown in Fig. 4.

In this paper, we take the average AoI as the evaluation criterion for optimization. Over an interval $(0, \mathfrak{t})$, the average AoI is

$$\Delta_{\mathfrak{t}} = \frac{1}{\mathfrak{t}} \int_0^{\mathfrak{t}} \Delta(t) dt. \tag{10}$$

III. Problem Formulation

A. AoI-based Utility Function

In this paper, we focus on the AoI of the received sensing information at both CV and SV. The sensing information with shorter AoI will be more valuable. In addition, with the increase of AoI, the value will decay more quickly. Considering these two features, we use a non-linear function to model the value of sensing information with respect to AoI. In specific, we define the AoI-based utility function as $u(\Delta(t)) = 1/\Delta^2(t)$. Then, we can derive the average AoI-based utilities for the CV and SV by integrating over the five intervals shown in Fig. 3 and Fig. 4, respectively.
For CV :

$$u_n^{\tau} = \frac{1}{4T_s}\left[\int_{g_1}^{r_1^{\mathrm{c}}} u(\Delta(t))\, dt + 3\int_{r_1^{\mathrm{c}}}^{r_2^{\mathrm{c}}} u(\Delta(t))\, dt + \int_{r_4^{\mathrm{c}}}^{g_5} u(\Delta(t))\, dt\right]. \tag{11}$$

And for SV:

$$u_n^{\alpha} = \frac{1}{4T_s}\left[\int_{g_1}^{r_1^{s}} u(\Delta(t))\, dt + 3\int_{r_1^{s}}^{r_2^{s}} u(\Delta(t))\, dt + \int_{r_4^{s}}^{g_5} u(\Delta(t))\, dt\right], \tag{12}$$

where T_s represents the length of one time slot. Then, the achieved AoI-based utility for the vehicle pair n is given as

$$u_n = u_n^{\tau} + u_n^{\alpha}. \tag{13}$$

B. Problem Modelling

Considering the significance of AoI, we aim to maximize the total AoI-based utility of all vehicle pairs, with the constraint of sensing quality requirement, while ensuring that sensing information can be successfully transmitted within each time slot for all vehicle pairs. Thus, the optimization problem is formulated as

$$\max_{\{\alpha_n\}\{\tau_n\}} \sum_{n\in\mathcal{N}} \psi_n u_n \tag{14a}$$

$$\text{s.t. } \mathit{\Gamma}_n^{sen} \geqslant \gamma_n^{sen}, \forall n \in \mathcal{N}, \tag{14b}$$

$$\alpha_n \geqslant \frac{MI_n}{R_n}, \forall n \in \mathcal{N}, \tag{14c}$$

$$0 \leqslant \alpha_n + \tau_n \leqslant T_s, \forall n \in \mathcal{N}, \tag{14d}$$

$$\alpha_n \geqslant 0, \tau_n \geqslant 0, \forall n \in \mathcal{N}, \tag{14e}$$

$$\sum_{n\in\mathcal{N}} \psi_n = 1, \psi_n \in [0,1], \forall n \in \mathcal{N}, \tag{14f}$$

where $\psi_n \in [0, 1]$ is the non-negative constant weight for vehicle pair n, γ_n^{sen} denotes the requirement of the sensing SINR, reflecting the sensing accuracy requirement and correlated with the sensing time duration (i.e., the decision variable τ_n). That is, constraint (14b) represents the sensing requirement for each vehicle pair. (14c) is to ensure that all sensing information can be transmitted efficiently within the communication time. (14d) is the definition of an upper bound on the sum of those two time periods. (14e) restricts the decision variables to be positive, while (14f) constrains the sum of the weights of all vehicle pairs to 1.

IV. Optimization Algorithm

It is observed that the coupling of decision variables to each other in (14) leads to a complex situation. Applying transformations, we can obtain a solvable convex problem.

Firstly, we derive the specific equation of AoI-based utility for each pair of vehicles via the integrals in (11), (12), and (13).

$$u_n = \frac{1}{4T_s}\left(\frac{2}{\Delta_0} - \frac{2}{T_s}\right) \tag{15a}$$

$$+ \frac{1}{4T_s}\left(\frac{-1}{\Delta_0 + \tau_n} + \frac{-3}{T_s + \alpha_n}\right) \tag{15b}$$

$$+ \frac{1}{4T_s}\left(\frac{-1}{\Delta_0 + \tau_n + \alpha_n} + \frac{-3}{T_s + \tau_n + \alpha_n}\right) \tag{15c}$$

$$+ \frac{1}{T_s}\left(\frac{1}{\tau_n} + \frac{1}{\alpha_n + \tau_n}\right). \tag{15d}$$

For the maximization problem (14), the objective function u_n should possess concave property. Accordingly, we decompose u_n into four blocks and work through these step by step. (15a) and (15b) are constant terms and concave function terms without coupling among the decision variables, respectively. The variables in (15c) are coupled and the two terms in (15d) are convex, so further processing needs to be done.

We justify the joint concave property of (15c) to τ_n and α_n in Appendix A. Next, we convert (15d) to a concave function through the equivalent quadratic transformation method.

$$\frac{1}{\tau_n} + \frac{1}{\tau_n + \alpha_n} \Rightarrow 2e_n - e_n^2 \tau_n + 2\varphi_n - \varphi_n^2(\alpha_n + \tau_n), \tag{16}$$

where $\boldsymbol{e} = \{e_n \in \mathbb{R} \mid \forall n \in \mathcal{N}\}$ and $\boldsymbol{\varphi} = \{\varphi_n \in \mathbb{R} \mid \forall n \in \mathcal{N}\}$ are the collections of newly introduced auxiliary variables

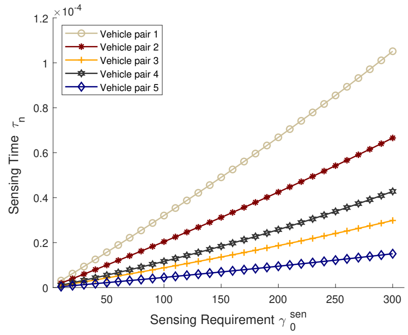

Fig. 6. The sensing time duration versus sensing requirement for each vehicle pair.

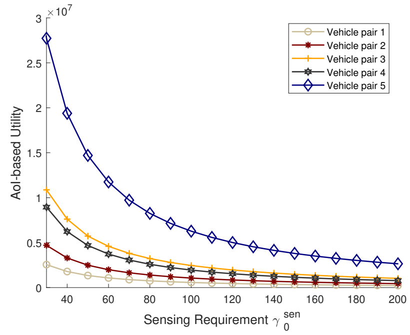

Fig. 7. AoI-based utility versus sensing requirement for each vehicle pair.

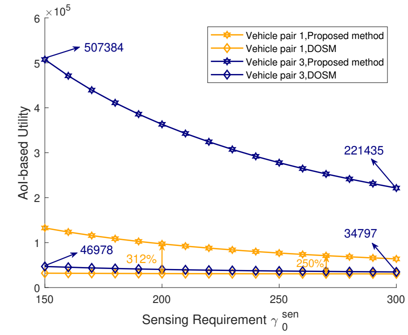

Fig. 8. AoI-based utility comparison between proposed method and DOSM.

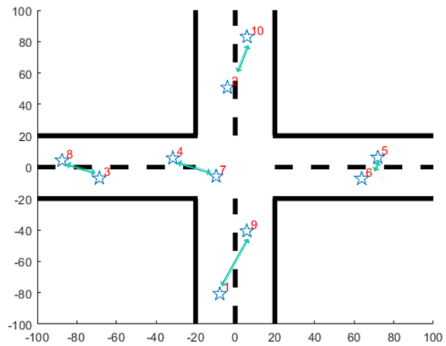

Fig. 5. Intersection scenario.

without any constraint. Thus, employing the transformations in (16), we finally obtain a concave objective function for the maximization problem.

For the variables coupled in constraint (14c), we adopt some transformations and verify the joint convexity of α_n and τ_n after the transformations. To start with, we make an equivalence expansion of it.

$$\frac{\tau_n}{2\alpha_n \mathrm{R}_n} \log_2 \left(1 + \frac{\tau_n P_n \left(h_n^s\right)^2}{\sigma^2 + \sum_{n' \in \mathcal{N} \setminus n} \varrho \tau_n P_{n'} \left(h_{n,n'}^s\right)^2} \right) \leqslant 1. \tag{17}$$

Then, we can derive the following inequality

$$\frac{P_n \left(h_n^s\right)^2 \tau_n}{2^{\frac{2\alpha_n \mathrm{R}_n}{B\tau_n}} - 1} - \sum_{n' \in \mathcal{N} \setminus n} \varrho \left(h_{n,n'}^s\right)^2 P_{n'} \tau_n - \sigma^2 \leqslant 0. \tag{18}$$

Subsequently, our objective is to demonstrate the joint convexity of τ_n and α_n in the left-hand side of inequality (18), and we verify this conclusion in Appendix B.

Finally, simply by applying the transformations in (16), we can obtain an equivalent convex problem to (14) and then use the function in the Optimization Toolbox of MATLAB to get the optimal solution.

V. Performance Evaluation

In this section, we demonstrate the performance of the proposed method and optimal design in ISAC-enabled V2V scenario. As shown in Fig. 5, we simulate an intersection area with the size of 100m$\times$100m, where the total width of the two-lane roads is 10m and 10 vehicles are formed into 5 pairs. All vehicles are set at a height of 1.5 m. In specific, vehicles 1 and 9, 2 and 10, 3 and 8, 4 and 7, 3 and 8 form into the 1st, 2nd, 3rd, 4th, and 5th vehicle pair, respectively, and the corresponding in-pair vehicle distance is 42m, 33m, 21m, 24m, and 15m, respectively. The carrier frequency and bandwidth are 28 Ghz and 100 Mhz. Sensing path loss is calculated according to the one-way standard radar equation, as the inverse of the square of the distance. The communication channel is designed according to the 3GPP-3D channel in TR 38.901.

Fig. 6 depicts the sensing time versus different sensing requirements. It is observed that the sensing time duration increases with the increase of sensing accuracy requirement. Meanwhile, with the same sensing requirement, the larger distance within the vehicle pair, the longer the sensing time duration and the sensing data delivery time due to the worse channel condition. Fig. 7 depicts the achieved AoI-based utility with different sensing requirements. It is observed that with the increase of sensing accuracy requirement, the achieved AoI-based utility decreases. This is because to satisfy the high sensing accuracy requirement, longer sensing time duration and longer sensing data transmission will be taken. Therefore, CV and SV need to wait for a longer time to receive and update the sensing information, resulting in a longer AoI and a smaller AoI-based utility.

In Fig. 8, we compare our proposed method with the direct one-time sensing method (denoted as DOSM) used in the literatures [3], [4], under the same sensing requirements within the scheduling period. It is observed that our proposed method and optimal design can achieve significant improvement in terms of AoI-based utility compared with DOSM. In specific, our proposed method can increase the achieved AoI-based utility by 312% and 250% when the sensing SINR requirement is 200 and 270, respectively, for the first vehicle pair. In addition, we perform integration to obtain the comparison of AoI, and the results show that our proposed method can provide a faster update of the sensing information. In specific, our proposed method can reduce AoI by 48% and 57% with SINR requirements of 200 and 270, compared with DOSM.

VI. Conclusion

In this paper, we have designed the optimal time arrangement in ISAC-enabled V2V scenario to maximize the AoI-based system utility while satisfying the sensing quality requirements. Through several transformations, we have turned a non-convex complex problem with multivariate coupling into a convex problem and finally derived the optimal solution. Simulation results have demonstrated the effectiveness of our proposed method and optimal design. In specific, our proposed method can significantly improve the AoI-based utility and provide a faster update of the sensing information by highly reducing the AoI of the received sensing information.

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Appendix A

Apparently, the two parts of the formula in (15c) have a similar shape, thus we just require to prove that one of them is a concave function. So, we take $\mathcal{G}\left(\tau_n,\alpha_n\right)=\frac{-1}{\Delta_0+\tau_n+\alpha_n}$ in (15c) as an example. Exploiting the rotational symmetry of the two variables and the property of their linear equal weights adding up in the denominator, we can easily yield

$$\frac{\partial^2\mathcal{G}}{\partial\tau_n^2}=\frac{\partial^2\mathcal{G}}{\partial\alpha_n^2}=\frac{\partial^2\mathcal{G}}{\partial\tau_n\partial\alpha_n}=\frac{\partial^2\mathcal{G}}{\partial\alpha_n\partial\tau_n}\leqslant 0. \tag{19}$$

Hence, this equation is a jointly concave function with respect to both variables.

Appendix B

To start with, we adopt the first part of (18) as $f_n\left(\alpha_n,\tau_n\right)$, from which we can also take

$$g_n\left(\alpha_n\right)=\frac{\left(h_n^s\right)^2 P_n}{2^{\frac{2\mathrm{R}_n\alpha_n}{B}}-1}. \tag{20}$$

Note that we are able to conclude that

$$\tau_n g_n\left(\frac{\alpha_n}{\tau_n}\right)=f_n\left(\alpha_n,\tau_n\right). \tag{21}$$

Therefore, $f_n\left(\alpha_n,\tau_n\right)$ is a perspective function of $g_n\left(\alpha_n\right)$. We just need to prove that (20) is a convex function with respect to α_n. Taking the second-order derivative of $g_n\left(\alpha_n\right)$, we obtain

$$\frac{\partial^2 g_n}{\partial\alpha_n^2}=\frac{\left(h_n^s\log 2\right)^2 P_n b^2\left(2^{2b\alpha_n}+2^{b\alpha_n}\right)}{2^{3b\alpha_n}-3\cdot 2^{2b\alpha_n}+3\cdot 2^{b\alpha_n}-1}, \tag{22}$$

where $b=\frac{2R_n}{B}$ is considered to be a constant positive during this stage of the optimization procedure. The numerator part of this equation is obviously non-negative and all we must do is to prove that the denominator is constantly positive. We denote it as $m\left(\alpha_n\right)$ and find the first-order derivative

$$\frac{\partial m}{\partial\alpha_n}=3b\log 2\left(-2^{2b\alpha_n+1}+2^{3b\alpha_n}+2^{b\alpha_n}\right). \tag{23}$$

Applying AM-GM inequality, we derive

$$2^{3b\alpha_n}+2^{b\alpha_n}\geqslant 2\sqrt{2^{3b\alpha_n}\cdot 2^{b\alpha_n}}=2^{2b\alpha_n+1}. \tag{24}$$

On the condition that $m\left(\alpha_n\right)$ is a monotonically increasing function of α_n, we are capable of verifying that m = 0 if α_n is equal to 0. Meanwhile, considering the actual situation in our model, α_n would necessarily be greater than 0. So $m\left(\alpha_n\right)>0$, which implies that the second-order derivative of $g_n\left(\alpha_n\right)$ is constant and positive. Eventually, we successfully demonstrate that the constraint (14c) is a convex function about all of the decision variables.

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