Joint Radio Resource Allocation and Control for Resource-Constrained Vehicle Platooning

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***Abstract*—Vehicle platooning is an effective way to improve the efficiency and safety of transportation systems, in which a group of vehicles maintains a moving pattern by minimizing the tracking error of each vehicle. In this paper, a joint optimization of radio resource allocation for kinetic status information transmission and platoon control is considered under resource-constrained conditions to maintain the targeted inter-vehicle spacing. The formulated problem is approximately solved by the decomposition method, where the radio resource allocation and the platoon control are considered alternatively in two stages. In the first stage, a tracking error based scheduling strategy is presented for radio resource allocation. In the second stage, the control inputs of each vehicle are optimized based on the model predictive control (MPC). Simulation results show that the proposed scheme can achieve the objective of platoon control while having a low tracking error compared with other scheduling strategies.**

***Index Terms*—Vehicle platooning control, radio resource management, intra-platoon communications.**

I. Introduction

With the development of the automobile industry and urbanization, more and more vehicles travel on the highways connecting neighboring cities. It is estimated that there are currently more than 1 billion motor vehicles registered worldwide. As a result, a series of key problems in modern transportation systems are becoming more and more serious, such as traffic congestion, traffic accidents, energy waste and pollution [1]. To address these issues, an effective approach is to change the driving pattern from conventional individual driving to platoon-based driving.

A vehicle platooning is a group of vehicles that share a common moving pattern, in which each platoon member vehicle (PM) follows platoon leader vehicle (PL) and maintains a targeted inter-vehicle spacing to the preceding PM. In vehicle platooning, the inter-vehicle spacing and velocity of each PM are regulated by a centralized controller that relies on the periodic collection of information about the PM's kinematic state (including position, velocity, acceleration, etc.) through vehicle-to-vehicle (V2V) communications. Clearly, vehicle platooning is a complex networked control system that integrates communication, control technologies and so on. Therefore, for vehicle platooning, it is necessary to study not only the advanced platooning control scheme but also the efficient platoon-based V2V communication mechanism.

In the past decades, many researches have separately focused on the platoon communication or the platoon control. For the communication protocol design, some advanced inter-vehicle communication protocols for the dissemination of periodic beacon messages and event-driven safety messages have been proposed [2]–[5]. For the radio resource allocation, some sub-channel allocation schemes and power control mechanisms for vehicle platooning have been studied [6], [7]. On the other hand, in recent years, some advanced platoon control laws have been proposed, including cooperative adaptive cruise control (CACC) [8], sliding-mode control (SMC) [9], and model predictive control (MPC) [10], [11]. However, for the work related to platoon communications, existing platoon-based V2V communication protocols and radio resource allocation schemes aimed to improve the spectrum efficiency or reliability while ignoring platoon control requirements. For the platoon control, these works ignored the impact of intra-platoon communications on the platoon control. To handle these issues, [12]–[15] have jointly dealt with both communication and control of vehicle platooning. Although [12], [13] focus on designing the platoon-based V2V communication mechanism subject to the stability requirements of the platoon control, they do not optimize the performance of the platoon control. [14], [15] optimize the performance of the platoon control, but they do not consider the disturbances and uncertainty in the vehicle dynamics.

This paper studies the joint optimization of radio resource allocation for kinetic status information transmission and platoon control under resource-constrained conditions to maintain the targeted inter-vehicle spacing while considering the disturbances and uncertainty in the vehicle dynamics. We assume that the platoon moves in a straight line under the targeted inter-vehicle spacing moving pattern, PM can communicate with PL. The controller of PL optimizes the control inputs according to the periodic collection of information about the PM's kinematic state to keep the platoon driving safely and stably.

The remainder of this paper is organized as follows. Section II describes the system model. Section III formulates the considered problem. Section IV presents the solution to the formulated problem. Section V presents simulation results and analyses. Finally, Section VI concludes the paper.

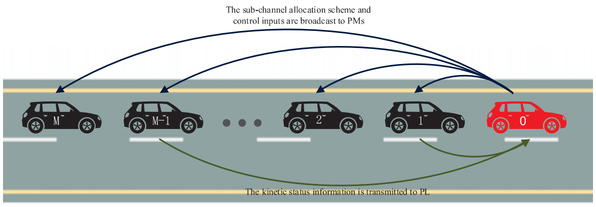


Fig. 1. A typical vehicle platooning.

II. System Model

Consider a platoon of $M+1$ vehicles running on a horizontal road, shown in Fig. 1, including a PL and M PMs. Label the vehicles as $0, 1, ..., M$, where vehicle 0 is PL and the others are PMs. The constant spacing policy is adopted for vehicle platooning, which aims to maintain constant inter-vehicle spacing. Under resource-constrained conditions, consider that there are B sub-channels per control cycle with $B \leq M$. To realize the platoon control, PMs allocated sub-channels can communicate with PL to transmit their kinematic state information. Then, based on these information, PL's controller can regulate PMs acceleration or deceleration.

A. Vehicle Dynamics

The model of vehicle dynamics captures the relationship between vehicle kinetic status and control variables. The control variable is specified as acceleration, and the kinetic status consists of vehicle position and velocity. The discrete-time dynamics models for PM m are respectively expressed as

$$x_m(t+1) = x_m(t) + v_m(t)T, \text{and} \tag{1a}$$
$$v_m(t+1) = v_m(t) + u_m(t)T, \tag{1b}$$

where $x_m(t)$ and $v_m(t)$ denote the position and velocity of PM m at time t, respectively; T is the discrete time interval; and $u_m(t)$ is PM m's control input, i.e., its desired acceleration. Let vector $\mathbf{y}_m(t) = [x_m(t), v_m(t)]^T$ denote the kinetic status of PM m at time t, so that (1) can be rewritten as

$$\begin{aligned}\mathbf{y}_m(t+1) &= \mathbf{F}[\mathbf{y}_m(t), u_m(t)] \\ &= \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_m(t) \\ v_m(t) \end{bmatrix} + \begin{bmatrix} 0 \\ T \end{bmatrix} u_m(t),\end{aligned} \tag{2}$$

where matrix $\mathbf{F}[\cdot, \cdot]$ denotes the vehicle dynamics function.

B. Objective of the Platoon Control

The objective of platoon control is making the followers track the leader's speed, while maintaining a desired constant distance gap D between adjacent vehicles. Mathematically,

$$\begin{cases} \lim\limits_{t \to \infty} |v_m(t) - v_0(t)| = 0, \\ \lim\limits_{t \to \infty} |x_m(t) - (x_0(t) - mD)| = 0, \end{cases} \quad m = 1, ..., M. \tag{3}$$

C. Intra-Platoon Communications

The PMs allocated sub-channels send their real-time kinetic status information to PL through V2V communications, and the controller of PL performs joint optimization of radio resource allocation and platoon control according to the periodically received status information, and the results are broadcast to PMs, as shown in Fig. 1. Repeat the above process for each control cycle to keep the platoon driving safely and stably.

D. MPC-Based Platoon Control Model

A platoon control model determines how to calculate the vehicles' control inputs in each control cycle. Inspired by [11], we present a platoon control model using a modified MPC model. The MPC model differs significantly from [11] in that it considers resource allocation as well as disturbances and uncertainty in the vehicle dynamics. In the following, we take PM m as an example to present the control model.

As shown in Fig. 2, PL's controller predicts the control inputs in N cycles. These N cycles are called the prediction window. Focusing on time t, we define two types of PM m's kinetic status over the prediction horizon $[t, t+NT]$, i.e., $\mathbf{y}_m^p(k|t)$ and $\mathbf{y}_m^a(k|t)$, where the former is the predicted kinetic status of PM m at time $t+(k-1)T$ and the latter is the assumed kinetic status of PM m at time $t+(k-1)T$. $y_m^p(k|t)$ is estimated in the cycle at the start of time t according to the vehicle dynamics function (2), which depends on $\mathbf{y}_m^p(1|t)$. If PM m is allocated a sub-channel at time t, it can send its actual kinetic status information to the PL so that $\mathbf{y}_m^p(1|t)$ is actual kinetic status of PM m at time t, otherwise $\mathbf{y}_m^p(1|t)$ is predicted kinetic status of PM m in the previous cycle. Considering the disturbances and uncertainty in the vehicle dynamics, the actual kinetic status is the predicted kinetic status plus Gaussian noise. The way to get $\mathbf{y}_m^a(k|t)$ is similar to $\mathbf{y}_m^p(k|t)$. PL's controller calculate predicted control inputs, i.e., $u_m^p(k|t), k = 1, 2, ..., N$; and $u_m^p(N+1|t)$ is set to 0. $u_m^p(1|t)$ is set as $u_m(t)$, the actual control input of PM m in time t, which is transmitted to PM m from PL. $u_m^a(k|t)$, the assumed control input of PM m at time $t+(k-1)T$, which is a shifted version of the predicted control input calculated in the cycle starting at time $t-T$, shows as follows:

$$u_m^a(k|t) = u_m^p(k+1|t-T), k = 1, 2, ..., N. \tag{4}$$

According to the platoon control objective, each vehicle tracks the speed of the leader and maintains a desired distance gap with the preceding vehicle. In this model, the platoon control objective function is applied to the entire prediction window. Then, the control model can be formulated as an optimization problem to keep a desired status.

III. Problem Formulation

Radio resource allocation and platooning control affect the performance of a platoon simultaneously. Therefore, this paper aims to jointly deal with sub-channel allocation and control of each PM to maintain the constant inter-vehicle spacing by minimizing the tracking error of each PM.

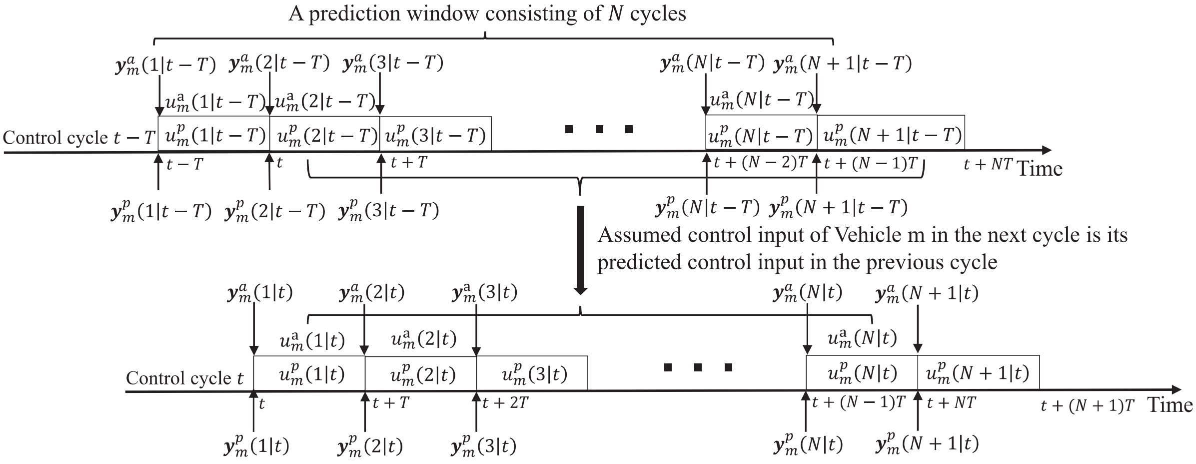


Fig. 2. MPC-based platoon control model on PL's controller.

Towards this aim, the kinetic error between adjacent cars is expressed as

$$e_{m,m-1} = \sum_{k=1}^{N} C_{m,m-1} ||\mathbf{y}_m^p(k|t) - (\mathbf{y}_{m-1}^a(k|t) - (D,0)^T)||_2, \quad m = 2,3,...,M. \tag{5}$$

where $C_{m,m-1}$ and $e_{m,m-1}$ are the weighting factor and the kinetic error between PM m and PM $m-1$, respectively. Then, the kinetic error between PM and PL is expressed as

$$e_{m,0} = \sum_{k=1}^{N} C_{m,0} ||\mathbf{y}_m^p(k|t) - (x_0(t) - mD, v_0(t))^T||_2, \quad m = 1,2,...,M. \tag{6}$$

where $C_{m,0}$ and $e_{m,0}$ are the weighting factor and the kinetic error between PM m and PL, respectively. The objective function of PM m takes its tracking error into consideration, which can be represented as

$$e_m = e_{m,m-1} + e_{m,0}. \tag{7}$$

Based on the objective function of each PM, the objective function of the vehicle platooning can be defined as the sum of each PM's tracking error. At each control cycle, the problem of joint sub-channel allocation and control inputs optimization for the vehicle platooning is formulated as

$$\min_{\Omega_{l,t},\Omega_{u,t}} \sum_{m=1}^{M} e_m \tag{8a}$$

$$\text{s.t.} \quad \mathbf{y}_m^p(k|t) = [x_m^p(k|t), v_m^p(k|t)]^T, \tag{8b}$$

$$\mathbf{y}_m^a(k|t) = [x_m^a(k|t), v_m^a(k|t)]^T, \tag{8c}$$

$$\mathbf{y}_m^p(k+1|t) = \mathbf{F}[\mathbf{y}_m^p(k|t), u_m^p(k|t)], \tag{8d}$$

$$\mathbf{y}_m^a(k+1|t) = \mathbf{F}[\mathbf{y}_m^a(k|t), u_m^a(k|t)], \tag{8e}$$

$$\mathbf{y}_m^p(1|t) = \begin{cases} \mathbf{y}_m(t), & l_{m,t} = 1 \\ \mathbf{y}_m^p(2|t-T), & l_{m,t} = 0, \end{cases} \tag{8f}$$

$$\mathbf{y}_m^a(1|t) = \begin{cases} \mathbf{y}_m(t), & l_{m,t} = 1 \\ \mathbf{y}_m^p(2|t-T), & l_{m,t} = 0, \end{cases} \tag{8g}$$

$$\sum_{m=1}^{M} l_{m,t} = B, \tag{8h}$$

$$u_{min} \le u_m^p(k|t) \le u_{max}, \tag{8i}$$

$$\mathbf{y}_m^p(N+1|t) = \mathbf{y}_{m-1}^a(N+1|t) - (D,0)^T, \tag{8j}$$

where $l_{m,t} = \{0,1\}$ is a binary variable, which represents the allocation result of the sub-channels. If PM m is allocated a sub-channel at time t, $l_{m,t} = 1$, otherwise $l_{m,t} = 0$. $\Omega_{l,t} = \{l_{m,t}, m = 1,2,...,M\}$ denotes the sub-channel allocation scheme for the PMs and $\Omega_{u,t} = \{u_m(t), m = 1,2,...,M\}$ denotes the control inputs for the PMs. Besides, all the above constraints hold when $m = 1,2,...,M$. Constraints (8b) and (8c) represents that PM m's predicted kinetic status and assumed kinetic status consist of its position and velocity, respectively. Constraints (8d) and (8e) represent vehicle dynamics requirements of predicted kinetic status and assumed kinetic status, respectively. Constraints (8f) and (8g) represent the effect of sub-channel allocation on predicted kinetic status and assumed kinetic status, respectively. If PM m is allocated a sub-channel, the kinetic status at the start of the control cycle is the actual kinetic status of PM m at time t, otherwise it is predicted kinetic status of PM m in the previous cycle. Constraint (8h) ensures the number of sub-channels allocated to PMs is B, where the case of reuse is not considered, and each PM can only be allocated at most one sub-channel. Constraint (8i) represents the limit on the control inputs of each PM. Constraint (8j) is to make the control process convergent, which means that PM m has the desired kinetic status error with PM $m-1$ at the end of the predictive horizon.

IV. Solution For the Formulated Problem

In actual scenarios, PL can hardly know the global information at the start of each control cycle, the actual kinetic status

Algorithm 1 Procedures of the Two-Stage Algorithm to Solve Problem (8)

Input: B, D, N, T, u_{min}, u_{max}, $C_{m,m-1}$ for $m = 2, ..., M$ and $C_{m,0}$ for $m = 1, ..., M$

Output: $\Omega^*_{l,t}$ and $\Omega^*_{u,t}$

Initialization: at time $t = 0$, initialize the assumed values for each PM. Take PM m for example, initialize $u^a_m(k|0)$, $\mathbf{y}^a_m(k|0)$ and $\mathbf{y}^p_m(k|0)$ based on (11), (12).

1. **Stage I**: at any time $t > 0$, according to the tracking error of PMs at time $t-T$ (i.e., e_m, $m = 1, ..., M$), set the index of the largest B tracking errors to set $\mathcal{M}$.

for m = 1 : M **do**
  if $m \in \mathcal{M}$ **then**
    $l^*_{m,t}$ = 1
  else
    $l^*_{m,t}$ = 0
  end if
end for

2. Obtain $\Omega^*_{l,t}$ from $l^*_{m,t}$.
3. **Stage II**: at any time $t > 0$, for all PMs $m = 1, ..., M$, the steps to be followed are as follows.
1) According to $\Omega^*_{l,t}, \mathbf{y}_m(1|t), \mathbf{y}^a_{m-1}(k|t)$ and $\mathbf{y}_0(t)$, solve nonlinear constrained optimization problem (10) with interior point method, yielding optimal control sequence $u^*_m(k|t), k = 1, ..., N$.
2) Compute the assumed control inputs for next cycle based on (13).
3) Implement the control effort using the first element of optimal control sequence, i.e., $u_m(t) = u^*_m(1|t)$.
4. Obtain $\Omega^*_{u,t}$ from $u_m(t)$.
5. Increment t and go to Stage I.

information of each PM needs to be transmitted to PL through a sub-channel. As a result, finding its global optimal solution is intractable, and it is practical to solve our formulated problem approximately by the decomposition method, where the sub-channel allocation and the control for each PM are considered alternatively in two stages. In the first stage, PL allocates sub-channels according to the tracking errors of PMs. In the second stage, PL solves the control inputs of each PM based on the results of the sub-channel allocation and MPC-based platoon control model. Although we use a two-stage method to solve the problem, the optimization of the two stages is not independent, and they will interact. Because optimizing the control inputs is based on the sub-channel allocation scheme, the solution of the first stage will affect the control optimization of the second stage; the control inputs optimized in the second stage determine the tracking errors, which will affect the sub-channel allocation optimization of the first stage in the next cycle.

A. Stage I: Tracking Error Based Scheduling Strategy for Sub-channel Allocation

Unlike traditional communication networks, the radio resource scheduling in vehicle platooning aims at reducing the tracking error, which is essential to the platoon control. For PL, if it can receive the actual kinetic status information of PM m, it can better reduce the tracking error, e_m. In order to minimize the tracking error of each PM, the scheduler tends to allocate sub-channels to the PMs with larger tacking error rather than those with smaller tracking errors. Following this core idea, the tracking error based scheduling strategy can be formulated as

$$\max_{\Omega_{l,t}} \sum_{m=1}^{M} e_m l_{m,t} \quad \text{s.t. (8h)}, \tag{9}$$

where e_m represents the tracking error of PM m at time $t-T$. It can be seen that if PM m has a large tracking error, the PM m-PL link will have a significant probability of getting a sub-channel and then PL can obtain the actual kinetic status information of PM m. Utilizing the actual kinematic status information of PM m, PL can better reduce its tracking error.

B. Stage II: Optimizing Control Inputs of Each PM Based on MPC

After obtaining the sub-channel allocation scheme $\Omega^*_{l,t}$, problem (8) can be reduced as

$$\min_{u^p_m(1|t),...,u^p_m(N|t)} e_m \quad \text{s.t. (8b)-(8g), (8i), (8j)}. \tag{10}$$

This optimization problem is proved to be a convex problem and can be solved efficiently with the algorithm of MPC, which is shown as follows.

1) Initialization: At time $t = 0$, assumed that all the PMs are moving at a constant speed, and initialize the assumed values for PM m as,

$$\begin{cases} u^a_m(k|0) = 0, \\ \mathbf{y}^a_m(k|0) = \mathbf{y}^p_m(k|0), \end{cases} \quad k = 1, ..., N. \tag{11}$$

where $\mathbf{y}^p_m$ is iteratively calculated by

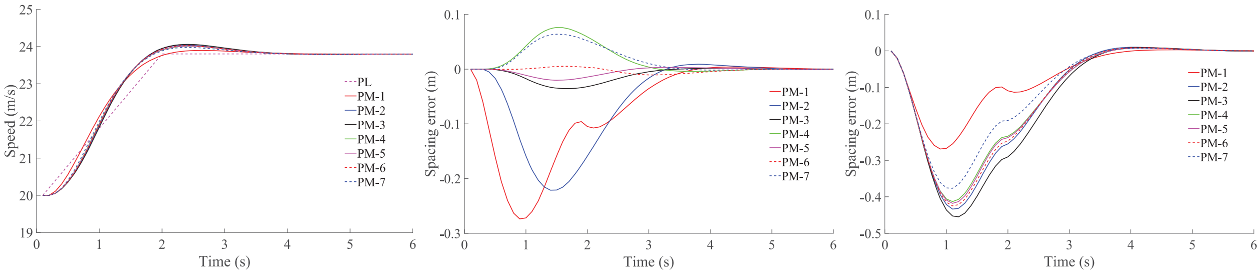
$$\begin{cases} \mathbf{y}^p_m(1|0) = \mathbf{y}_m(0), \\ \mathbf{y}^p_m(k+1|0) = \mathbf{F}[\mathbf{y}^p_m(k|0), u^a_m(k|0)], \end{cases} \quad k = 1, ..., N. \tag{12}$$

2) Iteration of MPC: At any time $t > 0$, for all PMs $m = 1, ..., M$, the steps to be followed are as follows.

1) According to current kinematic status $\mathbf{y}_m(1|t)$ determined by the sub-channel allocation result of the stage I, the assumed kinematic status of previous vehicle $\mathbf{y}^a_{m-1}(k|t)$ and the kinematic status of PL

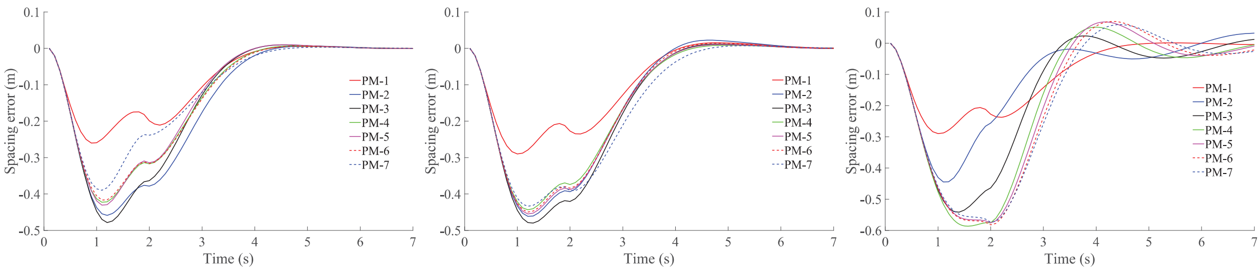
TABLE I
SIMULATION DEFAULT PARAMETER VALUES

Parameter	Value	Parameter	Value
T	0.1 s	u_{min}	$-6\ m/s^2$
M	7	u_{max}	6 m/s^2
B	4	σ	0.01 m/s^2
D	10 m	$C_{m,m-1}$	5
N	20	$C_{m,0}$	10



(a) Speed of vehicles (b) Spacing error with respect to the preceding vehicle (c) Spacing error with respect to PL

Fig. 3. Platoon control performance of our proposed scheme when $B = 6$.



(a) Global scheduling strategy (b) Tracking error based scheduling strategy (c) Round robin scheduling strategy

Fig. 4. Spacing error of PMs with respect to PL under different sub-channel allocation strategies.

$(x_0(t), v_0(t))^T$, solve nonlinear constrained optimization problem (10) with interior point method, yielding optimal control sequence $u_m^*(k|t), k = 1, ..., N$.

2) Compute the assumed control inputs, i.e., $u_m^a(k|t+T)$ for next cycle, that is

$$u_m^a(k|t+T) = \begin{cases} u_m^*(k+1|t), & k = 1, ..., N-1 \\ 0, & k = N. \end{cases} \tag{13}$$

3) Implement the control effort using the first element of optimal control sequence, i.e., $u_m(t) = u_m^*(1|t)$.
4) Increment t and go to step (1).

Note: One key part of MPC is how to construct the assumed kinematic status of each PM. Here, the assumed variable is a shifted optimal result of the previous cycle problem (10), synthesized by disposing the first value and adding a last value. The last added value ensures that the vehicle moves at a constant speed. In this MPC framework, all PMs are synchronized in each control cycle.

C. Summary of the Two-Stage Algorithm

To summarize, the procedures of the two-stage algorithm for solving problem (8) are illustrated in Algorithm 1.

V. Simulation Results

In this section, simulations are conducted to evaluate the proposed joint radio resource allocation and control scheme. The initial state of the platoon at $t = 0$ is set at a desired state: PL with $x_0(0) = 0\ m$ and $v_0(0) = 20\ m/s$, and PMs with $x_m(0) = -mD\ m$ and $v_m(0) = 20\ m/s$, $m = 1, 2, ..., M$, where the desired spacing D is 10 m. Consider a Gaussian noise with mean 0 and standard deviation σ in actuator of PMs. The trajectory of PL is given by,

$$a_0 = \begin{cases} 2\ m/s^2, & 0 < t < 2 \\ 0, & t \geq 2. \end{cases} \tag{14}$$

where a_0 is the acceleration of PL. Unless otherwise stated, the default values of the proposed scheme parameters are as in Table I.

In the simulation, we first evaluate the platoon control performance of our proposed scheme from the time domain perspective when the number of sub-channels is 6. Fig. 3 plots the speed of vehicles, the spacing error of PMs with respect to the preceding PM and the spacing error of PMs with respect to PL. It can be seen that the proposed scheme can control the spacing and speed within a normal range. The curves converge to 0, which indicates that the proposed scheme achieves the objective of platoon control (3).

We also evaluate the impact of radio resource allocation on the platoon control performance. For comparison, we simulated the other two scheduling strategies. The first one is the global scheduling strategy. It is assumed that PL knows the global information (the actual kinetic status information of each PM) at the beginning of each control cycle, then we can search for the global optimal solution to this problem by exhausting each sub-channel allocation scheme, which serves as a lower bound. The second one is the round robin scheduling strategy, in which each PM is scheduled in order. Fig. 4 plots the spacing error of PMs with respect to PL under

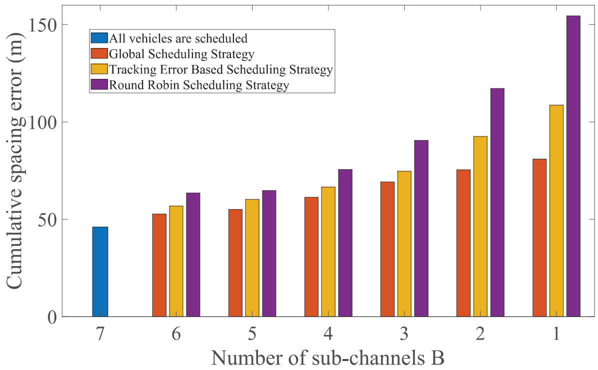


Fig. 5. Cumulative spacing error under different scheduling strategies and different numbers of sub-channels.

different sub-channel allocation strategies. It can be seen that the global scheduling strategy has the smallest absolute value of the spacing error and eliminates the spacing error shortly after PL has accelerated to a steady speed. This is because PL knows the global information of the PMs at the start of each control cycle. The tracking error based scheduling strategy is suitable for practical scenarios, and its performance is close to the global scheduling strategy and much better than the round robin scheduling strategy, which proves the feasibility of the tracking error based scheduling strategy.

To make the comparison more intuitive, we sum the spacing errors of all PMs with respect to PL and accumulate them in time to obtain the cumulative spacing error, which is used as an indicator of platoon control performance under different scheduling strategies and different numbers of sub-channels. Fig. 5 plots the cumulative spacing error under different scheduling strategies and different numbers of sub-channels. It can be seen that under the determined number of sub-channels, the performance comparison of different scheduling strategies is the same as before. The global scheduling strategy has the best performance, the tracking error based scheduling strategy is the second, and the round robin scheduling strategy is the worst. As the number of sub-channels decreases, the control performance of the platoon gradually deteriorates because the smaller the number of sub-channels, the less actual kinetic status information of the PMs can be obtained by PL in each control cycle.

VI. Conclusion

In this paper, we have investigated how to jointly optimize the radio resource allocation for the kinetic status information transmission and control of PMs to maintain the targeted inter-vehicle spacing. Thus, a joint optimization of radio resource allocation and control for vehicle platooning has been proposed and solved by a two-stage algorithm. Through simulation, we have evaluated the platoon control performance of our proposed scheme and analyzed the effects of the radio resource allocation on platoon control. Simulation results have validated that our proposed scheme can provide good control performance and indicated that it is necessary to design the vehicle platooning system from a joint communication-control perspective to improve control performance.

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