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Cluster-based Handoff Scheme Design for Platoons in Cellular V2X Networks

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***Abstract*—In this paper we propose a cluster-based platoon handoff protocol (CPHP), in which the platoon is divided into clusters to minimize its handoff delay between two adjacent cells. Via the vehicle-to-vehicle (V2V) communications, multiple clusters are constructed within one platoon and only the cluster head (CH) communicates with the base station (BS) via the vehicle-to-infrastructure (V2I) communications. In this way, the number of V2I links can be greatly saved and the signaling overhead is reduced, thereby shortening the handoff delay. Specifically, we formulate a delay minimization problem based on a discrete-time Markov chain and then optimize the number of clusters and spectrum resource allocation. Simulation results demonstrate a significant decrease in the handoff delay of the platoon. The optimal expected delay under a platoon with 50 vehicles by utilizing the proposed CPHP is 15% smaller than that of the traditional handoff scheme.**

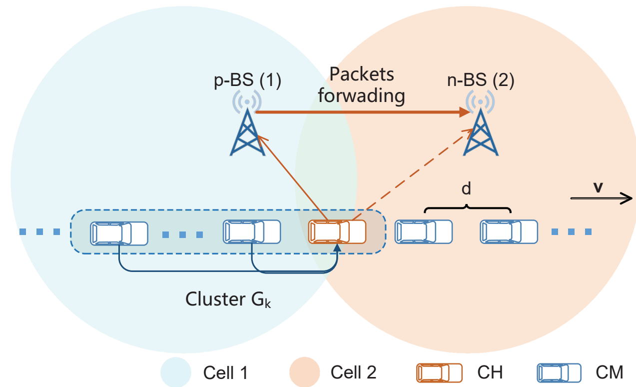

Fig. 1. Illustration for the platoon.

I. Introduction

Vehicular networks have attracted tremendous interests in the last decade, which are composed of wireless connectivity-enabled vehicles that can communicate with their internal and external environments [1]. Grouping vehicles into platoons is a promising strategy of the management for vehicular networks and an important use case for the fifth generation (5G) and beyond [2], since it improves the traffic flow throughput, reduces the energy consumption, and increases the driving safety by cooperative driving [3]. Typical applications include automatic driving on highway and platoon-based drive-thru internet access [4].

However, the stable formation of a platoon requires low communication latency, which is challenging when performing handoffs [4]. When a platoon moves across the coverage of multiple cells with high mobility, the frequent handoffs make it more necessary to shorten the handoff delay. In the literature, some works on the handoffs in the platoon-based [5] or cluster-based [6] vehicular networks have been studied. In [5], a group handoff scheme is proposed concerning the Long Term Evolution (LTE) message flow and handoff triggering rule. In [6], the authors propose a lightweight clustering authentication scheme for 5G-based vehicle-to-everything (V2X) communications, which reduces the computation overhead, thereby reducing the communication and handoff delays. However, these works leave out the optimization of the total handoff delay for a whole platoon, and the intra-cluster communications has not been fully utilized.

Different from these existing works, we study a handoff delay minimization problem for a whole platoon in the cellular networks. To provide scalability for large platoons, we adopt the divide and conquer technique, i.e., to divide a platoon into multiple clusters and analyze the handoff of each cluster. During the handoff, we adopt vehicle-to-vehicle (V2V) communications within the clusters and vehicle-to-infrastructure (V2I) communications between the cluster head (CH) and the base station (BS). The strategy allows flexible cluster handoff for a platoon with unfixed length and limited spectrum resources.

The utilization of this strategy brings in some new challenges. First, a protocol that supports flexible cluster formation and group handoff is required. Second, the impact of intrinsic characteristics of platoons on the handoff delay has to be taken into account, e.g., the size of the clusters should be designed carefully considering the spectrum resources of the network. Specifically, a large cluster size may cause high delay for the V2V communications, while a small cluster size corresponds to a large amount of clusters, which brings a heavy data traffic for the V2I communications and thus increase the delay.

To tackle these challenges, we propose a cluster-based platoon handoff protocol (CPHP). In the CPHP, we focus on optimizing the size of clusters and allocating spectrum resources within each cluster. We form Markov chains for the V2V and V2I communications, and analyze the handoff delay with different sizes of the clusters. A cluster number optimization and spectrum resource allocation algorithm is proposed to minimize the total handoff delay of the platoon.

The rest part of this paper is organized as follows. In Section II the scenario of the platoon handoff is introduced, and the proposed CPHP is illustrated. In Section III we analyze the expected delays by constructing discrete-time Markov chains. In Section IV, we formulate the delay minimization problem and propose a cluster design and resource allocation algorithm to solve it. We demonstrate the simulation results in Section V, which is followed by the conclusions in Section VI.

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II. System Model

In this section, we first describe the communication system of the platoon, and then introduce the handoff model.

A. Scenario Description

As shown in Fig. 1, we consider a vehicular network where N vehicular users (VUs) form a platoon, denoted by $\{1, 2, \cdots, N\}$. The VUs in the platoon move in the same direction with a uniform speed $\mathbf{v}$, and the distance between two adjacent VUs is denoted by d. Each VU of the platoon communicates with the nearby BS via V2I communications to maintain the topology and keep road safety.

When a VU roams across neighboring BSs, the connection should be handed off from the previous BS (p-BS) to the new BS (n-BS). For a traditional handoff scheme [7], the handoff process may suffer severe delay when the platoon contains a large number of VUs since the VUs hand off one by one and the signaling overheads are cumulated linearly. Among the overheads, mobility control information causes a large amount of delay increase [8]. Since the movement and environment of the VUs in the platoon are highly correlated, some of the signaling overheads are redundant and can be saved efficiently by data compression. To shorten the handoff delay, we form the platoon into clusters and design the CPHP.

In a cluster, one of the VUs works as the CH while the others work as cluster members (CMs). The CH communicates with each of the CMs via V2V communications to obtain required messages, such as movement control, accident monitoring, environment sensing and handoff information. The CH then communicates with the BS via V2I communications to send compressed data of the cluster and receives response information from the BS, which will be delivered to the CMs accordingly. In this way, duplicate information for the handoff of multiple VUs can be effectively reduced, thereby significantly reducing the delay. The details of the CPHP will be articulated in Section II-B and Section II-C.

B. Cluster-based Platoon Handoff Protocol

The handoff schemes in existing networks such as LTE and 5G [7] cannot be directly applied to the cluster-based handoff scenario due to the existence of new features such as cluster organization, cluster handoff triggering, and coordination of the communications for the CH, CMs, and BSs. To tackle these challenges, we propose the CPHP as shown in Fig. 2 consisting of three parts: *handoff preparation, handoff transition and handoff execution*.

1) Handoff Preparation: Before the handoff process, the VUs connect with the p-BS and send *Measurement Report* messages to it periodically. The p-BS sends *Measurement Control* messages to the VUs correspondingly to configure their movement. The p-BS also divides the platoon into clusters and assigns a potential CH for each cluster by *Measurement Control*, according to the current size of the platoon. The potential CH will periodically measure the received signal strength (RSS) of the BSs. When it moves from the range of the p-BS to the n-BS, it makes a handoff decision under a triggering rule, i.e., when the RSS between the CH and the n-BS is larger than that of the p-BS, the handoff process is triggered. The potential CH then informs the p-BS of a *Handoff Decision* message. The p-BS sends a *Handoff Request* message to the n-BS. If the n-BS is able to receive a new connection, it will send back a *Handoff Request Acknowledge* message to tell the p-BS to be ready for the handoff.

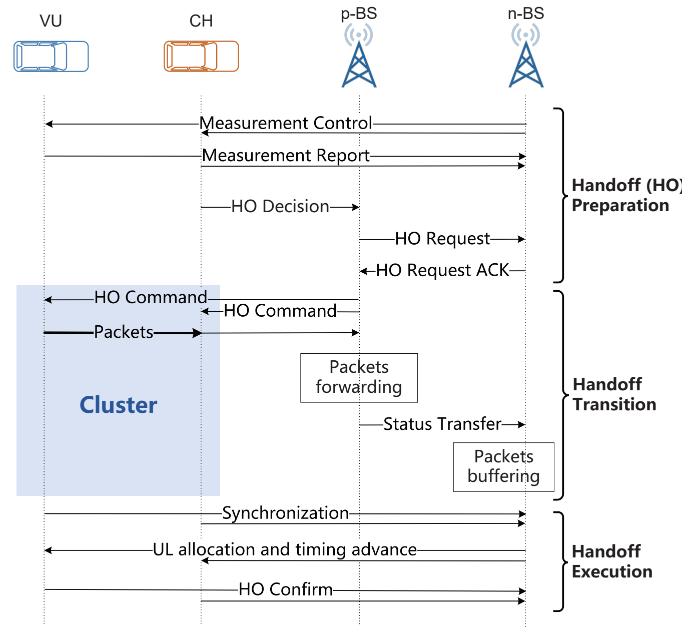

Fig. 2. The message flow of the handoff process for a cluster in the CPHP.

2) Handoff Transition: The p-BS sends the *Handoff Command* to all the VUs in the cluster where the potential CH belongs and starts forwarding the downlink packets to the n-BS. It is noted that the p-BS also sends *RRC Connection Reconfiguration*, *Mobility Control Information* and the status information indicating the packets that were acknowledged by the members of the cluster. The n-BS then buffers the forwarded packets. After receiving the *Handoff Command*, the CMs will stop current connections with the p-BS and establish V2V communications with their CH[1]. The CH can thus collect messages of the cluster and compress the highly-correlated part of them to reduce redundancy. The compressed cluster information and data from the unfinished V2I communications of the CMs will be sent to the p-BS by the CH via V2I communications.

3) Handoff Execution: After handoff transition, the VUs synchronize with the n-BS individually and the n-BS will send back the uplink allocation and timing advance information. In the end, the VUs send *Handoff Confirm* to the n-BS and the handoff process is finished.

The proposed CPHP can ensure that the intra-cluster communications and the cluster-BS communications work seamlessly and the duplicate information of different VUs can be reduced to shorten the handoff delay of the platoon. We will analyze the delay of the CPHP numerically in Section III.

[1]The number of available communication channels is limited. When the CMs outnumber the channels, the CH will allocate resources to the CMs.

C. Communication Model

In this part, we provide the mathematical model of the CPHP. We divide the platoon into M clusters, with s_k VUs in the k-th cluster. Let $q = \lfloor \frac{N}{M} \rfloor, r = N - Mq$, then

$$s_k = \begin{cases} q, & k = 1, \cdots, M - r \\ q + 1, & k = M - r + 1, \cdots, M. \end{cases} \quad (1)$$

We denote the clusters by $G_1, G_2, \cdots, G_M$, where $G_k = \{(k-1)q + 1, \cdots, (k-1)q + s_k\}$. As shown in Fig. 1, the CH is set as the first VU of a cluster, which first triggers the handoff process. When the platoon roams across neighbouring BSs, $G_1, \cdots, G_M$ trigger the handoff process in turn.

In the V2V communications, the CH receives data from each CM in the cluster. The channel gain from CM u to its CH in time slot t and in cluster G_k is denoted by

$$|h_{V,u}(k)|^2 = G \cdot (|(k-1)q + 1 - u|\, d)^{-\alpha} \cdot |h_0|^2, \quad (2)$$

where G is the constant power gain factor introduced by amplifier and antenna, $h_0 \sim \mathcal{CN}(0,1)$ is a complex Gaussian variable representing the Rayleigh fading, and α is the path loss coefficient.

We assume that each CM transmits data with fixed power, denoted by P_V. The signal-to-noise ratio (SNR) of the link between CM u and its CH in cluster G_k can be expressed as

$$\gamma_{V,u}(k) = \frac{P_V \, |h_{V,u}(k)|^2}{\sigma^2}, \quad (3)$$

where σ^2 is from the additive white Gaussian noise (AWGN) with 0 mean and σ^2 variance. The V2V channels in a cluster are orthogonal and there is no intra-cluster interference.

In the V2I communications, the channel gain from the CH of cluster G_k to BS b ($b \in \{1, 2\}$, where BS 1 refers to the p-BS and BS 2 refers to the n-BS as illustrated in Fig. 1) in time slot t is denoted by

$$|h_{I,b}(k,t)|^2 = G \, |\mathbf{d}_{I,b}(k,t)|^{-\alpha} \, |h_0|^2, \quad (4)$$

where $\mathbf{d}_{I,b}(k,t)$ is the distance vector from the CH of cluster G_k to BS b. The change of $\mathbf{d}_{I,b}(k,t)$ in two consecutive time slots can be presented as $\mathbf{d}_{I,b}(k,t+1) = \mathbf{d}_{I,b}(k,t) + \mathbf{v}$.

We assume that the CH transmits the data with fixed power, denoted by P_I. Another assumption is that there is no inter-cluster interference between the V2I links. The SNR of the V2I link between the CH of cluster G_k and BS b in time slot t can be expressed as

$$\gamma_{I,b}(k,t) = \frac{P_I \, |h_{I,b}(k,t)|^2}{\sigma^2}. \quad (5)$$

III. Delay Analysis

The delay of the handoff process comes from handoff preparation, handoff transition and handoff execution as described in Section II-B. Among them the delay of handoff preparation and the delay of handoff execution do not vary significantly with the proposed CPHP, as we make few modifications to these two parts. Therefore, we focus on the analysis of the handoff transition. In the following, we first describe the modeling of the Markov chain, and then derive the handoff delay.

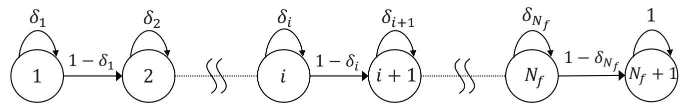

Fig. 3. Illustration for the Markov chain.

A. Markov-Chain Modeling Description

The delay of the process that p-BS sends the *Handoff Command* to the CH and CMs can be ignored as the size of *Handoff Command* is very small. Therefore, the communication process of handoff transition can be summarized as two procedures:

(i) The CMs send cluster information and unfinished messages to the CH via the V2V transmissions;
(ii) The CH sends compressed cluster information and unfinished messages to the p-BS via the V2I transmission.

We first analyze procedure (i) and the result of (ii) will be similarly obtained afterwards. In procedure (i), we focus on the communications between a single CM and the CH since the communication links between the CH and all the CMs in the cluster are mutually independent. In the V2V transmission, a CM needs to transmit multiple frames to the CH consecutively. The success of each frame transmission is a probabilistic model determined by the outage probability of the communication link. The CM keeps transmitting a frame until it is successfully received by the CH. The V2V communications are completed when all the frames have been successfully received by the CH. In the following, we form each V2V transmission link as a Markov chain, where the state of the Markov chain is the transmitted frame, and the state transition is the successful transmission of a frame.

We define a transmission step as the sum of durations required by a frame to generate, wait for an idle channel and transmit for once. Let $X_n^V(u,k)$ denote the number of the frame transmitted at the n-th transmission step between CM u and the CH in cluster G_k during the V2V communication. The state space is composed of the transmission steps.

We assume that each CM has to send N_f frames to the CH of its cluster denoted by $M_1, \cdots, M_{N_f}$ with lengths denoted by $L_1, \cdots, L_{N_f}$ respectively. Let $\delta_i^V(u,k)$ denote the probability of transmission failure of the i-th frame between CM u and the CH in cluster G_k during the V2V communication. The state space of $\{X_n^V(u,k)\}$ is $\Omega = \{1, \cdots, N_f, N_f + 1\}$, where $N_f + 1$ refers to the state that all frames are transmitted successfully. Hence, when $X_n = i$ $(i = 1, \cdots, N_f)$, the Markov chain either transits to state $i+1$ or remains at i, based on whether or not the transmission of the i-th frame is successful at the end of the n-th transmission step, as illustrated in Fig. 3.

B. Handoff Delay Derivation

We assume that a maximum number of N_C channels can be allocated to the V2V communications of the cluster performing handoff in each time slot. The CH will assign the channels to the CMs. We bring in a binary variable $\beta(u,k,t)$ to describe the channel assignment, where $\beta(u,k,t)=1$ if an idle channel is available to CM u in cluster G_k and in time slot t, otherwise $\beta(u,k,t)=0$. $\beta(u,k,t)$ of all CMs in cluster G_k satisfies

$$\sum_u \beta(u,k,t) \le N_C,\ \forall k,t. \tag{6}$$

For Markov chain $\{X_n^V(u,k)\}$, let $p_{ij}^V(u,k,t)$ denote the one-step transition probability from state i to state j, given as

$$p_{ij}^V(u,k,t)=\begin{cases}\big(1-\delta_i^V(u,k)\big)\beta(u,k,t), & \\ & j=i+1=2,\cdots,N_f+1\\ \delta_i^V(u,k), & j=i=1,\cdots,N_f\\ 1, & j=i=N_f+1\\ 0, & \text{otherwise.}\end{cases} \tag{7}$$

The outage probability is defined as the probability that the SNR falls below a predetermined threshold γ_{th}, which can be expressed as

$$\delta_i^V(u,k)=\Pr\left\{\log\left(1+\gamma_{V,u}(k)\right)<\gamma_{th}\right\}. \tag{8}$$

According to (2) and (3), the outage probability can be rewritten by

$$\begin{aligned}&\delta_i^V(u,k)=\Pr\Big\{|h_0|^2\le A\Big\},\\ &A=\frac{\left(e^{\gamma_{th}}-1\right)\sigma^2}{P_V G\left(|(k-1)q+1-u|\,d\right)^{-\alpha}},\end{aligned} \tag{9}$$

where A is constant and $|h_0|^2$ is the square of the modulus of a standard complex Gaussian random variable, which satisfies $|h_0|^2\sim \text{Exp}(\frac{1}{2})$.[2] Therefore we obtain

$$\delta_i^V(u,k)=\int_0^A \frac{1}{2}\exp\Big(-\frac{x}{2}\Big)dx = 1-\exp\left(-\frac{A}{2}\right). \tag{10}$$

Given the one-step transition probabilities in (7), the first passage time probabilities can be obtained using

$$\begin{aligned}&f_{ij}^{V(1)}(u,k,t)=p_{ij}^V(u,k,t)\\ &f_{ij}^{V(n)}(u,k,t)=\sum_{l=1,l\ne j}^{N_f+1} p_{il}^V(u,k,t) f_{lj}^{V(n-1)}(u,k,t),\ n>1,\end{aligned} \tag{11}$$

where $f_{ij}^{V(n)}(u,k,t)$ denotes the n-step first passage time probability from state i to state j.

Let $D_{ij}^V(u,k,t)$ denote the first passage delay from state i to state j, i.e., the delay that the Markov chain requires to transit to state j for the first time from current state i ($j>i$). We can derive that

$$\begin{aligned}\mathbb{E}\big(D_{ij}^V(u,k,t)\big)=&\sum_{n=j-i}^{\infty}\mathbb{E}\Big(D_{ij}^{V(n)}(u,k,t)\Big)f_{ij}^{V(n)}(u,k,t),\\ & i,j\in\{1,\cdots,N_f+1\} \text{ and } j>i,\end{aligned} \tag{12}$$

[2]According to the definition of $|h_0|^2$, it is obvious that $|h_0|^2\sim\chi^2(2)$. The probability density function of $\chi^2(2)$ is identical to that of the exponential distribution with rate parameter $1/2$.

where $D_{ij}^{V(n)}(u,k,t)$ denotes the n-step first passage delay from state i to state j. According to [9], the expected value $\mathbb{E}\Big(D_{ij}^{V(n)}(u,k,t)\Big)$ can be calculated by

$$\begin{aligned}\mathbb{E}\Big(D_{ij}^{V(n)}(u,k,t)\Big)=&\sum_{l\in\Omega_{ij}^n}\Big(\mathbb{E}\Big(D_{il}^{V(1)}(u,k,t)\Big)\\ &+\mathbb{E}\Big(D_{lj}^{V(n-1)}(u,k,t)\Big)\Big)\frac{p_{il}^V(u,k,t)f_{lj}^{V(n-1)}(u,k,t)}{f_{ij}^{V(n)}(u,k,t)},\\ & i,j\in\{1,\cdots,N_f+1\},\ j>i \text{ and } n\ge\max(j-i,2),\end{aligned} \tag{13}$$

where $\Omega_{ij}^{(n)}$ denotes all possible indexes of the first state to which the Markov chain transits from state i, given that the Markov chain transits from state i to state j for the first time in n steps, which is given by

$$\Omega_{ij}^{(n)}=\begin{cases}\{i\}, & j=i+1\\ \{i+1\}, & j=i+n\\ \{i,i+1\}, & \text{otherwise.}\end{cases} \tag{14}$$

In the V2I communications of procedure (ii), the CH transmits information to the p-BS and the one step transition probability from state i to state j can be expressed as

$$p_{ij}^I(k)=\begin{cases}1-\delta_i^I(k), & j=i+1=2,\cdots,N_f+1\\ \delta_i^I(k), & j=i=1,\cdots,N_f\\ 1, & j=i=N_f+1\\ 0, & \text{otherwise.}\end{cases} \tag{15}$$

The duration of the traditional handoff is below 100 ms [10], so the moving distance of the CH during the handoff process is much shorter than the distance between the CH and the p-BS. Therefore, we assume that the location of the cluster does not change during the handoff process.

The expectation of the first passage delay $D_{ij}^I(k)$ is

$$\begin{aligned}\mathbb{E}\big(D_{ij}^I(k)\big)=&\sum_{n=j-i}^{\infty}\mathbb{E}\Big(D_{ij}^{I(n)}(k)\Big)f_{ij}^{I(n)}(k),\\ & i,j\in\{1,\cdots,N_f+1\} \text{ and } j>i,\end{aligned} \tag{16}$$

where $D_{ij}^{I(n)}(k)$ denotes the n-step first passage delay from state i to state j during the V2I communication.

IV. Problem Formulation and Delay minimization algorithm

In this section, we formulate a delay minimization problem by optimizing the number of the clusters and spectrum resource allocation for V2V communications in the handoff transition process.

A. Problem Formulation

Since multiple CMs can communicate with the CH via V2V communications simultaneously, the delay of V2V communications in cluster G_k can be expressed as the maximum expectation of the delay of the communication between a single CM and the CH, i.e.,

$$D_{\text{V2V}}(k)=\max_u\Big\{\mathbb{E}(D_{1,N_f+1}^V(u,k))\Big\},\ u\in G_k. \tag{17}$$

The delay of V2I communications of cluster G_k can be expressed as

$$D_{\text{V2I}}(k) = \mathbb{E}(D^I_{1,N_f+1}(k)). \tag{18}$$

Therefore, the handoff delay of cluster G_k is

$$D(k) = D_{\text{V2V}}(k) + D_{\text{V2I}}(k) + D_f, \tag{19}$$

where D_f is the communication delay of the other parts in our handoff scheme, which is viewed as a fixed value for each cluster.

Given that the handoff delay of each cluster is required to be less than or equal to D_0, the delay minimization problem can then be formulated as

$$\min_{M,\{\beta(u,k,t)\}} \sum_{k=1}^{M} D(k), \tag{20a}$$

$$\textit{s.t.}\ D(k) \le D_0,\ k = 1, \cdots, M \tag{20b}$$

$$\sum_u \beta(u,k,t) \le N_C,\ \forall k, t. \tag{20c}$$

Constraint (20b) is the maximum handoff delay constraint on each cluster. Constraint (20c) is the constraint of the number of channels in the V2V communications.

B. Delay Minimization Algorithm

To minimize the total delay, we consider the effect of M and $\beta(u,k,t)$ on both the V2V delay and V2I delay. The number of clusters M has a range of reasonable values: $[M_0, N]$, where M_0 refers to the minimum number of clusters to satisfy constraint (20b), i.e., the delay of each cluster is less than D_0, and N infers the traditional handoff. By traversing all reasonable values of M, we can find the optimal value of M.

Considering the limited number of channels, we have to find a proper solution to $\beta(u,k,t)$, i.e., the scheduling of the V2V channels. This is a parallel machine problem, which is NP-hard and the longest processing time first (LPT) algorithm is a good solution to it [11]. An algorithm based on the LPT algorithm is utilized to optimize the spectrum resource allocation variables $\beta(u,k,t)$, which is illustrated in Algorithm 1. The LPT algorithm works when the number of CMs is larger than that of the channels. The basic idea is to assign tasks to the least-loaded channel first, where the load of a channel is defined as the total time to finish all the tasks one by one. To achieve it, we assign the CMs in decreasing order of expected delays to the channel that has the smallest load. When the number of CMs is less than that of the channels, the basic idea is to allocate resources to the CM with the longest delay first. We modify the LPT algorithm such that more channels are assigned to the CM with a larger expected delay.

In Algorithm 1, the complexity of the case that $N_C \le n$ is $O(n \log n)$, and the complexity of the case that $N_C > n$ is $O(\max(n, N_C - n))$. According to (1), $n = \Theta(\lfloor \frac{N}{M} \rfloor)$. Therefore, the complexity of Algorithm 1 is $O\left(\max\left(N_C - \lfloor \frac{N}{M} \rfloor, \lfloor \frac{N}{M} \rfloor \log \lfloor \frac{N}{M} \rfloor\right)\right)$, and the complexity of the traversal is $O\left(N \cdot \max\left(N_C - \lfloor \frac{N}{M} \rfloor, \lfloor \frac{N}{M} \rfloor \log \lfloor \frac{N}{M} \rfloor\right)\right)$.

Algorithm 1: Resource Allocation Algorithm

Input: number of channels N_C, index of the cluster k, size of the cluster s_k, cluster size parameter q, expected delay of each CM using one channel $\{t_i\}$
Output: D_{V2V}
Initialize $\beta(u,k,t) = 0,\ \forall t$;
Set number of CMs $n = s_k - 1$;
if $N_C \le n$ **then**
  Let $\{f_i\}_{i=1}^{N_C}$ denote the load of each channel and initialize $\{f_i\}_{i=1}^{N_C} = 0$;
  Sort $\{t_i\}_{i=1}^{n}$ from largest to smallest;
  for $j = 1, \cdots, n$ **do**
    $k = \arg\min_{1 \le i \le N_C} f_i$;
    $\beta((k-1)q + 1 + j, k, t) = 1,\ t \in [f_k, f_k + t_j]$;
    $f_k = f_k + t_j$;
  return $\max_{1 \le i \le N_C} f_i$;
else
  $\beta(u,k,t) = 1,\ u \in [(k-1)q + 2, (k-1)q + s_k],\ \forall t$;
  Let $\{f_i\}_{i=1}^{n}$ denote the delay of each CM and initialize $f_i = t_i$;
  Let $\{c_i\}_{i=1}^{n}$ denote the number of channels assigned to each CM and initialize $\{c_i\}_{i=1}^{n} = 1$;
  for $j = 1, \cdots, N_C - n$ **do**
    $k = \arg\max_{1 \le i \le n} f_i$;
    $c_k = c_k + 1$;
    $f_k = t_k / c_k$;
  return $\max_{1 \le i \le n} f_i$;

V. Simulation Results

In this section, we evaluate the performance of the CPHP. The simulation parameters are selected based on the 3GPP specifications [7], as listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Path loss coefficient α	3.0
Noise variance σ^2	10^{-15}
Power gain G	10^{-4}
Distance between vehicles d	5 m
Distance between the CH and the p-BS $\lvert \mathbf{d}_{I,1} \rvert$	500 m
V2V transmission power P_V	23 dB
V2I transmission power P_I	46 dB
V2V number of frames N_f	6
V2I number of frames N_f	1
V2V threshold for outage probability γ_{th}	1.5 dB
V2I threshold for outage probability γ_{th}	1.5 dB
Other delay except V2V and V2I D_f	5 ms
Handoff delay limit for each cluster D_0	100 ms

Fig. 4 depicts the expected handoff delay of the platoon, i.e., $\sum_{k=1}^{M} D(k)$ versus different numbers of V2V communication channels N_C. The platoon size N is set as 50 and

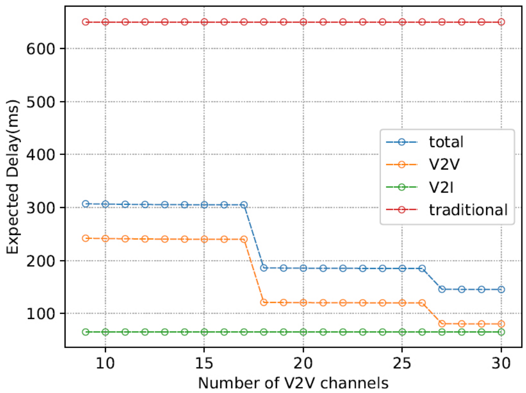

Fig. 4. Expected handoff delay vs. number of V2V communication channels.

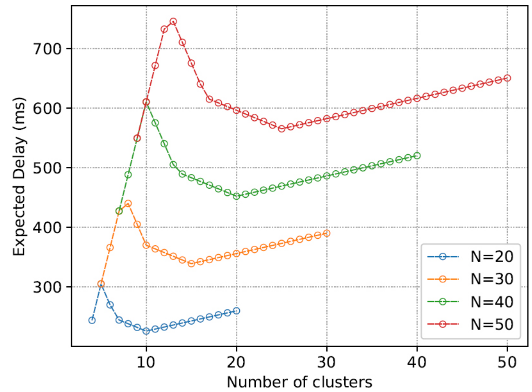

Fig. 5. Expected handoff delay vs. number of clusters.

the number of clusters M is set as 5. The V2I delay is not affected by the number of V2V channels, while the V2V delay decreases as the number of V2V channels increases because each CM can be allocated with more spectrum resources and the average time for waiting an idle channel decreases. The simulation results show that the handoff delay using the CPHP is more than 50% smaller than that of the traditional handoff[3].

Fig. 5 depicts the expected handoff delay of the platoon versus different numbers of clusters M with different sizes of the platoon N. The number of V2V communication channels N_C is set as 5. The leftmost point of each curve shows the minimum number of clusters that satisfies constraint (20b), i.e., M_0 as stated in Section IV-B. On the rightmost side of each curve, the number of clusters equals N, which infers the traditional handoff. There are two potential solutions to the minimum expected delay: the M_0 point and the $N/2$ point. The M_0 point is optimal with a large N and the $N/2$ point is optimal with a small N, which reflects the trade-off between V2V delays and V2I delays. At the M_0 point, the sizes of the clusters grow with N while the number of clusters do not change much, resulting in a significant increase in V2V delays and no significant change in V2I delays. At the $N/2$ point, the number of clusters increases linearly with N while the size of each cluster remains unchanged, resulting in a significant increase in V2I delays and no change in V2V delays. The simulation results imply that the increase in V2I delays at $N/2$ is significantly larger than the increase in V2V delays at M_0. The optimal expected delay exhibits a great reduction in the total delay of the handoff of the platoon, compared to that of the traditional handoff. The minimal expected delay under $N = 50$ is 15% smaller than that of the traditional handoff. It should also be noted that the maximal expected delay is attained around $\frac{N}{N_C}$.

VI. Conclusion

This paper has studied the handoff of a platoon with the proposed CPHP, in which a platoon has been formed into multiple clusters. V2V communications have been performed within the clusters and V2I communications have been adopted between the CHs and the BSs during the handoff process. We have analyzed the expected delay of the V2V and V2I communications by discrete-time Markov chains and have formulated a handoff delay minimization problem. To solve this problem, we have optimized the number of clusters and spectrum resource allocation. Simulation results have demonstrated a significant decrease in the handoff delay of the platoon. The optimal delay can be obtained at the minimum number of clusters when the delay of each cluster is less than D_0, or at the number of clusters equal to half the platoon size. In other words, the former is optimal with a large platoon, and the latter is optimal with a small platoon.

[3]The traditional handoff refers to the case that all the VUs hand off individually via the V2I communications.

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