Sustain Vehicle-Crowds via Traffic Signal Adjustments

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***Abstract*—Vehicle-crowd (V-crowd) based cloudlets are envisioned to support high-demand mobile edge computing applications. Yet, a v-crowd's capability to host cloudlet applications is significantly affected by the sustainability of itself. Among the factors that may contribute to the capability and sustaining the v-crowd, traffic signal coordination plays an important role. In this paper, we study the interdependence between them through an empirical approach. We'll define new metrics to quantify the impact, and use data driven simulation to obtain results by manipulating signals offset as a control knob of traffic signal coordination. The goal is to use the results in terms of the metrics to develop guidelines that offer choices of offsets preferable for certain levels of v-crowd properties so as to achieve better performance of cloudlet applications.**

I. Introduction

With the great success and development of Intelligent Transportation System (ITS), vehicles can offer many new applications and services, such as safety assistance, traffic monitoring, self-driving, smart parking, etc. Such applications typically require intensive computation and a large amount of data storage. Mobile Edge Computing is considered as a promising solution to address the ever-increasing computation and storage demand in ITS. The platforms like cloudlet and cyber-foraging are ready to host high-demand ITS applications [10].

We envision that a group of connected vehicles, vehicle-crowd (v-crowd), can self-organize using research results from Vehicular Ad Hoc Network (VANET) and Vehicular Delay Tolerant Network (VDTN) to share computing and storage resources among them to support edge computing such as cloudlet so that these high-demand ITS applications can run on top of v-crowds. A v-crowd based cloudlet has the capability coming from harvesting the computing and storage resources by collaborations among grouped vehicles which are knitted together via the vehicular networking protocols. The sustainability of a v-crowd significantly affects its capability to host cloudlet applications. Vehicle mobility is the major player in sustaining the v-crowd, which is influenced by many factors, such as speed, volume, original-destination pairs, etc. Yet in urban areas, vehicle mobility is highly coupled with traffic signals and the coordination of adjacent signals, especially under heavy traffic load.

Early work [6] has shown that there exists interdependence between traffic signal control and the persistence of v-crowds. However, there are still open issues such as: how to define a v-crowd's capability to host cloudlet applications? how to quantify the impact from traffic signals on a v-crowd' sustainability? how to adjust traffic signals to benefit cloudlet applications?

In this work, we will answer the above questions by quantifying the impact from traffic signal coordination on the capabilities of v-crowds. Our objective is to deliver practical guidelines for adjusting signal offsets in terms of desired capability of v-crowds. In urban areas, signals of adjacent intersections impact the occurrence and lifetime of the v-crowd at the intersection in question. While both signal plan and offset play a role, we focus on the offset between adjacent intersections, because it captures coordinated mobility well.

We use real traffic load and signal events from real road system. But the need for making the offset as a variable in this study led us to use simulations, because it is not feasible to frequently manipulate traffic signal offsets on a real road. As such, we use a data driven, empirical approach, i.e., we use the real road map, the traffic load and the signal events to drive the simulations. We set up one control road segment in a way that one end of the segment will vary its offset according to the other end. While road traffic is bi-directional, this setup can only control the coordination in one-direction. Even though, our results still show patterns due to the impact.

In the paper, we introduce metrics to quantify the capabilities of v-crowds. The metrics indicate the capability from different aspects of cloudlet when executing high-demand applications. The collected bi-directional simulation data show insights that we use to develop guidelines. Specifically, the guidelines offer choices of offsets preferable for certain levels of v-crowd properties (hence, supporting cloudlet applications) in terms of different signal plans. The guidelines are aimed at sustaining the v-crowds across multiple intersections so as to achieve better execution performance of cloudlet applications.

The rest of the paper is organized as follows. Section II briefly introduces the related work. Section III discusses the influence of traffic signal coordination on the sustainability of v-crowds. Section IV describes the simulation plan. Section V presents results and delivers practical guidelines for signal

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adjustments. Finally, Section VI concludes the paper.

II. Related Work

Adjustment of traffic signal to improve the reliability and efficiency of transportation system has been importantly studied and some of the results are already implemented in the USA. Broadly, these adjustments can be explained in terms of Traffic Signal Preemption (TrSP), Traffic Signal Priority (TSP), Traffic Responsive Plan Selection (TRPS) and Adaptive Traffic Signal Control (ATSC) [14]. TrSP alters normal operation of traffic signal control to special control mode of operation such that emergency vehicles can be provided with the right of the way to improve efficiency and minimize accidents [12]. TSP generally involves adjustment of green time allocation of non-emergency priority vehicles to help in their delay minimization [4][11]. TRPS enables different signal plans based on (historical) study about existing traffic conditions [2]. ATSC enables a signal adjustment for general vehicles based on real-time prediction and sensing of vehicles at road sections in an intersection to minimize congestion and delays [3][13].

Apart from the traffic signal adjustments, there are works in the literature that make use of connected vehicle technology to achieve similar goals. Hu *et al.* present a scheme with flexible green timing based on the information from connected vehicles [7]. A scheme for a fixed traffic signal plan where the acceleration and the deceleration of a vehicle is controlled to arrive to green signal on the intersection is presented by Asadi *et al.*. [5]. Similarly, Yang *et al.* look into density of connected vehicles in an intersection to adjust the departure periods (green signal timing) [16]. Moreover, some works present a complete new way of intersection control without traffic lights through interaction among vehicles around the intersection [15][9].

Our work is different from the existing works in the literature in terms of goal achieved since it studies traffic signal timing adjustment through connected vehicles to increase sustainability of v-crowd to achieve better performance of cloudlet applications.

III. Traffic Signal Coordination

The occurrences of multiple v-crowds are not independent, especially for v-crowds at adjacent intersections. When traffic signals interrupt vehicle flow, the occurrence of v-crowds would be disrupted as well. The offset in the time indices is the most critical parameter in sequencing the time series of groups of vehicles at each intersection. Therefore, the offset value can determine the sustainability of a v-crowd. In Fig. 1, if a platoon of vehicles discharge from the upstream intersection (INT.6) when green time begins, whether they catch a green light or a red light at the coordinated downstream intersection (INT.5) depends on the offset value between the two adjacent intersections [14]. The left of figure shows a case when the offset value is the traveling time from INT.6 to INT.5 during which the platoon of vehicles pass through INT.5 without stopping. It is because the vehicles that discharged from INT.6 when green time starts can catch the green light when they arrive at INT.5. However, the same group of vehicles will be stopped because of the red light if the offset value is set to the traveling time plus red time, as the right of figure shows. Since v-crowds are formed by vehicles around the intersection, the mobility of vehicles determines the occurrence and lifetime of v-crowds.

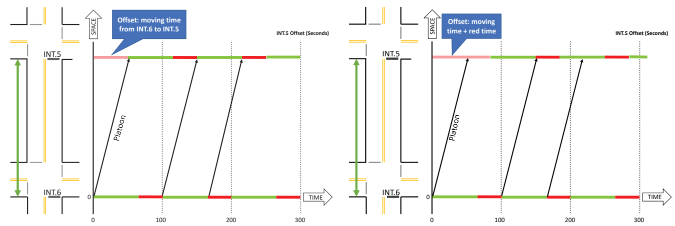

Fig. 1. Influence of Traffic Signal Coordination on Sustainability of V-Crowd

Obtaining good offsets for sustaining a v-crowd is a non-trivial task. In realistic traffic conditions, the best offset depends on many conditions, such as, the traffic amount, the arrival time at the upstream intersection, and the lane change behavior. Our simulation will investigate the relations between the offset value of two adjacent signals and sustainability of a v-crowd at the downstream intersection. Our goal is to identify the range of some offset values that contribute to a sustainable v-crowd.

IV. Simulation Plan

In this section, we introduce metrics to quantify the capabilities of v-crowds from different aspects of cloudlet when executing the applications. Then we introduce the real data from ITS testbed that we use for our simulation, followed by the configuration of the data driven simulation.

A. Capability of V-Crowds

Cloudlet applications require computing and storage resources. The resources are reflected in the v-crowds' capability to host cloudlet applications. A v-crowd occurs when a minimum number of vehicles exist within the transmission range centered at an intersection. The intersection is said to be in *holding* state at the time. The capabilities of a v-crowd can be measured in several aspects: the geographic size and vehicle density of v-crowd, indicating amount and density of the participating vehicles; the time duration from a v-crowd occurs to its disappearance, indicating the available duration. The metrics are calculated centered at an intersection. Details are given below.

- *Holding density*: is the mean value of total number of vehicles within a transmission range of the intersection at each time period. It indicates the number of vehicles that can be reached through a single hop and can participate in computing and storing tasks in a v-crowd. Larger holding density means richer computing and storage resources of the v-crowd.

- *Holding size*: is the geographic area of a v-crowd. It is the distance from the head vehicle of a v-crowd to its tail vehicle. Holding size measures how large a connected component can be in terms of network topology. Any vehicles inside a v-crowd can reach each other through a single hop or multi-hop links.
- *Holding time*: counts for the time duration from a v-crowd's appearance to its disappearance. It is the total time periods that an intersection is in holding state. Holding time indicates how long a v-crowd can sustain to host cloudlet applications.

B. Real Data from ITS Testbed

The field of our simulation contains eight conjoint major intersections (indexed from 2 to 9, north to south) along Highway 69, Tuscaloosa, Alabama (Fig. 2). Those intersections have been monitored by Alabama Department of Transportation with modern data-logging traffic signal controllers. These data loggers record various discrete events, such as a light turning green, a light turning red, a vehicle detector turning on, a vehicle detector turning off. All recorded data are stored in a database [1].

Fig. 2. Simulation Field

We fetch all related data that are recorded at the eight intersections from 7AM to 8AM on 2017-9-15. After processing the data, we are able to identify traffic volume and signal plans at each intersection in the period. Traffic volume contains both northbound traffic and southbound traffic. A signal plan contains three phases: green, yellow and red. By converting signal event data, we can calculate time durations for each phase. From results, we find the yellow time is always 4 seconds because it relates to road speed limit only.

To better understand the occurrences of different signal plans, we collected more data for further study. Typically, we collected real signal timing event data at intersection 6 from 7AM to 8AM for ten weekdays (from 2017-9-11 to 2017-9-15, from 2017-9-18 to 2017-9-22). By k-means clustering algorithm, we identified nine clusters based on their green time and red time. The idea of clustering signal plans has also been used to achieve traffic responsive control in memory-constrained controller [2], but our purpose is to see whether there are patterns for all the signal plans in terms of their green and red time. The clustering result allows us to develop a representative plan for each cluster and use the representative plans as signal parameters in simulation. To study the impact from green time and red time, according to the clustering result we define two signal parameter sets that have variable green time (40s, 60s, 80s) and variable red time (20s, 35s, 50s) separately.

C. Data Driven Simulation

The real map of our simulation field has been imported into SUMO [8]. The feeding traffic flows in the simulation are at northern road of intersection 2 (southbound traffic) and southern road of intersection 9 (northbound traffic), which are from real traffic detections. For simplification, there is no feeding traffic from side roads. Our simulation used default car following model and lane changing model in SUMO.

Signal timings at all intersections are also fed by real data, except for *base signal* at intersection 6 and *target signal* at intersection 5. The target signal uses the same signal plan (red time, green time and yellow time) as the base signal, but the target signal is shifted. We use signal offset to determine the degree of shift. For example, offset=10 means target signal and base signal use the same signal plan but start/end time for each phase of target signal is 10 seconds later than those of base signal. In our simulation, each run stands for simulating one-hour urban traffic using a certain offset value for target signal against signal timing of base signal. And we collect metric results for capabilities of v-crowds at the target signal.

We choose signal offset as the key variable in our simulation because it is an important parameter in sequencing the time series at each intersection and it reflects temporal correlation between adjacent signals. The direct manipulation of traffic signals cannot be achieved in real road system. Thus, we use simulation to adjust traffic signal offset while still using real traffic flow data and real signal plans for other uncontrolled signals.

V. Results and Guidelines

The setting of our experiment allows us to manipulate traffic signals in a simulated environment and obtain desired metrics. In this section, we present simulation results for the capabilities of v-crowds and investigate the impacts from signal coordination (via offset) and parameters (like green time and red time). Through simulation, we find the signal parameters have significant impacts on capabilities of v-crowds. Also, we are able to identify the offset values that result in best performance in terms of the metrics (we call it best offset). In addition, we can identify offset thresholds between which the performance is acceptable. These findings lead to a few guidelines for signal adjustments in order to sustain v-crowds.

A. Impact from Signal Parameters

Fig. 3 shows the change of holding density for different signal parameters as the increment of signal offset. There are some interesting findings. First of all, the repeated patterns suggest that the change of holding density is corresponding to the signal coordination. The pattern length of each curve is corresponding to the cycle length of the selected signal plan (green time + red time + yellow time). Secondly, from the left of figure that compares different green time, we find that shorter green time leads to higher holding density and from the right of figure where red time changes, we observe that longer red time contributes to higher density. The reason is that the only factor that affects holding density is vehicle queue length, which is minimized when vehicles pass through the intersection without stopping (shown as the left of Fig. 1). The results suggest that the percentage of red time in total signal cycle length determines the holding density. The more percentage of red time, the higher holding density can be. It makes sense because the vehicle queue length is longer during longer red time. Thirdly, we find that the offset for lowest holding density is same for all parameters, but the offset for the highest holding density is not same in the right of figure where red time varies. It is because the queue length can only be impacted by red time. We can further deduct that the offset value for lowest holding density is the average traveling time from base signal to target signal (shown as the left of Fig. 1), and the offset for highest density (best offset) is the offset for lowest density added red time (shown as the right of Fig. 1).

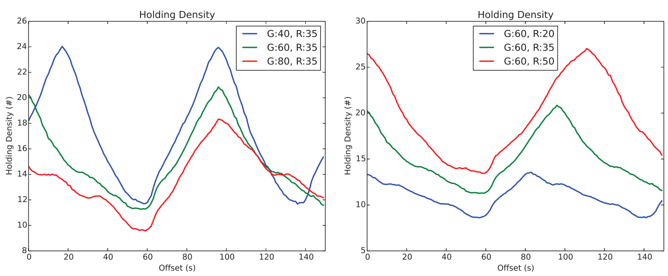

Fig. 3. Holding Density for Different Signal Parameters

Fig. 4 presents the impacts from signal offset on holding size given signal parameters. Similar to holding density, holding size displays repeated patterns corresponding to the signal coordination, and the length of pattern is the cycle length of the given signal plan. However, holding size differs from holding density where holding size measures the maximum size of a v-crowd while holding density indicates the number of vehicles within intersection's transmission range. Thus holding size reveals several different trends. On one hand, longer green time leads to larger holding size. It is due to the fact that longer green time allows more vehicles to pass the intersection each round, which enlarges the holding size. Also, the impact from red time on holding size is not as obvious as its impact on holding density. On the other hand, the best offsets for holding size (the peaks of all curves) have small shifts to the left. It is because the holding size is largest when all vehicles form crowds around intersection but not fully stopped. Also, we find that the worst offsets for holding size differ in different green time and shorter green time has shorter worst offset.

Fig. 5 presents the change of holding time for different signal parameters as the increment of signal offset. Similar to holding density, longer red time leads to longer holding

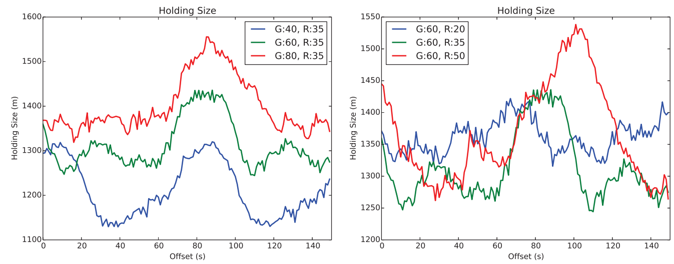

Fig. 4. Holding Size for Different Signal Parameters

time. It can be explained that longer red time forces vehicles staying at the intersection for longer time, which increases the holding time. The results suggest that the percentage of red time in total cycle length determines the holding time. The more percentage of red time, the longer holding time can be. In addition, it is interesting to notice that the peaks of the holding size occur when the correspondent holding time is at the lowest. This is because vehicles pass intersections without stopping, which leads to better spread out of their positions. We also find that holding time has obvious changes only when green time and red time are close to each other. It is because if green time is much longer than red time, the offset value doesn't play a significant role in impacting the results.

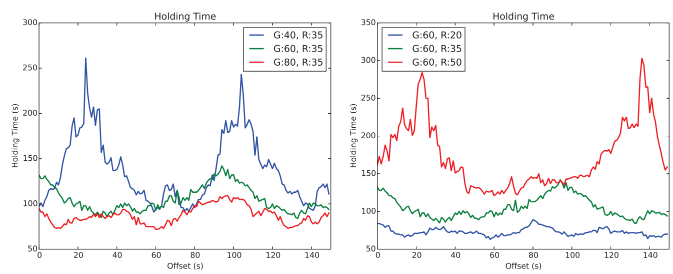

Fig. 5. Holding Time for Different Signal Parameters

B. *Best Offset for Different Metrics*

In practice, it is only possible to use one plan and one offset. Our early results show that different metrics may not be at their best at the same time given a plan and an offset. In Fig. 6, we show how best offset changes for different metrics under nine sets of signal plan parameters, which correspond the nine cluster centers from our previous signal plan clustering results. The data points, namely, the best values for the metrics and the corresponding offsets, are picked from Fig. 3, Fig. 4 and Fig. 5. The offset points, when they exceeds the cycle length, are subtracted by the cycle length so to show the real effective offset. Because different metrics indicate various application requirements, the results will guide us to adjust signals by setting offset to achieve best performance for specific application. The usefulness of this result is that given a signal plan and an offset, we know the metric performance to be achieved. Or, given a plan, we can find the offset that needs to be chosen to achieve required performance metric. Such results can guide the practical use by allowing identifying the best offset to achieve the selected metrics given a signal plan.

The result shows that longer green time and longer red time will increase best offset value for all the metrics. When the red time is short (20 seconds or 35 seconds), holding density and holding time always have similar best offset values while green time increases. When the red time is long (50 seconds), the three metrics have different best offset values. Thus, given a signal plan, we are able to identify which value of signal offset can achieve which aspect of capabilities. Notice that even though in simulation the offset value can be larger than the cycle length, in practice the signal offset should be set within the cycle length.

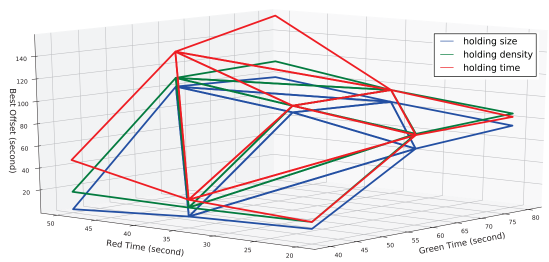

Fig. 6. Best Offset for Different Metrics

C. Guidelines

From previous results, we are able to obtain several trends relating to performance metrics for different signal parameters. The following are a few guidelines.

- Given a signal plan, one can obtain the offset thresholds for achieving the desired metric with a certain level. For example, when the signal plan is [G:40, R:35], which is a representative plan for one of the nine signal plan clusters, if an application needs a computing power that requires at least 20 vehicles, the results of holding density can help. With holding density (Fig. 3), the offset should be set between 5 seconds to 30 seconds for intersection 6. These 20 vehicles can occur within close vicinity of the intersection.
- If the best performance for a certain metrics is desired, one can refer to Fig. 6. It shows the offset values that contribute to the best performance for different metrics. Since the plans corresponding to each (X, Y) point are representative, it is safe to say that the offset value would work for the plans in the same cluster. For example, when the signal plan is [G:60, R:35], the v-crowd can achieve best holding density and holding time performance if the offset is set to 90 seconds. To achieve best holding size, the offset needs to be set to 80 seconds.
- Since each signal plan in our simulation represents one cluster of real signal plans, the results can be applied to any signal plan inside the cluster. In addition, different signal plans may have same best offset. For example, for signal plan [G:60, R:35] and [G:80, R:35], the increasing green time from 60 to 80 doesn't have much impact on the best offset.

VI. Conclusion

In this paper, several metrics are presented to quantify the impact from the traffic signal coordination on capabilities of v-crowds. The results showing the patterns relating to the signal adjustments are obtained from real data driven and controlled simulations. These results allow us to obtain guidelines for the needed capability of v-crowds to sustain cloudlet executions. The results presented here give a glimpse of how transportation operations can impact the edge computing. Our future work will consider more aspects of signal coordination and traffic load as input of guidelines.

References

[1] Automated Traffic Signal Performance Measures. http://spm.ua.edu/.

[2] M. M. Abbas and A. Sharma. Multiobjective Plan Selection Optimization for Traffic Responsive Control. *Journal of Transportation Engineering*, 132(5):376–384, May 2006.

[3] B. Abdulhai, R. Pringle, and G. J. Karakoulas. Reinforcement Learning for True Adaptive Traffic Signal Control. *Journal of Transportation Engineering*, 129(3):278–285, May 2003.

[4] F. Ahmed and Y. Hawas. An Integrated Real-Time Traffic Signal System for Transit Signal Priority, Incident Detection and Congestion Management. *Transportation Research Part C: Emerging Technologies*, 60:52 – 76, November 2015.

[5] B. Asadi and A. Vahidi. Predictive Cruise Control: Utilizing Upcoming Traffic Signal Information for Improving Fuel Economy and Reducing Trip Time. *IEEE Transactions on Control Systems Technology*, 19(3):707–714, May 2011.

[6] X. Hong, Y. Lou, M. Kuai, and S. Wang. Quantify Self-Organized Storage Capacity in Supporting Infrastructure-less Transportation Operation. In *Proceedings of the Second Workshop on Mobile Sensing, Computing and Communication*, MSCC '15, pages 13–18, New York, NY, USA, June 2015. ACM.

[7] J. Hu, B. Park, and A. Parkany. Transit Signal Priority with Connected Vehicle Technology. *Transportation Research Record: Journal of the Transportation Research Board*, (2418):20–29, December 2014.

[8] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker. Recent Development and Applications of SUMO - Simulation of Urban MObility. *International Journal On Advances in Systems and Measurements*, 5(3&4):128–138, December 2012.

[9] J. Lee and B. Park. Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment. *IEEE Transactions on Intelligent Transportation Systems*, 13(1):81–90, March 2012.

[10] Y. Li and W. Wang. Can Mobile Cloudlets Support Mobile Applications? In *IEEE INFOCOM 2014 - IEEE Conference on Computer Communications*, pages 1060–1068, April 2014.

[11] H. Liu, W.-H. Lin, and C.-w. Tan. Operational Strategy for Advanced Vehicle Location SystemBased Transit Signal Priority. *Journal of Transportation Engineering*, 133(9):513–522, September 2007.

[12] J. F. Paniati and M. Amoni. Traffic Signal Preemption for Emergency Vehicle: a Cross-Cutting Study. *US Federal Highway Administration*, January 2006.

[13] Y. Ren, Y. Wang, G. Yu, H. Liu, and L. Xiao. An Adaptive Signal Control Scheme to Prevent Intersection Traffic Blockage. *IEEE Transactions on Intelligent Transportation Systems*, 18(6):1519–1528, June 2017.

[14] T. Urbanik, A. Tanaka, B. Lozner, E. Lindstrom, K. Lee, S. Quayle, S. Beaird, S. Tsoi, P. Ryus, D. Gettman, et al. *Signal Timing Manual*. Transportation Research Board, 2015.

[15] B. Yang and C. Monterola. Efficient Intersection Control for Minimally Guided Vehicles: A Self-Organised and Decentralised Approach. *Transportation Research Part C: Emerging Technologies*, 72:283 – 305, November 2016.

[16] K. Yang, S. I. Guler, and M. Menendez. Isolated Intersection Control for Various Levels of Vehicle Technology: Conventional, Connected, and Automated Vehicles. *Transportation Research Part C: Emerging Technologies*, 72:109 – 129, November 2016.