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A study on traffic signal control at signalized intersections in vehicular ad hoc networks

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ABSTRACT

The Seoul metropolitan government has been operating a traffic signal control system with the name of COSMOS (Cycle, Offset, Split MOdel for Seoul) since 2001. COSMOS analyzes the degrees of saturation and congestion which are calculated by installing loop detectors. At present, subterranean inductive loop detectors are generally used for detecting vehicles but their maintenance is inconvenient and costly. In addition, the estimated queue length might be influenced by errors in measuring speed, because the detectors only consider the speed of passing vehicles. Instead, we proposed a traffic signal control algorithm which enables smooth traffic flow at intersections. The proposed algorithm assigns vehicles to the group of each lane and calculates traffic volume and congestion degree using the traffic information of each group through inter-vehicle communication in Vehicular Ad-hoc Networks (VANETs). This does not require the installation of additional devices such as cameras, sensors or image processing units. In this paper, the algorithm we suggest is verified for AJWT (Average Junction Waiting Time) and TQL (Total Queue Length) under a single intersection model based on the GLD (Green Light District) simulator. The results are better than random control method and best-first control method. For a generalization of the real-time control method with VANETs, this research suggests that the technology of traffic control in signalized intersections using wireless communication will be highly useful.

1. Introduction

Nowadays, many countries are struggling with severe daily traffic congestion that causes a huge amount of social and economic loss. According to the report of Improvement of the Estimation Method for Traffic Congestion Costs from The Korean Transport Institute, the economic loss due to traffic congestion in 2007 is estimated to be approximately $14.4 trillion [1]. Additional waste of time and energy are also a significant loss for individuals and nations.

To resolve such traffic congestion, traffic signal control methods are applied to improve traffic flow at intersections. The control methods can be largely classified into time-of-day (TOD), fixed-time control and real-time control methods. The time-of-day control method follows a predefined signal timing plan by hour/day. The fixed-time control method uses a signal timing plan set by an administrator, while real-time control analyzes traffic information acquired by sensors and builds a proper signal timing control [2].

Time-of-day and fixed-time control methods have advantages in the sense that they do not require additional hardware and nor a complicated control algorithm. However, traffic congestion in modern urban areas is caused not only by periodical rush-hours but also occasional events interfering with the traffic flow, such as traffic accidents and road construction. In addition, speed bumps, curved roads and vehicle speed instability due to careless drivers can also cause traffic congestion. Therefore, time-of-day and fixed-time control methods can possibly even increase traffic congestion instead [3].

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Nomenclature

RQL	queue length in the present cycle length	*MAX_Q*	maximum queue length
QL	final queue length for real-time signal control	*R_CL*	temporal required cycle length
D	identifier which is combined with path and incoming direction	N_{MAX_Q}	number of vehicles in the maximum queue length
VL	vehicle length	*h*	vehicle-to-vehicle headway
ADBV	average distance between vehicles	*GT*	green time
N	number of group memebers	GT_T	total green time
l	length of lane	*R_GT*	required green time
CL	cycle length	*V*/*C*	flow ratio

On the contrary, the real-time control method is based on real-time sensing which potentially makes it an appropriate strategy to resolve traffic congestion in modern urban cities. Moreover, recent improvement in converged technologies of sensing and wireless networks has enabled the development of various real-time control methods.

Attaining information of accurate vehicle detection is the most important factor for real-time signal control. The most widely used sensors for vehicle detection at present are spot traffic detectors and regional traffic detectors. Spot traffic detectors such as loop detectors and ultrasonic detectors are sensors buried under the road, which makes their maintenance inconvenient and costly. Other types are microwave detectors and image detectors, which are easy to install but also have high maintenance cost. The types of regional traffic detectors are AVI (Automatic Vehicle Identification), beacon and GPS (Global Positioning System) probe. Regional traffic detectors are generally high priced and occasionally show low accuracy with regards to road conditions. In addition, both spot traffic detectors and regional traffic detectors are only able to cover a limited local area, and cannot used for route prediction [4].

In this study, a method of queue length estimation using communication between vehicles in a Vehicular Ad-hoc Networks (VANETs) environment is proposed. This method does not require the installation of additional detectors and allows the estimation of optimal cycle length and green split to enable real-time control of signalized intersections.

The remainder of the paper is organized as follows.

- Traffic control system using VANETs (Section 3.1).
- Intersection model and phase configuration. (Section 3.2)
- Queue length estimation algorithm using VANETs (Section 3.3).
- Cycle length and green split estimation. (Section 3.4).
- Simulation environment (Section 4).
- Simulation results (Section 5).
- Conclusions (Section 6).

2. Related works

In this chapter, research on vehicle queue length estimation and signal control system is described. Vehicle queue length is defined as the number of vehicles that cannot pass the intersection within red time and can be used to determine whether green time needs to be extended. It also allows controllers to clear the queue at the intersection in order to improve traffic flow.

The Seoul metropolitan government has been operating a traffic signal control system with the name of COSMOS (Cycle, Offset, Split Model for Seoul) since 2001. COSMOS analyzes the degrees of saturation and congestion which are calculated by installing loop detectors such as forward detectors, left-turn detectors, spillback detectors and queue length detectors. Traffic control using queue length is one of the most optimal real-time control methods. Its disadvantage is that it requires detectors to be installed in each lane since it relies on the data from both the upstream queue length detector and the downstream spillback detector. In addition, the estimated queue length might be influenced by errors in measuring speed, because the detectors only consider the speed of passing vehicles. To overcome such limitations, research with various sensors has been conducted. Some of the research proposed a method of obtaining local vehicle information using RFID tags attached to vehicles and RFID readers installed in each lane [5].

Malik et al. [6] proposed a method to obtain traffic information by installing sensor nodes in each lane and controllers in each lane within a sensor network environment. Also, Khalil et al. [7] proposed a method to aggregate vehicle information by installing pairs of arrival and departure nodes with one traffic signal server at intersections. Park et al. [8] proposed a queue length estimation model that uses occupancy time to minimize errors caused by the dependence on the average vehicle length and Instantaneous speed of the estimation process.

Jeong et al. [9] proposed a method that estimates de-queuing time by measuring the delay time of individual vehicles before calculating the saturation flow ratio with the estimated de-queuing time. The estimated saturation flow ratio is used to calculate the queue length of each lane and the final queue length is obtained after compensating for errors. Lee and Oh [10] proposed a queue length estimation algorithm using a pair of image detectors installed at upstream and downstream lanes.

This study proposes a real-time queue length estimation algorithm that generates vehicle groups in each lane by using traffic signal cycle length and calculates the queue length using inter-vehicle communication within a

VANETs environment. The proposed system enables more accurate queue length calculation than the existing loop detector methods, and it does not require additional hardware or complex calculations. A real-time traffic control method using the estimated queue length is also proposed.

3. VANETs-based traffic signal control system

3.1. System design

The proposed system is divided into following three parts: (1) traffic information generator, (2) traffic signal controller, and (3) VANETs. The traffic information generator equipped in vehicles and traffic signal controller installed at intersections are onboard devices including CPU, GPS modules, memory and a power source. It is assumed that a wireless VANETs environment can be used to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.

A traffic signal control algorithm which enables smooth traffic flow at intersections is proposed. This algorithm assigns vehicles to a group within each lane and calculates traffic volume and congestion degree using traffic information of each group obtained via VANETs inter-vehicle communication. It does not require the installation of additional devices such as cameras, sensors or image processing units. Fig. 1 illustrates the proposed system.

3.2. Single intersection control model and phase configuration

In this study, a single intersection model for two arterial roads with 2-lane crossing is used for real-time traffic control. Roads at the intersection are labeled according to their direction as E (east), W (west), S (south) and N (north). Roads in each direction consist of two lanes, represented as L (left) and F (forward). Here, a right-turn is always allowed. Hence, an intersection can be represented as a combination of roads and lanes, and it is expressed as a

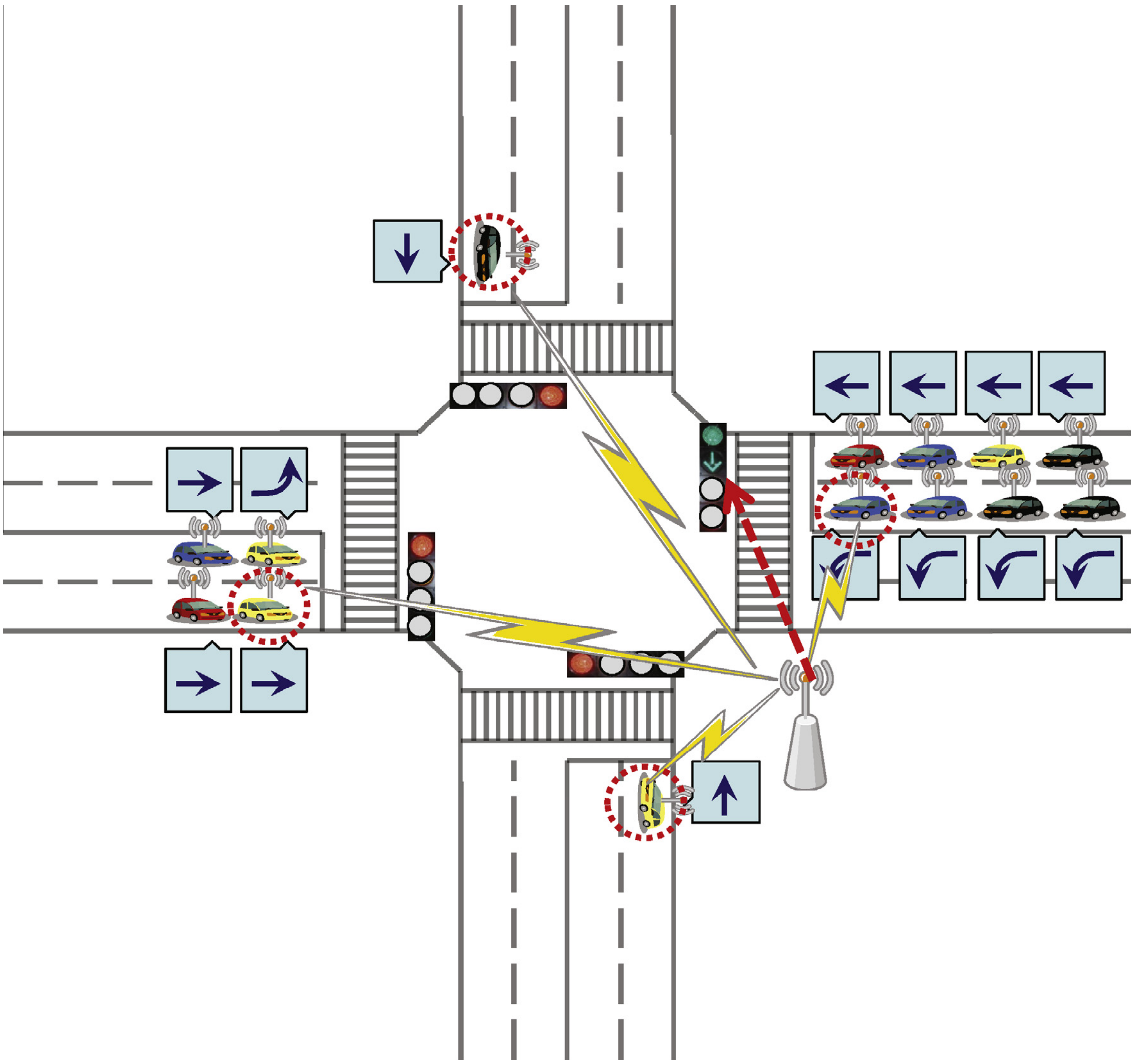

Fig. 1. Intersection traffic control using VANETs.

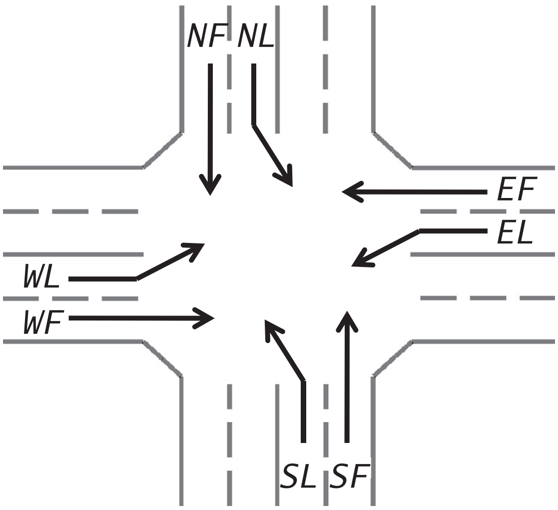

Fig. 2. Single intersection with four ways.

direction indicator, D. D has the following eight components. D = EF, EL, NF, NL, WF, WL, SF, SL. Each component of an intersection is illustrated in Fig. 2.

For a real world experiment, the existence of pedestrians must be considered. Installing extra sensors to detect pedestrians is beyond this study, so it is assumed that pedestrians always exist and a certain period of time is allocated to take their crossing of the road into account. Therefore a dual ring configuration is used for adequate phase control and pedestrians movement through the traffic flow in each lane. In this study, a lead forward dual-ring is used as shown in Fig. 3.

3.3. Queue length estimation algorithm using VANETs

For signal control at intersections, obtaining information on queue length information for each forward direction is crucial. Vehicles with wireless communication are able to transmit information directly to the signal controller. However, communication congestion might occur if there is a large number of vehicles in the queue. Also, the concentration of data transmitted to the signal controller increases computation which may decrease the performance of signal controller. The proposed method therefore generates groups of vehicles in the same lane from the end of one green time to the beginning of the next, then elects group leaders who each transmit a group queue length to

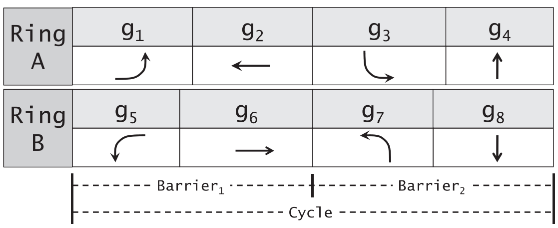

Fig. 3. Lead forward dual-ring for green split.

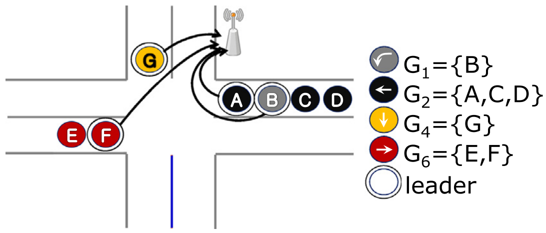

Fig. 4. Example of grouping vehicles.

the signal controller. Fig. 4 shows an example of grouping vehicles.

3.3.1. Vehicle group generation

Groups are generated in each direction. There are four paths marked as E (east), W (west), S (south) and N (north) leading to the road intersection and each path has two lanes in the incoming direction, which are left-turn (L) and go-forward (F). Each passing vehicle can thus have a path PA of E, W, S, N and a direction DI of L, F, and each lane where a vehicle is running can be determined by a pair of PA, DI. As a result, there are at most eight lanes operating relative to the pair (PA, DI). This pair is represented by the direction identifier D. According to the direction identifier, each group leader is elected by the group members. An election period for the group leader starts at the beginning of green time and depends on the dual ring phase configuration. A group leader periodically communicates with group members during red time and calculates the group's queue length. The calculated queue length is sent periodically to the signal controller. The detailed vehicle grouping method is as follows.

1. The signal at intersection is controlled by the phase configuration in Fig. 3. After green time, vehicles stopping at the intersection broadcast a group leader volunteer message to anonymous vehicles with the maximum transmission power. Here, the message includes a unique ID, time-stamp, location, velocity, route, intersection ID and the number of stops. The vehicle that receives this message does not generate its own message but instead re-broadcasts the received message.
2. The vehicle which issues the message compares its own message to messages from other leader volunteer vehicles, then sends a group leader yielding message to the vehicle which owns an earlier message issuing time and is closer to the signal controller. Finally, the group leader is elected through this process.
3. The group leader broadcasts its election to its group members, and vehicles that receive a completion message of leader election send their information (ID, location, speed, direction, vehicle size, leader ID, number of stops and intersection ID) back to the group leader. Once the group leader receives the message, it broadcasts a group member acceptance message to the member vehicle. After the member receives the acceptance message, it updates its group leader's ID and shares this information with vehicles in its vicinity using periodic beacon messages.

4. A group leader receives information from group members during the whole cycle length excluding its own green time and periodically transmits group queue length data to the signal controller.
5. When its own green time begins, the group leader accepts no more group member and passes through.
6. After the green time ends, steps 1–5 are repeated.

The time for group generation and queue length estimation by signal cycle length is shown in Fig. 5.

Each group is generated and the group leader elected after green time. The elected leader then receives traffic information from the group members and calculates the group queue length before the next green time. Group leaders periodically transmit the group queue length to the signal controller.

At the beginning of green time, the group leader passes through the intersection after transmitting the final group queue length to the signal controller. The signal controller computes the next cycle length and green split time on the basis of the received group queue lengths when the green time of phase 4 starts. After the green time of phase 4 ends, the traffic controller applies the new cycle length and green split time.

3.3.2. Queue length estimation

A group is generated after a green time, and a group leader receives vehicle information from its group members. (Vehicle data include vehicle ID, time-stamp, location, velocity, direction, group ID, intersection ID, number of stops, and vehicle length.) The equation to estimate queue length is as follows:

$$RQL_D(t) = \sum_{i=0}^{N} VL_i + ADBV \times (N-1) \qquad (1)$$

where $RQL(t)$ represents the queue length in the present cycle length; D represents an identifier which is combined with each path and incoming direction; VL represents the vehicle length; $ADBV$ represents the average distance between vehicles; and N represents the number of group members.

A group leader sends group information to the signal controller periodically. Here, the controller calculates the weighted average of the current and previous two queue length values and uses the calculated result as the final queue length needed for real time signal control.

$$QL_D(t) = A \times RQL_D(t) + B \times RQL_D(t-1) + C \times RQL_D(t-2) \qquad (2)$$

where

$$A + B + C = 1;\ A = \frac{RQL_D(t)}{l_D}; B = (1-A) \times A; C = 1 - (A+B)$$

and l represents a length of each lane

As seen in Eq. (2) above, the weight is varied by the number of vehicles in each lane. That is, if the number of vehicles increases, the weight for the current queue length is also increased so that a prompt congestion control is possible. In contrast, if there are only few vehicles, the weight for previous queue lengths increase, which enables smooth control without abrupt changes.

3.4. Cycle length and green split estimation

A signal control system must consider smooth traffic at the intersection and pedestrian safety as its highest priority. At the same time, it must meet the following objectives:

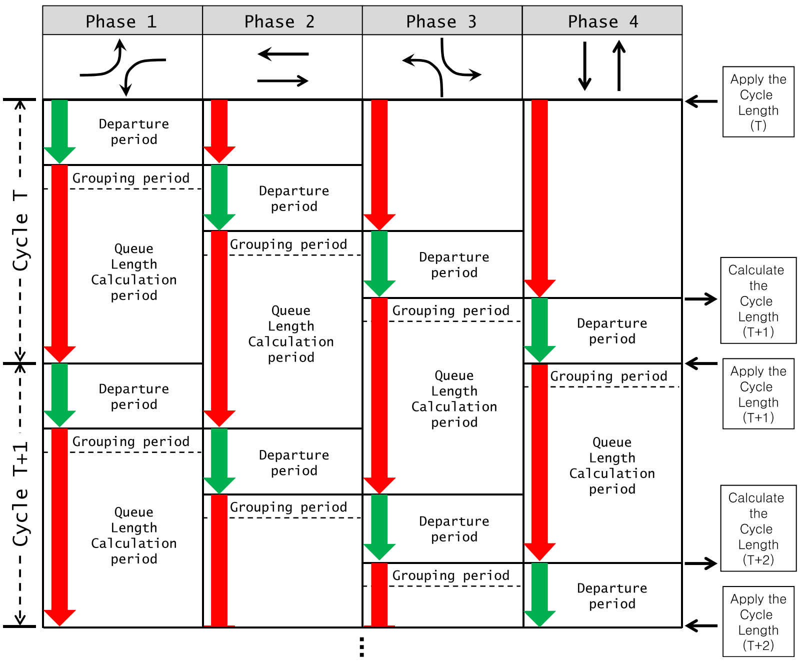

Fig. 5. Sequence of grouping vehicle and calculating queue length.

- minimize delays,
- minimize the number of stops,
- maximize progression efficiency,
- minimize queue size at approaches,
- maximize system throughput.

All the control objectives listed above might not be met simultaneously under certain road and traffic conditions. A delay is a measurement representing how much time a vehicle spends traversing and stopping on the road. As a method to minimize delay, decreasing the cycle length decreases delays during red time. Once red time decreases, delays between cycles decrease too. However, a decreased cycle length also reduces green time so that the minimum number of stops increases in turn. For the optimal traffic signal control at intersections, cycle length and green split need to be configured appropriately based on an estimation of the queue length. This paper aims to provide minimum delay time and minimum queue length. For this purpose, optimal cycle length and green split calculations are required.

3.4.1. Cycle length estimation algorithm

A cycle length needs to be long enough to expose the critical movements in the longest lane at an intersection, but if should not be exceedingly long. If a cycle length is too short, phase changes occur too frequently and green time is also shortened, which takes up more time than necessary or desired. On the contrary, a great cycle length leads to increased waiting time and causes vehicles to wait too long to be exposed from the intersection. Fig. 6 depicts the relationship between cycle length and delay.

In this paper, we propose a cycle length estimation algorithm based on vehicle queue length. A description of the algorithm is shown in Table 1.

3.4.2. Green time estimation algorithm

Once a cycle length is determined, a green time can be derived by substracting an intergreen time (the sum of yellow and red time) from the time of a cycle length. From the full green time, a green time ratio used for each phase is described in (3).

$$GT_D = \frac{V_D/C_D}{\sum_{D=1}^{N} V_D/C_D} \times GT_T \quad (3)$$

where GT_D represents the green time at each lane; V_D/C_D represents a flow ratio in each lane; N represents the number of lanes (in this paper $N = 8$); and GT_T represents the total green time.

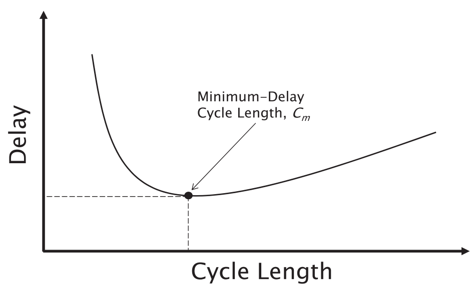

Fig. 6. Shape of a typical delay-versus-cycle length curve for an isolated signal.

Table 1
Cycle length estimation algorithm.

Algorithm 1: *Cycle length estimation algorithm(CLEA)*

Input: $QL_i, i = 1, \ldots, 8$
Output: $CL(t+1)$
1. Receive vehicle queue length from each group
$QL_1(t), QL_2(t), \ldots, QL_8(t)$
2. Estimate the maximum queue length at each barrier
$MAX\_Q_1(t) = Max\{QL_1(t), QL_5(t), QL_2(t), QL_6(t)\}$
$MAX\_Q_2(t) = Max\{QL_3(t), QL_7(t), QL_4(t), QL_8(t)\}$
3. Estimate the temporal required cycle length
$R\_CL_1(t) = N_{MAX\_Q_1(t)} \times h$
$R\_CL_2(t) = N_{MAX\_Q_2(t)} \times h$
4. Compute a required cycle length
$R\_CL(t) = R\_CL_1(t) + R\_CL_2(t)$
5. Estimate the required cycle length by adding intergreen time
$R\_CL(t) = R\_CL(t) + intergreen\_time$
$intergreen\_time = yellow\_time + red\_time$
6. Determine the final cycle length compared with current cycle length
$if\{\Delta C \leqslant (R\_CL(t) - CL(t)) \leqslant \Delta C\} then$
$CL(t+1) = CL(t)$
else
$CL(t+1) = R\_CL(t)$
end if
7. Verify whether the computed cycle length satisfies mininum and maximum conditions

Table 2
Green time estimation algorithm.

Algorithm 2: *Green time estimation algorithm(GTEA)*

Input: $CL(t+1)$, R_CL_i, GT_T, $i = 1, 2$
Output: GT_D
1. Estimate a required barrier green time using cycle length
$GT_{Barrier\_1} = \frac{R\_CL_1}{(R\_CL_1 + R\_CL_2)} \times CL(t+1)$
$GT_{Barrier\_2} = 1 - GT_{Barrier1}$
2. Estimate a ratio of green time for each lane
$R\_GT_D = \frac{V_D/C_D}{\sum_{D=1}^{N} V_D/C_D}$
3. Choose a pattern in Table 3 and apply the ratio of green time to each lane
4. Determine the final green time for each lane
$GT_D = R\_GT_D \times GT_T$

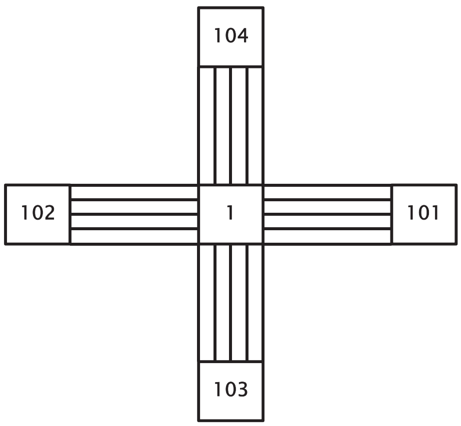

Fig. 7. Single intersection model for simulation.

Table 3
Green split combinations in lead forward dual-ring.

	Condition	Phase Combination					
1	EF=WF, WL=EL NF=SF, SL=NL	EF/WF	WL/EL	NF/SF	SL/NL		
2	EF>WF, WL<EL NF=SF, SL=NL	EF/WF	EF/EL	WL/EL	NF/SF	SL/NL	
3	EF<WF, WL>EL NF=SF, SL=NL	EF/WF	WL/WF	WL/EL	NF/SF	SL/NL	
4	EF=WF, WL=EL NF>SF, SL<NL	EF/WF	WL/EL	NF/SF	SL/SF	SL/NL	
5	EF=WF, WL=EL NF<SF, SL>NL	EF/WF	WL/EL	NF/SF	NF/NL	SL/NL	
6	EF>WF, WL<EL NF>SF, SL<NL	EF/WF	EF/EL	WL/EL	NF/SF	SL/SF	SL/NL
7	EF<WF, WL>EL NF<SF, SL>NL	EF/WF	WL/WF	WL/EL	NF/SF	NF/NL	SL/NL
8	EF>WF, WL<EL NF<SF, SL>NL	EF/WF	EF/EL	WL/EL	NF/SF	NF/NL	SL/NL
9	EF=WF, WL=EL NF=SF, SL=NL	EF/WF	WL/WF	WL/EL	NF/SF	SL/SF	SL/NL

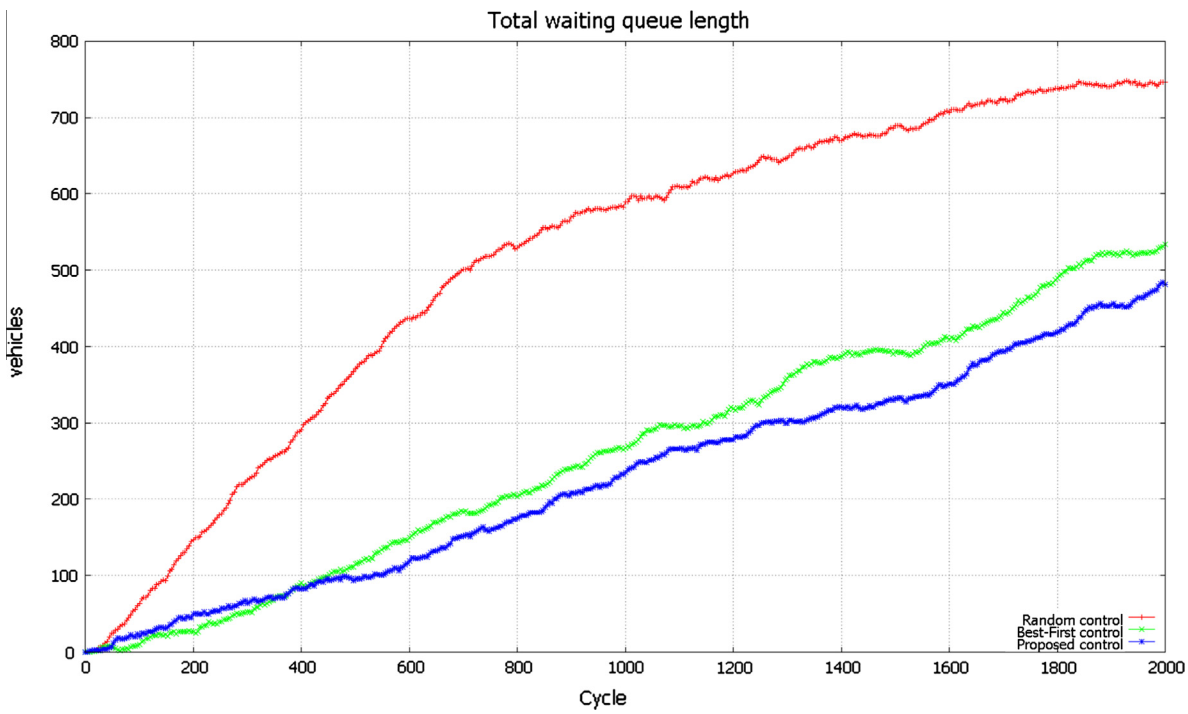

Fig. 8. Total waiting queue length.

Table 4
Input flows for a single intersection.

Approaches	Vehicle category	Flow (vehicles/s)
101	Sedan	1.00
	bus	0.25
102	Sedan	1.00
	bus	0.25
103	Sedan	0.25
	bus	0.05
104	Sedan	0.25
	bus	0.05

In this paper, we propose a green time estimation algorithm based on vehicle queue length. A description of the algorithm is shown in Table 2 and green split combinations in lead forward dual-ring is shown in Table 3.

4. Experimental environment

To test the proposed algorithm, a Green Light District Simulator (GLD) was used [11]. GLD is an open-source Java-based traffic simulator that enables road/intersection design and allows the expansion of source codes to add new algorithms for traffic signal control. New maps were generated and the source code was expanded to add the algorithm proposed in this paper. For the inter-vehicle communication, a packet-based communication simulator such as NS-2 required, but a GLD simulator with added inter-vehicle communication can also be used since the proposed system utilizes only inter-vehicle communication in VANETs environment.

4.1. The structure of the intersection

The simulations have been conducted to optimize queue length in a single intersection without considering the influence of adjacent intersections in Fig. 7.

4.2. Input vehicle generation

In the data generation process for the experiment, time intervals between arrivals are randomly generated for a single intersection, and service time is generated to follow a single queuing model, M/M/1, which is an exponential distribution, and the number of vehicle arrivals follows Poisson distribution. For the experiment, a congested traffic during rush-hour is assumed and the number of entering vehicles for the 4-way approaches at an intersection is shown in Table 4.

5. Performance evaluation

The experiments have been carried out for enough time (2000 cycles) to analyze the congestion at an intersection and each experiment has been repeated 10 times. The result was compared with the following two algorithms to evaluate the performance of the proposed algorithm. One is the random control and the other is best-first control. Best-first control always selects the traffic light configuration which sets the lights to green for the largest amount of vehicles in the lane [11].

Random control is not able to consider the increasing number of vehicles at an intersection so that it shows the largest average waiting time and the largest waiting queue length. Since best-first control prioritizes the approaches

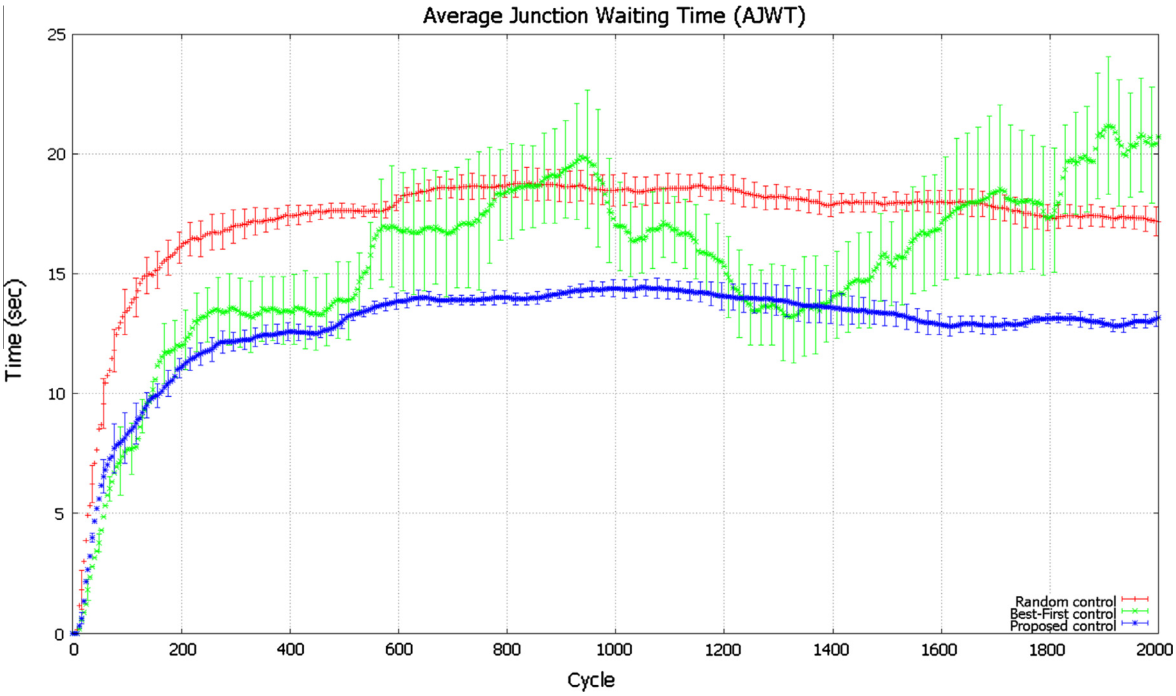

Fig. 9. Average junction waiting time with 95% confidence interval.

101, 102 with a large number of vehicles, it gives a very long waiting time in the approaches 103, 104 with a small number of entering vehicles. Therefore, the total waiting queue length of the proposed algorithm does not show a distinguishable difference from best-first control depicted in Fig. 8. This effect is offset because vehicles in a congested lane have less waiting time while other vehicles in not congested lanes have a longer waiting time.

However, the best-first method has long and irregular waiting time on average as shown in Fig. 9. As can be seen from the graph, the confidence interval for the best-first control method is larger than other control methods. It means that the best-first method might not guarantee attainment of the stable control in congested traffic environment. On the other hand, the proposed algorithm shows that it has stable waiting time on average at the junction. Table 5 shows the means and 95% confidence intervals of each control method.

Group formation in a vehicular ad hoc networks is considered as costly and difficult problem. In many approaches, the overhead in communication increases with the network dynamics, a single change in the group can lead to a complete re-grouping of the network. However, this problem does not arise in our approach. Because the group formation procedure is started when the vehicles of the same direction are stopped near the intersections. Thus, the cost of group management caused by joining and leave operations of new vehicles is minimized.

Proposed algorithm makes use of control messages for the group formation. Table 6 presents a summary of the communication parameters and their values.

Fig. 10 compares the overhead of the two communication method in bytes. As can be seen from the graph, the overhead depends on the number of vehicles. In direct communication, all vehicles send their information periodically to the signal controller. Therefore, the amount of overhead in communication is proportional to the number of vehicles as well as the waiting time in the intersections. On the other hand, proposed communication method by using grouping does not depend on the waiting time. Because the vehicle members send their information back to the group leader only when they receive a completion message of leader election.

Table 5
Average junction waiting time – mean, 95% confidence interval.

Control method	Mean	CI	Lower CI	Upper CI
Random control	17.277	0.228	17.049	17.505
Best-first control	15.456	0.332	15.124	15.788
Proposed control	12.778	0.195	12.583	12.974

Table 6
Configuration values for inter-vehicle communication.

Parameter	Value
Transmission data rate	3 Mbit/s
One hop communication distance	250 m
Packet size	100 bytes
Packet generation rate	500 ms

6. Conclusions

In this study, a real-time traffic control system on the basis of VANETs is proposed. This system estimates the queue lengths in each lane and determines cycle lengths and green splits for a traffic signal controller. The performance of the proposed algorithm is evaluated by conducting simulations compared to the existing control methods. The result of this study can be summarized as follows.

First, an algorithm to estimate queue lengths for each lane based on inter-vehicle communication is proposed. A group leader is elected and a group is generated for vehicles driving in the same direction according to the cycle length of a traffic signal controller, and information from the generated group is sent to the controller. The controller calculates the weighted average of the current and previous two queue length values and uses the calculated result

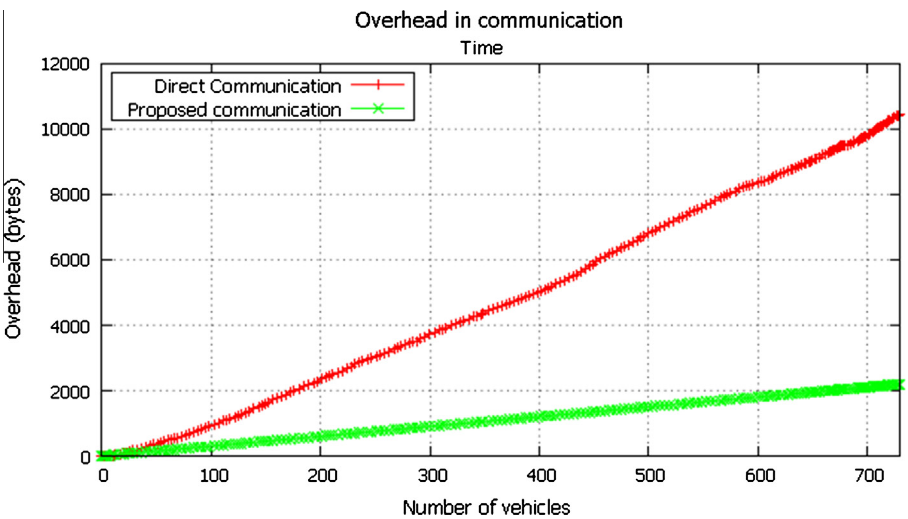

Fig. 10. Comparison of overhead.

as the final queue length needed for real time signal control.

Second, an algorithm to estimate cycle length and green split is proposed. A cycle length is calculated on the basis of the estimated queue length. After the cycle length is calculated, a barrier length can be determined by estimating the time required for the four directions. A green time is assigned in proportion to the required time for each direction.

The proposed algorithm was compared to the random and best-first control methods. The total waiting queue length is shortened compared to random control, and the proposed algorithm shows a minimized waiting time for each individual vehicle when the green split is assigned for each direction in accordance with the amount of traffic flow.

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