Adaptive Traffic Light Control of Multiple Intersections in WSN-based ITS

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Abstract—**We investigate the problem of adaptive traffic light control of multiple intersections using real-time traffic data collected by a wireless sensor network (WSN). Previous studies mainly focused on optimizing the intervals of green lights in fixed sequences of traffic lights and ignored the traffic flow's characteristics and special traffic circumstances. In this paper, we propose an adaptive traffic light control scheme that adjusts the sequences of green lights in multiple intersections based on the real-time traffic data, including traffic volume, waiting time, number of stops, and vehicle density. Subsequently, the optimal green light length can be calculated from the local traffic data and traffic condition of neighbor intersections. Simulation results demonstrate that our scheme produces much higher throughput, lower average waiting time and fewer number of stops, compared with three control approaches: the optimal fixed-time control, an actuated control and an adaptive control.**

I. Introduction

Intelligent Transportation System (ITS) refers to a system that integrates communications-based information and electronics technologies, into transportation infrastructure and vehicles, to relieve traffic congestion, improve safety, reduce transportation time and fuel consumption. The conventional surveillance methods used in ITS to detect real-time traffic data, e.g. video image processing and inductive loops detection, have several shortcomings, such as limited coverage and expensive cost of implementation and maintenance [1]. Meanwhile, Wireless sensor networks can offer the potential to cover these drawbacks while providing real-time traffic data. Hence, WSN-based ITS has been proposed. Traffic lights control plays a key role in the system, for that optimal traffic lights control scheme can increase the traffic throughput and reduce the delay through outputting different traffic signals.

A number of traffic control systems have been implemented worldwide, such as SCOOT [2] [3] and SCAT [4] [5]. Furthermore, various computational intelligence have been applied in the optimization traffic light control design, such as Fuzzy Logic Control [6] [7], Neural Network [8] [9] [10], Genetic Algorithm [9] [11] and so forth. As far as we are concerned, most existing work [2]–[11] consider cycle time, split and offset optimizations with a fixed green light sequence, with objectives of minimum average waiting time and number of vehicle stops. However, they pay little attention to traffic flow's characteristics, and lack consideration of special traffic circumstances, such as ambulance, fire engine or traffic accident.

In our previous work [12], we already proposed an adaptive control algorithm applied in isolated intersection, and implemented into our WSN-based ITS testbed, iSensNet [13], which

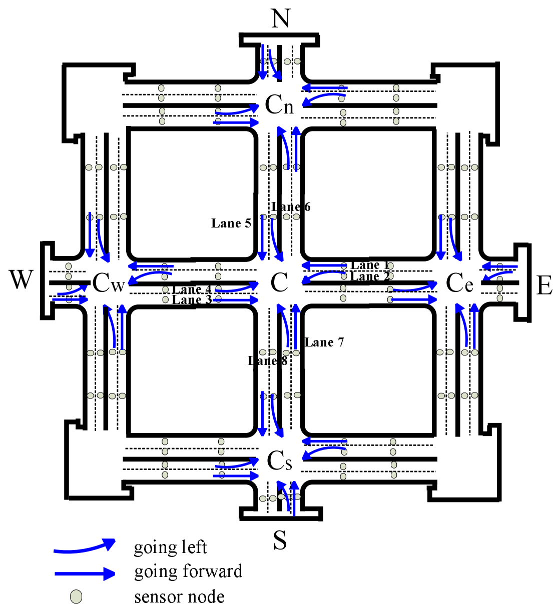

Fig. 1: Multiple Intersections

can schedule both the green lights sequence and length with consideration of discontinuous traffic flow and special traffic circumstances, to increase the throughput and decrease the average waiting time.

In this paper, we extend the previous work to investigate traffic light control of multiple intersections. We propose an adaptive traffic light control scheme to schedule both the green lights sequences and lengths based on detected traffic information. The proposed scheme includes real-time traffic data detection, green light sequence determination algorithm and light length determination algorithm. Our scheme's performance is compared with the optimal fixed-time control, an actuated control and an adaptive fuzzy control [6]. The simulation results shows that our scheme can achieve higher throughput, lower vehicle's average waiting time and fewer number of stops.

II. Problem formulation and notations

Given a traffic network (see Fig. 1) with five four-directions (east, west, north, and south) intersections, one central intersection C and four minor intersections (C_e, C_w, C_n, C_s). Each direction has four lanes, two are approaching lanes (ALs) (left and forward), two are leaving lanes which also are ALs of corresponding neighbor intersection. Each AL is controlled by a traffic light which offers two signals, red for stop and green

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for go. This traffic network installs several wireless sensor nodes to detect real-time traffic condition, e.g. traffic volume.

TABLE I: Notations

P = {1,2,3,...,12}, $k \in P$	L = {1,2,3,...,8}, $r \in L$
v: element of set{C,C_e,C_w,C_n,C_s}.	T: total time period.
Dst: distance between adjacent intersections.	
$AR(v, r, t)$: number of arrival vehicles in r of v at t.	
$DP(v, r, t)$: number of departure vehicles in r of v at t.	
$WTL(v, r, t)$: total vehicles' waiting time in r of v at t.	
$TVL(v, r, t)$: number of vehicles in r of v at t.	
$NSL(v, r, t)$: number of vehicles' stops in r of v at t.	

To formulate the problem, we define the notations in Table I, and assume that all vehicles have the same constant $speed$, and the sensor node used should be the same type.

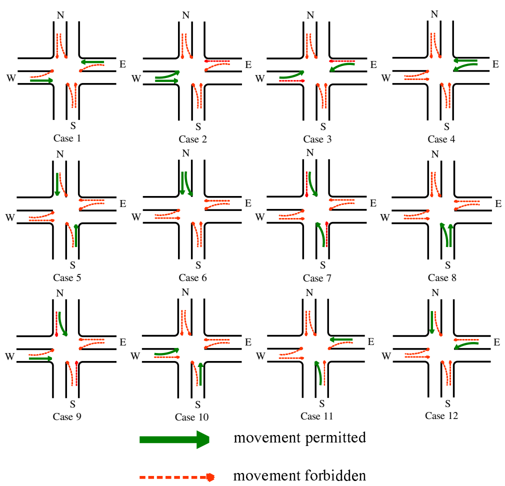

Fig. 2: Twelve cases in each intersection [12]

As mentioned in our previous study [12] (see Fig. 2), each intersection has 12 cases to be candidate to obtain green light. Therefore, in face of dynamically changing traffic environment, the problem is to schedule the sequences and lengths of traffic lights of these intersections cooperatively, to decide which case should obtain green light next in each intersection and how long. The objective is to increase the network throughput, decrease the average delay and average number of stops. In order to maintain fairness for each case in each intersection, we define two upper bounds, maximum vehicle waiting time and an upper bound of hunger level [12].

III. Adaptive Traffic Light Control Scheme

In order to achieve the three objectives, we propose an adaptive traffic light control scheme, including real-time traffic data detection, green light sequence determination algorithm, and light length determination algorithm. Real-time traffic data detection is responsible for detecting and calculating traffic condition in a real-time manner. Green light sequence determination algorithm is to determine which case should be assigned the next green light in each intersection based on the traffic data calculated, including traffic volume, waiting time, number of stops, hunger level, blank circumstance and special circumstance. Light length determination algorithm can determine the duration of next green light in each intersection using local traffic volume and traffic condition from neighbor intersections.

A. Real-time Traffic Data Detection

The real-time traffic data can be detected and calculated by sensor nodes which are installed as shown in Fig. 1, e.g. traffic volume, waiting time, number of stops, traffic flow characteristic. When a vehicle enters the AL, its type and ID can be detected by the upstream sensor node (USN) and so that the length of vehicle $L_{vehicle}$ can be determined. Once detected, USN would send the detected data, such as the arrival rate, to the intersection sensor node (ISN). Meanwhile, ISN would detect the real-time departure rate so that the number of vehicles can be calculated in Eq. 1.

$$TVL(v,r,t)=max\{TVL(v,r,t-1)+AR(v,r,t)-DP(v,r,t),0\} \quad (1)$$

About the waiting time of each vehicle, we can change to calculate the total waiting time of vehicles in each lane at time t. In the lane with green light (named as GLL), the waiting time should be equal to zero; while in the lane with red light (named as RLL), the waiting time of vehicles in time t should be equal to number of vehicles in each lane at time t. When ISN determine the $TVL(v, r, t)$, it can determine the current $WTL(v, r, t)$ in Eq. 2.

$$WTL(v,r,t)=\begin{cases} TVL(v,r,t), & r \text{ is } GLL \\ 0, & r \text{ is } RLL \end{cases} \quad (2)$$

Number of stops of each vehicle can be calculate using the approach in [14]. If USN detects the location of a vehicle did not change within a period T_{ns}, we can determine that the vehicle stops within this period. And then, the times of stops can be determined by checking whether the vehicle stops at the same lane. The value of T_{ns} is constant and 1 second could be a suitable value.

B. Green Light Sequence Determination Algorithm

Using the traffic data detected and calculated, the case that obtains next green light can be determined.$GLD(v, k, t)$ is defined as green light demand of case k at intersection v at time t. The case which gets the greatest value would be assigned the next green light. Six impact factors are considered in GLD computation (see Eq. 3), traffic volume, waiting time, number of stops, hunger level, blank circumstance, and special circumstance. a_i is defined as their respective weight, $i = 1, 2, ..., 6$.

$$\begin{aligned} GLD(v,k,t)=&a_1\times TV(v,k,t)+a_2\times WT(v,k,t)+a_3\times NS(v,k,t) \\ &+a_4\times HL(v,k,t)+a_5\times BC(v,k,t)+a_6\times SC(v,k,t) \end{aligned} \quad (3)$$

In each case, there are two $GLLs$. CL is defined as a matrix that the two elements in i-th row means the two $GLLs$ of $P(i)$. Hence, $CL(k, 1)$ and $CL(k, 2)$ are two $GLLs$ of case k. We also define M as a matrix mapping to CL that the element $M(i, j)$ means the direction of lane $CL(i, j)$ towards. $M(k, i)$ is equal to $[\frac{CL(k,i)+1}{2}]$. i = 1,2, j = 1,2. $M(k, 1)$, $M(k, 2)$ are the directions the $CL(k, 1)$, $CL(k, 2)$ towards respectively.

$$CL^T=\begin{pmatrix} 1 & 3 & 2 & 1 & 5 & 5 & 6 & 7 & 3 & 4 & 1 & 2 \\ 3 & 4 & 4 & 2 & 7 & 6 & 8 & 8 & 6 & 7 & 8 & 5 \end{pmatrix}$$

$$M^T=[\frac{CL^T+1}{2}]=\begin{pmatrix} 1 & 2 & 1 & 1 & 3 & 3 & 3 & 4 & 2 & 2 & 1 & 1 \\ 2 & 2 & 2 & 1 & 4 & 3 & 4 & 4 & 3 & 4 & 4 & 3 \end{pmatrix}$$

And then, we can get the way to compute $TV(v,k,t)$, $WT(v,k,t)$, $NS(v,k,t)$, $HL(v,k,t)$, $BC(v,k,t)$ and $SC(v,k,t)$.

To calculate $TV(v,k,t)$, we need to obtain the corresponding $TVL(v,r,t)$ first, which can be calculated in Eq. 1. When i is $RLLs$, $DP(v,r,t)$ is equal to zero. Thus, traffic volume in case k of intersection v at time t can be obtained in Eq. 4. Higher TV brings more influence in GLD computation.

$$TV(v,k,t)=TVL(v,CL(k,1),t)+TVL(v,CL(k,2),t) \tag{4}$$

To calculate $WT(v,k,t)$, we need to obtain the corresponding $WTL(v,r,t)$ first, which can be calculated in Eq. 2. Thus, waiting time in case k of intersection v at time t can be obtained in Eq. 5. Higher WT brings more influence in GLD computation.

$$WT(v,k,t)=WTL(v,CL(k,1),t)+WTL(v,CL(k,2),t) \tag{5}$$

To calculate $NS(v,k,t)$, we need to obtain the corresponding $NSL(v,r,t)$ first, whose collection has been mentioned previously. $NS(v,k,t)$ should be equal to the total number of stops of the vehicles in the two corresponding lanes (in Eq. 6).

$$NS(v,k,t)=NSL(v,CL(k,1),t)+NSL(v,CL(k,2),t) \tag{6}$$

To calculate $HL(v,k,t)$, we need to obtain $N(v,k,t)$ first, which is defined as the times of previous green lights of case k of intersection v at time t, so that $HL(v,k,t)$ is equal to the ratio between $N(v,k,t)$ and the total times of previous green lights of all cases (in Eq. 7).

$$HL(v,k,t)=\frac{N(v,k,t)}{\sum\limits_{k\in P} N(v,k,t)} \tag{7}$$

The consideration of blank circumstance is regarding to the discontinuous traffic flow that we try to reduce the frequency of the circumstance in which there is no vehicle of GLL to reach the intersection. The computation method is the same as in our previous work [12] that number of blanks in each lane, and their length are considered. The case without any blank would be assigned higher priority to obtain green light. If all case has a blank, the case with the shortest blank length should achieve higher priority.

Special circumstance refers to some situations, such as traffic accidents, fire engine, in which a green or red light must be activated urgently. The computations is also the same as in our previous work [12], that when some special type vehicles are detected, the certain case would be assigned higher priority to obtain green light; when traffic accident is detected, the certain case would be assigned higher priority to obtain red light.

In coefficient determination, we choose a_1, a_2, a_3 to be adjusted through simulations within a given range, due to the dominance of these factors' influence, and other factors with fixed value. Subsequently, the GLD of each case of these intersections can be calculated, and in each intersection the case with largest GLD value would be selected to assign the next green light.

C. Light Length Determination

After the green light sequence determination, the length of the green light should be determined. $Len(v,t)$ is defined as the length of green light in intersection v at time t, which can take both local traffic condition and neighbor traffic condition requirement into consideration.

At first, we can compute a preliminary value of the length in each intersection, based on the traffic condition of the next green case. $Len_{pre}(v,t)$ is defined to represent it in intersection v at time t, and it should be equal to the sufficient time for the vehicles in the two $GLLs$ to pass through the intersection (see Eq. 8).

$$Len_{pre}(v,t)=\frac{max\{TVL(v,CL(g(v),1),t),TVL(v,CL(g(v),2),t)\}}{speed} \tag{8}$$

And then, the offset between adjacent intersections to get green waves is considered, which can lead the vehicles to meet red lights as few as possible when running through the intersections. $Len_{os}(v,t)$ is defined as the sufficient time for the vehicles permitted from intersection v's neighbor intersection ($NeiInt$) to pass through intersection v. In order to guarantee the fairness, we also define a maximum green light length T_{max} that $Len(v,t)$ should be smaller than T_{max}.

$$Len(v,t)=Len_{pre}(v,t)+Len_{os}(v,t) \tag{9}$$

1. Neighbor Intersection's Influence Analysis

Before computing $Len_{os}(v,t)$, the influence from $NeiInt$ should be taken into account and analyzed. The shorter Dst brings more possible effect from the four $NeiInts$. In each $NeiInt$, there are several possible impact factors, such as traffic volume, the corresponding waiting time, their number of stops, remaining green light duration and so on.

Let's take C_e as an example to analyze the effect from $NeiInt$ for C. In C_e, 12 cases would be possible to obtain the green light. Within them, 5 of them, case 1,4,7,8,11, would admit the vehicles to pass through and approach to intersection C when getting green light. We define a set of these five cases as impact case set (ICS) and a set of the others as non-impact case set ($NICS$). In ICS, when case 11 obtains green light, vehicles in the both two $GLLs$ would approach to intersection C, while in the other four cases, only one GLL would let their vehicles approach to C. We define these impact $GLLs$ in $NeiInts$ as possible impact lanes ($PILs$) for C. Hence, there are two $PILs$ for C when green case of C_e is case 11, and there is only one PIL for C when case 1, 4, 7, 8 has green light in C_e.

$$NCS=\begin{pmatrix} 1 & 4 & 7 & 8 \\ 1 & 2 & 6 & 7 \\ 3 & 4 & 5 & 6 \\ 2 & 3 & 5 & 8 \end{pmatrix}, \quad NCT=\begin{pmatrix} 11 \\ 9 \\ 12 \\ 10 \end{pmatrix}, \quad FB=\begin{pmatrix} 1 & 8 \\ 3 & 6 \\ 2 & 5 \\ 4 & 7 \end{pmatrix}$$

We define two matrixes, NCT and NCS. NCT contains all the cases which would take two $PILs$, and NCS contains all the case which would take only one PIL. We also define a matrix NC to contain all the cases taking PIL, of which NCT and NCS are two block matrixes to consist. The element in i-th row of NC, NCT and NCS, means the case in the $NeiInts$ at the i direction of intersection C, i=1, 2, 3, 4.

$$NC{=}[NCS{,}NCT]{=}\begin{pmatrix} 1 & 4 & 7 & 8 & 11 \\ 1 & 2 & 6 & 7 & 9 \\ 3 & 4 & 5 & 6 & 12 \\ 2 & 3 & 5 & 8 & 10 \end{pmatrix}$$

On the other hand, there exist some forward-backward-lanes (FBL) pairs between two adjacent intersections, which means vehicles in the backward lane of $NeiInt$ would approach to the forward lane of the central intersection. A set FB is defined to include all the possible $FBLs$. $FB(i,j)$ means the vehicles in the j lane of the $NeiInt$ at the i direction of intersection C.

At each time, there is one case having green light, which can be represented by $g(v)$ of intersection v. $CL(g(v),1)$ and $CL(g(v),2)$ are the two $GLLs$, $M(g(v),1)$ and $M(g(v),2)$ are the directions that $CL(g(v),1)$ and $CL(g(v),2)$ towards. We define $g(M(g(v),i))$ as the green case of $NeiInt$ at the $M(g(v),i)$ direction of intersection v, i=1,2. When $M(g(v),1)$ is equal to $M(g(v),2)$, if $g(M(g(v),1))$ is the impact case, there is only one influential neighbor intersection INI, $M(g(v),1)$ direction $NeiInt$; else there is no INI. When $M(g(v),1)$ is not equal to $M(g(v),2)$, if both of $g(M(g(v),1))$ and $g(M(g(v),2))$ are the impact case, there exist two $INIs$, $M(g(v),1)$ direction $NeiInt$ and $M(g(v),2)$ direction $NeiInt$; if one of them is the impact case, there is only one INI; else there is no INI.

The corresponding backward lanes of GLL in $M(g(v),i)$ direction $NeiInt$, are $FB(M(g(v),i),1)$ and $FB(M(g(v),i),2)$; meanwhile, $CL(g(M(g(v),i)),1)$ and $CL(g(M(g(v),i)),2)$ are the two $GLLs$ of $M(g(v),i)$ direction $NeiInt$. i=1,2. A lane belong to the *bigcap* of set of backward lanes and set of $GLLs$ of $M(g(v),1)$ or $M(g(v),2)$ direction $NeiInt$ can be treated as the impact lane (IL), in which vehicles can go through the $NeiInt$ and enter into the GLL.

We define $NLS(g(v),i)$ to represent the ILs set in $M(g(v),i)$ direction $NeiInt$ (see Eq. 10),and use $n(NLS(g(v),i))$ to represent the number of elements in $NLS(g(v),i)$. It can be 0,1,2. When $n(NLS(g(v),i))$ is equal to zero, $g(M(g(v),i))$ should belong to $NICS$. When $n(NLS(g(v),i))$ is equal to one, $g(M(g(v),i))$ should be one element of matrix $NCS(M(g(v),i))$. When $n(NLS(g(v),i))$ is equal to two, $g(M(g(v),i))$ should be one element of matrix NCT, i=1,2.

$$\begin{aligned} NLS(g(v),i)={} & \{FB(M(g(v),i),1),FB(M(g(v),i),2)\}\bigcap \\ & \{CL(g(M(g(v),i)),1),CL(g(M(g(v),i)),2)\} \end{aligned} \tag{10}$$

2. Offset Length Computation

After the $INIs$ and ILs analysis, the remaining duration of $g(M(g(v),i))$ at time t, defined as $T_{rm}(M(g(v),i),t)$, also should be taken into account due to its significance in the offset length computation, i=1,2. If the remaining duration is large, the traffic condition in INI would affect the central intersection significantly. If the remaining duration is short, the traffic condition in INI would give a slight effect to the central intersection. Due to the existence of T_{max}, $Len_{os}(v,t)$ should be smaller than a threshold $Thd(v,t)$, which is equal to $T_{max} - Len_{pre}(v,t)$. Based on the previous analysis, we can divide into one INI and two $INIs$ to discuss.

1) One INI: It indicates $g(v)$ is one of the case 2,4,6,8, $M(g(v),1) = M(g(v),2)$. We use $M(g(v),1)$ to represent them. There are three possibilities of ILs, none IL, one IL and two ILs. When there is no IL, $Lenos(v,t)$ is equal to zero. When there exists one IL, we discuss two possibilities, when $T_{rm}(M(g(v),1),t) \geq Thd(v,t)$ and when $T_{rm}(M(g(v),1),t) < Thd(v,t)$ which are shown in Eq. 11. When there exists two ILs, it is similar to when only exists one IL.

$$Len_{os}(v{,}t){=}\begin{cases} Thd(v{,}t), & \text{if } T_{rm}(M(g(v),1),t) \geq Thd(v,t) \\ T_{rm}(M(g(v){,}1){,}t), & \text{if } T_{rm}(M(g(v),1),t) < Thd(v,t) \end{cases} \tag{11}$$

2) Two $INIs$: It indicates $g(v)$ is one of the case 1,3,5,7,9,10,11,12, $M(g(v),1) \neq M(g(v),2)$. Similarly there are three possibilities in each INI, which lead to nine circumstances (see Table II) to discuss.

TABLE II: Number of Impact Lanes of Intersection v

Circumstance	$n(NLS(g(v),1))$	$n(NLS(g(v),2))$
1	0	0
2	1	0
3	2	0
4	0	1
5	1	1
6	2	1
7	0	2
8	1	2
9	2	2

When in circumstance 1, $Len_{os}(v,t)$ should be equal to zero. When in circumstance 2 and 3, there exists one IL or two ILs in $M(g(v),1)$ direction $NeiInt$, $Len_{os}(v,t)$ computation is same in Eq. 11. When in circumstance 4 and 7, there exists one IL or two ILs in $M(g(v),2)$ direction $NeiInt$. Similar to circumstance 2 and 3, the $Len_{os}(v,t)$ can be computed in Eq. 12.

$$Len_{os}(v{,}t){=}\begin{cases} Thd(v{,}t) & \text{if } T_{rm}(M(g(v),2),t) \geq Thd(v,t) \\ T_{rm}(M(g(v){,}2){,}t) & \text{if } T_{rm}(M(g(v),2),t) < Thd(v,t) \end{cases} \tag{12}$$

When in circumstance 5, 6, 8 and 9, both $INIs$ have IL. We define $T_{rm}(v,t)$ to represent the minimum of T_{rm} $(M(g(v),1),t)$ and $T_{rm}(M(g(v),2),t)$. And then, $Len_{os}(v,t)$ can be computed in Eq. 13.

$$Len_{os}(v{,}t){=}\begin{cases} Thd(v{,}t) & \text{if } T_{rm}(v,t) \geq Thd(v,t) \\ T_{rm}(v{,}t) & \text{if } T_{rm}(v,t) < Thd(v,t) \end{cases} \tag{13}$$

Based on the analysis above, the next green light length in each intersection can be determined.

IV. Performance Evaluation

To evaluate our scheme's performance, we conduct simulations compared with a optimal fixed-time traffic control (FTC) and an actuated traffic control (ATC) and an adaptive

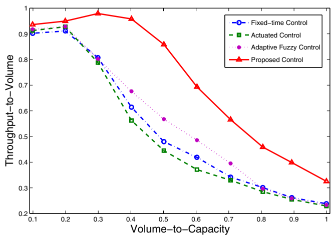

Fig. 3: Throughput-to-volume comparisons between FTC, ATC, AFLC and our proposed method

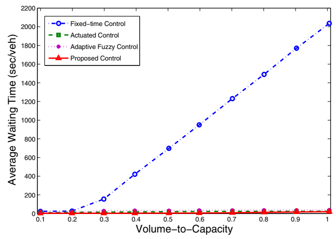

Fig. 4: Average waiting time comparisons between FTC, ATC, AFLC and our proposed method

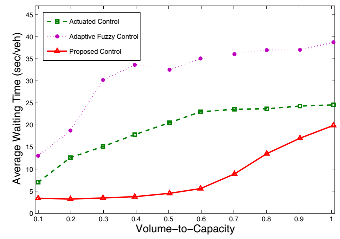

Fig. 5: Average waiting time comparisons between ATC, AFLC and our proposed method

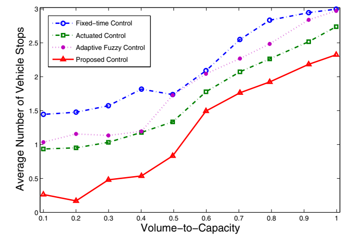

Fig. 6: Average number of stops comparisons between FTC, ATC, AFLC and our proposed method

fuzzy logic control (AFLC) [6] due to the same traffic network type, under the same random arrival rate of each lane, $speed$, $L_{vehicle}$ and L_{lane}.

We define a traffic structure consisting of 13 inter-connected intersections, with one central intersection, four minor intersections which are neighbors of central intersection, and eight tertiary intersections which are neighbors of minor intersections. The five intersections (the central and minor intersections) can schedule the traffic lights in a distributed way. We define $volume\text{-}to\text{-}capacity$ to indicate the busy degree of traffic conditions. The performance metrics include throughput-to-volume, average waiting time and average number of stops. Throughput-to-volume is defined as the ratio of number of departure vehicles to the total traffic volume.

Fig. 3 presents the throughput-to-volume comparisons.We can observe that our scheme can achieve the highest throughput. When $volume\text{-}to\text{-}capacity$ is lower than 0.2, all the approaches can achieve good performance and ours obtains the best performance. When $volume\text{-}to\text{-}capacity$ is in interval [0.2, 0.4], the other three start to perform worse while ours increases to an almost 100% throughput. When $volume\text{-}to\text{-}capacity$ is in [0.4, 1], the throughput-to-volume gained by our scheme begins to decrease when the other three continue getting lower throughput.

The average waiting time comparisons is presented in Fig. 4. Average waiting time in FTC increase rapidly with $volume\text{-}to\text{-}capacity$ growing, and much faster than the other three. Due to the difficulty to identify the performances of ATC, AFLC and our scheme, we enlarge the three's performance in Fig. 5. With the $volume\text{-}to\text{-}capacity$ increasing to 0.6, average waiting time by proposed scheme keeps lower than 5 seconds, while average waiting time of the other two control algorithms grows to approximate 20 seconds and 35 seconds respectively. With the $volume\text{-}to\text{-}capacity$ increasing from 0.6 to 1, the waiting time in all the three algorithms keep growing and our approach always bring the lowest waiting time.

Fig. 6 shows the average number of stops comparisons. Before the $volume\text{-}to\text{-}capacity$ increases to 0.4, the number of stops of the other three algorithms are almost twice or triple of our scheme, which keeps under 0.5. When $volume\text{-}to\text{-}capacity$ increase from 0.4 to 1, number of stops of all the methods increase and ours maintains fewest number of stops.

V. CONCLUSION

In this paper, we have proposed an adaptive traffic light control scheme of multiple intersections with the purpose of increasing traffic throughput, reducing average waiting time and average number of stops. Our experimental results demonstrate that the proposed scheme could produce higher throughput, lower vehicles' waiting time and fewer number of stops compared with the optimal fixed-time control, an actuated control and an adaptive control.

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