# A Realtime Dynamic Traffic Control System Based on Wireless Sensor Network

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## Abstract

*One disadvantage of most conventional vehicle detection methods in a traffic control system is that they can only detect the vehicle in a fixed position. This paper proposed a new vehicle detection method using the Wireless Sensor Network (WSN) technology. The striking feature of the proposed WSN-based method is that it can monitor the vehicles dynamically. This paper also developed a new signal control algorithm to control the state of the signal light in a road intersection. Simulations of the real-life intersection traffic control system are conducted in the paper. The simulation results show that the proposed method is effective for the traffic control in a real road intersection.*

## 1. Introduction

Automobile is a great invention for people to extend their territory. Unfortunately, the increasing number of cars causes a series of economic and social problems across the world. In order to generate additional capacity from the existing physical infrastructures, governments and scholars make great effort to develop Intelligent Transportation System, a system to gather the information, monitor and schedule the traffic flow, as well as guide and control the vehicles.

An Intersection is a basic node of the urban traffic network. How to gather the traffic information and control the traffic flow around it is a hot research topic. There are two main methods in signal control: periodical signal control and sensor-based signal control. Due to the randomness of the traffic flow, the periodical signal control method is unable to adapt the signal control to the dynamic traffic flow, and it only works for the less busy intersections.

The sensor-based method optimizes the signal control according to the data gathered by sensors. Presently, the sensors are ultrasonic sensor in Japan [1,2] and inductive loops in the other countries [3]. A new method based on video recognization is under development [3,4]. The main optimizing algorithms include agent, fuzzy logic system (FLS), neural network-fuzzy (NNF), multi-objective genetic algorithms (MOGA) and Markov Process [5-9]

The current sensor-based control techniques solve some problems. However, there are still some disadvantages with them. For example, the ultrasonic sensor is very sensitive to the weather. Inductive loop typically affects the traffic during installation and are prone to breakage as a result of other construction. The video recognization technique is still under development and is not mature enough for real traffic control. What's more, all of the above sensors can only detect the vehicles in a fixed spot. They can not trace the vehicles out of this spot.

The main difficulty of the traffic control is usually the forecast of the incoming vehicles. If we know the exact time when the vehicles arrive at the intersection, the algorithm will be easy to implement. This paper proposes a new approach to precisely forecast the incoming vehicles in an intersection with the help of the emerging wireless sensor network technology.

The rest of this paper is organized as follows: Section 2 describes the algorithm for the signal light control for an intersection. Section 3 describes the structure of the proposed WSN-based traffic control system. The simulation results and some discussions are presented in Section 4. Finally, Section 5 concludes this paper.

## 2. Algorithm for Intersection Signal Control

### 2.1. Model of Intersection and Phases of Signal Lights

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The selection of signal phase mode depends on the traffic flows through the intersection [5-9]. This paper uses the typical mode shown in Fig. 1 for the explanation of the proposed algorithm. From the figure, we see there are four approaches (marked as ***N***, ***S***, ***W*** and ***E***) leading to the intersection and each approach has three lanes in the incoming direction, which are turn-left (L), go-forward (F) and turn-right (R) respectively. In the following discussion, we use variable $\eta$ to denote the approach, $\eta \in \{E,S,N,W\}$, and variable $\theta$ to denote the direction of turning, $\theta \in \{L,F,R\}$. Thus, a lane where a vehicle is running can be determined by a pair of $\{\eta, \theta\}$.

In Fig. 1, the dotted turn-right arrow means that if there is a sky pass or an underpass for pedestrians and cyclists, or pedestrians and cyclists are not crowded, right turn is permitted. However, in order to make the discussion simple, we assume that right turn is permitted at all time.

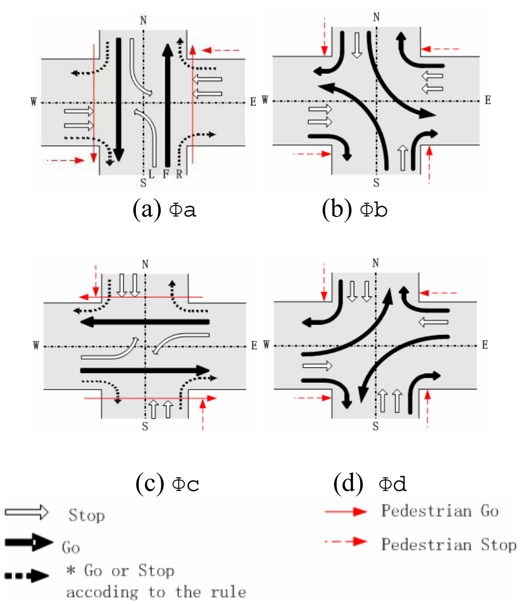


**Figure 1. Four phases of signal light**

Define ***Expectant Phase*** of a vehicle as the phase in which a vehicle pass the intersection, which is denoted as **EΦ.** Clearly, EΦ depends on lane which the vehicle is on and it can be denoted as **EΦ($\eta$, $\theta$).** With above denotations, we obtain:

$$E\Phi(N,F) = E\Phi(S,F) = \Phi a;\ \ E\Phi(N,L) = E\Phi(S,L) = \Phi b;$$
$$E\Phi(W,F) = E\Phi(E,F) = \Phi c;\ \ E\Phi(W,L) = E\Phi(E,L) = \Phi d;$$

## 2.2. The main algorithm for the phase shifting

The signal light phase shifts among Φa, Φb, Φc and Φd in turn. So it is a 4-status finite state machine. The algorithm is designed to adjust the duration for each phase. In this system, the duration is determined by the vehicles conditions that the wireless network detected.

Define ***Lane Waiting Queue*** as the vehicles that waiting on or running on the lane $\{\eta, \theta\}$ but will reach the intersection at the end of current phase at the time ***t***. Denote it as ***Q(*** $\eta, \theta, t$ ***)***. For those that current time or t is not concerned, use ***Q(*** $\eta, \theta$ ***)*** instead. Attention that the queue includes some running vehicle as well as the parking vehicles. We use $Q_R$ and $Q_P$ to denote them respectively.

Define ***Queue Passing Time*** as the duration that all of the vehicles in queue Q($\eta, \theta$) pass the intersection. Denote it as ***TQ(*** $\eta, \theta$ ***).*** Denote the passing time of first vehicle as ***T1***, the time that a vehicle goes from its original position to its predecessor's position (in rear) as $\tau_i$. Use ***TV(V_i)*** to denote the passing time of a vehicle $V_i$, i.e.,

$$TV(V_i) = \begin{cases} T1 & i=1,\ \ V \text{ is the first vehicle in the queue} \\ \tau_i & \text{else} \end{cases} \qquad (1)$$

$$\begin{aligned} TQ(\eta,\theta) &= \sum_j TV(V_j) = T1 + \sum_i \tau_i \\ &= TQ_P(\eta,\theta) + TQ_R(\eta,\theta) \\ &= \sum_m TV(V_m) + \sum_n TV(V_n) \end{aligned} \qquad (2)$$

$$\text{Where } i \in Q(\eta,\theta), i \neq 1;\ j \in Q(\eta,\theta);$$
$$m \in Q_R(\eta,\theta);\ n \in Q_P(\eta,\theta)$$

T1 and $\tau_i$ are related to the length of the path to across the intersection and the length of the vehicle, and some other factor such as the type of the vehicle. We use *xCar* and *xRoad* to represent the factor of vehicle and road, so the relationship can be mapped as:

$$T1 = T1(xCar,\ xRoad,\ \eta,\ \theta); \qquad (3)$$
$$\tau_i = \tau_i(xCar,\ xRoad,\ \eta,\ \theta)$$

Define ***Expectant Phase Time of phase Φx*** as the duration that the vehicles in all of the queues with EΦ=**Φx** up to the current time t passing through the intersection. Denote it as TQ(Φx,t). For the occasion that t is not concerned, denote it as TQ(Φx ), or TQx. Then,

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$$TQx = MAX(TQ(\eta, \theta)) \tag{4}$$

$$Where \quad (\eta, \theta) \in \{E(\eta, \theta) = x\};$$
$$\eta \in \{E,S,N,W\}; \quad \theta \in \{L,F\};$$
$$x \in \{a, b, c, d\};$$

Define ***Presetting phase time (TPx)*** as the duration of phase Φx set by the controller.

The basic idea of the algorithm is to set TPx equal to TQx so that no time will be wasted on waiting for vehicles. Normally, TPx should not be shorter than 15 seconds to ensure that a single vehicle has enough time to pass the intersection safely. On the other hand, TPx should not be longer than 90 seconds to avoid influencing the drivers' psychological endurance. [5-9]. However, since we have considered the passing time of a single vehicle in the algorithm (T1), Tmin can be omitted. If there is no vehicle in the lane waiting queue, the phase will be passed through; if there is no vehicle waiting on the other phase, the current phase is kept.

So, the main control program of the signal light can be described as the following algorithm.

***[Algorithm 1]:***

**(i)** *Initialization. Set Phase= Φx ( x∈ {a,b,c,d} ) arbitrarily, Set Tmax=90; TPx = MIN(TQx,Tmax).*

**(ii)** *Switch (or keep) the signal light of each approach to this phase and wait a time TPx*

**(iii)** *If TQx >0, then Tmax = Tmax-TPx, TPx= MIN(TQx,Tmax), go to(ii);*

**(iv)** *Check TQ of the next phases in turn.*
*If a nonzero value (TQx') detected, then*
*set Phase = Φx'; Tmax=90,*
*TPx' = MIN(TQx',Tmax), go to (ii)*
*Else, if TQ of all other phases equal to zero, then*
*set Tmax=90; TPx=MIN(MAX(1,TQx),Tmax),*
*go to (ii).*

Note that TQx is changed dynamically according to the traffic flow.

## 3. Gather Information with Wireless Sensor Network

The above algorithm assumes that we know TQx in real time. Below, we will describe the wireless sensor network model that is designed to compute the TQx in real time.

### 3.1. Module Structure

With the development of microelectronic and computer technologies, a low power-consumption, low-cost and relatively powerful wireless sensor network (WSN) technology has been applied in many areas [10,11]. However, the application of WSN in the traffic control system is rarely documented. This paper attempts to apply this technology into this area. We use WSN to gather the traffic information and control the signal light.

As illustrated in Fig. 2, the module is composed of 3 main components, i.e., RF (Radio Frequency), MCU (Micro Control Unit) and Power Supply. The RF encodes, modulates and sends the signal, and also it receives, decodes and demodulates the signal. MCU integrates processor and memories, where the programs resides and executes. For a simple application, an 8-bit MCU is sufficient. The power part supplies the power to all the modules. Due to the low power consumption of this module, solar cell or a combination of solar cell and small size rechargeable battery can be applied. This palm-size module can be installed everywhere easily.

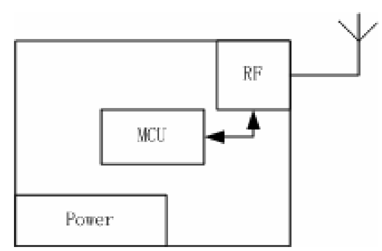



Figure 2. Module structure of a WSN node used in this paper

### 3.2. Module Categories and Data Transferring

As shown in Fig. 3, the WSN nodes can be classified into 3 categories, i.e., ***control node, detector node*** and ***vehicle node.*** The main function of **control node** is to summarize the information from all the four directions, and to control the signal light according to the algorithm 1. Only one control node is installed in an intersection and it is connected to the controller of the signal light directly. The main functions of **detector node** are to gather the information of the vehicles around, and relay them to the control node. Detector nodes are installed on the lamp posts along the road every 50~200m according to the wireless cover range. The main functions of **vehicle node** are to calculate the parameter of the vehicle itself and report them to the detector nodes. Vehicle node is installed in every vehicle. The control node, detector nodes and vehicle nodes are marked as A, B, C in the figure.

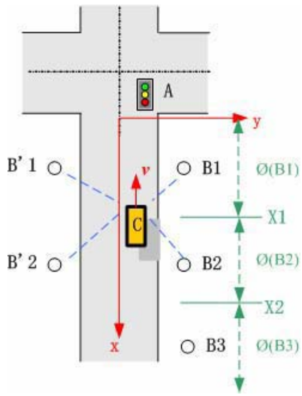



Figure 3. Control node (A), detector node (B) and vehicle node (C) and their distribution on the road

There are 3 steps to get TQx and control the signal: (i) Vehicles detecting and locating; (ii) data synthesizing and relaying; (iii) summarizing and executing.

***(i)*** There are some detector nodes on both sides of the road. (Left side: $B'_1$, $B'_2$ …; Right side: $B_1$, $B_2$ …). Detector nodes broadcast messages every second. A message includes the ID of the detector node itself and its relative location to the intersection ($\boldsymbol{x_B}$, $\boldsymbol{y_B}$). Normally, vehicle node is in the listening state. When a vehicle comes into the road where detector nodes are installed and receives the broadcasted message, vehicle node switches to the active state. According to the wireless locating measure [12-14], if vehicle node receives more than three nodes' broadcast, it can calculate the location (**x, y**) and velocity ***v*** of itself. Then vehicle node sends the information (*x, y, v*) to the detector node nearby.

***(ii)*** Every detector node counts the vehicles around itself. Obviously, only the vehicles on the right side of the road need to count. The vehicle information which is not in its scope will be ignored. Let $Ø(B_j)$ stand for the scope of $B_j$. After receive (*x, y, v*) message from vehicle node, detector node knows which lane the vehicle is on ( θ ), and the distance between the vehicle and the intersection (|x|).

From the distance and velocity, the detector node know the vehicle status is (a)it has reached the intersection (in $Q_P$); (b) it will reach the intersection before the current phase expired (in $Q_R$);or (c) it will not reach the intersection in time. If the status is (c), the vehicle is ignored; otherwise, TV(Vi) is got by applying formula (1) and (3). Then, according to formula (2), in the scope of $B_j$ ($Ø(B_j)$), the expectant time:

$$TQ(\eta,\theta)(Ø(B_j)) = \sum_j TV(V_j)(Ø(B_j))$$
$$\text{where } (\eta,\theta)\in\{E(\eta,\theta)= x\}; \quad \eta\in\{E,S,N,W\};\ \theta\in\{L,F\} \quad x\in\{a,\ b,\ c,\ d\}; j=1,2,\dots \tag{5}$$

TQ is re-calculated dynamically. As long as a vehicle status is changed, TQ will be updated in time.

Detector node is used as relay node as well. The TQ data is passed from remote detecotr node to control node. In order to reduce the transmitting data, detector node merges the TQ value in its scope and the TQ value relayed to it. Then,

$$TQ(\eta,\theta)(B_j\ transmit) = TQ(\eta,\theta)(Ø(B_j)) + TQ(\eta,\theta)(Ø(B_{j+1})) = \sum_j TQ(\eta,\theta)(Ø(B_j)) \tag{6}$$

When the data reach B1, TQ( η , θ )( $B_1$ transmit ) = TQ( η , θ ).

***(iii)*** After the control node receiving the TQ( η , θ ) from the four directions, TQx (x=a, b, c, d) is calculated according to formula (4). Then, the control node executes the algorithm 1 to get TPx, and control the alternating of the signal phase. It also sends back the TPx to the detector nodes.

## 4. Simulation Result and Discussions

### 4.1. Simulation Result

To demonstrate the effect of the proposed algorithm, some simulations are conducted in the PC using the data of a real intersection which is reported in [5]. The conditions of the real intersection are listed in Table 1. In our simulations, it is assumed that that $\tau_i = 1$ vehicle/second, T1=5 (seconds) for F-direction and T1=7 (seconds) for L-direction.

Table 1. Conditions of a real intersection (abstracted form [5])

| Approach | Incoming Vehicles (vehicles/hour) | | | Initial Queue Length (Vehicles) | | |
|---|---|---|---|---|---|---|
| | L | F | R | L | F | R |
| E | 251 | 779 | 242 | 5 | 12 | 4 |
| W | 346 | 896 | 430 | 5 | 10 | 6 |
| S | 410 | 944 | 275 | 6 | 10 | 5 |
| N | 430 | 854 | 243 | 6 | 12 | 4 |

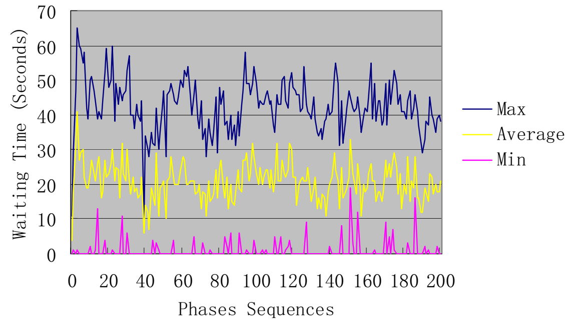
As done in [5,6], the performance of a traffic control system is usually evaluated by the total number of the vehicles that are delayed in the intersection. However, in this paper, since the phase time is adjusted according to the incoming vehicles dynamically, a vehicle will never be postponed to next signal cycle as long as the intersection is not saturated. So we evaluate of the algorithm based on the waiting time of the vehicles at the intersection. A smaller waiting time means a better performance of the algorithm. In our simulation, the maximum, the minimum as well as the average waiting time of the vehicles are calculated.

Fig. 4(a) shows the waiting time of the vehicles in the period of 200 phases. From the figure, we see that most vehicles wait for less than 60 seconds and the average waiting time is around 20 seconds.

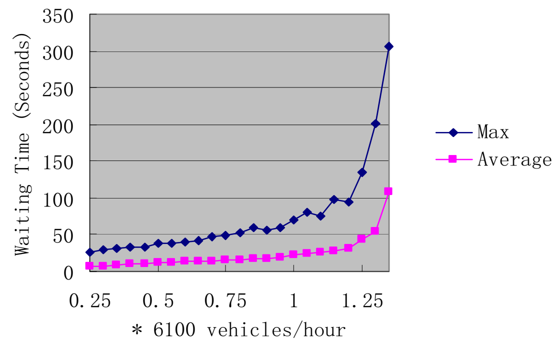
The maximal and average waiting time changes if traffic load changes. From table 1, we know there are 6100 vehicles pass through the intersection per hour, i.e., the traffic load is 6100 v/h.

We do a sequence of experiments to study the relationship between the traffic load and the waiting time. The traffic load value is changed by multiply a ratio from 0.25 up to 1.35 to the original data in table 1 and keeps the proportions among the approaches and lanes. The program is executed for 200 phases for each different traffic load. In each traffic load, the maximal and the average waiting times of the vehicles are calculated, which are illustrated in Fig. 4(b). We can see that the waiting time keep a low level when the ratio is low than 1.2 and they increase drastically later.

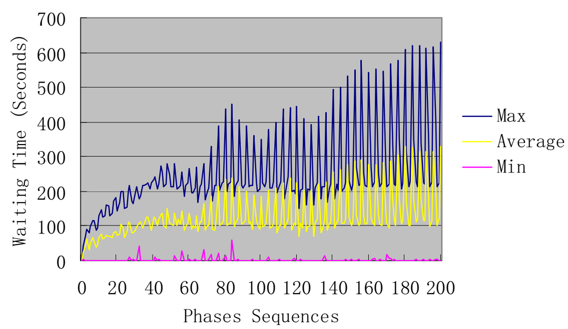
When this ratio is between 0.25 and 1.35, the system is stable. If this ratio is above 1.4, the waiting time increases with the traffic load. Fig.4(c) shows the instance when the ratio is 1.4. This means that the number of the incoming vehicles is greater than the number of the outgoing vehicles at least on one lane and traffic congestion is resulted.




(a) Maximal, minimal and average waiting time in 200 phases when traffic load = 6100 v/h




(b) Maximal and average waiting time in terms of different traffic load




(c) Maximal, minimal and average waiting time in 200 phases when traffic load=6100*1.4 v/h

Figure 4. Simulation result

When τi = 1, the maximum number of outgoing vehicles that is allowed for each lane is 3600 per hour (T1=1). Since the three lanes can not be full simultaneously and T1 is always greater than 1, this upper limit of the outgoing vehicles can never be achieved at the same time. By the simulation, we found that the upper limit of this intersection is about

1.35*6100 = 8235 v/h, under the condition that the proportion among the approaches and lanes are not changed.

### 4.2. Pedestrians and cyclists handling

Algorithm 1 doesn't yet consider the pedestrians and cyclists. Now, let us briefly describe how the pedestrians can be handled by our system. The pedestrians should pass through the road at go-forward phase – Φa and Φc. Tmin should be reviewed to ensure that the pedestrian can walk through the road in time. What's more, in the algorithm 1, if no vehicle is detected, the phase will be passed through in despite of there is pedestrian or not. In order to ameliorate this situation, there should be installed a press button at the entrance of the crosswalk, or a wireless detector should be employ there.

### 4.3. Smart Vehicle License Plate and Emergency Handling

Vehicle node can be used for other purpose than what described in this paper. For example, a global unique sequence number (*electronic tag*) can be solidified into the module to identify and verify the vehicle. In this way, the module is homologous with the vehicle license plate and is referred to as "Smart Vehicle License Plate (SVLP)" in this paper.

Algorithm 1 considers the principle of high-efficiency and equalities. In the real life, the high-priority emergencies should be considered into the traffic control system as well.[15] For example, the police car, the fire engine, the ambulance that have the privilege of passing the intersection need the special treatment.

With the help of the proposed SVLP, the emergency handling mechanism can be easily added to our system. When the SVLP of an emergency car sends the message to the detector nodes, an "emergency" flag is sent simultaneously. The detector nodes pass it to the control node. When the control node receives the "emergency" flag, it computes the passing duration of the current queue waiting on the same expectant phase with the emergent car. Then it adjust the phase switching procedure, in order to clear the queue right before the emergency car arrives the intersection, and hold the passing phase until the emergency car passes over.

### 4.4. Extended Application with WSN System

To implement this system, nearly all the vehicles should install SVLP. It is a disadvantage to popularize it. We can do it step by step. The emergency car can be implemented first to reduce interference with the ordinary vehicle. Then, bus, taxi, freight carrier can be implemented to support locating and scheduling.

This paper presents an example of an isolated intersection. However, this WSN model realized the traffic flow and velocity measurement in real time. In addition, every vehicle's information can be acquired and there is a capability of dual-direction communication. So the whole urban traffic network can be monitored in real time. For an individual vehicle, a real time road guider will indicate the traffic load on the road near the vehicle, and propose a best path. Compared with system based on GPS, this one is more accurate. The traffic flow has a feature of locality; it is fit with the decentralization feature of this model. So there need no high-performance computer to handle a global task, it ensure the response time.

## 5. Conclusion and Future Work

This paper proposes a traffic control system using the WSN technology. The advantages of the proposed system include: 1) accurate monitoring and measurement of the vehicle number and vehicle speeds in real time due to the introduction of the WSN technology; 2) low cost of the system due to the simplicity of the three types of nodes. Each node only needs to execute a very simple computation because the overall computation is distributed among different nodes, which reduces the complexity of each individual node; 3) it is easy to append more functions to this system since the system not only know the statistical information but also the information of a special vehicle as well; and the roadside system can communicate with the vehicles.

This paper also proposes a traffic control algorithm for the signal control in an intersection. Since the vehicle state is monitored dynamically, the phase time is determined exactly instead of by forecasting. Compared with conventional algorithm, the advantages of the algorithm includes: 1) eliminate the phase time when no vehicle passing across; 2) Let all of the waiting vehicles pass if possible, which reduces the waiting time.

Extensive simulations have been conducted to demonstrate the effect of the proposed traffic control system. As we see from Section 4, our algorithm is efficient for traffic control in terms of the vehicle waiting time at the intersection.

WSN open a broad way in the area of traffic control. Next, we will do some research on its application on urban traffic network instead of a single intersection.

## 6. Acknowledgment

The authors are grateful to Mr. GU Yongfeng from University of Boston, and Mr. LI Ping from Philips Electronics Singapore Pte Ltd, for their insightful comments and suggestions.

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