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Intelligent Traffic Light Flow Control System Using Wireless Sensors Networks

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Vehicular traffic is continuously increasing around the world, especially in large urban areas. The resulting congestion has become a major concern to transportation specialists and decision makers. The existing methods for traffic management, surveillance and control are not adequately efficient in terms of performance, cost, maintenance, and support. In this paper, the design of a system that utilizes and efficiently manages traffic light controllers is presented. In particular, we present an adaptive traffic control system based on a new traffic infrastructure using Wireless Sensor Network (WSN) and using new techniques for controlling the traffic flow sequences. These techniques are dynamically adaptive to traffic conditions on both single and multiple intersections. A WSN is used as a tool to instrument and control traffic signals roadways, while an intelligent traffic controller is developed to control the operation of the traffic infrastructure supported by the WSN. The controller embodies traffic system communication algorithm (TSCA) and the traffic signals time manipulation algorithm (TSTMA). Both algorithms are able to provide the system with adaptive and efficient traffic estimation represented by the dynamic change in the traffic signals' flow sequence and traffic variation. Simulation results show the efficiency of the proposed scheme in solving traffic congestion in terms of the average waiting time and average queue length on the isolated (single) intersection and efficient global traffic flow control on multiple intersections. A test bed was also developed and deployed for real measurements. The paper concludes with some future highlights and useful remarks.

Keywords: wireless sensor networks, intelligent traffic controller, traffic congestion, dynamic traffic adaptation, traffic flow control

1. INTRODUCTION

The continuous increase in the congestion level on public roads, especially at rush hours, is a critical problem in many countries and is becoming a major concern to transportation specialists and decision makers. The existing methods for traffic management, surveillance and control are not adequately efficient in terms of the performance, cost, and the effort needed for maintenance and support. For example, The 2007 Urban Mobility Report estimates total annual cost of congestion for the 75 U.S. urban areas at 89.6 billion dollars, the value of 4.5 billion hours of delay and 6.9 billion gallons of excess fuel consumed. On smaller scale, the traffic engineering department in Jordan estimates

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that the total cost due to congestion in the year 2007 was around 150 million USDs [1]. As such, there is a need for efficient solutions to this critical and important problem.

Many techniques have been used including, aboveground sensors like video image processing, microwave radar, laser radar, passive infrared, ultrasonic, and passive acoustic array. However, these systems have a high equipment cost and their accuracy depends on environment conditions [2]. Another widely-used technique in conventional traffic surveillance systems is based on intrusive and non-intrusive sensors with inductive loop detectors, micro-loop probes, and pneumatic road tubes in addition to video cameras for the efficient management of public roads [3, 4]. However, intrusive sensors may cause disruption of traffic upon installation and repair, and may result in a high installation and maintenance cost. On the other hand, non-intrusive sensors tend to be large size, power hungry, and affected by the road and weather conditions; thus resulting in degraded efficiency in controlling the traffic flow.

As such, it is becoming very crucial to device efficient, adaptive and cost-effective traffic control algorithms that facilitate and guarantee fast and smooth traffic flow that utilize new and versatile technologies. An excellent potential candidate to aid on achieving this objective is the Wireless Sensor Network (WSN) [5]. Many studies suggested the use of WSN technology for traffic control [4, 6, 7, 9-11]. In [7], a dynamic vehicle detection method and a signal control algorithm to control the state of the signal light in a road intersection using the WSN technology was proposed. In [11], energy-efficient protocols that can be used to improve traffic safety using WSN were proposed and used to implement an intelligent traffic management system. In [10], Inter-vehicle communication scheme between neighbouring vehicles and in the absence of a central base station (BS) was proposed.

In this paper, an intelligent and novel traffic light control system based on WSN is presented. The system has the potential to revolutionize traffic surveillance and control technology because of its low cost and potential for large scale deployment. The proposed system consists of two parts: WSN and a control box (*e.g.* base-station) running control algorithms. The WSN, which consists of a group of traffic sensor nodes (TSNs), is designed to provide the traffic communication infrastructure and to facilitate easy and large deployment of traffic systems.

In our proposed scheme, each TSN will mainly collect and generate the traffic data (represented by the number of vehicles during arrival and departure processes), vehicle speed, and length of the vehicles, based on processing of the sensor data. Then the collected data is sent in real time to the BS over the radio. In our scheme, TSNs detect the traffic status in a fast, adaptive, and dynamic fashion. These nodes are installed in the roadbed in a safe manner for detecting and communicating traffic information for decision making. Two test beds were designed and implemented for demonstrating the operation of the proposed system. Another crucial part in the proposed system is the design of efficient communication and control algorithms that coordinate the operation of all system components in a manner that work on both single and multiple road intersections.

Although the work in this paper adopts the WSN for traffic control as some previous studies did, it distinguishes itself from these studies in many aspects. *First,* our work introduces an itelligent traffic light controller system with a new method of vehicle detection and dynamic traffic signal time manipulation. In particular, the dynamic process of selecting the traffic flow sequences for all traffic directions and based on the traffic conditions is a genuine part of the proposed system. Moreover, the flow of the traffic stream will not be fixed such as the case in the current traffic control systems. *Second*, a real testbed that verifies the feasibility of the proposed system is developed in addition to extensive simulation experiments. *Third*, the proposed system can handle the case of controlling traffic over multiple intersections, while other schemes can only handle the single intersection case. *Finally*, the proposed system follows the international standards for traffic light operation, which makes it easy to adapt or use in the international market.

2. SYSTEM MODEL AND NOTATIONS

In this section, we present the system model including some definitions and assumptions. We assume a single intersection at urban areas with each side having two legs. A configuration example for the system is given in Fig. 1 (a) for an urban intersection. Vehicles arrive to the traffic light intersection (TLI) according to certain random distribution and depart after waiting for some time, which also follows a certain random distribution. For simplicity, and without loss of generality, we assume that each side of the TLI is modeled as M/M/1 queue. For urban areas with multiple intersections, we assume a mesh network of intersections with rectilinear topology. An open queuing network is used to model the traffic flow between these multiple intersections.

In the mesh topology, the intersections that are at the boundary are called edge intersections while the remaining intersections are called receiving and forwarding intersections. The average speeds for all intersections are assumed to be constant. All queues' lengths for all active directions are initialized to zero. The distances (horizontal or vertical) between any pair of the intersections are assumed fixed and equal to a predefined base distance (d).

The vehicle detection system requires four components: a sensor to sense the signals generated by vehicles, a processor to process the sensed data, a communication unit to transfer the processed data to the BS for further processing, and an energy source. We adopt a simple time division multiple accesses (TDMA) scheme at the MAC layer since it is more power efficient as it allows the nodes in the network to enter inactive states until their allocated time slots. The scheme embodies a simple scheduling algorithm that minimizes the time needed for collecting data from all nodes back at the BS. The algorithm assigns a group of non-conflicting nodes to transmit in each time slot, in such a way that the data packets generated at each node reaches the BS by the end of the scheduling frame. Each traffic light controller will operate in traffic phases as will be described in section 4.

To streamline our presentation, we present some useful notations and definitions that will be used throughout the paper presented in the following bulletins and Table 1:

- *Traffic Phase:* defined as the group of directions that allow waiting vehicles to pass the intersection at the same time without any conflict.
- *Traffic Phase Plan:* defined as the sequence of traffic phases in time.
- *The Traffic Cycle:* defined as one complete series of a traffic phase plan executed in a round robin fashion.
- *The Traffic Cycle Duration* (T)*:* is the time of one traffic cycle needed for the green and red time durations for each traffic signal.

Table 1. Notations used in this paper.

Notation	Meaning	Notation	Meaning
N	Number of queues (lanes) or TSNs in a traffic intersection.	M	Number of cycles the arrival and departure rates should change.
D^i	Set of directions that are active on an intersection $i \in (1 \ldots 12)$.	T	Traffic cycle duration.
λ_i	Arrival rate of vehicles detected by *i*th TSN.	μ_i	Departure rate of vehicles detected by *i*th TSN.
λ^i	Arrival rate of vehicles detected by *i*th active direction.	μ^i	Departure rate of vehicles detected by *i*th active direction.
Q_j^i	Total number of vehicles waiting at the traffic signal at *i*th active lane in the *j*th cycle.	WT_j^i or W_j^i	Waiting time at the traffic signal at *i*th active lane in the *j*th cycle.
AQL_v^i	Average queue length at the *i*th active direction on the intersection *v*.	AWT_v^i	Average waiting time at the *i*th active direction on the intersection *v*.
R^k	Red period of the phase *k* where $k \in (1 \ldots 4)$.	G^k	Green period of the phase *k* where $k \in (1 \ldots 4)$.
$\bar{\lambda}^i$	Average arrival rate on the *i*th active direction.	$\bar{\mu}^i$	Average departure rate on the *i*th active direction.

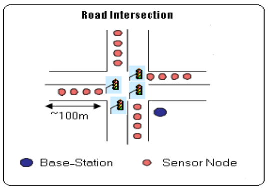

Fig. 1. (a) Single intersection configuration example of WSN.

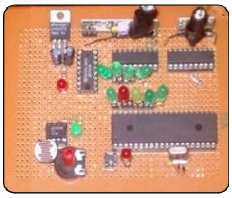

Fig. 1. (b) The in-house built traffic sensor node.

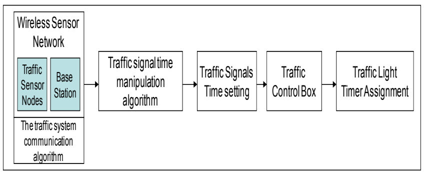

Fig. 2. Components of traffic control system.

3. DESIGN OF TRAFFIC WIRELESS SENSOR NETWORK

In this section, we show the design of WSN that is used as communication infrastructure in the proposed traffic light controller. We have designed, built, and implemented a complete functional WSN and used it to validate our proposed algorithms. Fig. 1 (b) shows the final product of the in-house developed TSN. The functional TSN was built using some available of-the-shelf components (NB. commercial sensor nodes like MICA motes were not available). The entire TSN is encased in such a manner to be placed on pavement made on the testing roads.

For the system components to be able to communicate (*e.g.*, traffic control box and the BS), a traffic WSN communication and vehicle detection algorithms were devised. To be specific, two algorithms are developed, namely, the traffic system communication algorithm (TSCA) that is presented in this section and the traffic signals time manipulation algorithm (TSTMA), which is presented in the next section. These algorithms interact with each other and with other system components for the successful operation of the control system. To illustrate, Fig. 2 shows the components of our traffic control system and their interactions. The process starts from the traffic WSN (which includes the TSNs and the traffic BS), the TSCA, and the TSTMA, and ending by applying the efficient time setting on the traffic signals for traffic light durations.

The TSCA is developed to find and control the communication routes between all the TSNs and the BS as well as the interfacing with the traffic control box in a simple and power efficient manner. As such, the algorithm uses the direct routing scheme, where all TSNs are distributed to be within the range of the BS. Each TSN is responsible for detecting the vehicles and counting them and then relaying this information periodically to the BS. Depending on the number of TSNs, the system operation is divided into time slots in which each TSN will operate *i.e.* TDMA. The collected traffic information aggregated by the BS is then passed to the TSTMA to set practical time durations for the traffic signals in a dynamic fashion according to the vehicles counts on each traffic signal. After that, the traffic control box (TCP) applies the returned time slots setting on the traffic signals. These steps are summarized in Figs. 3 and 4. A high level description of TSCA algorithm is described Fig. 5.

The TSNs are designed to be installed directly in the roadbed in a pothole in the streets centered in each lane. For this purpose, small holes are made in the streets and a TSN is placed in each one of them. These holes are designed to be safe, protected from the environmental and roadbed condition and not interfered with the TSN operations.

The distance between the TSN and the traffic signal is chosen such that a queue length of eight cars is observed similar to the average queue length found in [13, 14], and this distance can be modified based on the traffic condition and the real implementation. Since, the road networks differ from town to town, the controlled intersections will also be quite different. To circumvent such situations, a base intersection is defined and used to assist in the numbering strategy and to ease traffic WSN implementation. The architecture of the base intersection is as follows:

- There are four paths marked as N (North), S (South), W (West) and E (East) leading to the road intersection and each path has three lanes in the incoming direction, which are turn-left (L), go-forward (F) and turn-right (R). So each passing vehicle can have a path P of {E, S, N, W} and a direction D of {L, F, R} [6]. Thus, a lane where a vehicle is running can be determined by a pair of {P, D}. As a result, there is at most twelve lanes operating relative to the pair (P, D):{WR, WF, WL, ER, EF, EL, NR, NF, NL, SR, SF, SL}.
- The TSNs are distributed on each lane as in Fig. 4. There exist at least two TSNs; one that is placed before the traffic signal and one after to detect the arrival and departure rates as well as the variation of the queues' lengths of all the lanes that is required by the TSTMA. Thus, at least a total of twenty four TSNs are needed on each intersection to control the traffic flow in addition to the traffic BS.

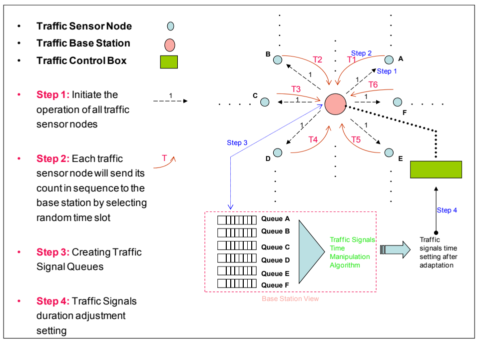

Fig. 3. TCP components interaction.

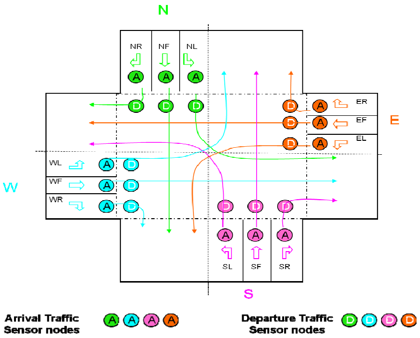

Fig. 4. Intersection and TSN architecture.

	WR	WF	WL	ER	EF	EL	NR	NF	NL	SR	SF	SL
WR	🟥					⊗		⊗				
WF		🟥				⊗		⊗	⊗	⊗	⊗	⊗
WL			🟥	⊗	⊗			⊗	⊗		⊗	⊗
ER			⊗	🟥							⊗	
EF			⊗		🟥		⊗	⊗	⊗		⊗	⊗
EL	⊗	⊗				🟥		⊗	⊗		⊗	⊗
NR					⊗		🟥					⊗
NF	⊗	⊗	⊗		⊗	⊗		🟥				⊗
NL		⊗	⊗		⊗	⊗			🟥	⊗	⊗	
SR		⊗							⊗	🟥		
SF		⊗	⊗	⊗	⊗	⊗			⊗		🟥	
SL		⊗	⊗		⊗	⊗	⊗	⊗				🟥

⊗ Not allowed 🟥 Illegal Case

Table 2. Conflict directions matrix.

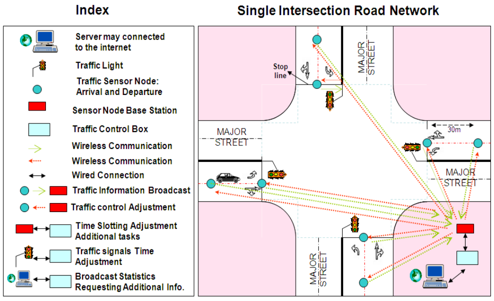

Fig. 6. Traffic WSN complete architecture.

All the previous traffic rules in addition to inoperative same-time intersections are summarized in the conflict directions matrix represented in Table 2. Each column in the table demonstrates a direction in the intersection and its status whether being allowed to operate {blank} or inoperative {⊗}. The inoperative (not allowed) case occurs when other directions along the rows for the same column are allowed *i.e.* traffic flow on it is permitted. For example, the direction WR in the second column is inoperative when either of the directions EL in the seventh row or NF in ninth row is operating.

4. TRAFFIC CONTROL ALGORITHM FOR A SINGLE INTERSECTION

The proposed traffic light control system works for both single and multiple intersections. In this section, we present the details of the control algorithm for single intersection case, while the extended version for the multiple intersection case is presented in the next section. In the former case, the intersection works in isolation and is not influenced by changes on other intersections. Furthermore, fixed time control and adaptive time control can be used. With the fixed time control, both the duration and the order of all traffic phases are fixed. An advantage of this scheme is that the simplicity of the control enables the use of simple and inexpensive equipment. The big disadvantage is that the control does not adapt to variable traffic situations. For the adaptive time control, the duration and the order of all traffic phases is dynamic. An advantage of this scheme is the adaptation to the traffic situations and the maximization of the traffic flow and thus solves many of the roads' traffic problems. The TSTMA is an adaptive time control algorithm developed to compute the red/green light duration for each traffic signal found by using the conflict directions matrix that was presented in the previous section.

Algorithm 1: *Traffic System Communication Algorithm Description (TSCA)*

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Input: $N$, $\lambda$, $\mu$, and $Q_i$, $i = 1, N$
Output: Guarantee successful communication between all the components of the traffic control system in order to set the time duration for all the traffic signals using the traffic control box.
Operations:
1. The traffic BS that is running sets the listening period ($L$) to hear from TSNs.
2. The traffic BS sends an "Operating Message" that Turn-ON all the TSNs putting them in the communication mode.
3. Each TSN identifies itself as either an arrival detecting vehicles or departure detecting vehicles sensor node.
4. Each TSN selects randomly a time slot within "$L$" to send its traffic status ($\lambda_i$, $\mu_i$ and $Q_i$) to the traffic BS.
5. The traffic BS applies the TSTMA, which returns the time durations of traffic signal various directions.
6. The traffic BS sets the dynamic durations obtained on the traffic signals using the traffic control box.
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Fig. 5. High level description of TSCA.

The main objective of the TSTMA is to set the traffic signal duration in an efficient and dynamic manner so that the average queue length (AQL) and the average waiting time (AWT) are minima. A traffic model is defined for this purpose based on Fig. 6 that depicts the complete architecture and WSN components interaction and communication. The model has twelve directions each of which comprises two TSNs. Each direction has its own average rate and departure rate as well as the queue length. An M/M/1 queuing model is used to represent each traffic signal (direction), which has an average arrival rate (λ), service rate (μ) of vehicles, AQL or simply Q_i and AWT or simply W_i all at time t over a certain number of traffic cycles. Thus, the intersection is viewed as a model of twelve queues and each queue with λ_i, μ_i, Q_i, and W_i, $i = 1, N$.

4.1 Single Intersection Base Model Formulation

An M/M/1 queue model [16] is used to model each lane in a single intersection with random arrivals and exponential service times. The arrivals follow Poisson distribution with constant average rate λ. The length of the M/M/1 queue can be computed as follows (see Fig. 7). Assume that each traffic signal is to be associated with a certain lane (*e.g.* NF). The proportion of the time the traffic signal (server) is idle is assumed to be given by P_0 and the proportion of time the system is busy is given by ρ. Figs. 7 and 8 demonstrate that in the green time, the traffic signal queue has both arrivals and departures, while in the red time there are arrivals, but there are no departures. Hence, the queue length equation is given by: $Q_L = \rho^2/(1 - \rho)$ and using Little's Law, the AQL is given by $Q_L = \lambda W$ (W: is the average time spends in the system) [16], and hence the AWT in the queue is given by: $W = Q_L/\lambda$. It follows that the queue length varies according to the following fundamental equation:

$$Q_{L_j} = \overbrace{Q_{L_{j-1}}}^{\substack{\text{remaining vehicles}\\ \text{from the prev. cycle}}} + \overbrace{\lambda_G G}^{\substack{\text{vehicles arrive}\\ \text{in green time}}} - \overbrace{\mu_G G}^{\substack{\text{vehicles departure}\\ \text{in green time}}} + \overbrace{\lambda_R R}^{\substack{\text{vehicles arrive}\\ \text{in red time}}} . \tag{1}$$

Where: j represents the traffic cycle number, Q_{L_j}: represents the expected queue length of one lane for the next cycle j, $Q_{L_{j-1}}$: represents the queue length from the previous cycle ($j - 1$), λ_G represents the arrival rate in the green phase, λ_R represents the arrival rate in the red phases and is considered equal to λ_G within the same cycle, G represents the green period of one phase in seconds, and R represents the red light period in seconds and is equal to difference between the T and the green time period.

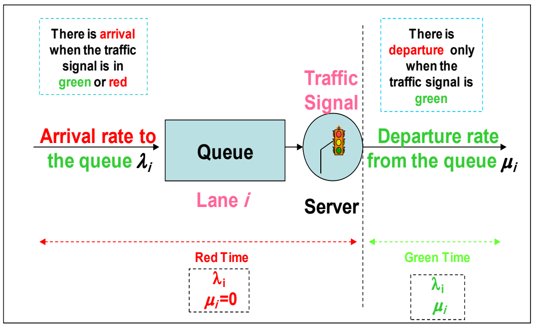

Fig. 7. Traffic signal queue flow.

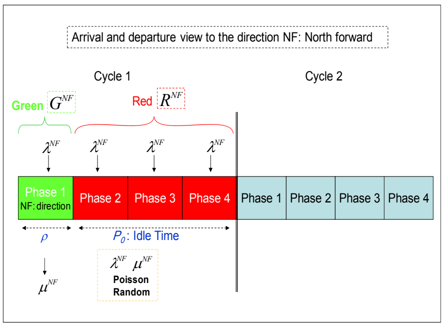

Fig. 8. Queue length calculation view.

Another important aspect that we need to consider is the change in the queue length on the roadways. This is particularly important for computing the adaptive time control corresponding to that queue length change. To generalize the change of the queue length for all the operating lanes (twelve directions) provided in the intersection base model, then equation 1 becomes:

$$Q^D_{L_j} = Q^D_{L_{j-1}} + \lambda^D G^D - \mu^D_G G^D + \lambda^D R^D. \tag{2}$$

Where D: represents the direction identifier {1 … 12} corresponding to directions {WR, WF, WL, ER, EF, EL, NR, NF, NL, SR, SF, SL}, respectively.

4.2 Traffic Signal Time Manipulation Algorithm (TSTMA)

The TSTMA is running on the traffic BS and makes use of the traffic information that is gathered at the traffic BS from TSNs. This information is used to calculate, in intelligent manner, the expected queue length, for the next traffic cycle, and then schedule efficient time setting for the various traffic signals. As mentioned before, the main objective of the TSTMA is to maximize the traffic flow while reducing the AQL and the AWT. This objective is achieved by using the following dynamic strategies (a) Dynamic selection and ordering of the traffic phases based on the adaptive user selection of the intersection infrastructure *i.e.* number of lanes allowed in the intersection; (b) Dynamic adaptation to the changes in the arrival and departure rates and thus dynamic decisions about queues' lengths and their importance; (c) Dynamic control of the traffic cycle timing of the green and red periods.

One of the important phases of the TSTMA is the traffic signal phase selection. The selection of the phases is dynamic and is based on the queues (lanes) that hold maximum lengths. The selection process of phases is performed every cycle, and hence there is no fixed order of phases. The selection process works as follows. First, from the intersection structure, the directions that are active are known. Based on the number of active directions and conflict directions matrix, a truth table of all possible combinations of the traffic phases is generated. After the queues' lengths for all directions are updated for the next cycle, the next step is to distribute these queues' lengths into a suitable number of phases depending on the number of active directions and which phases contain the directions with high traffic flow. To this extent, several cancellation processes are performed in order to obtain the best set of traffic phases representing the active directions. The selected traffic phases are then used as a round-robin in T allowing all the active directions to turn-on the traffic signal for their traffic stream. The timing schedule between the selected traffic phases is set based on the waiting sum of the largest queue length of each selected traffic phase. Thus, each traffic phase based on the largest queue length along the phase obtains a proportion of green time from T. So to summarize, the operations of the algorithm are based on the intersection structure, the average arrival and departure rates, the updated queue length and the traffic phases that have the largest queue length sum. A high level description of the algorithm is shown in Fig. 9 entitled as Algorithm 2.

Lastly, it is important to mention that the traffic cycle duration (T) is an important parameter in the traffic control, because a shortening of T will reduce the traffic queue capacity and waiting time within the cycle itself, while on the other hand, when the cycle duration increases, this will lead to a longer waiting times and longer queues. Thus, by experimentation, we have upper-bounded and lower-bounded T to not exceeding ninety seconds and not going below fifteen seconds. Another important aspect is that the timing complexity of the TSTMA is found to be constant $O(1)$ for both the AQL and the AWT.

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Algorithm 2: Traffic Signal Time Manipulation Algorithm Description
Input: $D^i$, $N$, $M$, $\overline{\mu}^i$, $\overline{\lambda}^i$, $T$.
Output: $AWT^i$, $AQL^i$.
Operations:
1.  Generate a truth table for all possible combinations of the directions based on $D^i$. Then, generate another truth table using the Conflict Directions Matrix to generate all safe combinations of directions by canceling the combinations which include any traffic conflict in the first truth table.
2.  Define the traffic array to hold all the safe combinations up to $r$ rows, the queue length for each $D^i$, and the green and red periods.
3.  Initialize all queues' lengths to zero, the green period to $T/4$ and red periods to $(T-(T/4))$ for all active directions.
4.  Compute the queue for each active direction $i$ as follows:
        • (Inter-arrival time) $t_a = -\ln(U)/\overline{\lambda}^i$ for every instance $a$ of the $T$ period.
        • (Inter-service time) $s_a = -\ln(U)/\overline{\mu}^i$ for every instance $a$ of the green period.
        • Average inter-arrival time for active direction $i$ and average inter-service time respectively as follows:
          $\bar{t}_i = \left[\sum_{a=1}^{T} t_a\right]/T$ ,   $\bar{s}_i = \left[\sum_{a=1}^{G^i} s_a\right]/T$
        • $\lambda^i = 1/\bar{t}_i$   $\mu^i = 1/\bar{s}_i$   $\therefore \rho^i = \lambda^i/\mu^i$   $Q_j^i = (\rho^i)^2/1-\rho^i$
5.  From the traffic array, the queues' lengths for all the directions is summed after updating the queues' lengths from the previous step to find the number of phases (safe combinations). So, this step involves:
            • Computing $\sum_{i=1}^{12} Q_j^i$ , for $j = 1$ to $r$ (safe configurations).
            • Selecting the phase with the largest sum as the first phase. The next largest sum becomes the second phase, and so on.  The process repeats until all directions are found in the safe array and fit into a maximum of four phases.
6.  Use the safe array and the maximum values of the four phases, to find the green and red times for each phase.
            • $G_i^k = \frac{\max_k}{\max_1 + \max_2 + \max_3 + \max_4} \times T$ ,   $R_i^k = T - G_i^k$
7.  Compute the expected queue length and waiting time for the next cycle for each active direction and update all the directions queues' lengths
            • $Q_j^i = Q_{j-1}^i + \lambda^i G_i^k - \mu^i G_i^k + \lambda^i R_i^k$ , $j \in (1 \ldots T)$: represents cycle #
            • $WT_j^i = Q_j^i / \lambda^i$
8.  Check if the current number of cycles matches the simulation cycles entered by the user,
            • if yes goto step 12.   if($j == N$) then goto step 13
9.  Check if the current number of cycles matches the cycles entered by the user to regenerate new arrival and departure rates,
            • if yes go to step 11 else goto step 5
            • if($j == M$) then goto step 11 else goto step 5
10. Input from the user to enter the arrival and departure rates parameters for the Poisson generation for each active direction ($\overline{\mu}^i$, $\overline{\lambda}^i$)
11. Go to step 5.
12. Calculate the average queue length and the average waiting time for each active direction.
        • $AQL^i = \left[\sum_{j}^{N} Q_j^i\right]/N$        • $AWT^i = \left[\sum_{j}^{N} WT_j^i\right]/N$
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Fig. 9. High level description of traffic signal time manipulation algorithm.

5. TRAFFIC CONTROL ALGORITHM ON MULTIPLE INTERSECTIONS (TCAMI)

In this section, the traffic light control algorithms presented earlier for single intersection are extended to work on multiple intersections to coordinate their operations and to smooth the traffic flow. In particular, the TSTMA is extended to cater for the indeterministic traffic flow encountered in the multiple intersection scenarios and additional functionality is added to it to schedule the efficient global time settings. In TSCA, a higher communication layer is added. This layer enables each traffic intersection running the TSCA to communicate with surrounding intersections through the traffic base stations. This communication is needed in order to exchange the traffic information incurred at these intersections. These updated algorithms are referred to be the traffic control algorithm on multiple intersections (TCAMI).

TCAMI has the ability to find an efficient time allocation to the light signals at each single intersection despite the fact that the traffic streams leaving one intersection and distributed to successive intersections exhibit, in general, indeterminate behavior especially because of the dependency between the intersections. Mainly, multiple intersections forming a mesh topology with rectilinear structure are considered in this paper.

It is to be noted that the most important part in the design of the TCAMI is the coordination and setting of traffic parameters and conditions on the multiple intersections in general and on the successive intersections in specific, with the objective of minimizing delays, caused by stopping, waiting and then speeding up during road trips. We call this process as "the green wave" where drivers need not stop on multiple intersections thus achieving, if implemented correctly, an open route for the vehicles. As such, the main theme of TCAMI algorithm is the provisioning of the green wave process. To simplify the design and implementation, we view the multiple intersections as a set of nodes interacting with each other so that each intersection has the characteristics of the base model introduced in section 3, namely, M/M/1 model. The TCAMI executed on each intersection will generate traffic information, which in turn represents an input to the subsequent intersection, and so on. As such, the traffic flow will be controlled in a flexible manner.

The TCAMI[1] operations start with setting the structure of the intersections under control and their relative distances and average speed limit between them. Based on these parameters, each intersection sets the best traffic cycle duration (T) for the active directions based on the TSTMA. TSTMA performs the efficient dynamic control to support the green wave process, through the three dynamic processes described in section 4. This control process is repeated for every traffic cycle. The timing complexity of the algorithm is found to be constant $O(1)$. It is important here to mention that TCAMI does not specify the routes of various traffic streams, but rather control how the traffic stream flows through intersections at minimum AWT or minimum AQL.

6. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed traffic control algorithms. The performance is evaluated using two methods, namely, experimenting with real testbed and extensive simulations. For the real testbed, a set of the in-house built sensor nodes were installed on a system prototype for single intersection and also on real intersection in a selected urban area. Several measurements were collected and analyzed from this implementation. Secondly, extensive computer-based simulations were conducted for both cases of single intersection and multiple intersections.

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[1] Due to the lack of space, the high level description of the TCAMI is not being presented here. Interested reader can e-mail one of the authors for details about the algorithm.

For the single intersection part, the simulation environment consists of traditional setup like the one previously shown in Figs. 1 and 4. Settings of various parameters follow ones defined in Algorithm 2 and clarified later in this section. For multiple intersection simulation settings, all the twelve directions in all intersections in a predefined mesh structure are considered active to guarantee that there is a valid complete mesh infrastructure. Moreover, the traffic flow rates are changed during the simulation after certain number of cycles, determined by the user, to reflect the real life traffic variations during the day. Typically, the departure rates of the intersections must be larger than the arrival rates for all cases to achieve system stability. The main simulation metrics of interest are AQL_v^i and AWT_v^i. These metrics are chosen because they indicate the traffic flow patterns and their diminishing effect on the traffic congestion. These two metrics, although they are related, can show different views about the system performance as will be shown below. The simulation results are divided into two classes corresponding to single intersection and multiple intersections cases, respectively. For multiple intersections, only the results for the rectilinear mesh structure are presented. The TSNs were programmed using MikroBasic Compiler for Microchip PIC microcontrollers Version 1.1.6.0 [18]. A simulator was built using Microsoft Visual C++ 6.0 and MATLAB 7.0 for experimenting with various settings of the proposed algorithms. Simulations experiments were run on a Personal Computer of 3.2 GHz and 1GB RAM.

For the real implementation, two test beds are provided. One of the test beds is created to test the functionality and detection accuracy of the TSN. The test bed consists of two TSNs installed in potholes in the street, and connected to a laptop to record the nodes' traffic measurements. Fig. 10 demonstrates the installation of the TSNs when the testing is performed. The TSN detects a vehicle once it passes over the pothole and report the measurement to the laptop. The laptop's readings are checked against manual readings of the traffic in order to check the accuracy of the results. The results showed that the designed TSN is able to detect correctly the presence of the vehicles with 95% accuracy. A second test bed is created consisting of five TSNs, four of them were installed on each leg of the four directions as shown in Fig. 11 for a single intersection, while the fifth node plays the role of gateway to the BS. The traffic was generated manually on each TSN separately by using toy cars controlled by wired controllers.

Fig. 10. TSN installed in pothole (road testbed).

Fig. 11. Traffic WSN pilot test bed.

6.1 Single Intersection Simulation Results

Fig. 12 shows one of the simulations of running TSTMA with T equal to 90 seconds and simulation period of 150 traffic cycles. In the simulation experiment, the twelve directions of the intersection based model are active, and the traffic stream flow is set to be changed every 50 traffic cycles (not fixed) to simulate real road traffic variation. In Fig. 12, the results were reported only for the three queues of East path for the sake of demonstration. We are interested in the queue length variations over time. Two styles of traffic control are presented and compared for the same simulation setup, namely, fixed time control and dynamic traffic control. Note how the dynamic control is able to adaptively control the variations of the traffic streams. On the other hand, in the fixed time control, once the congestion occurs on a certain direction, then other directions will be affected and the problem will only be resolved when the traffic stream itself is changed and reduced. Another experiment were performed to calculate the AWT for a particular road intersection when traditional fixed time control is used versus when the dynamic time settings where used. Fig. 13 shows the AWT as it evolves over time for the two methods. As the figure shows, the dynamic setup was able to achieve much lower AWT and the difference is apparently clear as time elapses. This is due to the fact that cars in a congested lane wait less time when other lanes are not congested. Note that fixed time control doesn't distinguish between congested and non-congested lanes on a particular road intersection. Also, we have counted the number of cars that passes through different directions or traffic controlled paths in a congested road intersection. As Fig. 14, except for some unexpected behavior during time period from 20-30, the traffic was smoothly passing in a fair manner. Finally, the queue size accumulation for a particular road intersection when traditional fixed time control is used versus when the dynamic time settings where used is shown in Fig. 15. As can be seen from the figure, dynamic approach was able to handle queues quickly not to accumulate cars during the observed time period.

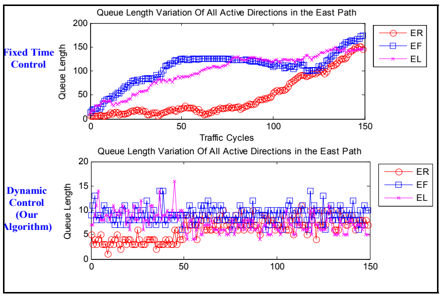

Fig. 12. Single intersection simulation comparisons (Fixed and Dynamic).

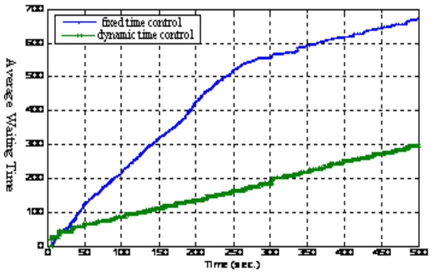

Fig. 13. AWT: fixed vs. dynamic control.

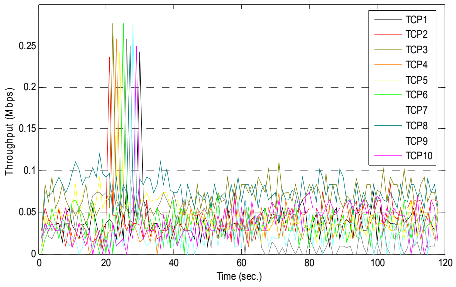

Fig. 14. Throughput of various traffic controlled path for various directions.

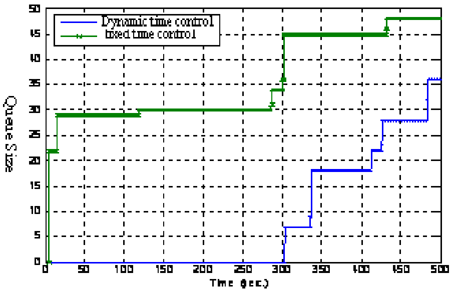

Fig. 15. Cumulative queue size vs. time.

6.2 Multiple Intersections Simulation Results

To simulate the operation of multiple intersections under the proposed TCAMI algorithm, two structures are implemented. The first structure is the rectilinear mesh structure. The second structure is a real structure depicted from the real traffic roadways, which consists of eight successive intersections in one of the main traffic roadways in Amman-Jordan. The latter structure is simulated to verify how the algorithm adapts to traffic when compared to the real traffic data collected from traffic traces. For the rectilinear mesh structure, there are sixteen regular space intersections. The base distance between the intersections is fixed and equal to d. The average speed limits between all the intersections are fixed and equal to s. T is 90-second for all the intersections as in [6]. Since cycle duration $= 2d/s$, then base distance (d) is selected 0.63km and the average speed (s) is 50km/hr. TCAMI is tested for 150 traffic cycles on the previously defined mesh rectilinear structure of intersections. The traffic stream is randomly generated from the edges intersections into the internal intersections in every simulation cycle. The internal intersections try to ensure that the green wave traffic phase is implicitly satisfied.

Fig. 16 shows partial simulation results for only five intersections. Note that the AQLs for these intersections are reasonable and no one queue is overloaded, which shows that the traffic algorithm can adapt to traffic volumes at different directions to maintain normal operations. Then, we setup an experiment where two cars traversing a path of 10 intersections over rectilinear mesh structure were noticed. The AWT was collected over time and the results are reported in Fig. 17 and it seems that the algorithm is able to handle different cars in a fair manner. Also, we have counted the number of cars that passes through the 5 intersections for traditional fixed vs. dynamic control. As Fig. 18 shows, the dynamic approach maintains smooth transitions of cars over the consecutive five intersections except for some rare unexpected behavior for fixed control. Finally, real traces of waiting times for one complete path with 10 consecutive intersections were collected and compared to ones from our proposed algorithms. As Fig. 19 shows, our algorithms were able to resemble in a fair manner the traffic dynamics over the real complete path.

7. CONCLUSION AND FUTURE WORK

In this paper, the design of an intelligent traffic control system, utilizing and efficiently managing WSNs, is presented. An adaptive traffic signal time manipulation algorithm based on a new traffic infrastructure using WSNs is proposed on a single and mul-

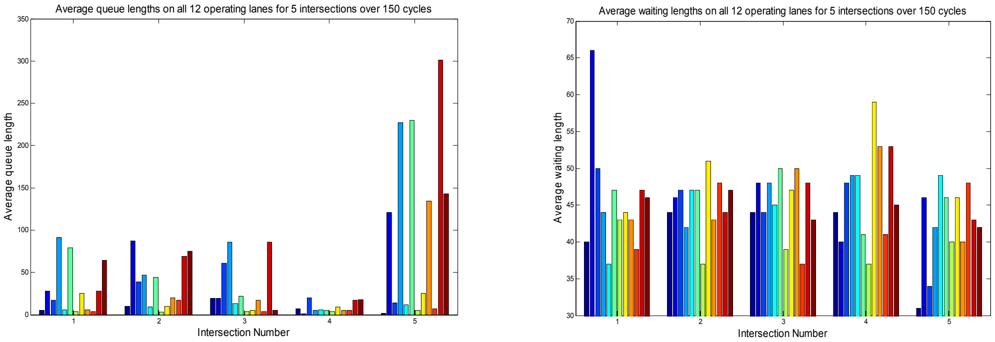

Fig. 16. Multiple intersections mesh structure simulation: partial results.

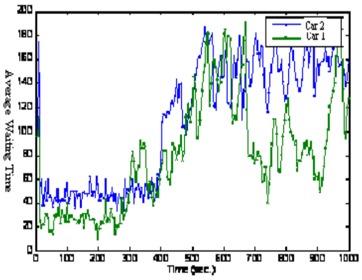

Fig. 17. Average waiting time of two cars traversing a path of 10 intersections.

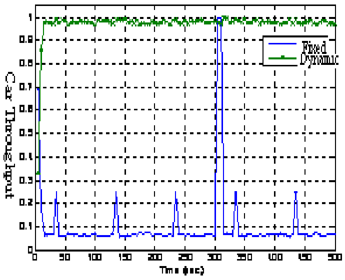

Fig. 18. Throughput of control algorithm (Fixed Vs. dynamic control).

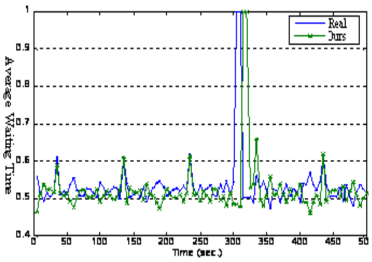

Fig. 19. Traces of AWT over two distinct paths using dynamic traffic control.

tiple road intersections. A new technique for changing the traffic phase's sequence, during the traffic control, is another contribution of this paper. The proposed system with its embedded algorithms is proved to play a major role in alleviating the congestion problem when compared to inefficient classical traffic control systems. Furthermore, our traffic control system can be easily installed and attached to the existing traffic road infrastructure at a low cost and within a reasonable time. The system is self-configuring and operates in real-time to detect traffic states and exchange information with other nodes via a wireless communication with self-recovery function. In addition, no traffic disruption will be necessary when a new traffic sensor is to be installed. In the future work of this study, we plan to simulate the human driving behaviors and package the entire system using FPGA technology. In addition, different types of intersections and different types of crossing directions in the system will be considered.

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