International Journal of Computer Information Systems and Industrial Management Applications.
ISSN 2150-7988 Volume 6 (2014) pp. 196-205

Signalized Traffic Intersections Control with Uncertainties Over Lossy Networks

Magdi S. Mahmoud, Faisal A. Al-Nasser, Fouad M. AL-Sunni
Systems Engineering Dept., KFUPM
Dhaharan, Saudi Arabia
msmahmoud@kfupm.edu.sa,g199785010@kfupm.edu.sa,alsunni@kfupm.edu.sa

Abstract: In this paper, different traffic light control structures over communication links, including the decentralized, quasi-decentralized and distributed control, are considered for coordinating multiple intersections, which could be a great application of networked control signalized traffic light problem. It will help the designer to achieve certain objectives such as minimize the waiting time during the red light period and perform a better control in the next green cycle and more will be highlighted in this paper. A state space model of traffic dynamics under these different control structures is proposed considering most of the major effects of lossy communication links and the traffic uncertainties. Also, a sufficient condition for system stability is provided based on Linear Matrix Inequality (LMI). Finally, comparison of different types of networked control systems was done using simulation.

Keywords: Intelligent traffic control, Decentralized/ Quasi-decentralized/ Distributed networked control, Uncertainties.

I. Introduction

In modern urban areas, the number of vehicles is growing larger and larger and the requirements for traveling by vehicles are becoming more demanding than ever. Many large and sound traffic networks (freeways and roads) are already constructed, traffic congestion still cannot be avoided efficiently and it is time and money consuming to build more common transportation infrastructures or reconstruct the already existing one. So, traffic jams may occur frequently and it will lead to severe impacts, especially when people need to use the common infrastructures with limited capacity at the same time, during rush hours [1], [2]. Traffic congestion will cause traffic delays, economic losses, traffic pollution, driver misbehavior and so on. Therefore, effective traffic control methods are necessary to reduce traffic jams. Several traffic control strategies were proposed and implemented in the field but were mainly focusing on controlling a single intersection without global scope, and have limited control effect for the whole traffic network. It is obvious that each intersection is affected by situation in other intersections and this motivate to investigate the coordinated control approaches that can better coordinate/control traffic networks. For a

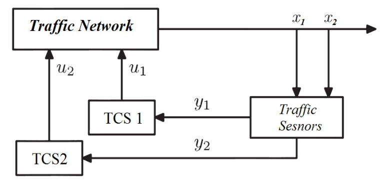

Fig. 1. Traditional Traffic Control System with 2 Control Loops

system with multiple control loops, each intersection is a control loop and the controllers can be designed to work in a decentralized fashion (see Fig. 1). The two traffic control systems (TCS 1, TCS 2) are designed to not exchange information and operate in a decentralized fashion which makes each intersection isolated from others. Similar system is shown in Fig. 2 but here it is over communication links, so it will be called Decentralized Networked Control Systems (DecNCS), and the red dashed lines represents the communication network links. Communication networks make the transmission of data much easier, provide a higher degree of freedom in the configuration of control systems, allows for easy modification of the control strategy, higher redundancy and allows higher level of supervisory control. In the context of networked control systems, key issues that need to be carefully handled at the control system design level such as data losses due to field interference, time delays due to network traffic, transmission constraints and more issues. As a result, The controller will do a control over network not through network and design shall be robust to all previously mentioned issues [5], [8]. Other control strategies will be discussed in this work such, namely the Quasi-Decentralized [9]-[10] and Distributed control [11] and the networked versions of each one. Data that will fed using Sensors Network (Wired/Wireless), to the control system with the number of incoming traffic data, passing vehicles and crossing the signals [3]. All of previously mentioned control structures can be used for the traffic signal intersection control to achieve wide range of objective functions [3]-[4],[13]-[24] such as:

1) Minimize (overall delay to vehicles, waiting time, delays to pedestrians/ emergency services/ public transport,
2) Minimize accident potential for all users and en-

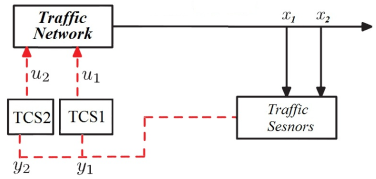

Fig. 2. Decentralized Networked Control System

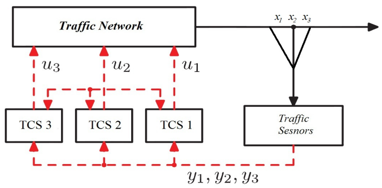

Fig. 3. Distributed Networked Control System

vironmental impact of vehicular traffic (noise, atmospheric pollution, visual intrusion, drivers misbehaviour)

3) Equitable distribution of delays between competing traffic.
4) Maximize (reliability/ network capacity/ Energy efficiency).
5) Handling of the red light crossing violations.
6) Indication to the police traffic control room.

It is important to note that some of the objectives do conflict and a compromise may have to be made in the selection of objectives. However, some objectives can be met in tandem, for example minimizing delay to vehicles would also help to minimize fuel consumption [16], atmospheric pollution and increase network throughput. In practice most traffic lights are controlled by fixed-cycle controllers [16]-[18] in which all traffic gets a green light at some point. For pre-timed or fixed cycle controllers, we need to manually fine tune from time to time to perform well which needs a lot work.

II. Traffic Dynamics and Problem Definition

Basically most of the traffic signals intersections have four main directions queues, North (N), South (S), East (E) and West (W). The other queues possibilities are North West (NW), South East (SE), East North (EN) and West South (WS) (Fig. 5). Each intersection can run different number of phases (a phase is the period that nonconflicting movements can run), example of four phases in Fig. 4. For simplicity, we will give a number for each queue q_i where $i = 1, ..., 8$ for the following in order $(N, S, E, W, NW, SE, EN, WS)$ assuming all right side movements are free and do not require a signal. The state equation for the continuous traffic flow process associated with any movement i that is sampled every Δt seconds, where time is indexed with the integer k, can be expressed

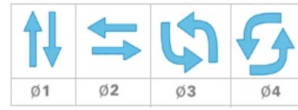

Fig. 4. Example of Four Phases

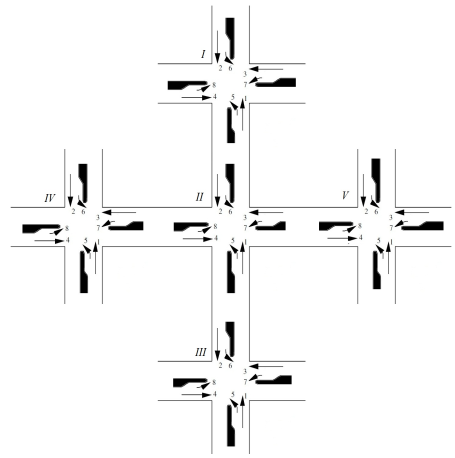

Fig. 5. A Traffic network with five intersections

by the current queue $q_i(k)$:

$$\begin{aligned} q_i(k+1) &= q_i(k) + \Delta q_i(k) + \Delta p_i(k), i = 1, 2, ...8 \\ \Delta q_i(k) &= q_i^{in}(k) - q_i^{out}(k) \\ \Delta p_i(k) &= p_i^{in} - p_i^{out} \end{aligned} \quad (1)$$

where $q_i^{in}(k)$ is the incoming new vehicles at time interval $[k-1, k]$ in link or queue i, $q_i^{out}(k)$ is the number of vehicles able to pass the intersection during the green signal interval Tg from link or queue i, also Tg can be called as the control interval or green time for a certain phase, $q_i(k-1)$ is the queue of vehicles waiting for green signal to happen at time k, $\Delta p_i(k)$ represents the fluctuation between a parking lot and link i or the effects of any non-controlled intersection between any two intersections where p_i^{in} used for vehicles left the parking or came from non-controlled intersection and joined the traffic in the queue i and p_i^{out} for vehicles left the queue i and went for a parking or went into a sub road or what we call it non-controlled intersection. These disturbing flows can be considered either as disturbance or as known perturbations if they can be well measured or estimated. In case of these uncertainties or perturbations are unknown and can't be measured, then robust control system will be used. The general discrete LTI state space representation the following:

$$\begin{aligned} Q(k+1) &= AQ(k) + BG(k) + Fd(k) \\ Q^{out}(k) &= CQ(k) \end{aligned} \quad (2)$$

where the following constraints need to be taken into account:

- Bounded Queue Length: $0 \le q_i(k) \le q_{i,max}(k)$.

- Bounded Green Time: $Tg_{i,min} \leq Tg_i(k) \leq Tg_{i,max}$
- Waiting Time Shall not be too long.$Tw_{ij} \geq \sum_{m\neq i}[Tg_{mj}], < m = 1, 2, 3 ..., p$
- Cycle Time, it can be long or short based on traffic density.$\sum Tc_j \leq Tc_{max}$

And $Q(k) = [q_1(k)q_2(k) < q_8(k)]'_j$ and $G(k) = [Tg_1(k)Tg_2(k) < Tg_8(k)]'_j$, The state matrix A is set to be as an identity matrix where the elements of the state vector $Q(k)$ represent the queues length $q_i(k)$. The matrix B composed of of saturation and turning rates with (-) sign and G store the green times Tg_i of all phases. The number of states is equal to the number of controlled links in the network. The product $BG(k)$ is shows the difference of in and out flow for the traffic in the link or queue i during the green interval. Each output inside of the network is a measured state (number of vehicles of the link i) that makes the output equation simplified to $y(k) = Q(k)$ and $C = I$. Finally, the traffic coming from non-controlled intersections or parking are considered as disturbance to the system in $d(k)$.

A. Communication Link Impacts

The use of communication link between sensors and intersection controller will introduce some network issues:

- Sensors Packet Dropout: if the packet does not arrive before the end of the sample period then packet is lost. So, the intersection controller may use the previous queue data to apply the control value but it should not be less than minimum value of the green time period. $y_k = \beta_k\hat{y}_k + (1 - \beta_k)y_{k-1}$ and $\beta_k \in \{0, 1\}$, we used the term $\hat{y}_k$ to indicate that it is the networked version that could be same as the original value or little vary from the original sent value.
- Varying sampling interval: Due to the nature of the network, the actual sampling times is not necessary to equidistant in time. For a constant sampling interval h and instead we will use h_k.
- Transmission constraints: it is possible to have a type of network that allows one node to access the network and transmits its corresponding values at each sampling time which will limit data transmission. $\hat{y}^i_k = \Gamma^y_{\sigma_k} y_k + (1 - \Gamma^y_{\sigma_k})\hat{y}_{k-1}$ where σ_k is used as switched function to determine which node will have the access to transmit, Γ^y_ℓ are diagonal matrices where the j^{th} diagonal value is 1 if output belongs to node and zero otherwise.
- Network induced errors: it shows discrepancies between current and the most recently transmitted input/output values of nodes' signals. It can be used to design dynamic output feedback, communication protocol and for transmission scheduling where the node with highest error will have the chance for transmission. $e^u_k = \hat{u}_{k-1} - u_k, \quad e^y_k = \hat{y}_{k-1} - y_k$. We can define threshold levels γ^u_i, γ^y_i for the induced error where $e^u_k < \gamma^u_i$ and $e^y_k < \gamma^y_i$ for each subsystem i.

B. Decentralized Networked Control Structure

Dividing a large traffic network into decentralized intersections will reduce the computation complexity but the traffic flow interactions between intersections are cut off (or disconnected) [17]. Because of that, the global optimal solution is not possible and the overall performance of the whole network will be deteriorated when we have a high traffic flow. By applying this structure we will have the generalized model for system that has 5 traffic light intersections as the following:

$$\begin{aligned} Q(k) &= [Q_1\ Q_2\ ....\ Q_j], j = 1, 2, ...5 \\ Q_j(k) &= [q_{1,j}(k)\ q_{2,j}(k)\ ....\ q_{8,j}(k)]^t, \\ q_{i,j}(k) &= q_{i,j}(k-1) + \Delta q_{i,j}(k), i = 1, 2, ...8, \\ \Delta q_{i,j}(k) &= -q^{out}_{i,j}(k) \end{aligned} \tag{3}$$

where j represents the intersection number. Here $\Delta q_{i,j}(k)$ is (-) because we don't consider the incoming traffic from other intersections, and hence the state space model will be

$$\begin{aligned} Q_j(k+1) &= A_jQ_j(k) + B_jG_j(k) \\ Q^{out}_j(k) &= C_jQ_j(k) \end{aligned} \tag{4}$$

C. Distributed Networked Control Structure

In DNCS, exchange of information between controllers is allowed which helps each one to make better decisions benefiting from other controllers status information to achieve the required coordination. However, if the amount of information that the local controllers take into consideration of increases, the computational complexity will become very high.

$$\begin{aligned} q_{i,j}(k) &= q_{i,j}(k-1) + \Delta q_{i,j}(k), i = 1, 2, ...8, \\ \Delta q_{i,j}(k) &= q^{in}_{i,j}(k) - q^{out}_{i,j}(k) \end{aligned} \tag{5}$$

as we can see that we consider all the incoming traffic from other intersections where for example the traffic coming from intersection III from queue $6, 3$ will affect the queue in intersection I in queue $6, 8$ and so on. and hence the state space model will be

$$\begin{aligned} Q_j(k+1) &= A_jQ_j(k) + B_jG_j(k) + H_j(k), \\ y^j_k &= C_jQ_j(k) + W_j(k) \end{aligned} \tag{6}$$

where $H_j(k) = \sum^5_{n=1,n\neq j} A_{n,j}x_n(k)$ that contains the information about the other intersections queues that may help the current intersection in case of long queue there to pro act to minimize the vehicles accumulation in that lane and $W_j(k) = \sum^N_{n=1,n\neq j} C_{n,j}x_j(k)$ to show the information about the output queues from other intersections that is exchanged between the controllers. For example, the

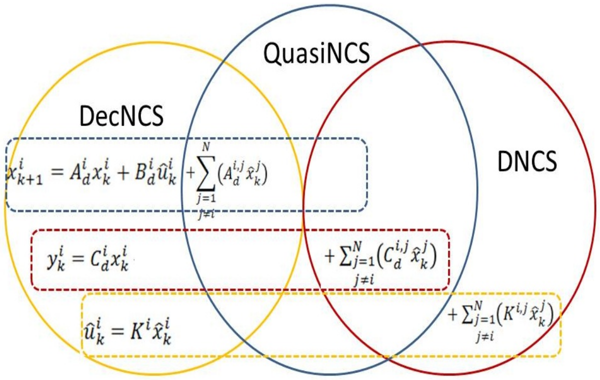

Fig. 6. QuasiNCS

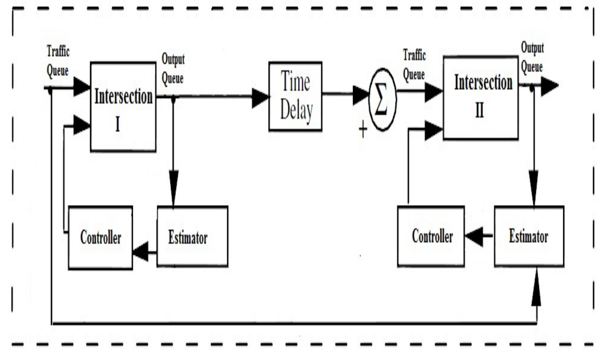

Fig. 7. Two Intersections Traffic Controllers (QuasiNCS).

intersection I controller in Fig. 5 will be able to know the status of the signal at line 6 from intersection III if it is green and also the queue length and the output queue during the green period will be also sent before that to controller at intersection I, then there could be several scenarios to minimize the queue length at line 6 in the intersection I by extending the Tg where $Tg < Tg_{max}$, if it is green or give the priority to this side if the other sides in the intersection I has lower queue length or minimize the the Tg for the other sides if the queue lengths are smaller.

D. Quasi-Decentralized Networked Control Structure

To solve the problem where a DecNCS structure cannot provide the required stability and performance properties, and to avoid the complexity and high exchange of information required between controller in DNCS , a quasi-decentralized networked control strategy, for simplicity we will call it as **QuasiNCS**, (it is partially decentralized and not fully distributed), (see Fig. 6), with minimum cross communication between the intersections offers a suitable compromise and it provides a way of ensuring partial knowledge of how the local controller is affecting the global system and can guarantee certain stability for the overall traffic network.

The term quasi-decentralized networked control refers to a situation in which most signals used for control are collected and processed locally, although some signals (the total number of which is kept to a minimum) still need to be transferred between local units and controllers to adequately account for the interactions between the different units and minimize the propagation of disturbances and process upsets from one unit to another.

$$\begin{aligned}
Q(k) &= [Q_1 \; Q_2 \; .... \; Q_j], \\
Q_j(k) &= [q_{1,j}(k) \; q_{2,j}(k) \; .... \; q_{8,j}(k)]^t, \\
q_{i,j}(k) &= q_{i,j}(k-1) + \Delta q_{i,j}(k), i = 1, 2, ...8, \\
\Delta q_{i,j}(k) &= q_{i,j}^{in}(k) - q_{i,j}^{out}(k)
\end{aligned} \tag{7}$$

where $q_{i,j}^{in}(k)$ is the incoming new vehicles at time interval $[k-1, k]$ for intersection j for queue lane number i , $q_{i,j}^{out}(k)$ is the number of vehicles that were able to pass the intersection j during the green signal interval, Tg for the queue lane i at that intersection and $q_{i,j}(k-1)$ is the queue of vehicles that were waiting for green signal to happen at time k.

The discrete state space for the generalized model with multiple intersections can be shown to be as follows:

$$\begin{aligned}
x_j(k+1) &= A_j x_j(k) + B_j u_j(k) + H_j(k), \\
y_k^j &= C_j x_j(k)
\end{aligned} \tag{8}$$

where $H_j(k)$ already defined in eq. 6.

III. Hierarchical Structure

The main aim of this structure [7] is to perform traffic management at a strategic level in urban, interurban or mixed areas. The city or traffic network where the traffic has to be supervised is divided into several sections called problem areas or zones. The decomposition of the city into zones allows for a better analysis and understanding of the causes and evolution of traffic problems than if performed from a global perspective. This split does not define a set of disjointed areas whose sum is the whole city, but every area represents a part of the city where a determined traffic behavior is usually present and where a set of signal elements can be managed to influence this behavior. Then, the zone may overlap with surrounding zones sharing, for instance, some signals but using them from different points of view. So, a problem area or zone is a part of a city where traffic behavior is locally studied and suitable control actions may be defined to improve the traffic state.

Every zone is controlled by a controller, called control agent, which understands the traffic conflicts that may appear, the usual behavior of vehicles in the area and the signal and/or VMS (Variable Message System) actions that may improve the traffic state, supervise every problem area. The control proposals generated by every agent are received by a higher level agent, called the

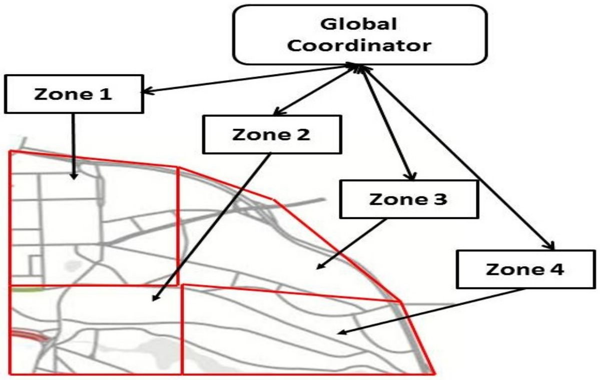

Fig. 8. Hierarchal Traffic Control - Dividing the Network into Problem Areas

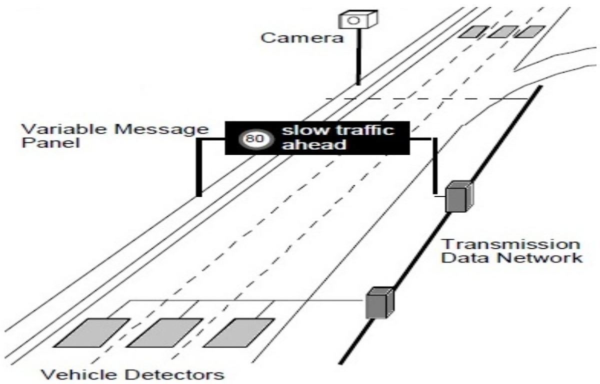

Fig. 9. Variable Message System

coordinator, whose aim is to produce global proposals for the whole city by putting together the local proposals provided by the agents and removing the inconsistencies among them.

IV. Closed Loop Models

The most common and systematic approach is to use a dynamic output feedback, where the controller (or compensator) has its own dynamics. The simplest form is an observer structure

$$\begin{aligned} \tilde{Q}_j(k+1) &= A_i\tilde{Q}_j + B_jG_j + L_j(y_j - C_j\tilde{x}_j) \\ G_j(k) &= -K_j\tilde{Q}_j, \quad j = 1, \ldots, 5 \end{aligned} \quad (9)$$

In this simple approach, $\tilde{Q}$ is an estimate for the actual Q for each intersection j and we need to pick a good observation gain L_j such that $\tilde{Q}_j$ will be as close as possible to Q_j. In this work, we will use observer-based controllers in the sense that for each intersection of the traffic network we have one observer-based controller. The j^{th} networked observer-based controller is given by considering the network side effects we have discussed in this work:

$$\begin{aligned} \tilde{Q}_j(k+1) &= A_j\tilde{Q}_j(k) + B_j\hat{G}_j(k) + O_j + H_j \\ O_j &= L_j\Gamma_j^y(\hat{y}_j(k) - C_j\tilde{G}_j(k)) \\ H_j &= \sum_{j=1, j\neq i}^{N} A_{i,j}\hat{Q}_j(k) \\ \hat{G}_j(k) &= -K_j\,\tilde{Q}_j(k) \end{aligned} \quad (10)$$

where $\tilde{Q}_j(k+1)$ represents the state estimate at time $k+1$ for the plant state $Q_j(k+1)$, $B_j = [\int_0^{h-\tau_{rt}^k} e^{As} ds]B$ when $\tau_{rt}^k \leq h$ where h is the sampling interval. The output related matrices $L_j(k)$, K_j, $j = 1, \ldots, 5$ are the subsystem gain matrices. The state estimation error is $\psi_j(k) = \tilde{Q}_j(k) - Q_j(k)$. To deal with the communication constraints, the observer structure is used where the standard output is applied only when a new measurement is received. The dynamic of all controllers can be shown in discrete model that composed of block diagonal matrices written as follows for the DNCS, Dec-NCS and Quasi-DecNCS

$$\begin{aligned} \xi_{k,DNCS} &:= \begin{bmatrix} x_k & \psi_k & e_k^y & H_k & W_k \end{bmatrix}^t \\ \xi_{k,DecNCS} &:= \begin{bmatrix} x_k & \psi_k & e_k^y \end{bmatrix}^t \\ \xi_{k,Quasi} &:= \begin{bmatrix} x_k & \psi_k & e_k^y & H_k \end{bmatrix}^t \end{aligned} \quad (11)$$

by combining the foregoing relations, the overall closed-loop dynamics can be expressed as

$$\begin{aligned} \xi_{k+1,DNCS} &= \mathcal{A}_{k+1,DNCS}\,\xi_k \\ \mathcal{A}_{cl,DNCS} &= \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} \quad (12) \\ a_{11} &= A_j + B_jK_j, \;\; a_{12} = -A_j + L_jC_j, \\ a_{22} &= A_j - L_jC_j, \\ a_{31} &= C_j(-A_j + \alpha_k K_jB_j + I), \\ a_{32} &= \alpha_k K_jB_jC_j, a_{33} = (I - \beta_k\Gamma_j^y) \\ a_{44} &= I, a_{55} = I, \end{aligned} \quad (13)$$

The others non mentioned elements are zeros. For the fully decentralized structure, the one in12 size will be reduced $(3x3)$ and for QuasiNCS will be $(4x4)$ because we allow limited communication. To sum up, the foregoing control structures can be cast into the generic form:

$$\begin{aligned} \zeta_{k+1} &= \mathcal{A}\,\zeta_k \\ \mathcal{A}_{cl} &= blockdiag\{\mathcal{A}_{1,cl}, \ldots, \mathcal{A}_{N,cl}\} \end{aligned} \quad (14)$$

V. Stability Analysis

In the sequel, we define a global Lyapunov functional by

$$V = \xi_k^t\mathcal{P}\xi_k, \;\; \mathcal{P} = blockdiag\{\mathcal{P}_1, \ldots, \mathcal{P}_N\}, \; \mathcal{P}_j > 0 \quad (15)$$

Evaluating the first difference ΔV along the solutions of (14) yields

$$\Delta V = -\mathcal{P} + \mathcal{A}_{cl}^t \mathcal{P} \mathcal{A}_{cl} \tag{16}$$

According to Laypunov stability theorem, necessary and sufficient condition for stability is $V > 0$, $\Delta V < 0$. The following is a preliminary result

Lemma 5.1: Given the gains K and L, system (12) is said to be asymptotically stable if there exists positive definite matrices $0 < \mathcal{P}_j = \mathcal{P}_j^t \in \Re^{n_i \times n_i}$, $0 < \mathcal{X}_j \in \Re^{n_i \times n_i}$, $0 < \mathcal{Z}_j = \mathcal{Z}_j^t \in \Re^{n_i \times n_i}$, $i = 1, \ldots, NumOfDirections$ such that the following LMIs

$$\begin{bmatrix} -\mathcal{P}_j & \mathcal{A}_{j,cl}^t \mathcal{X}_j \\ \bullet & -\mathcal{X}_j - \mathcal{X}_j^t + \mathcal{Z}_j \end{bmatrix} < 0, \quad j = 1, \ldots, N \tag{17}$$

have a feasible solution for $j = 1, \ldots, N$, where N is the number of intersections.

Remark 5.1: By looking at the closed-loop matrix (12)-(13) in the distributed-control case, it is instructive to let the matrix X has the following form where the size will be matching with the size of A_{cl} according to the control structure that we have selected:

$$\mathcal{X} = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} \\ 0 & X_{21} & X_{23} & X_{24} & X_{25} \\ 0 & 0 & X_{33} & X_{34} & X_{35} \\ 0 & 0 & 0 & X_{44} & X_{45} \\ 0 & 0 & 0 & 0 & X_{55} \end{bmatrix} \tag{18}$$

Indeed, the decentralized and quasi-decentralized cases can be done in a similar way and X will be smaller in size similar to A_{cl} matrix size for each control structure.

VI. Uncertainties and Robust Control

In our work, the state uncertainties were neglected in eq. 2 or considered as known parameters. Usually, these uncertainties may appear due to unexpected traffic fluctuations caused by parking places along the road or non-controlled junctions in the network. The measurements of these disturbing flows are too costly and very difficult in fact. Several approaches [12] for modeling uncertainties can be used such as the bounded additive disturbance model and the multiplicative approach which may involve state uncertainties in the traffic model. These uncertainties can be embedded in matrix A along the diagonal and we also, take the variations from eq. 19.

$$\begin{aligned} \Delta Q_j(k) &= Q_j(k) - Q_j^N(k), j = 1, 2, \ldots .5 \\ \Delta G_i(k) &= G_i(k) - G_i^N(k) \\ \Delta d_i(k) &= d_i(k) - d_i^N(k) \end{aligned} \tag{19}$$

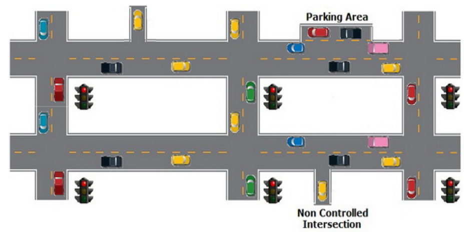

Fig. 10. Queues uncertainties in traffic between intersections

VII. Simulation Studies

In the simulation we considered 5 intersections (Fig.5) and we tried to compare the results from the proposed approaches. Average speed set to 80 Km/h, communication is over a lossy network, with total of 4 phases (N,S,E,W,NW,SE,EN,WS). A Poisson distribution with avg arrival rate of $\lambda = 40$ cars/min was used. The level of information exchanged is shown in Table 11. By looking to Fig. 12, we can see that at intersection I, we started with phase 1, then by the time the flow will reach to intersection II, (around 45 sec), the incoming flow plus the existing flow will move together without stoppage and same will happen at intersection III which shows the beauty of QuasiNCS approach over the DecNCS (Fig. 12). The total trip time in case of DecNCS will be more than 150 sec, from intersection I to III with 2 stoppages while in QuasiNCS it around 94 sec with zero stoppage. Also, we can observe from Fig. 12 that a synchronization can happen between intersection II , IV and V and the traffic between East and West can run smoothly in the successive intersections. In case of the packets delay or dropout or another communication constraints, the controller can depend on the last received data and in case of long stoppage of sensors or physical damage, the controller can depend on either fixed green time (45 sec) or based on average arrival rate from historical data. For the QuasiNCS and DNCS, the phase selection information will be affected in case of any delay or dropout, it will simply run based on arrival data coming from the sensors. Finally, the **computation time** for the DecNCS was < 1 sec , QuasiNCS around 2.5 sec and DNCS around 10 sec, for one loop. So, it is worth to go with QuasiNCS solution because it provides good platoon movements along the traffic network with very low computation time and lower level of information exchange, while in DecNCS the traffic need to stop several times and for the DNCS computation time was too high. An example of traffic data in intersection I, II and III are shown in Fig. 15 up to Fig. 23.

Also, it will be important to view the effect of some communication effects on the control performance and this will be summarized in the following:

- Communication Constraints: communication is an important factor for the controller to make the proper

	Traffic Arrival	Phase Selection	Traffic Arrival	Green Time	Traffic Jam Info	Avg arrivals speed
DecNCS	Y	N	N	N	N	N
QuasiNCS	Y	Y	N	N	N	N
DNCS	Y	Y	Y	Y	N	Y

Fig. 11. Data Exchange In Each Approach

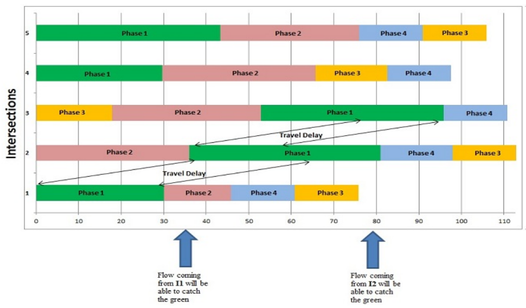

Fig. 12. Phase Selection in QuasiNCS for Each Intersection to maximize the flow from intersection 1 up to 3

coordinations with other controllers. In the case of DecNCS, there is no communication between controllers and decision will be made on the intersection data only. From the first look, you may see that the DecNCS is giving low cycle time but in reality it is much more because it did not consider the new arrivals. For the QuasiNCS, we have simulated the effect of communication constraints as shown in Fig. 24, you can see that the more communication we allowed, the more the cycle time changes and this is required for the proper coordination between intersections considering the current and new coming traffic for each intersection.

- Packets Dropout: another issue we can show also is the effect of β values (sensor packets dropout) which will affect more the QuasiNCS as shown in Fig. 25, and the dropout of sensors packets will reflect on the cycle time but not too much because usually such sensors applications will send few packets (number of cars, time, ...etc) cyclically, and if the packet

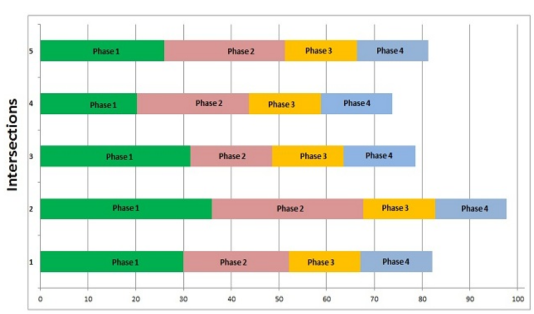

Fig. 13. Phase Selection in DecNCS for Each Intersection

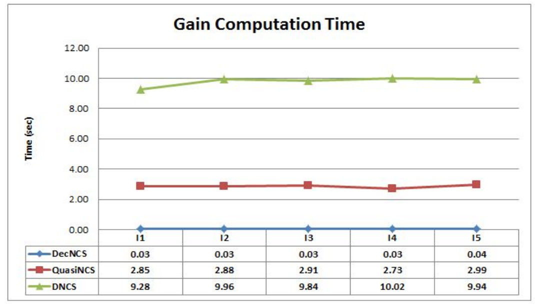

Fig. 14. Gains Computation Time

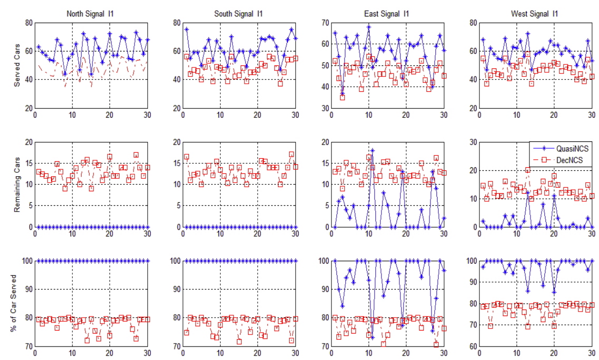

Fig. 15. QuasiNCS vs. DecNCS , Intersection 1 , Main Directions

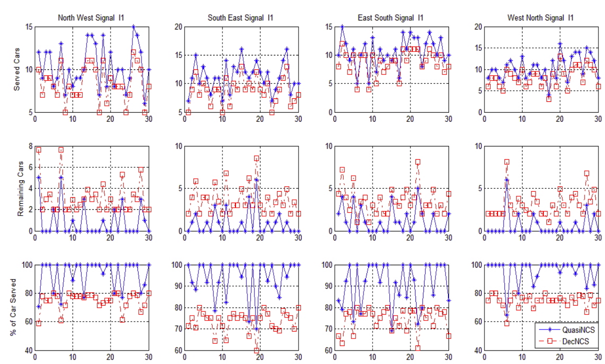

Fig. 16. QuasiNCS vs. DecNCS , Intersection 1 , Sub Directions

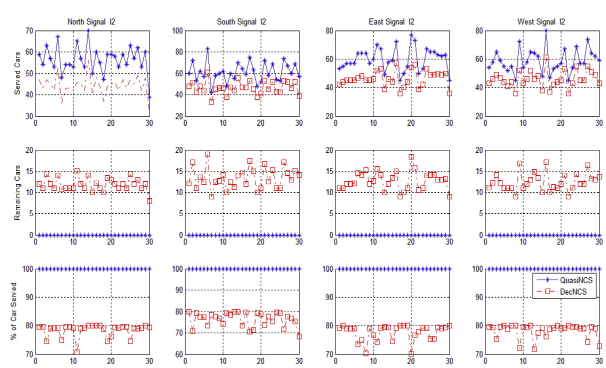

Fig. 17. QuasiNCS vs. DecNCS , Intersection 2 , Main Directions

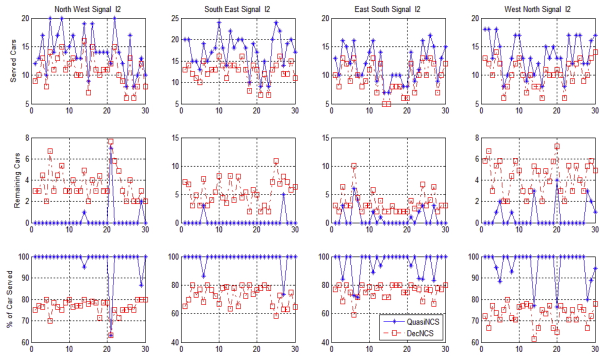

Fig. 18. QuasiNCS vs. DecNCS , Intersection 2, Sub Directions

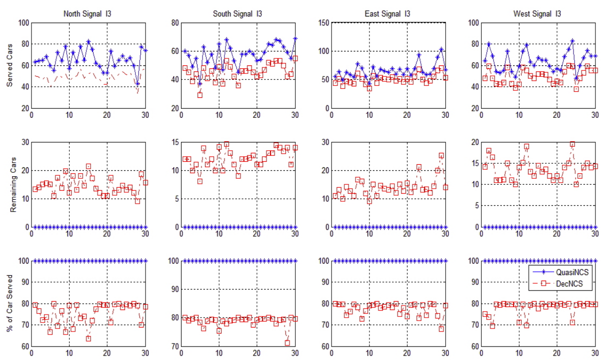

Fig. 19. QuasiNCS vs. DecNCS , Intersection 3, Main Directions

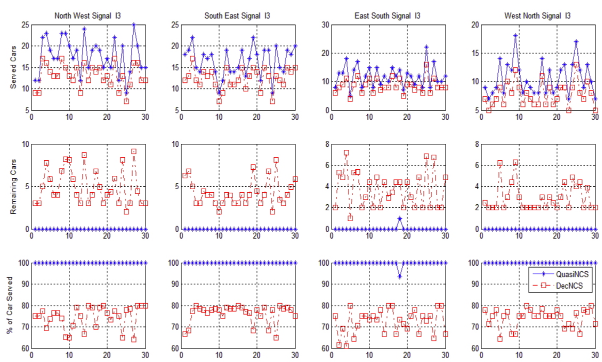

Fig. 20. QuasiNCS vs. DecNCS , Intersection 3, Sub Directions

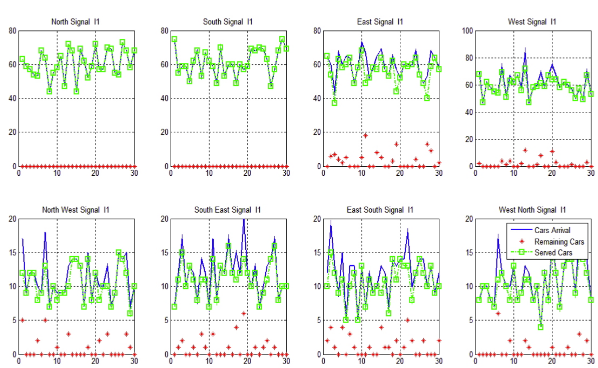

Fig. 21. QuasiNCS Served vs. Arrived Cars , Intersection 1

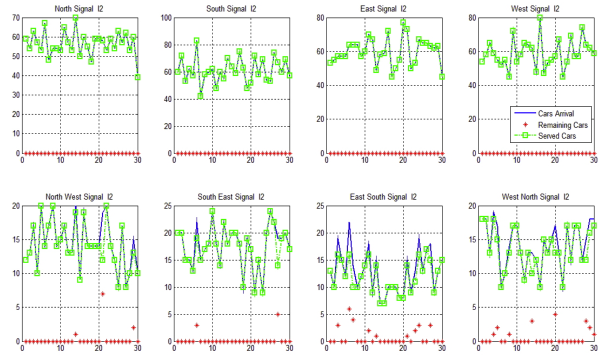

Fig. 22. QuasiNCS Served vs. Arrived Cars , Intersection 2

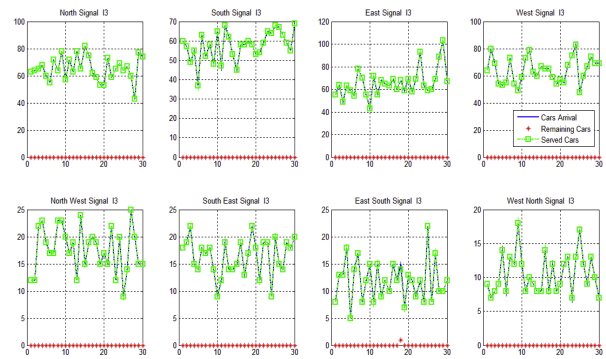

Fig. 23. QuasiNCS Served vs. Arrived Cars , Intersection 3

dropout is increasing, the controller will switch to the local intersection control because may be the sensors are malfunction or physically damaged.

- Computation Time: the traffic density is not really an issue for the computation time as we can see from Fig. 26.
- Waiting Time: this is very important measure for the control system, because the longer the waiting time the more the drivers will get frustrated and the potential of violation will be higher. So, in this simulation, we focused on the waiting time

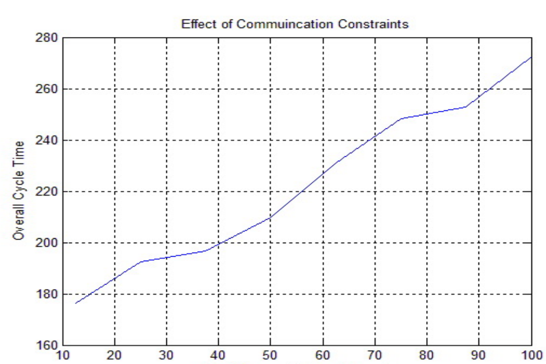

Fig. 24. Communication Constraints Effect

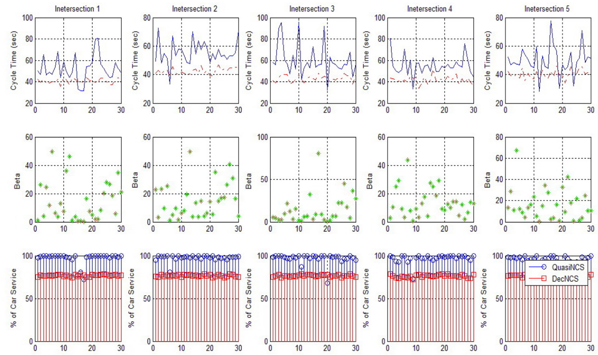

Fig. 25. Beta Values Effect

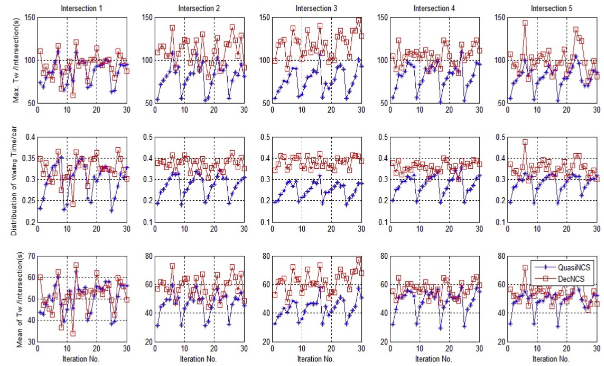

Fig. 28. Random Traffic Density Effect on Waiting Time

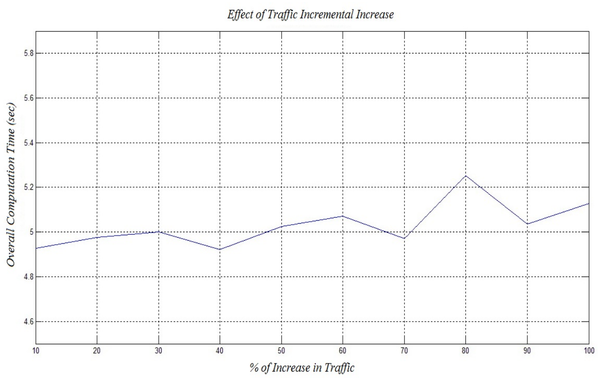

Fig. 26. Traffic Density Effect on Control Computation Time

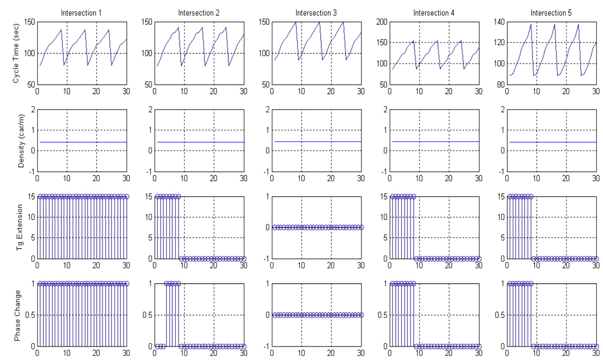

Fig. 29. Delay Effects on Cycle Time

behaviour during an incremental traffic by increasing the traffic arrival every cycle by 25% and we stop increasing it when the traffic density exceeds 1 as shown in Fig. 27 and Fig. 28 shows the waiting time during normal random arrival.

- Communication Delay: the effect of data packets delay from previous intersection controller to the next intersection controller will let the $2nd$ controller to increase the intersection cycle time to accommodate the incoming traffic up to a certain limit then it will not extend. If the packets delay exceeded the maximum allowed limit, then the controller will ignore the delayed packets and start a new control cycle and if this problem continues for certain number of cycles, which means that the link needs a longer time to be fixed, the controller will then use one of the options we mentioned earlier (Historical data, Fixed Time or behave like DecNCS locally), Fig. 29 explains this issue clearly. Also, we can see from same figure in Intersection 2 after certain time it will stop doing green time extension because the delay exceeded the limit, similarly we can observe with intersection 4 and 5.

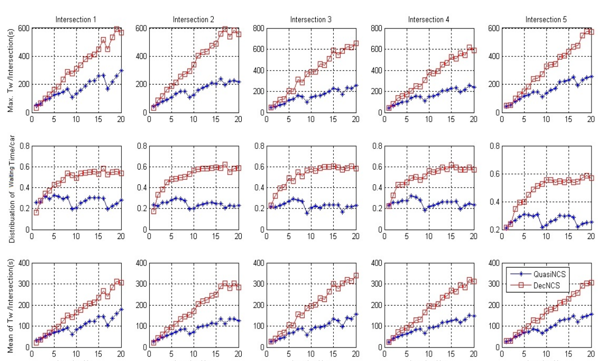

Fig. 27. Incremental Traffic Density Effect on Waiting Time

VIII. Conclusions

In this paper, we have examined different control techniques for traffic light intersections including decentralized, quazi-decentralized, distributed and hierarchal architectures. A comprehensive survey has been made about the traffic control methods including several traffic concepts and fundamentals. The paper has discussed the rationale for the individual architectures and illustrated the merits/demerits. We have developed a state-space model and considered the networked induced delays, packet dropout and varying sample interval. Simulation was performed on typical data to illustrate the differences between the various approaches.

Acknowledgment

This work is supported by the deanship of scientific research (DSR) at KFUPM through research group project No. **RG-1105-1**.

References

[1] F. A. Al-Nasser and H. Rowaihy, "Simulation of Dynamic Traffic Control System Based on Wireless Sensor Network", *IEEE Symposium on Computers & Informatics(ISCI 2011)*, pp. 302–307, 2011.

[2] D. Kitaw, E. Berhan and B. Beshah, "Performance Analysis on Public Bus Transport of the City of Addis Ababa", *International Journal of Computer Information Systems and Industrial Management Applications*, Vol.5, pp. 722–728, 2013.

[3] WEN Y, PAN J. L. and LE J. F; "Survey On Application Of Wireless Sensor Networks For Traffic Monitoring", *International Conference on Transportation Engineering - ICTE*, 2007.

[4] A. Albagul, M. Hrairi, Wahyudi and M. F. Hidayathullah; "Design and Development of Sensor Based Traffic Light System", *American Journal of Applied Sciences*, pp. 1745–1749, 2006.

[5] J. Wei, "Stability Analysis of Decentralized Networked Control Systems", *World Congress on Intelligent Control & Automation*, vol. 7, pp. 5477–5482, 2008.

[6] S.Yksel and T. Basar, "Optimal Signaling Policies for Decentralized Multi-controller Stabilizability Over Communication Channels". *IEEE Trans. Automatic Control*, vol. 52, 1969–1974, 2007.

[7] K. Rohloff, J. Ye, J. Loyall and R. Schantz. "A Hierarchical Control System for Dynamic Resource Management". *IEEE Real-Time and Embedded Technology and Applications Symposium*, 2006.

[8] J. Schendel, M. Donkers, W. Heemels and N. Wouw. "On Dropout Modeling for Stability Analysis of Networked Control Systems", *Proc. American Control Conference*, pp. 555–561, 2010.

[9] Y. Sun and N.H. El-Farra. "Quasi-decentralized Control of Process Systems Using Wireless Sensor Networks with Scheduled Sensor Transmissions". *American Control Conference*, 3390 - 3396, 2009.

[10] Y. Sun and N.H. El-Farra. "Quasi-decentralized Scheduled Output Feedback Control of Process Systems Using Wireless Sensor Networks". *IFAC Symposium on Advanced Control of Chemical Processes*, 2009

[11] S. Oh and S. Sastry. "Distributed Networked Control System with Lossy Links: State Estimation and Stabilizing Communication Control". *45th IEEE International Conference on Decision and Control*, 1942-1947, 2006.

[12] T. Tettamanti , I. Varga , T. Peni , T. Luspay. "Uncertainty Modeling and Robust Control in Urban Traffic". Preprints of the 18th IFAC World Congress Milano (Italy), pp. 14910–14915, 2011.

[13] V. Hirankitti, J. Krohkaew and C. Hogger. "A Multi-Agent Approach for Intelligent Traffic-Light Control", *Proc. of the World Congress on Engineering - WCE*, Vol I, July, 2007.

[14] Y. ZHAO-SHENG, C. XIN, T. YANG-SHAN and JIAN P. "Intelligent Cooperation Control of Urban Traffic Networks". *Proc. the 4th International Conference on Machine Learning and Cybernetics*, 18-21, August 2005.

[15] F. Martin and S. Radiocomun, "Vehicular Traffic Surveillance and Road Lane Detection Using Radar Interferometry", *IEEE Trans. Vehicular Technology*, vol. 61, pp. 959–970, March 2012.

[16] S. Eben Li , H. Peng , K. Li and J. Wang, "Minimum Fuel Control Strategy in Automated Car-Following Scenarios", *IEEE Trans. Vehicular Technology*, vol. 61, pp. 998–1007, March 2012.

[17] M. Mazo and P. Tabuada, "Decentralized Event-Triggered Control Over Wireless Sensor/Actuator Networks", *IEEE Trans. Automatic Control*, vol. 56, pp. 2456–2461, Oct. 2011.

[18] A. Gning, L. Mihaylova and R. K. Boel, "Interval Macroscopic Models for Traffic Networks", *IEEE Trans. Intelligent Transportation Systems*, vol. 12 , pp. 523–536, June 2011.

[19] J. Xu, Z. Hou, H. Zhong. "Freeway Traffic Control Using Iterative Learning Control-Based Ramp Metering and Speed Signaling", *IEEE Trans. Vehicular Technology*, vol. 56, pp. 466–477, March 2007.

[20] Y. Liu, G. Chang and J. Yu. "An Integrated Control Model for Freeway Corridor Under Non-recurrent Congestion", *IEEE Trans. Vehicular Technology*, Vol. 60, pp. 1404–1418, May 2011.

[21] S. Eben Li , H. Peng , K. Li and J. Wang, "Minimum Fuel Control Strategy in Automated Car-Following Scenarios", *IEEE Trans. Vehicular Technology*, vol. 61, pp. 998–1007, March 2012.

[22] M. Mazo and P. Tabuada, "Decentralized Event-Triggered Control Over Wireless Sensor/Actuator Networks", *IEEE Trans. Automatic Control*, vol. 56, pp. 2456–2461, Oct. 2011.

[23] A. Gning, L. Mihaylova and R. K. Boel, "Interval Macroscopic Models for Traffic Networks", *IEEE Trans. Intelligent Transportation Systems*, vol. 12 , pp. 523–536, June 2011.

[24] K. Aboudolas, M. Papageorgiou, and E. Kosmatopoulos, "Store-and-forward based methods for the signal control problem in large-scale congested urban road networks". Transportation Research Part C-Emerging Technologies, vol. 17, pp. 163-174, 2009.

[25] M. Pitu , W. Fei-Yue. "RHODES to Intelligent Transportation Systems", *IEEE Intelligent Systems Journal*, vol. 20, No. 1, January 2005.

[26] A. Montasir,C. Hassan, C. Nadeem and J. Youn. "Distributed Architecture and Algorithm For Robust Real-Time Progression Evaluation and Improvement", *Technical Report 0-4729-2, Project Number 0-4729*, Texas University, 2006.