Traffic Lights Control using Wireless Ad-Hoc Sensor Networks

AbdulMomen Kadhim Khlaif[1], Muayad Sadik Croock, Ph.D. [2]

Shaimaa Hameed Shaker, Ph.D. [3]

[1,2,3] Computer Engineering Department, University of Technology

e-mail: a.bluemix@gmail.com

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***Abstract* –** Wireless sensor networks undergo tremendous applications to be utilized for. In this paper, we propose a wireless ad hoc sensor network architecture that does not depend on a centralized unit to urban city's vehicular control, by applying different sensors distribution for main and side streets. On this architecture, we define and evaluate through simulation the effectiveness of our work against the traditional fixed-time traffic light model. Traffic lights coordination is addressed in master and local controllers by executing green-wave algorithm at our architecture. Simulation results show that this architecture achieves great reduction in total waiting time on the city been projected

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Keywords: – vehicular traffic control, wireless ad hoc sensor networks, green-waved traffic.

1. Introduction

Traffic lights (also called traffic signals or traffic control signals) play a vital role in controlling the conflicting flows of vehicles at the intersection. Their operation controls the way urban city *moves*, and hence taking care of and enhancing vehicular flow regulation which is a critical and an important issue.

On the other hand, wireless sensor networks have been deployed by many applications–ranging from structural health monitoring, pipeline monitoring, precision agriculture, active volcano, underground mining, healthcare, and surly, traffic control [1], in addition to being studied extensively in the recent decades, both in academia and in industry.

The integration between wireless sensor networks for collecting traffic information and between traffic signals to act upon and make decisions about those data can have practical benefits in terms of emissions, fuel consumptions, waiting time, and overall's city economy.

The following definitions are intended to make clear exposition in this paper as possible as to the reader [2] – [4].

- *Movement:* the flow of vehicles or pedestrians executing a particular movement.
- *Cycle*: a complete sequence of signal indications.
- *Cycle length*: the time required for a complete sequence of signal indications.
- *Phase*: the part of the cycle given to an individual movement, or combination of no conflicting movements during one or more intervals. An interval is a portion of the cycle during which the signal indications do not change. The predetermined order of phases is the sequence of operation. This order is fixed in a pre-timed (fixed) controller, and under certain circumstances, may be variable with an *actuated controller.*
- *Actuated controller:* phase time based on detection data.
- *Master controller*: a field device that controls a small number of intersections and that in some cases brokers communications with a signal system.
- *Local controller:* the controllers in a signal system that receive coordination information either from master controller or from signal systems, or both.
- *Green-waved traffic:*a green wave happens when a series of traffic controllers (usually three or more) are programmed or coordinated to allow continuous vehicular flow over several intersections in one main (mostly straight) direction.

In this paper, we extend our previous work [5], by assigning two-level groups per lane in main (major) streets, whereas, assigning only a single group of sensors in side streets using a wireless ad hoc sensor network architecture to the vehicular traffic control in urban areas. Section 2 reviews the related works that used wireless sensor networks in vehicular traffic control. Section 3 describes the proposed architecture of traffic lights aided by wireless sensor networks. The results obtained from our system are presented in section 4. And finally, section 5 concludes the paper.

2. Related Works

Regarding the field of intelligent transportation systems (ITS), there are vast numbers of researches and work being developed under the umbrella of *traffic lights control using wireless sensor networks*. In [6], an algorithm for traffic signals using sensors was designed and implemented. This algorithm was implemented using MATLAB, whereas hardware simulation of the sensor nodes was by LabVIEW. However, they did not show the vehicles behavior under the mentioned work (e.g., average waiting and travel time of vehicles), nor showed the sensors communications-related data (e.g., number of transmitted frames, frames collisions, MAC protocol used, etc.).

In [7], the authors used a wireless sensor network of two models (one and two sensor nodes) and compared the performance between those models according to the average trip waiting time. The authors did not provide telecommunications aspects of the sensor nodes. In [8], the authors addressed the intersection throughput alongside with average vehicular waiting time by proposing an adaptive traffic light control algorithm for isolated intersection running in multiple steps. Then, they compared the proposed algorithm against fixed-time and traffic-actuated counterparts. Additionally, the authors did not address the communications aspects nor specify 3.
the type of sensors used to detect vehicles 4.
IDs and vehicles types. 5.

In [9], an alerting system for red light crossing scenarios (in addition to the traffic light control algorithm) was presented for different models, and was implemented to alert the drivers in other sides to reduce the chance of accidents due to red light crossing violations using sensors according to lane occupancies. It hadn't used specific type of sensors, instead, mentioned types could be used (ultrasonic vehicle detector or cameras) to calculate the queue (lane) length. In [10], a sensor network architecture that does not depend on a centralized coordinator and separate it logically into four hierarchical levels was proposed. These levels are final computations/decision (layer 4), intermediate computations (layer 3), departures detection (layer 2), and arrivals detection (layer 1). It used conflict matrix to specify the desired behavior of each intersection. However, the cost of adding a leader election (when a sensor's battery drops below a threshold) and self-organizing protocols were not explained enough, and no information about their batteries consumption rate or sensors telecommunications properties provided. The authors of [11] extended their previous work of [10] with a special focus on communications and studying its reaction to losses and delays induced by the use of wireless communication.

Although [10] provided a state-of-the-art work and proved the efficiency and ease of implementation of their algorithm of [12] their work, and all previous [6] – [10], have not showed energy consumption for sensor nodes batteries under their proposed sensor network architecture and/or adaptive traffic signals algorithms.

3. Traffic Controllers Architecture

The proposed architecture is considered using two-level sensor groups per lane in main streets, and using only a single sensor per lane for side streets. The reason for having this distribution of sensors is that the main streets should have priority over side ones, since main streets represent the arterial flow of vehicles in the city, expecting large vehicular capacity to flow. For this reason, taking care of and measuring the flow of vehicles in main streets will be explained throughout the text.

Figure 1 and Figure 2 illustrate the proposed hierarchical wireless *ad hoc* sensor network architecture for both master and local controllers. By ad hoc we mean that the system have infrastructure-free network, no central or base station equipment maintaining the behavior of traffic controllers and sensors (i.e., decentralized management). Each traffic controller (alongside with attached sensors) at each intersection maintains its state without depending on external entity to organize its behavior, rather they operate autonomously either as an isolated controller or coordinated traffic controllers (when green wave mode is activated).

As can be seen, master controller has six groups of sensors (N: north, S: south, E: east, and W: west): two on the north side (N arrival and N departure sensors), two on the south side (S arrival and S departure sensors), on the east side (E arrival sensors), and on the west side (W arrival sensors). The arrival and departure sensors for each side act as bounds for the *queue* of vehicles. So, arrival (beginning) and departure (ending) sensors can be used to calculate the arrival rate (λ) and departure rate (μ), respectively, and hence, the *utilization rate* or ρ, which is:

$$\rho = \frac{arrival}{departute} = \frac{\lambda}{\mu}$$

Higher values of ρ mean that the number of arriving vehicles is larger than the vehicles departing, and hence, the queue gets stacked progressively over time. Whereas, lower values of ρ meaning that the number of departing vehicles is larger than the arriving ones, and so, the queue size gets smaller, giving priority for main street vehicles for movement. Local controller (Fig. 2) on the other hand, has only four groups of sensors: one arrival sensor node per lane for each side street around the intersection (N arrival, S arrival, E arrival, and W arrival sensors).

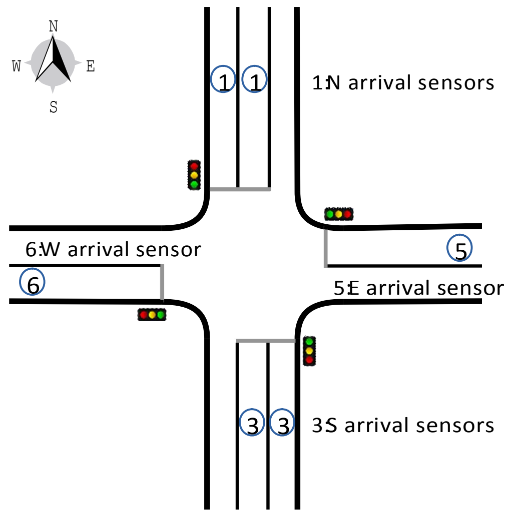

Figure 1*: Master controller sensor placements.*

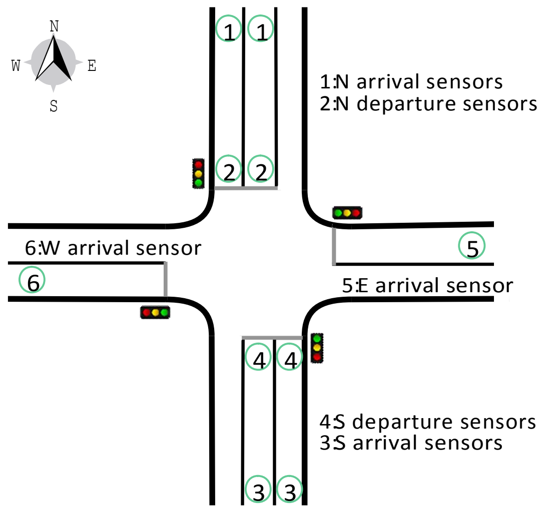

Figure 2: Local controller sensor placements.

If we assume that both east and west sides of the intersection are side streets and that main streets (north and south of the intersection) have scheduling priority over them, having only a single sensor per lane for indicating the presence/detection of vehicles would be sufficient, not effecting the overall operation and behavior of the traffic controllers and the traffic scheduling, besides, degrading sensor numbers would have system-wide advantages in terms of sensors cost, installation and maintenance.

Degree of saturation: if the number of arriving vehicles is greater than the number of departing ones, that is, $\lambda > \mu$, we have an *oversaturated* queue; and when $\lambda < \mu$ it is an *undersaturated* queue; otherwise is *saturated* when $\lambda = \mu$ (see [13] for more information).
For main streets, we want to have the vehicles flow as smooth as possible, that is we want most the time (also depending on the jurisdictional laws in the city) to have an undersaturated queue, otherwise the reason of using two-level group of sensors per lane would be pointless.
Utilization threshold θ is a limit by which we can control and enforce in master controllers the flow of vehicles to allow their movements when this threshold is reached. For example, if we have $\lambda = 12$ and $\mu = 6$, then $\rho = \frac{12}{6} = 2$ (oversaturated), then we can control ρ by not reaching certain limit, θ, say, $\theta = 0.9$.

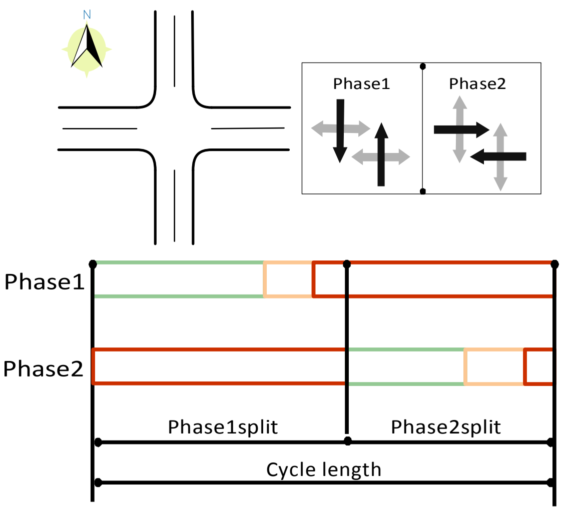

Figure 3: *Actuated-phasing operation flowchart for both master and local controllers (empty edges represent No output).*

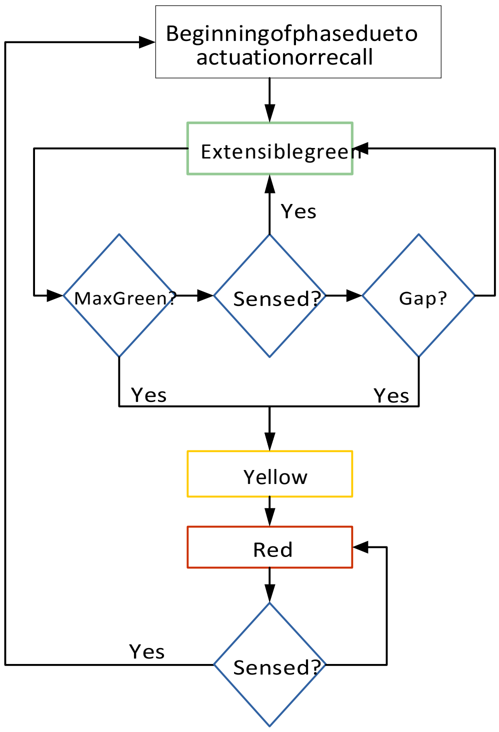

Figure 4: *Fixed-time phasing operation flowchart to local controllers only when switched to after a specified amount of time specified by the master controller message.*

Under normal conditions (θ is not reached), master controller runs in an actuated manner (see Fig. 3), that is, it equally distribute phases according to vehicles presence among main and side streets without any priority concern. The same behavior is applied for local controllers, in an actuated manner. This is the normal operation for both, but when certain θ is reached, only master controllers are kept in this operation (actuated), whereas local controllers are switched to fixed time operation (see Fig. 4) after certain time declared by the master controller message. So, when θ is reached, master controller *broadcasts* a message to every other local controller that is on the same main street as the serving master controller (coordination operation, see Fig. 6). Each message contains (1) the id (name) of the local controller and (2) when (time) this local controller will be switched to *fixed-time*

(Fig. 4) mode from the current clock tick using a general clock among all traffic controllers. Fig. 5 is a flowchart illustrating the master-local controllers' behavior under the aforementioned text. As can be seen, each local controller has a *gwBuffer* (green-wave buffer), that is used to store incoming messages from master controller(s). When it receives a message (the gwBuffer is not empty, its length is greater than zero), it waits certain time specified by the master controller message before switching to fixed-time mode.

4. Experiments and Results

The following section gives the results of having different sensor node placements distributed across the main and side streets, and their effect on the overall system-wide total waiting time.

The city (part of Al-Kadhimiya in Baghdad) that is used under our simulation work is shown in Fig. 6. This represents the framework by which all of our results were obtained from. We used a co-simulation between SUMO [14] as a vehicular simulation, and OMNeT++ [15] as a network simulator. We've used the IEEE 802.15.4 as the sensor node device and extend its network stack by adding a network layer upon its physical and data link layers in order for local controllers to receive messages from master controller. CSMA were used as the MAC protocol, and flooding as the routing algorithm to deliver messages.
The incumbent stochastic behavior of vehicular traffic necessitates the need to see the effect of different sensor placements on the overall total waiting time, both when the system operates under green-waved algorithm or only in an actuated one.

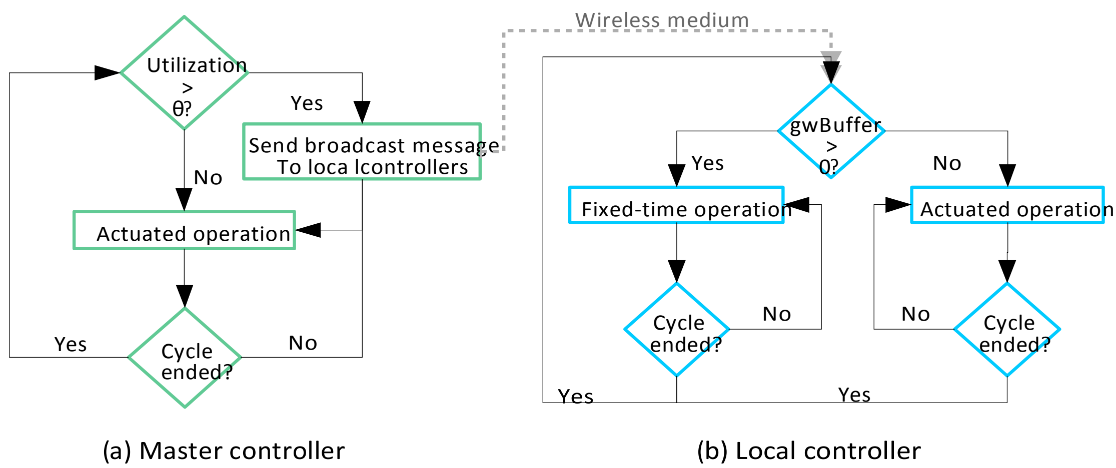

Figure 5: *A general overview of master-local controllers' coordination flowchart.*

4.1. The Effect of Sensor Placements on Total Waiting Time

The locations of sensors (distance from the edge of the lane) and the values of θs, are extremely effecting the overall system behavior scheduling, and hence, the total vehicular delay. For this reason, in this work, we created a multi-objective scenario, retaining various sensor placements and different values of θs. Our measure of effectiveness (MOE) that is

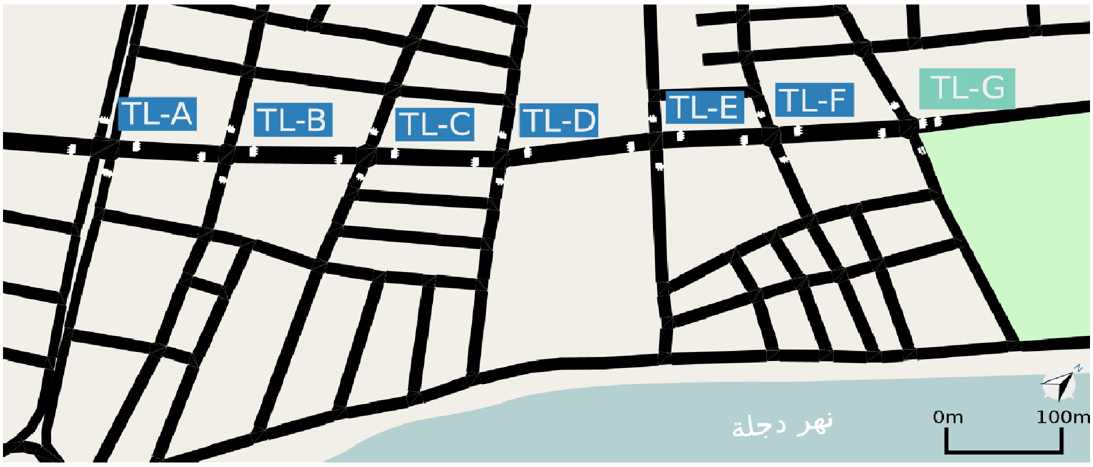

Figure 6: *Illustrating the locations of master and local controllers. Traffic lights named 'TL-G', the green one, represents the master controller, whereas all others, 'TL-A' to 'TL-F', the blue ones, are local controllers of 'TL-G'.*

used to evaluate both our network architecture and vehicular scheduling is the total waiting time, as will be shown in the results.

All scenarios have the same range of θs as well as the same sensor placements (and surely, the same coverage map area), but scenarios differ in vehicular routes (the path by which each vehicle will traverse streets during its trip time) and in the number of vehicles. This enables us to see the effect of random vehicle routes and theirs numbers under different values of sensor placements and θs.

Each scenario will have six experiments, one for each different sensor placements, see Table 1. We've selected two scenarios; each one has different routes and different number of vehicles.

Table 1: *Sensor groups placements*

	Master Controller						**Local controller**			
Sensors group	N arrival (m)	N departure (m)	S arrival (m)	S departure (m)	E arrival (m)	W arrival (m)	N arrival (m)	S arrival (m)	E arrival (m)	W arrival (m)
Exp.#1	75	5	75	5	25	25	50	50	50	50
Exp.#2	75	5	75	5	25	25	25	25	25	25
Exp.#3	75	5	75	5	25	25	5	5	5	5
Exp.#4	25	5	25	5	25	25	25	25	25	25
Exp.#5	50	5	50	5	25	25	25	25	25	25
Exp.#6	50	5	50	5	10	10	25	25	50	50

Scenario 1 results: this scenario has 1000 vehicles routing through the mentioned map, with different route for each one, in order to create the stochastic behavior in vehicular movement of real life. Fig. 7 and Fig. 8 are plots for different experiments and various values of θs under this scenario. Solid-shaped lines represent the system behavior under the green-wave algorithm. However, and as a comparison measure, the dashed (dotted) lines represent the system *without* green-waved activated, that is, local controllers don't switch to fixed-time mode (they operate in the same manner as their masters). Finally, the thick bluish line at the top is for fixed-time mode (conventional traffic lights). The y-axis represents the total waiting time for all vehicles. We can infer from Fig. 7 that lower θs have (system-wide) higher total waiting time, whereas higher θs induces lower delays. In this case, most of the vehicular routes were on the main streets, since higher levels of θs means more vehicles arriving than are leaving, hence, the queue gets cumulated progressively, beginning to eliminate main streets' vehicles importance, and so, delay ensues.

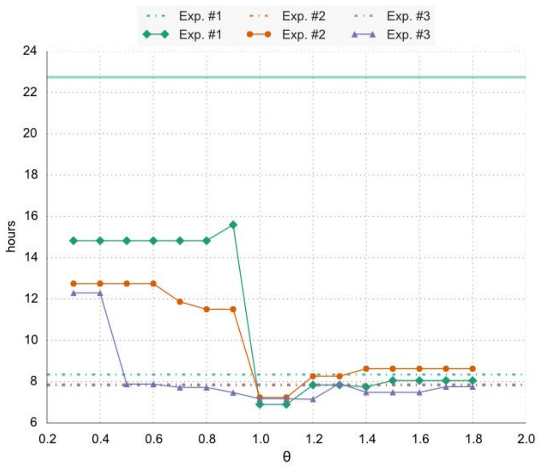

Figure 7: *Scenario 1 first three experiments. Green-waved activation is represented by the solid lines with different shapes for each; whereas the dashed lines represent the system behavior without the activation of green-waved traffic (the system operates in actuated mode only). The bluish thick line at the top is result of having all in fixed-time mode (SUMO default configuration of traffic lights).*

Scenario 2 results*:* this scenario contains 2000 vehicles travelling throughout the city, as plotted in Fig. 9 and Fig. 10. As can be seen in Fig. 9, limiting θs to lower values and giving priority to main streets raised the overall total waiting time and make side streets experience delays.

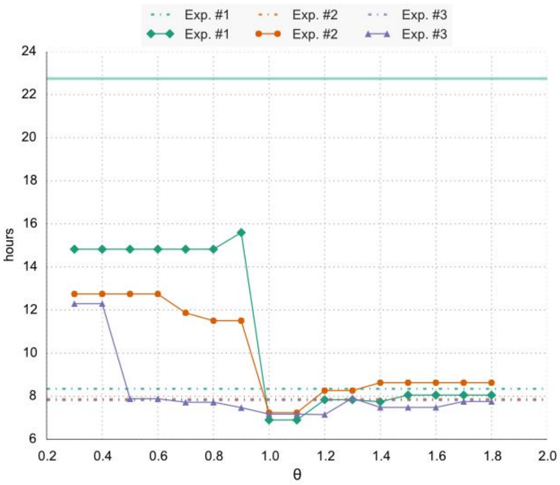

Figure 8: *Scenario 1 next three experiments*

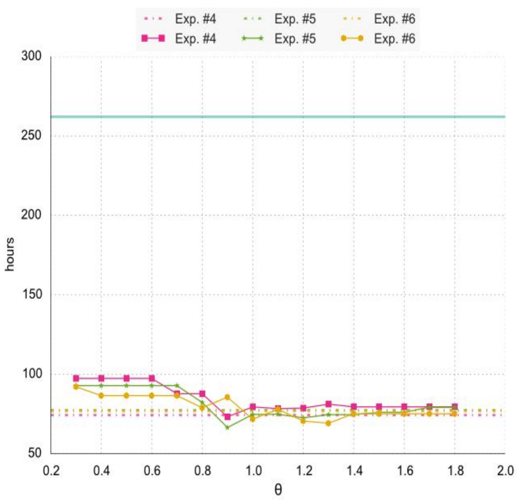

Figure 9: *Scenario 2 first three experiments*

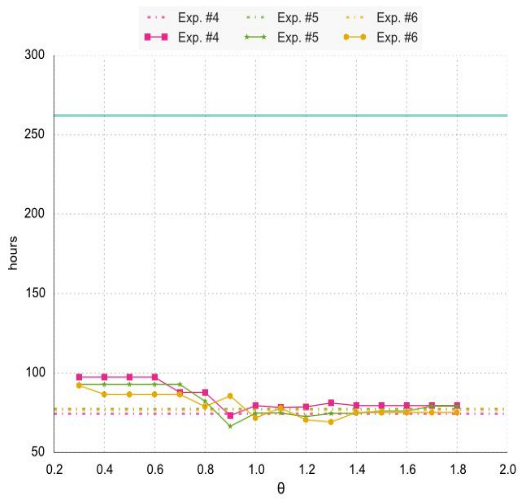

Figure 10: *Scenario 2 next three experiments*

4.2 Sensors' Data

The total number of sensors in this work is 75, each local traffic light has the groups associated with it, and the master controller too, been illustrated in section 3. However, for master controller, here we used only five groups of sensors, eliminating the use of south departure sensors, since this master controller controls vehicles moving towards the south, and placing this group for collecting vehicles moving toward the north will be of no benefit. Table 2 lists the sensors list that belongs to each traffic light.

Table 2: *Traffic lights' sensors*

TL name	Sensors sets (IDs)
TL-A	0-11
TL-B	12-21
TL-C	22-31
TL-D	32-41
TL-E	42-51
TL-F	52-61
TL-G	62-71

Number of Sensed Vehicles: Fig. 11 and Fig.12 show heatmaps (generated using matplotlib [16]) for scenarios 1 and scenario 2 sensors recording the number of times vehicles passed above them. In order to reach a specific sensor data value, sum the x-axis and the y-axis, e.g., sensor with ID of 11 will be reached by adding 1 from x-axis and 10 from the y-axis.

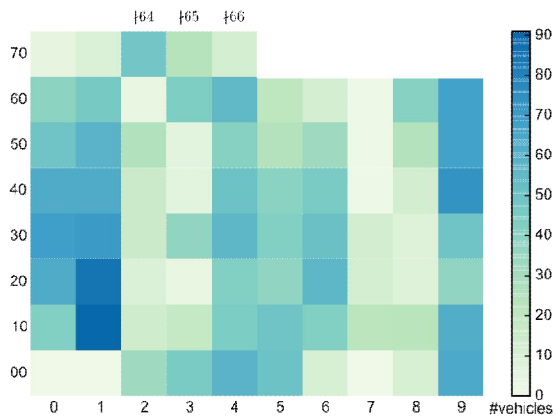

Figure 11: *Scenario 1 sensors data for detection of vehicles. Brighter areas represent nodes with low detection numbers.*

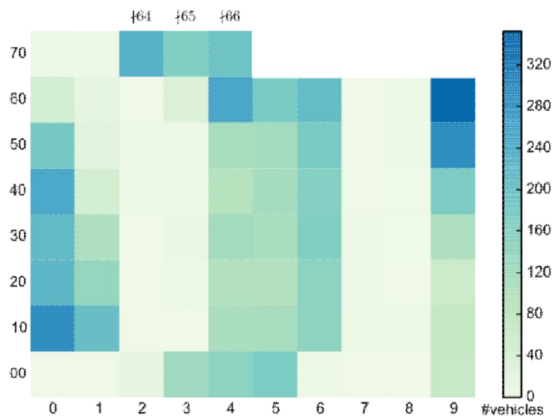

Figure 12: *Scenario 2 sensors data for detection of vehicles.*

Mean Power Consumption: Each sensor has a battery capacity of 6600 mAh with 3.3 V. Fig. 13 and Fig. 14 show heatmaps for scenarios 1 and scenario 2 sensors recording the mean power consumption of their batteries. As you can see, sensors that detect more number of vehicles will consume more power.

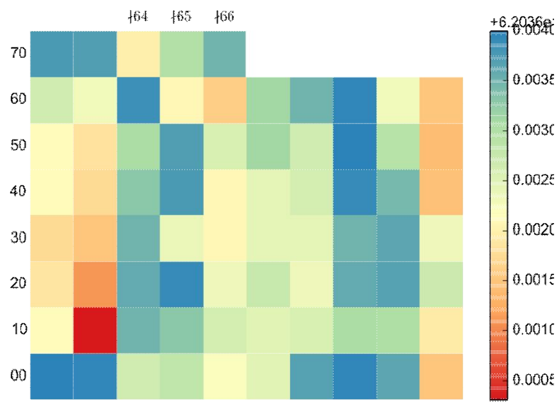

Figure 13: *Scenario 1 sensors data about mean power consumption. Darker red areas represent nodes with more energy consumed.*

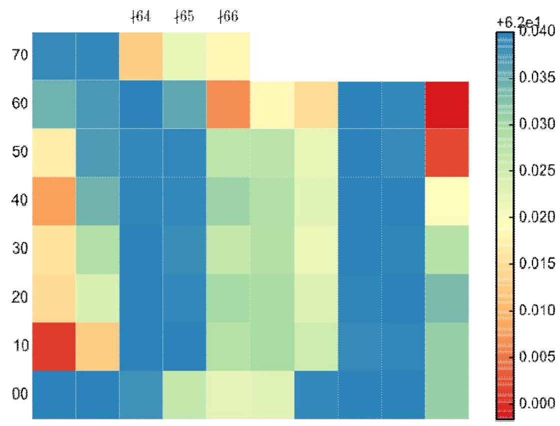

Figure 14: *Scenario 2 sensors data about mean power consumption.*

5. Conclusion

In this paper, we showed that the proposed architecture is more efficient in terms of reducing total waiting time than with fixed-time approach (conventional solution). We've executed traffic scheduling algorithms in our proposed architecture, the first, actuated based on vehicles demands at the intersection from sensors readings, and the second, executing green-wave algorithm for demonstrating the use of traffic controllers' cooperation and also giving importance to main street movements.

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