Smart Traffic Light Junction Management Using Wireless Sensor Networks

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Abstract: In recent years, Wireless Sensor Networks (WSN) have been increasingly involved in Intelligent Transportation System (ITS) optimization, especially in dynamic management of signalized intersections. This paper discusses the state of art and shows an IEEE 802.15.4 network architecture to monitor vehicular traffic flows near to a traffic light. The architecture is characterized by an innovative algorithm in order to determine green times and phase sequence of traffic lights, based on measured values of traffic flows. The main aim of this work is to reduce the average waiting time. To confirm the validity of the proposed approach, some case studies have been considered and several simulations have been performed.

Key–Words: Wireless Sensor Networks, Traffic Lights, Intelligent Transportation Systems, Real-Time Systems

1 Introduction

The main aim of Intelligent Transportation Systems (ITS) is to use Information and Communication Technologies (ICT) in order to design transportation products, services and systems based on advanced technologies. Many ICT/ITS researchers studied, analysed and developed several network architectures [1], communication protocols and algorithms [2] suitable for ITS applications. In recent years, the researchers focused on the possibility to incorporate Wireless Sensor Network (WSN) in ITS applications [3] in order to replace wired networks or integrate them in various scenarios.

In literature, several works discuss advantages provided by wireless technologies, like reduced installation costs, flexibility and the possibility to easily realize temporary deployments (e.g., for monitoring purposes), etc.. Also, they offer greater installation flexibility and lower maintenance costs than conventional inductive loop systems, video and radar detectors [4] [5] [6]. Moreover, sensor nodes are not invasive, provide mechanisms to minimize power consumption [7] [8] and can be placed everywhere. These features allow to collect information about vehicles travelling on roads. In fact, the increasing of road congestions in urban areas, suggests the use of a solution based on WSNs, for traffic flows monitoring.

In this paper, a novel network architecture for dynamic management of signalized intersections is proposed. This paper shows performances of the implemented algorithm compared with a classical solution, i.e. static. The paper is organized as follows. Section 2 shows main related works in order to determine the current state of art. Section 3 introduces the proposed system model while the novel algorithm for the dynamic management of traffic lights is presented in Section 4. Section 5 shows the performance obtained by the proposed approach. Finally, Section 6 summarizes the paper reporting conclusions.

2 Previous Works

WSNs have been exhaustively studied and used in several fields, like health [9], agriculture [10] and home automation [11] to mention some. Doubtless, one of the main application fields of this technology is road monitoring. In literature, signalized intersections management presents different approaches. All of them propose to reduce waiting times and queue lengths.

2.1 SCATS and SCOOT traffic control systems

With the availability of inexpensive microprocessors, several real-time adaptive traffic control systems were developed in the late 70's and early 80's to address this problem. These systems can respond to changes on traffic demand by performing local optimizations. The most notable of these are SCATS [12] [13] [14]

[15] and SCOOT systems [13] [16] which aim is to optimize the signals' cycle time, phase split, and offset. The cycle time is the duration for completing all phases of a signal; the phase split is the division of the cycle time into periods of green signal for competing approaches; the offset is the time relationship between the start of each phase among adjacent intersections.

A SCATS system organizes groups of intersections into subsystems. Each subsystem contains only one critical intersection whose timing parameters are adjusted directly by a regional computer based on the average prevailing traffic condition for the area. All other intersections in the subsystem are always coordinated with the critical intersection, sharing a common cycle time and coordinated phase split and offset. At lower level, each intersection can independently reduce or leave out a particular phase based on local traffic demand; however, time saved must be added to the subsequent phase to maintain a common cycle time among all intersections. The basic traffic data used by SCATS is the "saturation level", defined as the ratio between real used green time and total available green time. The cycle time for a critical intersection is adjusted in order to maintain a high saturation level for the lane with the greatest saturation level. The phase split for a critical intersection is adjusted in order to maintain equal saturation levels on competing approaches. Offsets among intersections of a subsystem are selected to minimize stops in the direction of dominant traffic flow. SCATS does not explicitly optimize any specific performance measure, such as average delay or stops.

SCOOT uses real-time traffic data to obtain traffic flow models, called "cyclic flow profiles". They are then used to estimate how many vehicles will arrive at a downstream signal when the signal is red. This estimate provides predictions of queue size for different hypothetical changes in the signal timing parameters. SCOOTs objective is to minimize the sum of the average queues in an area. A few seconds before every phase change, SCOOT uses the flow model to determine whether it is better to delay or advance the time of the phase change by a few seconds, or leave it unaltered. Once a cycle, a similar question is asked to determine whether the offset should be advanced or delayed by few seconds. Once every few minutes, the cycle time is similarly incremented or decremented by few seconds. Thus, SCOOT changes timing parameters in order to optimize an explicit performance objective.

2.2 WSNs for traffic control applications

In literature, the management of signalized intersections through the use of WSNs has been presented in several works. The capacity analysis of signalized intersections is presented in [17]. More in detail, the authors propose an approach for calculating the traffic capacity of straight-through lanes in mixed traffic circumstance. The approach proposed in [18] shows a technique for vehicles detection using magneto-resistive sensors. An algorithm identifies vehicles through the analysis of signals received from sensors. Less attention is paid to roadsides or junctions management; in fact, simulations are performed on a simple phase plan (only 2 phases). Moreover, in [18] it is not analysed the possibility to dynamically manage the phase order based on the real time traffic detected.

A fuzzy logic algorithm, used to determine the green time extension of traffic lights, is shown in [19]. In other words, the minimum green time can be extended based on the current traffic volume. Moreover, the phase sequence are determined by queue length only. Then, the algorithm does not consider the limit cases. A large difference in length among different queues, leads the algorithm to neglect waiting vehicles in shorter queues. Another fuzzy logic controller, for a flexible Quality of Service (QoS) management, is presented in [20]. The authors show an innovative WSN architecture and a novel algorithm that dynamically enables/disables some video-cameras according to the real need to monitor a given area. The algorithm is based on measured traffic volume values through through the WSN.

In [21], the authors want to optimize the evacuation routes in traffic lights junctions. An algorithm that considers the delaying time at junctions and the capacity of intersections is presented. This algorithm is aimed to find the optimal evacuation routes and the reasonable starting time of evacuation in an urban traffic network controlled by traffic lights. A novel approach to road-traffic control for interconnected junctions is presented in [22]. The proposed approach involves the use of a local fuzzy logic controller installed at each junction that derive the green time for each phase in a traffic-light cycle through a dynamic-programming technique. The performance of the proposed approach has been evaluated under several traffic conditions and the results are really promising.

In [23] a real time model that, able to simulate several traffic situations in an urban environment, is presented. Moreover, the authors propose a traffic light regulation system. The simulations results show that it is possible to simulate a great number of vehicles in a large control zone. In [24], the authors propose an algorithm that considers several values about traffic flow for green times calculation and phase sequence determination for each traffic light cycle. However, the solution proposed in [24] com-

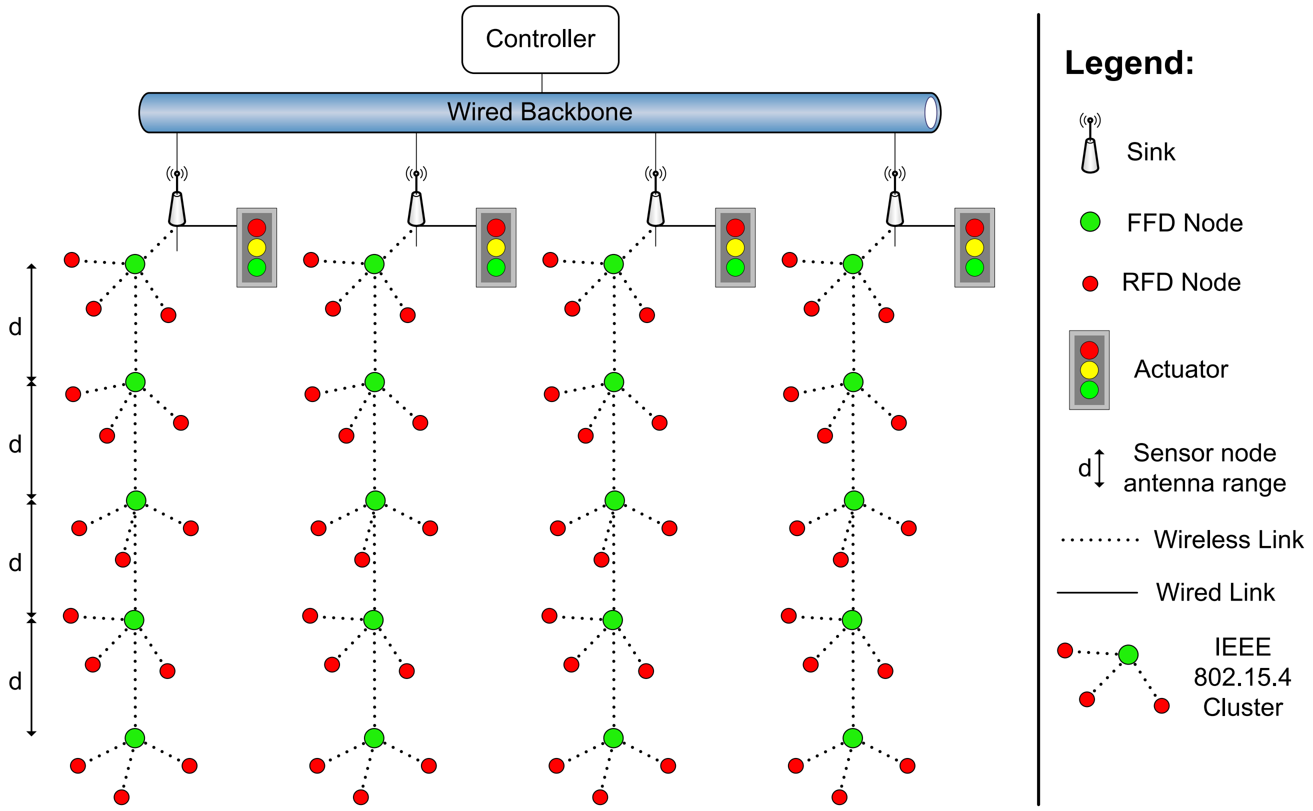


Figure 1: Network architecture

pletely replaces the concept of traffic light phase with a system of predetermined traffic light configurations for a system of compatible traffic flows. It is an alternative to the traditional road intersections management system; its real implementation needs long testing periods to evaluate its effective functioning.

The validity of traffic flows monitoring approaches using wireless sensor networks has been demonstrated in [25]. Anyway the approach shown is mainly focused on phase sequence estimation without green times re-calculation. Finally, the use of invasive methods [26] should be avoided. In fact, it requires hardware installation on each vehicle. Rather, it is conceivable to apply this system [26] to emergency vehicles, in order to provide higher priority than regular vehicles. Considering that sensor nodes are battery-powered, the authors of [27] and [28] propose a self-powered WSN in order to manage traffic lights. The sensor nodes of the network are powered through a piezoelectric that recharge the batteries due to vibrations generated by the vehicles crossing a traffic light junction.

This paper advances the state of art because introduces a network architecture to make an appropriate vehicular traffic flow monitoring. Moreover, a dynamic algorithm for the management of traffic lights, considering more complex junctions than those already studied in the literature, will be shown.

3 Intelligent System Model Proposed

The proposed architecture is a hierarchical network characterized by two layers: one layer is represented by a wireless sensor network based on the IEEE 802.15.4 protocol [29] while the other one consists of a wired backbone. The IEEE 802.15.4 protocol, in beacon-enabled mode, makes possible an a priori scheduled communication using Guaranteed Time Slot (GTS). The use of GTS allows to have a communication as deterministic as possible. Moreover, several works in literature dealing with this issue were assessed. In [30] the authors analysed the performances of the GTS allocation mechanism in terms of delay and throughput. The limit values that GTS must ensure are evaluated analytically. The obtained results show that for WSN applications, typically with low arrival rates and low burst size, it is convenient to use low superframe orders to provide low delay bounds. Moreover, as analysed in [31], a priority-based CSMA/CA mechanism is necessary in order to support a deadline-aware scheduling in monitoring applications. The GTS mechanism is also analysed in

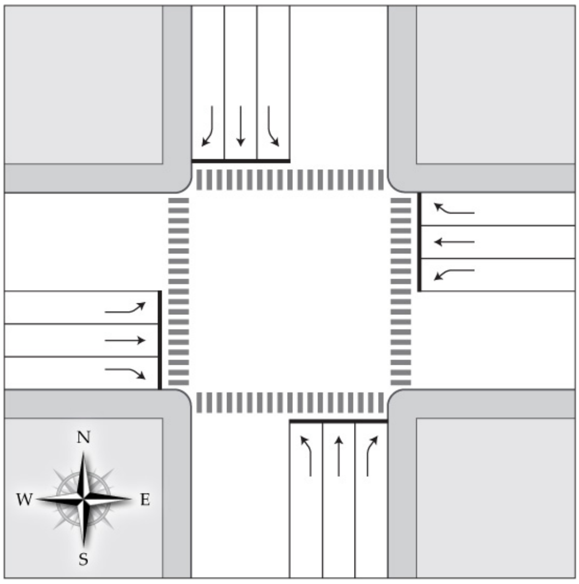


Figure 2: Examined intersection

[32] on a star WSN. To better understand, it is possible to have no more than 7 devices requiring GTS at the same time. Otherwise, real-time constraints will not be respected. The protocol is not very suitable for a sensor network with hard real-time constraints [33], but it is well suited to the ITS scenario here considered, because clusters do not have many nodes and time constraints of the application are soft.

The WSN architecture here proposed is based on the GTS mechanism. The designed two-tiered architecture is valid for a generic intersection. In Figure 1 we refer to a complete scenario while Figure 2 shows an isolated intersection with four approaches (North, South, East and West) with three lanes for each approach. Therefore, each direction has an exclusive lane. The North-South approaches form the main-street while the East-West approaches form the cross-street. For each intersection approach, several RFD (Reduced Function Device) sensor nodes, organized in clusters and coordinated by special FFD (Full Function Device) nodes, are used. In each approach, the whole network is coordinated by a sink node that collects and processes all data concerning vehicles. All sink nodes are connected through a wired backbone to a central controller.

3.1 Network Sensor Nodes

Each cluster consists of a FFD node and several RFD nodes. The FFD node is an 802.15.4 cluster coordinator and it also takes care of routing among clusters. The communication among nodes of the same subnetwork is realized using GTS. Periodically, the FFD node sends a data request to its RFD nodes; these nodes reply to the request by sending collected data. Each RFD node is able to detect vehicles in transit. Thanks to the use of beacons, nodes may enter in sleep mode and save energy during inactivity periods, while waiting for next beacon.

3.2 Network Sink

Each approach is provided with a sink node, which performs several tasks described below. The Scheduling module manages networks real-time traffic using the IEEE 802.15.4 protocol [29]. The latter, thanks to the GTS mechanism, allows bandwidth reservation and avoids collisions using a real-time algorithm (e.g. Earliest Deadline First [34]). The Error Handling module controls transmission errors. It works in cooperation with the Scheduling module, communicating the presence of errors, and it adapts the datas scheduling to ensure continuous flow of traffic. The Resources Monitoring module manages and shares the availability of resources, e.g. by periodically assessing the channels quality. The Actuator Interface module manages communication with the actuator, by sending commands for the timing of lighting and shutdown of the traffic lights optical units. At periodic intervals, the sink node receives data from sensors and sends them via the wired backbone to the controller.

3.3 Network Controller

The sink nodes send various data flow to the controller. The controller is characterized by several modules in order to realize the frequency management, the data collection, the data processing, the user interface and the traffic lights control. The Frequency Management module assigns a different radio channel to each network, in order to prevent co-channel interferences in radio communications. It operates during nodes initialization, by communicating with sink nodes which channel should be used for transmission. The Data Collection module receives and organizes data sent by sink nodes, classifying them by date, approach and vehicular flow. Data traffic is stored into a database, to allow future referencing for all measurements. The Processing module reads data organized by Data Collection module.

The algorithm processes these data in order to determine the phase sequence and the green time of each phase. Parameters like length of the queue for various lanes and the number of vehicles in transit are used by the algorithm. The Traffic Lights Control module uses the results produced by the algorithm in order to manage the sequence and the duration of traffic light phases, by sending commands to the sink. These data are then forwarded to the actuator. Finally, the

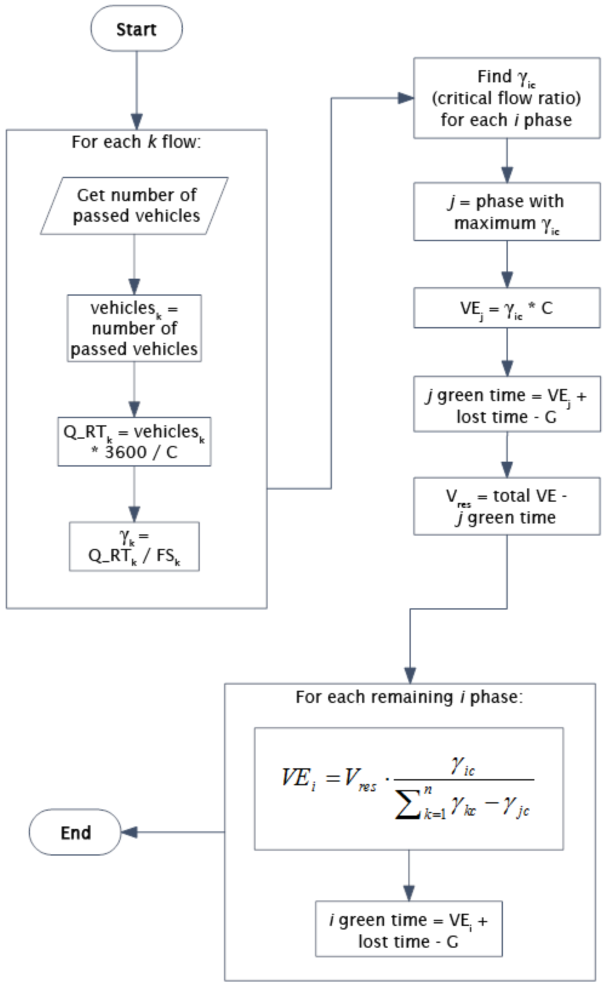


Figure 3: Green times calculation flowchart

User Interface module allows to view historical data by querying the database.

4 Dynamic Management Algorithm Description

The Dynamic traffic light management allows run-time and real-time regulation of phase sequence and green times duration, based on data gathered by a WSN deployed on the road. The dynamic management algorithm, here developed, is divided into two steps. In the first step the phase sequence is determined. In fact, the algorithm, based on the queue length for each flow (input variable), assigns a priority to each phase equal to the maximum queue length of that phase. Finally, it determines the phase sequence by sorting them in descending order priority. The second step realizes the green times calculation. The algorithm, for each flow, processes the number of vehicles passed during the previous traffic light cycle and uses this value to determine the current traffic volume (Q_RT). This value is used to recalculate the green time duration of the next cycle based on traffic detected. Figure 3 shows in detail green times calculation flowchart. The flow ratio γ for a generic flow i is defined as the ratio between the actual or expected incoming stream Q (or volume) and the saturation flow rate FS:

$$\gamma_i = \frac{Q_i}{FS_i} \tag{1}$$

Data coming from WSN is used to recalculate the incoming stream at every traffic light cycle. For each lane, the number of vehicles passed in each cycle is counted. This data is converted in vehicles/h and subsequently used to recalculate the flow ratio for each traffic flow. For each phase, the critical lane (the one with a higher flow ratio) is established. The phase with the highest flow ratio is found; to this j-phase we assign a saturation flow ratio equal to 1, giving rests to the remaining phases in proportion to their flow ratios [35]:

$$\frac{VE_j}{C} = \gamma_i \tag{2}$$

where VE_j is the effective green time for the j-phase and C is the traffic light cycle duration. Once VE_j is obtained, it is possible to calculate the j-phases V green time using the following formula:

$$V_j = VE_j + P - G \tag{3}$$

where P indicates lost time due to start-up and permission times and G indicates the yellow time. The seconds available for remaining phases are calculated as:

$$V_{res} = \sum_{i=1}^{n} VE_j - V_j \tag{4}$$

For remaining green time (V_{res}) allocation, the following formula can be used:

$$VE_i = V_{res} \frac{\gamma_{ic}}{\sum_{k=1}^{n} \gamma_{kc} - \gamma_{jc}} \tag{5}$$

Finally, we calculate the green time for each i-phase, using the formula (3). Obviously, as shown in [35], it is necessary to control that green times are enough to ensure pedestrian crossings.

4.1 Algorithm Testing Scenarios

In order to compare the proposed approach with the static management, a simulator in C language has been developed. This program allows the simulation of an isolated intersection with traffic lights, as shown

Table 1: Traffic Volume Levels Set in the Different Case Study

Case Study \ Approach	N-s	N-r	N-l	S-s	S-r	S-l	E-s	E-r	E-l	W-s	W-r	W-l
1.1	m	m	m	m	m	m	m	m	m	m	m	m
1.2	l	m	m	m	m	m	h	m	m	m	m	m
1.3	l	l	h	l	l	h	l	l	l	l	l	l
1.4	h	h	h	l	l	l	l	l	l	l	l	l
1.5	l	l	l	l	l	l	l	l	l	h	h	h
1.6	l	l	l	l	l	l	h	h	m	h	h	m
2.1	m	m	m	m	m	m	m	m	m	m	m	m
2.2	l	l	l	l	l	l	m	m	m	m	m	m
2.3	l	l	h	l	l	l	h	m	m	m	m	m
2.4	h	h	h	l	l	l	l	l	l	h	h	h
2.5	h	l	l	h	l	l	l	l	l	l	l	l
2.6	h	h	h	h	h	h	h	h	h	h	h	h

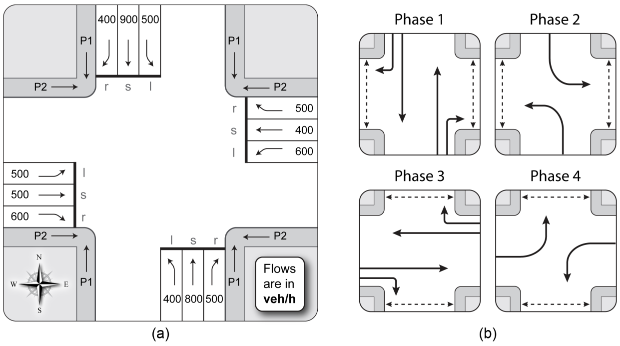


Figure 4: Junction layout (a) and traffic signal phases phasing plan (b) for scenario 1

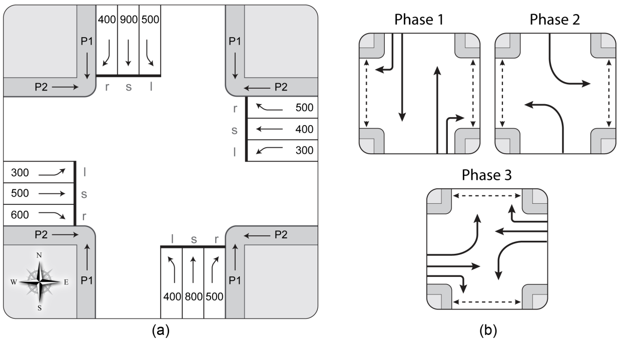


Figure 5: Junction layout (a) and traffic signal phases phasing plan (b) for scenario 2

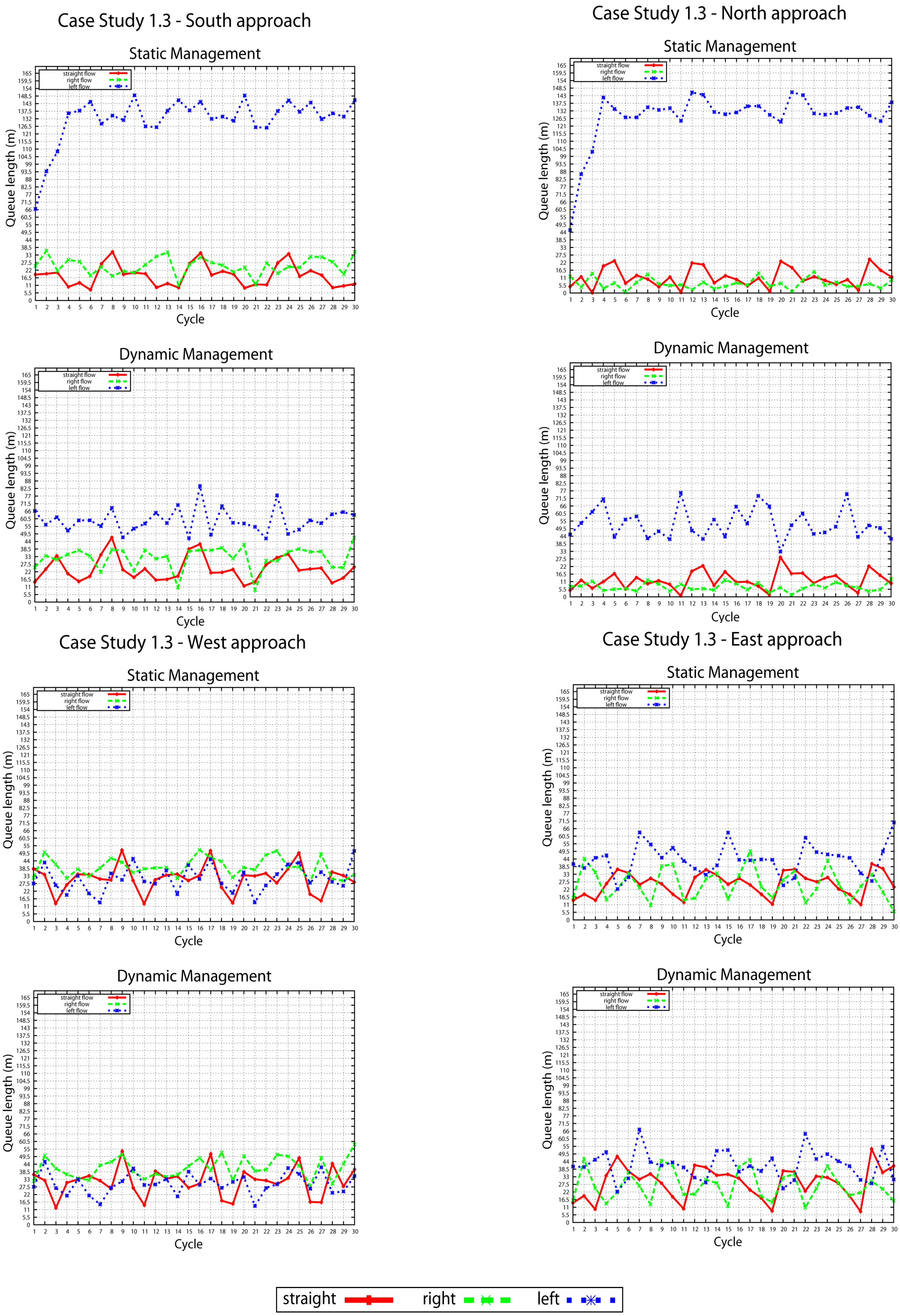
in Figure 2. The intersection specifications follow the instructions provided by the Highway Capacity Manual [36]. In particular:

- lane width of 3.5 m;
- 0% approach grade;
- absence of parking maneuvers;
- absence of bus stops;
- type of area: downtown;
- pedestrian volume: 110 p/h;
- minimum green time: 10 seconds;
- maximum green time: 30 seconds.

The simulations consider two scenarios that differ by: traffic volumes, adopted phase plan and traffic light cycle time (120 seconds for scenario 1 and 100 seconds for scenario 2). Scenario 1 has high traffic volumes for maneuvers to the left. So a four phases plan was adopted. This plan consists of two protected phases for these maneuvers, and two phases for remaining vehicular flows. Figure 4 shows each vehicular flow volume (a) and the phase plan (b) for scenario 1. In scenario 2 the cross-street traffic is reduced. In this way the maneuvers to the left in the main-street is protected. Figure 5 shows the hourly volume of each vehicular flow (a) and the phase plan (b) for the scenario 2. In order to evaluate algorithm performances for each scenario with different traffic conditions, six case studies were carried out, varying traffic level in each of them. For each case study two simulations were performed: one using static management while the other using the proposed dynamic management approach.

5 Findings

Each simulation provides average queue length trend for traffic light cycles. For example, in the case study 3 of scenario 1, high traffic has been set in the left turn



Case Study 1.3 - South approach

Case Study 1.3 - North approach

Case Study 1.3 - West approach

Case Study 1.3 - East approach

Figure 6: Graphs of case study 1.3

Table 2: Comparison of Q_c/Q_t between Static (S) and Dynamic (D) Management

Case Study	**Overall flow rate (Q_t)**	q_{al}		$Q_c(veh_p)$		Q_c/Q_t	
		S	**D**	**S**	**D**	**S**	**D**
1.1	6600	73.14	65.66	6424	6442	0.973	0.976
1.2	6600	69.82	58.83	6432	6458	0.975	0.979
1.3	6600	42.28	32.11	6498	6522	0.985	0.988
1.4	6600	45.14	37.67	6491	6509	0.984	0.986
1.5	6600	41.50	37.99	6500	6504	0.985	0.986
1.6	6600	58.54	55.59	6459	6466	0.979	0.980
2.1	6100	45.87	44.02	5986	5994	0.982	0.983
2.2	6100	32.87	29.36	6021	6029	0.987	0.988
2.3	6100	39.78	37.77	6004	6009	0.984	0.985
2.4	6100	35.61	33.91	6014	6018	0.986	0.987
2.5	6100	28.34	26.39	6031	6036	0.989	0.990
2.6	6100	46.95	44.56	5987	5993	0.982	0.983

vehicular flow in the North-South street, while traffic volume of remaining flows has been reduced. Figure 6 shows graphs both for static and dynamic management of each approach in case study 1.3. Charts related to North and South approaches clearly show that average queue length of maneuvers to the left (blue lines) is greatly reduced by using the proposed dynamic management. It can be pointed out that, because of the proper allocation of green times between phases, trend of traffic flow with low traffic volume for all case studies does not get worse (no starvation).

Table 1 shows traffic volume levels set in the different case studies (l: low, m: medium, h: high, N: North, S: South, E: East, W: West; s: straight, r: right; l: left). Obtained results (Figure 7) in each case study show a reduction of average queue length, with dynamic management. Also, it can be useful to associate the value of average queue length - q_{al} - with the value of junction approaches flow rate - Q_t - and their relationship with the total number of vehicles crossing the intersection in an hour - Q_c (see Table 2). It is helpful to highlight that the Q_c/Q_t ratio between static and dynamic management is quite steady because of the cycle traffic light duration (and therefore the actual green) has been unchanged in both management.

To understand in detail benefits obtained with traffic light dynamic management, Figure 8 compares peaks of average queue length, while Table 3 shows traffic flow were peak has been reached. It has been observed that for some case studies the difference between static and dynamic management is greater while in other cases it is smaller. It depends on traffic volume entering the intersection from each approach. Because of values considered, it has been found that the algorithm has greater efficiency when the gap between traffic volumes coming from different intersec-

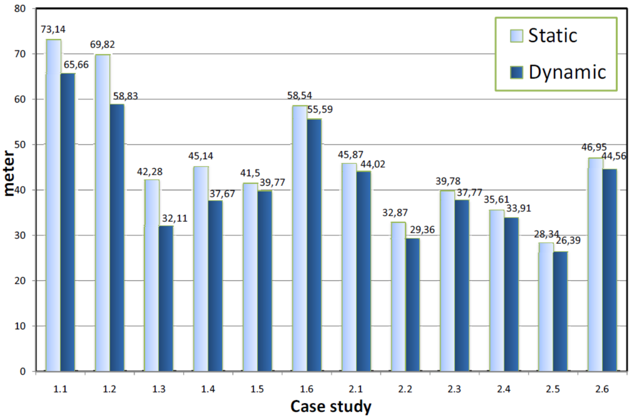


Figure 7: Average queue length: comparison between static and dynamic management

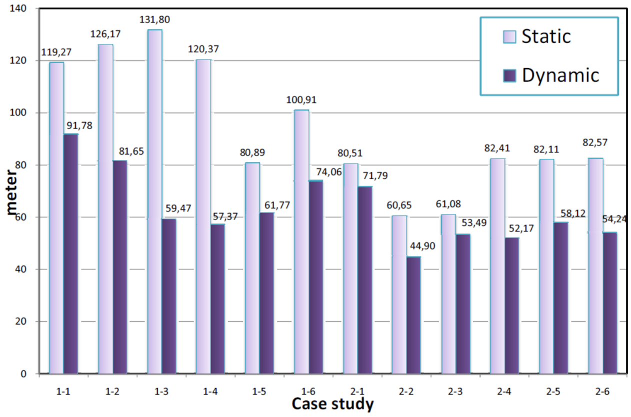


Figure 8: Peaks of average queue length: comparison between static and dynamic management

tions is higher (e.g. in case studies number 1.3, 1.4, 1.5, 2.2, 2.3, 2.5). The algorithm manages these situations balancing green times according to traffic volume information coming from sensors. There are some improvements even if traffic level is not high, although to a lesser degree. This is due to green times recalculation based on actual traffic conditions. The ability of the designed WSN to fit traffic light phases in order to rebalance the relationship between crossing flows and queued flows, makes the results achieved so far particularly interesting, as confirmed in Table 3, both in terms of total node efficiency (reduction of the average queue length value) and in terms of penalized / smoother maneuvers selection (transition of queue peaks among different entering maneuvers).

6 Conclusions

In this paper an IEEE 802.15.4 network architecture, with multiple levels for traffic flows monitoring in an isolated intersection with traffic lights, has been proposed. It has been implemented an algorithm for the dynamic management of intersections that use data collected by the WSN to determine the phase sequence and the green times duration. The obtained results illustrate that, using the implemented algorithm, it is possible to obtain a better management of isolated traffic light junctions. Moreover, the algorithm is suitable for intersections affected by irregularly traffic flows varying during the day on all approaches.

Regarding future intelligent system improvement, we are working on the algorithm and the proposed network architecture optimization. The architecture could be improved using a suitable scheduling mechanism in order to maintain a more efficient priority communication among nodes. Additionally, it could be inserted a priority system for emergency vehicles, as well as a preferential system for public transportation vehicles; furthermore, this approach could be extended to non-isolated junction and include the ability to skip a phase if a vehicle in a traffic flow is not detected.

Table 3: Vehicular Flows with Peaks of Average Queue Length considering Static Management (SM) and Dynamic Management (DM)

Case Study	SM	DM
1.1	N-l	N-s
1.2	S-l	E-l
1.3	S-l	S-l
1.4	N-l	N-s
1.5	W-r	W-l
1.6	E-l	N-s
2.1	N-s	S-s
2.2	W-r	W-r
2.3	N-l	W-r
2.4	N-s	W-r
2.5	N-s	N-s
2.6	N-s	W-r

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