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A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers

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ABSTRACT

This paper proposes a novel approach to dynamically manage the traffic lights cycles and phases in an isolated intersection. The target of the work is a system that, comparing with previous solutions, offers improved performance, is flexible and can be implemented on off-the-shelf components. The challenge here is to find an effective design that achieves the target while avoiding complex and computationally expensive solutions, which would not be appropriate for the problem at hand and would impair the practical applicability of the approach in real scenarios. The proposed solution is a traffic lights dynamic control system that combines an IEEE 802.15.4 Wireless Sensor Network (WSN) for real-time traffic monitoring with multiple fuzzy logic controllers, one for each phase, that work in parallel. Each fuzzy controller addresses vehicles turning movements and dynamically manages both the phase and the green time of traffic lights. The proposed system combines the advantages of the WSN, such as easy deployment and maintenance, flexibility, low cost, noninvasiveness, and scalability, with the benefits of using four parallel fuzzy controllers, i.e., better performance, fault-tolerance, and support for phase-specific management. Simulation results show that the proposed system outperforms other solutions in the literature, significantly reducing the vehicles waiting times. A proof-of-concept implementation on an off-the-shelf device proves that the proposed controller does not require powerful hardware and can be easily implemented on a low-cost device, thus paving the way for extensive usage in practice.

1. Introduction

One of the main goals of Intelligent Transportation Systems (ITSs) is to ensure road efficiency, especially where traffic jams are very likely to occur, for instance, in traffic lights junctions. The main aspects to be considered in traffic lights control are both the cycles and the phases of the traffic lights. A traffic light cycle is the sequence of traffic lights signals (e.g., green, yellow, red) at the end of which the same signals configuration that occurred at the beginning of the sequence itself restarts. A traffic light phase is the time period during which it is possible, for a given set of lanes, to proceed in the direction that is allowed. In case of more than two phases it is necessary to determine the activation sequence of the individual phases, also known as phase sequence.

Looking at the current state of practice, most of the traffic lights today feature fixed cycles, therefore the green time duration of each traffic light phase is very likely to be inappropriate and unbalanced, as it is determined without taking into account either the actual traffic flows or the actual queue lengths. Fixed-time control methods based on a predefined time-plan are suitable for managing stable and regular traffic flows, but are not able to efficiently cope with dynamically varying traffic conditions.

In some cases the green light duration varies based on the vehicles density assessed, for instance, by means of ring detectors installed under the road. However, there is still some limitation in these solutions. First, inductive loop detectors are highly intrusive and entail service disruption during installation and maintenance. As a result, reliable and cost-effective alternative solutions, which can provide traffic data with the same accuracy as inductive loop systems, while allowing flexibility and disruption time minimization are in high demand. Second, in many cases the green signal is granted to each phase following a static phase sequence. As a consequence, it may happen that, at a given moment, instead of executing a phase characterized by longer queues, another one, less critical, is selected. To overcome the limitations of state-of-practice solutions, the traffic lights phase sequence should not be static, but dynamically determined based on the real-time assessment of the queue lengths.

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This paper addresses the dynamic control of traffic lights in an isolated intersection, i.e., an intersection whose incoming vehicle flows are not affected by the effects of upstream traffic lights. The main performance target here addressed is the reduction of the vehicle average waiting times in the queues. To achieve this goal, the paper proposes a traffic lights dynamic control system that combines an IEEE 802.15.4 Wireless Sensor Network (WSN) for real-time traffic monitoring with multiple fuzzy logic controllers, one for each traffic light phase, for dynamically determining the green time duration of each phase. The challenge here is to design a flexible, scalable and effective system that avoids complex and computationally expensive solutions, which would not be appropriate for the problem at hand and would impair the practical applicability of the approach in real scenarios.

The proposed system works in two steps. In the first step (real-time traffic data acquisition and processing) the number of queued vehicles estimated by the nodes of a WSN deployed nearby the traffic lights is sent to the WSN base station (coordinator). Here, data processing is performed, with a twofold aim. Firstly, to sort the traffic lights phases according to a priority that depends on the number of queued vehicles. Secondly, to select the phase to be executed first. In the second step (Green time duration dynamic calculation) the green time duration of each selected phase is determined by the relevant fuzzy logic controller, that exploits the information about the number of queued vehicles of the selected phase.

Our approach represents a novel and effective solution that overcomes some limitations of previous approaches. In fact, several traffic-responsive control approaches were proposed in the literature over the years. Some of these approaches, such as the ones in Dion and Hellinga (2002) and Comert (2013), select phases and extend the phase durations based on predefined logic rules. Moreover, many traffic control systems in the literature, such as Abbas, Karsiti, Napiah, Samir, and Al-Jemeli (2015) and Sun, Jiang, and Wang (2010), take into account the traffic of the current phase only, without considering the length of the queues in the other phases. Conversely, the approach proposed in this paper is able to dynamically select the phase to handle thanks to the detection of the number of vehicles in the queue on the roadway.

Some other approaches proposed in more recent years, such as Zhou, Cao, Zeng, and Wu (2010) and Zhou, Cao, and Wu (2011), introduce *adaptive* algorithms for traffic lights control that adjust both the traffic lights sequence and duration according to the traffic conditions assessed in real-time through a WSN. The proposed algorithms consider several traffic factors (e.g., traffic volume, waiting times, vehicle density) in order to determine the optimal duration for the green light. The algorithms select the phase with the highest execution priority through a simple IF-THEN construct and calculate the green time duration as a "crisp" value. Although the algorithms proposed in Zhou et al. (2010, 2011) are interesting and present good simulation results, these works do not address the practical implementation of their approaches and the relevant design issues, as the wireless communication protocol is not specified and there is no indication about the computational cost of the presented algorithms. Moreover, in the works in Zhou et al. (2010, 2011) traffic flows are controlled by simple rules. Conversely, a rule-based inference system, such as that proposed in our paper, is more suitable for the design of traffic signal control system, thanks to its capability of dealing with uncertainties associated with input and output variables (e.g., the number of vehicles in the queue, the phase to handle and the green time of traffic lights).

Traffic signal control systems are large complex nonlinear stochastic systems and, as a consequence, it is hard to find optimal traffic signal settings. For this reason, other works in the literature propose traffic lights control systems based on Computational Intelligence (CI). Among CI techniques, fuzzy logic controllers are particularly suitable for traffic lights management, because they are based on human reasoning. This means that they take decisions on the basis of human direct experience of the considered environment, expressed through specific inference rules that embed the human feelings about the traffic lights system and reflect the human reaction to the system behavior.

A fuzzy controller for a single two-phase intersection which is able to dynamically manage the green time of traffic lights was presented in the seminal work of Pappis and Mamdani (1977). In such a work fuzzy rules were developed for deciding about extending the current green phase of an isolated traffic intersection featuring simple one-way East–West/North–South traffic control. Unfortunately, the work in Pappis and Mamdani (1977) does not address either turning movements or the dynamic management of the phases cycle. Conversely, the approach proposed in this paper addresses both aspects. Another limitation of Pappis and Mamdani (1977) is that it does not consider four phases, that represent a typical scenario in traffic light junctions. Conversely, our system deals with four phases.

Other approaches introduce a two-stage fuzzy logic control method, i.e., (Trabia, Kaseko, & Ande, 1999; Murat & Gedizlioglu, 2005), in which a first fuzzy controller is used to determine the phase to be handled, while a second one deals with the traffic lights green time management. The main contribution of these works compared to the work from Pappis and Mamdani (1977) is the dynamic selection of the traffic light phases. The two approaches in Trabia et al. (1999) and Murat and Gedizlioglu (2005), differ in the fuzzy controllers used, i.e., in the type of membership functions and in the number of inference rules.

Both the approaches in Trabia et al. (1999) and Murat and Gedizlioglu (2005) need two-stage fuzzy logic control because they use inductive loops or video cameras to estimate the amount of vehicles queued at the traffic lights and, for this reason, they need a fuzzy controller to determine the phase of the traffic light junction that has to be managed. Then, they also need the second controller to dynamically manage the green time increase/decrease. Conversely, our system does not need a fuzzy controller to determine which phase has to be managed, as the WSN located near the traffic light junction already provides the exact number of queued vehicles.

Nowadays, video monitoring and surveillance systems are used in many traffic management applications to assess traffic conditions. For instance, video monitoring systems are used in Kanungo, Sharma, and Singla (2014), Calderoni, Maio, and Rovis (2014), Qi, Zhou, and Ding (2013) for traffic density estimation and vehicle classification, while in other works (Diaz-Cabrera, Cerri, & Medici, 2015; Gomez, Alencar, Prado, Osorio, & Wolf, 2014) they are used for traffic lights detection and distance estimation. However, these solutions rely on expensive cameras and require hardware capable of performing image processing. While the use of video cameras and video monitoring systems is justified for more complex traffic management applications, it represents an overshooting for traffic lights management of isolated intersections, in which cost/benefit assessments lean towards simpler, low-cost but effective systems, like the one proposed in this work.

Similarly, sophisticated solutions based on complex fuzzy controllers, i.e., type-2 (Bi, Srinivasan, Lu, Sun, & Zeng, 2014) ones, that are more computationally demanding, are justified in the case of multiple intersections, but for the case like the one addressed in this paper are not required.

The strength of the traffic lights control system here proposed is that it combines the advantages of the WSN with the benefits of multiple fuzzy logic controllers.

Wireless Sensor Networks (WSNs) are very appealing candidates for the problem at hand, as they are easy to deploy and manage. The WSN accuracy proved to be comparable with (or even better than) that of inductive loop detectors (Zhaohui, Yanfei, Wei, & Jian, 2003) and, in addition, sensor nodes are definitely less intrusive. Moreover, using suitable protocols, WSNs are also able to acquire real-time data in a reliable way. Accurate and reliable real-time traffic data monitoring systems are essential for the efficient and successful execution of all ITS systems.

A sound motivation for the adoption of a WSNs for traffic monitoring is that they minimize the disruption during installation and maintenance and allow for easier coverage extension of ITS applications. In addition, WSNs allow for flexible and scalable deployments. Sensor nodes can be placed virtually anywhere on the road as long as they are within their communication range and they can cover even larger areas thanks to multi-hop communication. This characteristic is a big advantage over other traffic monitoring technologies.

Another benefit of the traffic light control system here proposed is that the adoption of one fuzzy controller for each traffic light phase. This way each controller is entrusted with the task of processing only the data relevant to the relevant traffic light phase to determine the green time duration for that phase.

As explained in (Wilamowski, 2012), the use of multiple parallel controllers instead of one improves fault-tolerance, performance and flexibility. In our case, if a fault occurs in a single controller, the corresponding phase suffers from disadvantages, but the control system runs correctly in the other three phases. The performance depends on the priority that the proposed approach assigns to each phase. At any time, the phase with the longest traffic queue gets the highest priority and so the best service. The proposed system is flexible as the existence of multiple controllers allow to apply phase-specific management and the fuzzy logic controller follows the real traffic conditions.

Another strength of the traffic lights control system here proposed is that it involves small data exchanges, as the data to be transferred to the controller is the number of queued vehicles in the lane of the considered phase. This fact entails a lower computational cost than, for instance, a video camera-based system, in which the estimation of the number of queued vehicles is made through image processing. Our approach therefore does not require expensive or complex hardware and does not need high bandwidth or high computational capability.

These properties of our design not only allow to implement our system on low-cost hardware, but are also expected to be beneficial in terms of lower data processing times and lower control actuation times for the fuzzy logic controllers.

The paper is organized as follows. Section 2 discusses related literature, while Section 3 describes the proposed system. Section 4 addresses the performance obtained via simulation and compares the results of comparative assessments with other approaches in the literature. Section 5 presents an implementation of the proposed system on commercial off-the-shelf (COTS) hardware. Finally, Section 6 concludes the paper and gives hints for future work.

2. Related works

Fuzzy logic controllers are suitable for managing traffic light intersections characterized by strongly varying conditions, that call for the adoption of "approximate" solutions, based on human reasoning. However, in the design of fuzzy logic controllers for this application, several factors must be considered, such as the computational complexity of the algorithm, the feasible implementation on COTS devices and the system scalability, as the length of the road to be monitored might increase and thus it could be necessary to introduce additional devices.

The work in Zou, Yang, and Cao (2009) proposes a fuzzy logic controller able to dynamically adjust the green time of traffic lights, but the phase sequence is considered static. This is a limitation, as the phase sequence should not be considered static and, moreover, cannot be determined at design time. So, this solution is neither scalable nor applicable to traffic light junctions with more than two phases and in cases in which the traffic flows are unpredictable. Another approach, introduced in Kulkarni and Waingankar (2007), presents a fuzzy logic controller used to process traffic information in order to extend the green time, with the twofold aim of improving the vehicular throughput (the number of vehicles that cross the traffic lights) and reducing the waiting time in the queue. Despite some similarity with the approach proposed in this paper, the works in Zou et al. (2009) and Kulkarni and Waingankar (2007) do not address the planning of the traffic lights phases, as the envisaged fuzzy controllers only manage the green time duration of one queue and not that of the set of queues for the specific phase. As a consequence, the fuzzy controllers might extend the green time duration of a phase that does not have particular execution urgency.

In Shahraki, Shahraki, and Mosavi (2013), a fuzzy control system for traffic lights is designed for a traffic junction with several consecutive intersections. The system is composed of three modules: a Next phase selector, a Green light extender and a decision maker. The first two modules are characterized by a fuzzy logic controller, which determines the next phase (green light assignment) and the possible extension of the current green light. The controllers process the number of vehicles in a link (where a link is the road connecting two adjacent intersections), the number of vehicles in queue during the red light signal, and the waiting time, measured by a timer that evaluates how long the first car at the traffic lights has been waiting in the queue. The decision-maker module determines whether to extend the green time of the current phase or to switch to the next phase. The fuzzy logic controller is used to dynamically determine the execution of the most urgent phase only.

In Wu, Zhang, and Shi (2010), a dynamic control technique for traffic lights is presented, which is based on the queue detection in the left and straight lanes assuming that the vehicles in the right lane are not in conflict with the others. For queue detection purposes, two induction coils are used, the first one to detect oncoming vehicles, the second to measure the vehicles that leave the intersection. The work considers 12 phases, scheduled according to the priority of each phase that depends on the queue lengths of the specific phase lanes. The additional green time is then calculated using a fuzzy logic controller that processes two parameters, i.e., the queue length of the lane with the green light and that of the lanes with the red light.

The phase duration depends on the traffic flow that the phase should serve and, in this respect, the main limitation of the works presented by Shahraki et al. (2013) and Wu et al. (2010) is that the green time extension is calculated by a single fuzzy controller for all the phases, whereas for better performance, fault-tolerance and flexibility, as explained before, a controller for each phase would be needed to determine the green time duration of the specific phase. The same problems in Shahraki et al. (2013) and Wu et al. (2010) also characterize the approach presented in Zaied and Othman (2011), whose aim is to dynamically regulate,-through a fuzzy controller, the green time duration of an 8-phase traffic lights in an isolated intersection. In this case, 8 inputs (i.e., the queues) and 16 outputs (i.e., the calculated green time for each allowed direction) have to be handled. This means that the fuzzy controller is characterized by multiple input variables.

Summarizing, the traffic light controller here proposed, comparing with related works, is easy to deploy/maintain and non-invasive, as it does not entail a radical intervention on the road infrastructure, since the WSN deployment does not require invasive excavations on the roadways. The proposed system is lightweight, as the data sent through the WSN are small (small integer numbers indicating the total number of vehicles in the queue) and thus there is a little cost from both the communication and the processing point of view. The solution proposed in this work can be therefore implemented in COTS devices. In order to highlight this feature, the paper also shows the experimental results obtained through an implementation of the proposed controller on a real prototyping board (Section 5). The proposed approach is scalable, as it is easy to extend the portion of the road to be monitored simply adding new wireless sensor nodes and exploiting multi-hop communication. Another notable property of the proposed approach is its flexibility, as it allows to increase/decrease the sampling rate of sensor nodes, thus increasing the detection accuracy without affecting the performance of both the WSN and the controller. Also, the presence of one controller for each phase allows to apply phase-specific control actions. Last, but not least, the adoption of multiple parallel controllers, in combination with the accurate detection of the number of vehicles provided by the WSN, allows for better performance than related works in terms of waiting time reduction and better balancing between the phases. This property is proven in Section 4, where the performance of the proposed system is compared with that of the fixed cycle approach and of the approaches in Shahraki et al. (2013), Wu et al. (2010) and Zaied and Othman (2011).

3. The proposed approach

The main target of this work is proposing a novel traffic lights control system for isolated intersections able to reduce the average waiting time of vehicles while managing the phase sequence, i.e., the time period during which it is possible, for a given set of lanes, to continue following the allowed direction. When dealing with highly crowded roads, it is really important to determine the correct phase sequence to ensure that the phases with the highest number of vehicles in queue will be executed with the highest priority and the longest green time. In this work a multi-controller system is envisaged, that consists of:

- A Wireless Sensor Network (WSN), for real-time traffic data acquisition.
- A Phase Sorting Module, for calculating the phase execution order according to the priority assigned to each phase on the basis of the number of enqueued cars in the lanes related to the specific phase.
- A fuzzy logic controller for each traffic lights phase, for calculating the appropriate green time duration of the relevant phase.

The proposed multi-controller system is represented in Fig. 1, while Fig. 2 shows the proposed system architecture.

The WSN is responsible for the collection of traffic data, such as, the number of cars queued in the lanes related to each traffic lights phase. The Phase Sorting Module determines the phase execution sequence, within each traffic-light cycle, in descending order based on the number of enqueued cars. It is implemented by a microcontroller within the intersection manager, a central device embedded into the First Pan Coordinator (FPC) of the WSN. Finally, each fuzzy controller determines the green time duration for the relevant phase considering the number of enqueued cars in the lanes that are under its control.

The WSN implements the IEEE 802.15.4 standard protocol (IEEE, 2006). The Reduced Function Devices (RFDs) are located along the roadside, within a road cavity, following a linear topology, like in Iannizzotto, La Rosa, and Lo Bello (2010), and detect the presence of enqueued cars by evaluating the distortion of the Earth's magnetic field produced by the presence of ferrous objects.

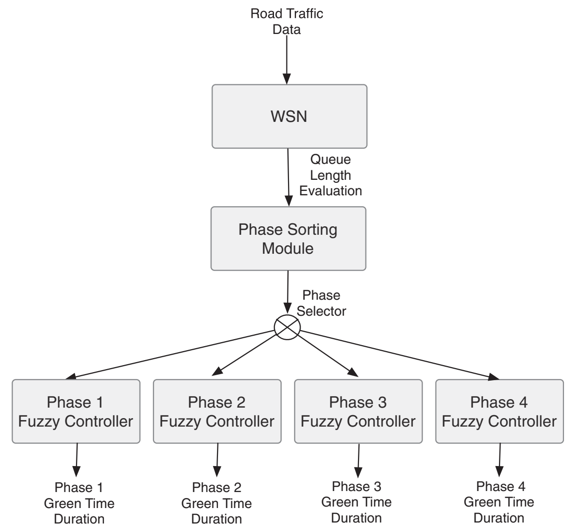

Fig. 1. The multi-controller system proposed.

As depicted in Fig. 2, the data related to each lane is collected by the Full Function Devices (FFDs), which poll the associated RFDs. The collected aggregate data is then forwarded to the First Pan Coordinator (FPC). The communication among the network devices is realized through the IEEE 802.15.4 protocol working in beacon-enabled mode, using the Guaranteed Time Slots (GTSs) in order to avoid collisions. The FPC is embedded in the intersection manager (see Fig. 3), which is located in the center of the traffic lights intersection.

The data received by the FPC is processed twice. First, by a sorter module that orders the traffic lights phases by priority. Second, by a fuzzy logic controller that determines the appropriate green time duration based on the queue lengths. Fig. 3 shows the functional architecture of the intersection manager which is connected to the 8 traffic lights through a microcontroller (e.g., the Microchip PIC24FJ256GB108 microcontroller, which provides 24 pinouts for the connection to the traffic lights).

Table 1 summarizes the mapping between the traffic lights of the intersection under study on the lanes of each road they control and their allowed directions.

As it is shown in Fig. 4, traffic lights are managed so as to make sure to prevent the cars coming from the different lanes of the same road from accessing the intersection simultaneously.

This choice is made for the sake of avoiding the collisions that could occur when the trajectories of the two lanes of the same road intersect. This way, with reference to Fig. 4, the cars coming from the two lanes of ROAD A cannot go straight and turn left, respectively, during the same phase.

3.1. Computing the green light duration for each phase using a fuzzy controller

The isolated intersection here considered is characterized by four phases as depicted in Fig. 5.

As explained before, a traffic lights phase is the time period during which it is possible, for a given set of lanes, to continue following the allowed direction. For example, when Phase 1 is enabled, only the cars of Lane 1 of the Roads A and C can go straight or turn right, while all the other lanes will have the red light.

Table 2 summarizes the notation adopted in this paper.

In fixed-cycle traffic lights, each cycle can be approximated to a periodic task with period T, characterized by a fixed green time (T_g)

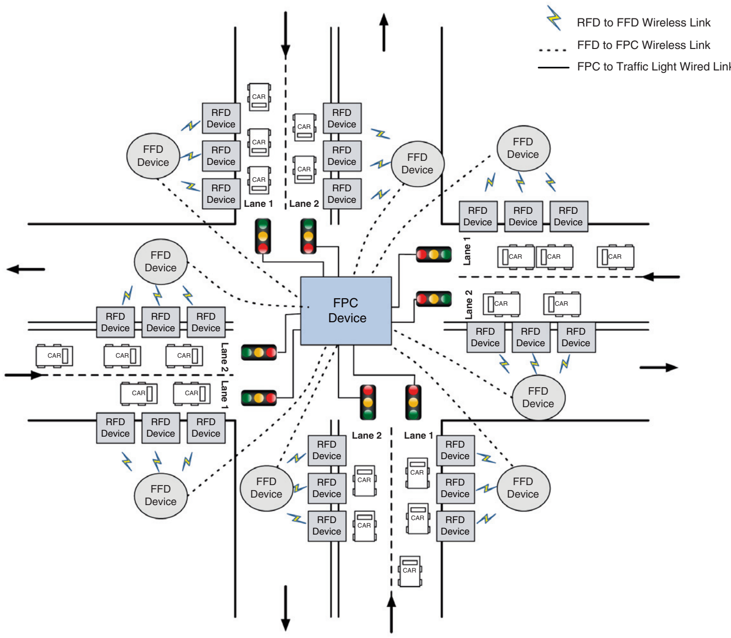

Fig. 2. The system architecture.

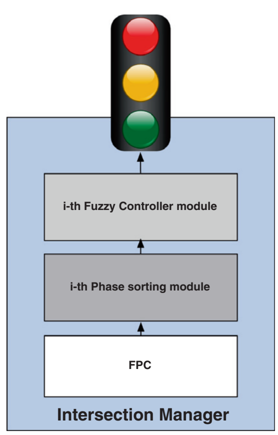

Fig. 3. Modules of the intersection manager.

and a fixed yellow time (T_y). For the remaining time, the traffic lights are red (T_r) as described by Eq. (1).

$$T = T_g + T_y + T_r \tag{1}$$

In the approach here proposed, in order to make the road traffic information as accurate as possible, each monitored road section of length L has been subdivided into smaller sub-sections, each one of length l_i, as shown in Fig. 6.

Table 1
Intersection roads and their associated traffic lights.

Traffic lights	Road and lanes controlled	Allowed directions
SEM_A1	Road A–lane 1	Straight/right
SEM_A2	Road A–lane 2	Left
SEM_B1	Road B–lane 1	Straight/right
SEM_B2	Road B–lane 2	Left
SEM_C1	Road C–lane 1	Straight/right
SEM_C2	Road C–lane 2	Left
SEM_D1	Road D–lane 1	Straight/Right
SEM_D2	Road D–lane 2	Left

Each subsection l_i is monitored by a node in order to detect the presence of vehicles through a magnetic sensor that measures the Earth's magnetic field distortion due to vehicles (Collotta, Pau, Salerno, & Scata, 2011). The queue length is estimated based on the number of the road subsections in which the presence of cars is detected, therefore the queue length is expressed in terms of the number of enqueued cars.

Let us call Th_N and Th_M the threshold values within which the queue length is considered normal and medium, respectively. For values above Th_M the queue is considered long. Table 3 shows the queue classification according to the vehicle count.

With reference to Figs. 4 and 5, the priority level of each phase is obtained as the sum of the queue lengths, intended as the number of enqueued vehicles during the red light in their respective lanes, as shown in Eqs. (2)–(5).

$$Phase1\_priority = queue\_len_{SEM_{A1}} + queue\_len_{SEM_{C1}} \tag{2}$$

$$Phase2\_priority = queue\_len_{SEM_{B1}} + queue\_len_{SEM_{D1}} \tag{3}$$

$$Phase3\_priority = queue\_len_{SEM_{A2}} + queue\_len_{SEM_{C2}} \tag{4}$$

$$Phase4\_priority = queue\_len_{SEM_{B2}} + queue\_len_{SEM_{D2}} \tag{5}$$

Once the priority level of each phase has been computed, the Phase Selector determines the next phase to be executed according to the phase priority. The priority levels are updated at the end of each cycle, during the yellow signal of the last phase, and sorted (in a list) based on the current traffic conditions. The approach here proposed envisages one fuzzy logic controller for each phase. An alternative design could have adopted a single controller working in a TDMA (Time Division Multiple Access) fashion on the different pairs of input variables corresponding to the different phases. However, the use of four parallel controllers instead of one not only improves fault-tolerance and performance (Wilamowski, 2012), but also flexibility, as it enables to apply phase-specific management. For this reason here one fuzzy logic controller for each phase is adopted to determine the optimal green light duration for that phase. As shown in Fig. 7, the ith controller processes two input variables, that correspond to the length of the queues relevant to the two lanes controlled by the specific phase.

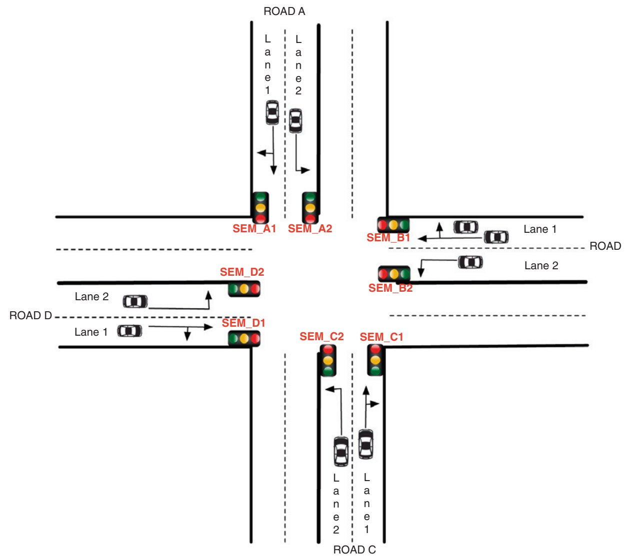

Fig. 4. The isolated road intersection under study.

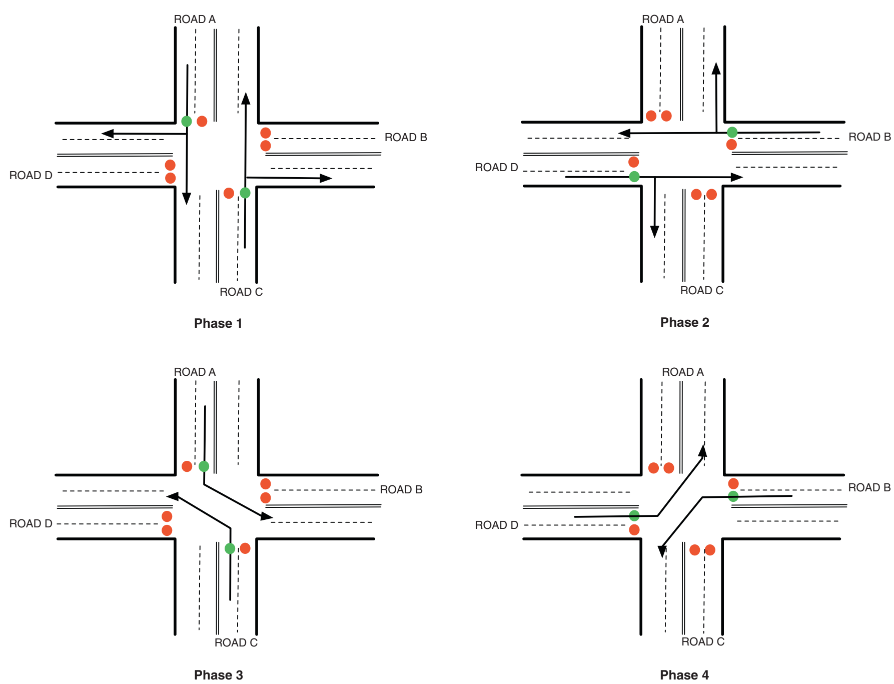

Fig. 5. Traffic lights phases.

Table 2
Notation.

Symbol	Meaning
T	Traffic lights cycle
T_g	Green light duration
T_y	Yellow light duration
T_r	Red light duration
L_{-}	Road total length
l_i	Subsection length
Th_N	Threshold for normal queue length
Th_M	Threshold for medium queue length

So, for instance, in the case of Phase 1, Controller 1 will determine the green light duration by processing the queue length of the Lane 1 of Road A and that of the Lane 1 of Road C, respectively. Similarly, Controller 2 will determine the green time duration by processing the queue length of the Lane 1 of Road B and that of the Lane 1 of Road D, and so on. The fuzzy controller works in three steps. During the first step, called fuzzification, the input variables relevant to the two queue length values are converted from their analog value to a crisp value characterized by a certain degree of membership, from 0% to 100%, in the three membership functions (Normal, Medium, Long) (with Ref. to Table 3). In our real scenario, that refers to an isolated intersection in a mid-size town, each lane is monitored for up to 400 meters, a reasonable value for the longest queue in such a scenario. Assuming a typical car length of 5 m, up to 80 vehicles can be enqueued and counted on each lane (i.e., a maximum of 160 vehicles for each phase). The number of

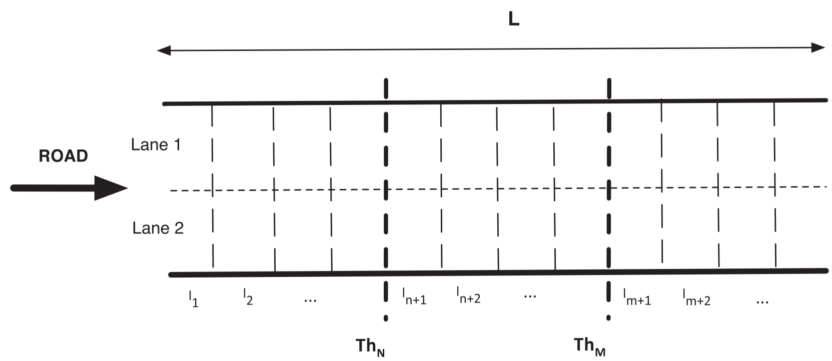

Fig. 6. Section of a monitored road.

Table 3
Queue classification.

Road section	Meaning
$l_i \leqslant Th_N$	Normal queue
$Th_N < l_i \leqslant Th_M$	Medium queue
$l_i > Th_M$	Long queue

enqueued vehicles is in the range [16–80]. In Fig. 8 the membership function of the input variables of the fuzzy logic controller are depicted.

The membership functions for the output value (green time duration) are three (Min, Medium, Max). Considering that in current practice the minimum green time should be no shorter than 15 s and no longer than 90 s, the membership functions can be represented as in Fig. 9.

The second step of our approach is characterized by an inference mechanism through which the fuzzified information are correlated, following a linguistic approach based on the IF-THEN construct. Table 4 summarizes the rules that match the antecedents and consequents for the *i*th controller.

If both the lanes of a phase are congested, i.e., their queue length is LONG, the phase needs the maximum green time duration in order to reduce the queues. On the contrary, if at least one of the

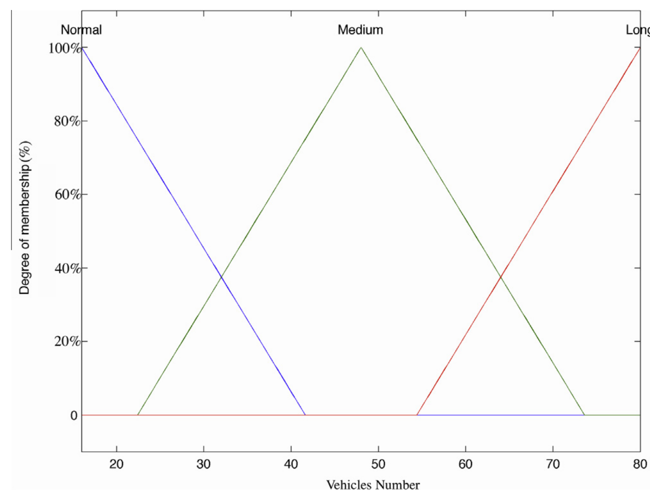

Fig. 8. Membership functions for the number of vehicles (input variables).

two lanes is characterized by a NORMAL queue length, it is not advisable to allot the maximum green time duration to that phase. In fact, as the green time duration of a phase prolongs the red light

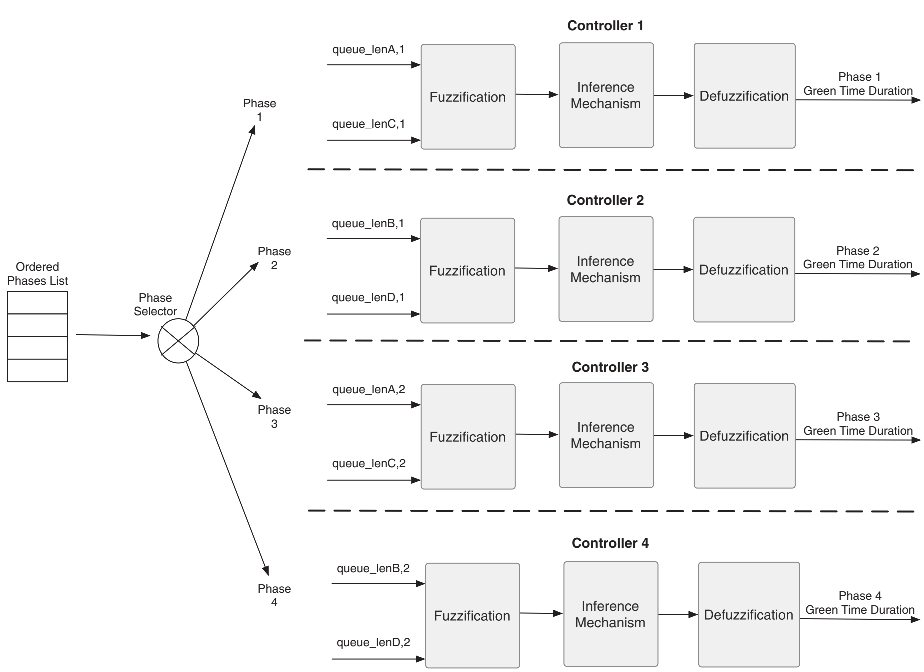

Fig. 7. The four parallel fuzzy logic controllers of the proposed approach.

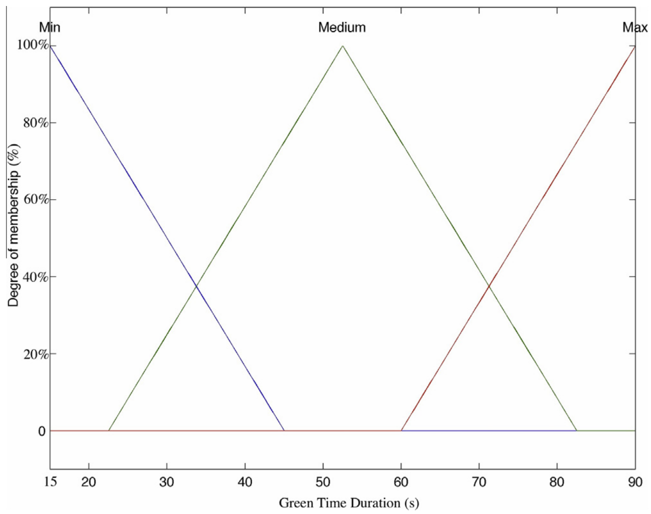

Fig. 9. Membership functions for the green light duration (output variables). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the other phases, there could be another phase that would be unnecessarily penalized. The last step is represented by the defuzzification, which finds a single crisp output value from the fuzzy space of the solutions. This value represents the green light duration for the *i*th phase of the traffic lights. Defuzzification is performed using the center-of-gravity method given by Eq. (6).

$$GreenTimeDuration_{ith} = \frac{\sum_{i=1}^{n} O_i * C_i}{\sum_{i=1}^{n} O_i} \quad (6)$$

where O_i is the output of the *i*th base rule and C_i is the center of the output membership function. In our approach the yellow time duration is considered fixed, since the yellow light does not allow crossing the intersection (unless the crossing had already started during the green light). If Phase *i* has the green light, then any other phase $j \neq i$ has the red light for a time equal to the sum of the green time of phase i and the fixed yellow time. Assuming, for simplicity, that the calculated phase execution order is {Phase 1, Phase 2, Phase 3, Phase 4}, once the entire sequence has completed, the system will calculate the new phase execution order based on the new priority calculated for each phase and will proceed as described before.

4. Performance evaluation

In order to assess the performance of the proposed approach, several tests were made using MATLAB for the evaluation of the fuzzy controllers and TRUETIME (Cervin, Henriksson, Lincoln, Eker, & Arzen, 2003) for simulating the IEEE 802.15.4 WSN infrastructure. Simulations have been performed making a comparison with the fixed cycle approach and the approaches proposed by Shahraki et al. (2013), Wu et al. (2010) and Zaied and Othman (2011). Measures have been collected for 3 h. As mentioned before, in our scenario each lane is monitored up to 400 m, the typical length of a car is assumed equal to 5 m, so up to 80 cars can be measured on each lane (max 160 cars for each phase). On each lane, three conditions may occur:

- Short queue, if the queue length does not exceed the Th_N threshold (133 m).
- Medium queue, if the queue length is between 133 (Th_N) and 266 m (Th_M).
- Long queue, if the queue length exceeds the Th_M threshold (266 m).

Three different scenarios were simulated with different random arrival rate values, i.e.

- Low – between 1 and 10 cars/minute.
- Medium – between 11 and 30 cars/minute.
- High – between 31 and 60 cars/minute, representing the worst-case arrival time of 1 car/s. The threshold values were heuristically set. Higher values were not considered, as they would produce an unmanageable traffic jam for any ITS solutions, as tested in Wu et al. (2010).

Table 5 summarizes all the simulation parameters.

The maximum and the average waiting time, with their relative confidence intervals, were obtained by measuring the time interval between a car arrival time and the time at which the car crosses the intersection. Tables 6–9 compare the waiting times obtained using the multi-controller system here proposed with the ones obtained by the fixed-cycle approach and the fuzzy-based ones proposed in Shahraki et al. (2013), Wu et al. (2010) and Zaied and Othman (2011). For the average waiting times values, also the confidence intervals are shown.

As shown in Table 6 the multi-controller approach significantly reduces both the maximum and the average waiting times comparing with the other solutions here considered. The reduction is more significant under high traffic, i.e., under a higher arrival rate the benefit of the combination of the WSN with the multi-controller approach become more evident.

The results in Table 6 are also confirmed by those shown in Tables 7–9 related to Phases II, III and IV. It is therefore possible to make these general observations:

- In all the scenarios here considered, the multi-controller system here proposed produces lower waiting times in queue, both in terms of the maximum and the mean value.

Table 4
Inference rules for the *i*th controller.

Rule	Road W-lane X length	Road Y-lane Z length	*i*th Phase green time duration
1	Normal	Normal	Min
2	Normal	Medium	Min
3	Normal	Long	Medium
4	Medium	Normal	Min
5	Medium	Medium	Medium
6	Medium	Long	Max
7	Long	Normal	Medium
8	Long	Medium	Max
9	Long	Long	Max

Table 5
Simulation parameters.

Parameter	Value
Number of FFDs	8
Number of RFDs on each lane	80
Protocol	IEEE 802.15.4 beacon–enabled
Distance between each RFD	5 m
Duration of the simulation	3 h
Length of each lane monitored	400 m
Scenario I: Low Arrival rate	[0–10] car/min.
Scenario II: Medium Arrival rate	[11–30] car/min.
Scenario III: High Arrival rate	[31–60] car/min.
Crossing rate	1 car/s
Th_N	133 m
Th_M	266 m

Table 6
Waiting times – phase I.

Scenario	Max value (s)			Average value (s)		
	I	II	III	I	II	III
Fixed cycle	53.94 ± 1.04	76.39 ± 1.08	85.31 ± 1.02	39.41 ± 1.02	51.45 ± 0.89	62.13 ± 0.94
Shahraki fuzzy controller	42.94 ± 0.99	54.29 ± 0.97	62.29 ± 1.03	28.13 ± 0.98	38.16 ± 0.87	52.08 ± 0.99
Wu controller	33.72 ± 0.94	43.99 ± 0.92	54.95 ± 0.80	21.23 ± 0.76	30.91 ± 0.89	46.95 ± 1.02
Zaied controller	39.23 ± 0.81	47.39 ± 0.85	59.35 ± 0.88	26.19 ± 0.78	37.22 ± 0.85	49.22 ± 0.88
Multi-controller approach	29.51 ± 0.93	34.96 ± 0.77	37.98 ± 0.75	15.95 ± 0.82	17.11 ± 0.87	25.91 ± 0.85

Table 7
Waiting times – phase II.

Scenario	Max value (s)			Average value (s)		
	I	II	III	I	II	III
Fixed cycle	65.18 ± 0.99	84.93 ± 1.03	95.99 ± 1.03	37.51 ± 0.98	58.02 ± 1.01	75.04 ± 0.97
Shahraki fuzzy controller	41.76 ± 1.03	68.96 ± 1.06	76.01 ± 1.02	28.49 ± 0.98	50.12 ± 0.99	61.28 ± 0.98
Wu controller	33.12 ± 1.05	60.11 ± 1.01	65.09 ± 0.99	24.09 ± 1.02	40.36 ± 0.97	49.95 ± 0.95
Zaied controller	36.24 ± 1.00	62.02 ± 1.02	66.39 ± 0.99	26.11 ± 0.98	42.76 ± 0.97	55.61 ± 1.02
Multi-controller approach	25.19 ± 0.95	34.95 ± 0.97	36.89 ± 0.99	16.01 ± 0.89	21.32 ± 0.98	28.93 ± 0.94

Table 8
Waiting times – phase III.

Scenario	Max value (s)			Average value (s)		
	I	II	III	I	II	III
Fixed cycle	68.04 ± 0.99	89.27 ± 1.02	94.21 ± 1.01	40.09 ± 0.92	56.03 ± 0.93	73.02 ± 0.99
Shahraki fuzzy controller	42.65 ± 1.03	64.98 ± 0.99	72.87 ± 1.01	30.21 ± 1.01	47.34 ± 0.98	59.12 ± 0.97
Wu controller	37.56 ± 0.97	61.03 ± 1.04	65.98 ± 1.02	25.04 ± 0.99	42.03 ± 0.98	51.03 ± 0.94
Zaied controller	39.95 ± 1.00	61.94 ± 1.03	70.92 ± 1.04	26.48 ± 1.02	44.23 ± 0.99	53.19 ± 0.99
Multi-controller approach	26.41 ± 0.99	35.01 ± 1.02	39.93 ± 1.03	17.99 ± 0.92	23.41 ± 0.97	27.78 ± 0.94

Table 9
Waiting times - Phase IV.

Scenario	Max value (s)			Average value (s)		
	I	II	III	I	II	III
Fixed cycle	61.85 ± 0.98	81.52 ± 0.98	89.56 ± 0.97	43.39 ± 0.99	51.98 ± 1.01	70.19 ± 1.00
Shahraki fuzzy controller	41.23 ± 0.93	58.09 ± 0.96	70.21 ± 0.99	28.91 ± 0.98	43.98 ± 1.01	56.99 ± 0.96
Wu controller	35.88 ± 0.99	49.91 ± 0.97	64.13 ± 1.01	26.05 ± 1.00	34.12 ± 0.99	49.93 ± 1.01
Zaied controller	39.43 ± 0.94	54.93 ± 0.95	68.91 ± 0.94	26.83 ± 0.99	39.56 ± 0.98	52.88 ± 0.97
Multi-controller approach	18.89 ± 0.91	25.04 ± 0.94	32.99 ± 0.94	18.44 ± 0.95	21.45 ± 0.99	25.95 ± 0.94

- The performance improvement of the multi-controller approach compared with the other ones here considered becomes more significant under high traffic conditions (scenario III).
- There is a very good balancing between the 4 traffic lights phases in terms of average waiting times, thanks to the combination of the Phase Sorting Module with the multiple fuzzy logic controllers that calculate the green light duration for each phase.

Tables 10 and 11 show that, comparing with the other approaches considered in this simulation study, i.e., the fixed-cycle traffic lights and the approaches proposed in Shahraki et al. (2013), Wu et al. (2010) and Zaied and Othman (2011) respectively, the multi-controller approach proposed in this paper significantly reduces the queue waiting times for all the phases of the isolated traffic light intersection here addressed, especially in road conditions characterized by high arrival rate. In particular, the fixed-cycle traffic lights always obtain the longest waiting times and cannot correctly drain the vehicular traffic, as it does not take into account the traffic real-time conditions.

The approach proposed by Shahraki et al. (2013), that we recall is based on a phase selector (based on fuzzy logic), a green light

Table 10
Waiting times percentage reduction using the multi-stage approach. Phases I and II.

Scenario	Phase I reduction (%)			Phase II reduction (%)		
	I	II	III	I	II	III
Fixed cycle	23.46	35.50	36.22	21.50	36.70	46.11
Shahraki fuzzy controller	12.18	22.21	26.17	12.48	28.80	32.35
Zaied controller	10.21	14.96	21.04	10.10	21.44	26.68
Wu controller	5.28	21.27	23.31	8.08	19.04	21.02

Table 11
Waiting times percentage reduction using the multi-stage approach. Phases III and IV.

Scenario	Phase III reduction (%)			Phase IV reduction (%)		
	I	II	III	I	II	III
Fixed cycle	22.10	32.62	45.24	25.05	30.53	44.24
Shahraki fuzzy controller	12.22	23.93	31.34	10.47	22.53	31.04
Zaied controller	8.49	20.82	25,41	8.39	18.11	23.98
Wu controller	7.05	18.62	23.25	7.61	12.67	26.93

extender (also based on fuzzy logic) and a decision maker module that decides whether to extend the green time duration or to switch the execution of the next phase, performs better than the fixed-cycle traffic lights. However, under heavy traffic conditions, a phase characterized by high traffic volume would continually need the extension of the green time, at the expense of increasing the average waiting time of all the other phases. For example, considering the average waiting time of cars in phase I (Table 6), the value obtained by the Shahraki fuzzy controller in case of high traffic volume (scenario III), i.e. 52.08 s, produces a significant increase of the cars average waiting times in phase II (61.28 s), under high arrival rate conditions (scenario III of Table 7). The multi-controller approach, instead, ensures the balancing of the waiting times and, at the same time, avoids that the green light for a specific phase last longer than necessary. With reference to the same example under a high arrival rate (scenario III), the average waiting time in phase I (Table 6) is 25.91 s while in phase II a car waits on average for 28.93 s (Table 7).

The approach proposed in Wu et al. (2010) slightly improves the results obtained by the approaches Shahraki et al. (2013) and Zaied and Othman (2011), but the performance of our multi-controller approach are still better.

Finally, three additional scenarios were simulated, in which each phase is characterized by different traffic conditions, in order to verify how the proposed multi-controller approach balances the waiting times. The scenarios are summarized in Table 12.

As Tables 13–15 show, the multi-controller approach realizes a better balancing of the waiting times, while with the other approaches here considered the waiting times of the phases with a high arrival rate are almost twice than the waiting times of the other phases.

5. Experimental model

In order to simulate how a traffic light controller works and dynamically selects the phase and manages the green time duration, a model has been built in Simulink/Matlab, as shown in Fig. 10. The queue levels of each phase are acquired as input parameters of the block called "Phase Selector". These are random values, generated through uniform random number blocks with ranges between 1 and 60 so as to consider different arrival rates from 1 to 60 cars per minute. These values emulate the values of the number of vehicles that in a real scenario are measured by magnetometers and are provided to the controller by the WSN. The output values of the Phase Selector block are the four phases of the traffic light junction. These phases are not managed simultaneously because the Phase Selector block returns as output the management order of these phases. This block manages the phases through the Simulink/Stateflow environment, an internal Matlab tool that allows to describe the evolution of a specific system (in this case the queue levels) by means of a finite state machine. The phase that has the longest queue is the one that will be handled first. Even in this case, as shown in Fig. 7, the ith controller processes two input variables, that correspond to the length of the queues relevant to the two lanes controlled by the specific phase. Its behavior is based on the membership functions and inference rules described in the previous Sections.

Table 12
Simulated scenarios.

Scenario	Phase I arrival rate	Phase II arrival rate	Phase III arrival rate	Phase IV arrival rate
I	Low	Low	High	High
II	Medium	Medium	Low	Low
III	Medium	Medium	High	High

Table 13
Average waiting times – scenario I.

Phase	Average value (s)			
	I	II	III	IV
Fixed cycle	39.02 ± 0.98	38.42 ± 0.97	61.23 ± 1.02	62.01 ± 0.99
Shahraki fuzzy controller	27.11 ± 0.96	27.51 ± 0.98	52.23 ± 1.02	51.96 ± 0.95
Wu controller	21.99 ± 1.04	22.03 ± 0.99	45.17 ± 0.99	45.41 ± 0.95
Zaied controller	24.91 ± 0.94	27.92 ± 0.99	49.13 ± 0.97	46.93 ± 0.98
Multi-controller approach	16.78 ± 0.99	16.37 ± 0.97	24.13 ± 0.96	22.99 ± 0.99

Table 14
Average waiting times – scenario II.

Phase	Average value (s)			
	I	II	III	IV
Fixed cycle	52.99 ± 0.99	52.23 ± 0.95	38.12 ± 0.97	38.67 ± 0.94
Shahraki fuzzy controller	38.51 ± 1.01	39.95 ± 1.04	25.48 ± 0.97	27.03 ± 0.96
Wu controller	31.58 ± 0.91	31.05 ± 0.94	22.45 ± 0.94	20.54 ± 0.98
Zaied controller	34.93 ± 0.96	35.23 ± 0.95	24.93 ± 0.99	24.32 ± 0.91
Multi-controller approach	20.14 ± 0.89	20.93 ± 0.91	16.81 ± 0.87	16.10±0.89

Table 15
Average waiting times – scenario III.

Phase	Average value (s)			
	I	II	III	IV
Fixed cycle	52.23 ± 0.91	50.27 ± 0.96	60.92 ± 0.94	60.23 ± 0.92
Shahraki fuzzy controller	39.75 ± 0.99	39.24 ± 0.99	53.28 ± 0.98	54.12 ± 0.91
Wu controller	32.43 ± 0.93	31.28 ± 0.96	47.12 ± 0.98	47.91 ± 0.92
Zaied controller	37.13 ± 0.90	37.95 ± 0.94	51.28 ± 0.96	51.78 ± 0.89
Multi-controller approach	19.01 ± 0.99	18.78 ± 0.93	24.03 ± 0.89	23.41 ± 0.87

The model depicted in Fig. 10 was implemented on the prototyping board that is shown in Fig. 11. The processing unit is the Microchip PIC24FJ256GB108 microcontroller (Microchip, 2009), which integrates the control features of a microcontroller unit with the processing and throughput capabilities of a digital signal processor. This 16-bit microcontroller has a maximum processing power of 16 MIPS and offers multiple serial ports (3xI2C, 3xSPI), 4xUARTS and 23 independent timers. The availability of 16 kB of RAM memory for buffering, of up to 256 kB of enhanced Flash program memory and other characteristics make this microcontroller very suitable for embedded control and monitoring applications.

The implementation here presented is just a proof-of-concept to show the feasibility of the proposed traffic light control system on COTS devices. For this reason, only the scenario with a Medium arrival rate was considered and a uniform random generation was chosen so as to have between 11 and 30 cars/minute. The green time values are displayed on the LCD screen connected to the prototyping board. In order to calculate and plot the performance, the microcontroller continuously sends the output data to a computer through a serial cable.

Table 16 compares the simulation results obtained by our multi-controller approach (the same as in Scenario II of Tables 6–9) with the results obtained by its implementation on the prototyping board in Fig. 11. The results in Table 16 show that the model implemented in the prototyping board obtains very good performance. In particular, the experimental waiting times for our system are

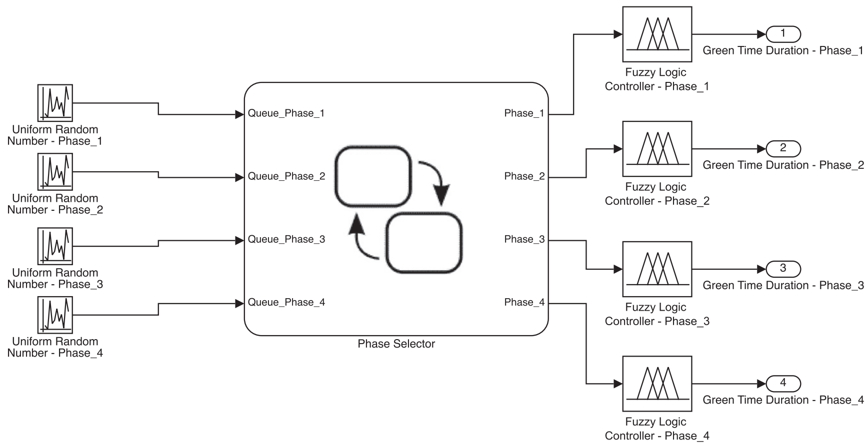

Fig. 10. Simulation model scheme.

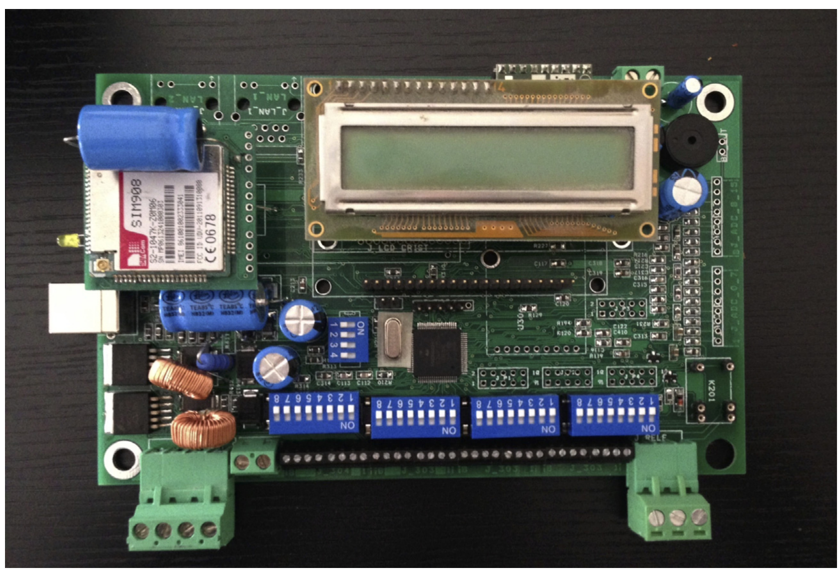

Fig. 11. Hardware board.

Table 16
Waiting times considering a medium arrival rate.

Phase	Max value (s)				Average value (s)			
	I	II	III	IV	I	II	III	IV
Simulation	34.96 ± 0.77	34.95 ± 0.97	35.01 ± 1.02	25.04 ± 0.94	17.11 ± 0.87	21.32 ± 0.98	23.41 ± 0.97	21.45 ± 0.99
Prototyping board	39.74	40.07	42.55	29.04	19.24	24.44	27.29	25.65

slightly higher than the simulation ones (this is natural, as simulation does not embed some timings that strictly depend on the hardware) and much lower than the simulation results for the other approaches in Tables 6–9.

All these results show that the main objectives of the work are fulfilled, as the system here proposed achieves better performance than other approaches without requiring expensive and complex design and can be therefore implemented on off-the-shelf devices.

6. Conclusions and future works

The paper proposed a traffic lights dynamic control system that combines an IEEE 802.15.4 Wireless Sensor Network (WSN) for real-time traffic monitoring with multiple fuzzy logic controllers, one for each phase, that work in parallel. Each fuzzy controller addresses vehicles turning movements and dynamically manages both the phase and the green time of traffic lights. The proposed system combines the typical advantages of WSNs (such as, easy deployment and maintenance, flexibility, low cost, noninvasiveness, and scalability) with the benefits of using four parallel fuzzy controllers, one for each phase, instead of a single controller for all the phases (i.e., better performance, fault-tolerance, and support for phase-specific management).

The work proposes a novel system that combines several technologies (WSN, fuzzy logic control) in an original way so as to obtain a lightweight but effective solution, implementable on COTS devices, that is proven to provide better performance than other approaches in the literature. Simulation results obtained in the paper clearly demonstrate that the multi-controller approach here proposed outperforms related works in terms of reduction of the vehicle waiting times in the queues, especially under heavy traffic. Moreover, the multi-controller approach is proven to be very effective in balancing the vehicles waiting times between the four phases, even in the presence of phases with unbalanced arrival rates. The designed system fulfills all the targeted design challenges, i.e., flexibility, scalability, lightweight computation and low cost.

The feasibility of the proposed system on real components is proven through an implementation on the Microchip PIC24FJ256GB108 microcontroller (Microchip, 2009), a COTS device available at affordable price. Experimental results are compliant with simulation ones and confirm the effectiveness of the proposed approach.

The potential impact of the proposed solution is broad as, being a non-expensive system to realize, it can be extensively and effectively applied in practice.

One direction for future research on the multi-controller system here addressed is to augment the approach proposed in this work with a neural network able to forecast the traffic conditions, i.e., to predict the traffic conditions at different times of the day or on different days of the week. This combination would allow the fuzzy controller to make its decision taking into account not only the current traffic situation as detected by the WSN, but also the probable short-term evolution of the traffic conditions. In this way, the choice of the phase would depend on the number of vehicles in the queue, while the green time duration of the traffic lights would be determined based on the traffic flow forecast by the neural network.

Another future research direction is to provide the system with the ability of detecting emergency situation (such as, the presence in the queue of ambulances, fire trucks, etc.) through non-expensive sensors and of implementing suitable contingency actions so as to prioritize the phase that hosts those vehicles.

A further area of investigation refers to the adoption of low-power mechanisms to reduce the WSN node power consumption (as shown in Collotta et al. (2011)), thus increasing the network lifetime.

Our approach also paves the way for more advanced applications. In fact, the WSNs that are used for real-time monitoring of traffic conditions (Iannizzotto et al., 2010) are not necessarily limited to this application only. For instance, a multi-function wireless traffic monitoring system can be developed by adding other sensing modalities to the existing sensor node platforms, such as, temperature or humidity sensors to detect ice, snow, rain or fog. This multi-functional characteristic of WSN offers a great potential for realizing even more advanced ITS applications.

Finally, the WSN nodes can play a role in an integrated framework, in which dynamic traffic lights management is integrated with Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication for advanced ITS in a Smart City context.

References

Abbas, M. K., Karsiti, M. N., Napiah, M., Samir, B. B., & Al-Jemeli, M. (2015). High accuracy traffic light controller for increasing the given green time utilization. *Computers & Electrical Engineering, 41*, 40–51. http://dx.doi.org/10.1016/j.compeleceng.2014.12.011. URL: http://www.sciencedirect.com/science/article/pii/S0045790614003206..

Bi, Y., Srinivasan, D., Lu, X., Sun, Z., & Zeng, W. (2014). Type-2 fuzzy multi-intersection traffic signal control with differential evolution optimization. *Expert Systems with Applications, 41*, 7338–7349. http://dx.doi.org/10.1016/j.eswa.2014.06.022. URL: http://www.sciencedirect.com/science/article/pii/S0957417414003637.

Calderoni, L., Maio, D., & Rovis, S. (2014). Deploying a network of smart cameras for traffic monitoring on a city kernel. *Expert Systems with Applications, 41*, 502–507. http://dx.doi.org/10.1016/j.eswa.2013.07.076. URL: http://dx.doi.org/10.1016/j.eswa.2013.07.076.

Cervin, A., Henriksson, D., Lincoln, B., Eker, J., & Arzen, K. (2003). How does control timing affect performance? analysis and simulation of timing using jitterbug and truetime. *IEEE Control Systems Magazine, 23*, 16–30. http://dx.doi.org/10.1109/MCS.2003.1200240.

Collotta, M., Pau, G., Salerno, V., & Scata, G. (2011). A fuzzy based algorithm to manage power consumption in industrial wireless sensor networks. In *Industrial informatics (INDIN), 2011 9th IEEE international conference on* (pp. 151–156). http://dx.doi.org/10.1109/INDIN.2011.6034854.

Comert, G. (2013). Simple analytical models for estimating the queue lengths from probe vehicles at traffic signals. *Transportation Research Part B: Methodological, 55*, 59–74. http://dx.doi.org/10.1016/j.trb.2013.05.001. URL: http://www.sciencedirect.com/science/article/pii/S019126151300074X.

Diaz-Cabrera, M., Cerri, P., & Medici, P. (2015). Robust real-time traffic light detection and distance estimation using a single camera. *Expert Systems with Applications, 42*, 3911–3923. http://dx.doi.org/10.1016/S0191-2615(01)00006-6.

Dion, F., & Hellinga, B. (2002). A rule-based real-time traffic responsive signal control system with transit priority: Application to an isolated intersection. *Transportation Research Part B: Methodological, 36*, 325–343. http://dx.doi.org/10.1016/S0191-2615(01)00006-6. URL: http://www.sciencedirect.com/science/article/pii/S0191261501000066.

Gomez, A., Alencar, F., Prado, P., Osorio, F., & Wolf, D. (2014). Traffic lights detection and state estimation using hidden markov models. In *Intelligent vehicles symposium proceedings, 2014 IEEE* (pp. 750–755). doi: http://dx.doi.org/10.1109/IVS.2014.6856486.

Iannizzotto, G., La Rosa, F., & Lo Bello, L. (2010). A wireless sensor network for distributed autonomous traffc monitoring. In *Human system interactions (HSI), 2010 3rd conference on* (pp. 612–619). doi: http://dx.doi.org/10.1109/HSI.2010.5514504.

IEEE (2006). IEEE standard for information technology – telecommunications and information exchange between systems- local and metropolitan area networks-specific requirements part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs). Technical Report IEEE. URL: http://dx.doi.org/10.1109/ieeestd.2006.232110. doi: http://dx.doi.org/10.1109/ieeestd.2006.232110.

Kanungo, A., Sharma, A., & Singla, C. (2014). Smart traffic lights switching and traffic density calculation using video processing. In *Engineering and computational sciences (RAECS), 2014 recent advances in* (pp. 1–6). http://dx.doi.org/10.1109/RAECS.2014.6799542.

Kulkarni, G., & Waingankar, P. (2007). Fuzzy logic based traffic light controller. In *Industrial and information systems, 2007. ICIIS 2007. International conference on* (pp. 107–110). doi: http://dx.doi.org/10.1109/ICIINFS.2007.4579157.

Microchip (2009). PIC24FJ256GB108 – 16-bit PIC and dsPIC Microcontrollers. Microchip technology. URL: http://ww1.microchip.com/downloads/en/DeviceDoc/39897c.pdf.

Murat, Y. S., & Gedizlioglu, E. (2005). A fuzzy logic multi-phased signal control model for isolated junctions. *Transportation Research Part C: Emerging Technologies, 13*, 19–36. http://dx.doi.org/10.1016/j.trc.2004.12.004. URL: http://www.sciencedirect.com/science/article/pii/S0968090X04000683.

Pappis, C., & Mamdani, E. H. (1977). A fuzzy logic controller for a trafc junction. *IEEE Transactions on Systems, Man and Cybernetics, 7*, 707–717. http://dx.doi.org/10.1109/TSMC.1977.4309605.

Qi, L., Zhou, M., & Ding, Z. (2013). Real-time traffic camera-light control systems for intersections subject to accidents: A petri net approach. In *Systems, man, and cybernetics (SMC), 2013 IEEE international conference on* (pp. 1069–1074). doi: http://dx.doi.org/10.1109/SMC.2013.186.

Shahraki, A., Shahraki, M., & Mosavi, M. (2013). Design and simulation of a fuzzy controller for a busy intersection. In *Computer applications technology (ICCAT), 2013 international conference on* (pp. 1–6). doi: http://dx.doi.org/10.1109/ICCAT.2013.6521986.

Sun, D., Jiang, R., & Wang, B.-H. (2010). Timing of traffic lights and phase separation in two-dimensional traffic flow. *Computer Physics Communications, 181*, 301–304. http://dx.doi.org/10.1016/j.cpc.2009.10.003. URL: http://www.sciencedirect.com/science/article/pii/S0010465509003142.

Trabia, M. B., Kaseko, M. S., & Ande, M. (1999). A two-stage fuzzy logic controller for traffic signals. *Transportation Research Part C: Emerging Technologies, 7*, 353–367. http://dx.doi.org/10.1016/S0968-090X(99)00026-1. URL: http://www.sciencedirect.com/science/article/pii/S0968090X99000261.

Wilamowski, B. (2012). Suitability of fuzzy systems and neural networks for industrial applications. In *Optimization of electrical and electronic equipment (OPTIM), 2012 13th international conference on* (pp. 1–7). doi: http://dx.doi.org/10.1109/OPTIM.2012.6231989.

Wu, L., Zhang, X., & Shi, Z. (2010). An intelligent fuzzy control for crossroads traffic light. In *Intelligent systems (GCIS), 2010 second WRI global congress on* (Vol. 3, pp. 28–32). doi: http://dx.doi.org/10.1109/GCIS.2010.59.

Zaied, A. N. H., & Othman, W. A. (2011). Development of a fuzzy logic traffic system for isolated signalized intersections in the state of kuwait. *Expert Systems with Applications, 38*, 9434–9441. http://dx.doi.org/10.1016/j.eswa.2011.01.130. URL: http://www.sciencedirect.com/science/article/pii/S0957417411001503.

Zhaohui, W., Yanfei, L., Wei, X., & Jian, M. (2003). Application of knowledge management in intelligent transportation systems. In *Intelligent transportation* *systems, 2003. Proceedings. 2003 IEEE* (vol. 2, pp. 1730–1734). doi: http://dx.doi.org/10.1109/ITSC.2003.1252779.

Zhou, B., Cao, J., & Wu, H. (2011). Adaptive traffic light control of multiple intersections in wsn-based its. In *Vehicular technology conference (VTC Spring), 2011 IEEE 73rd* (pp. 1–5). doi: http://dx.doi.org/10.1109/VETECS.2011.5956434.

Zhou, B., Cao, J., Zeng, X., & Wu, H. (2010). Adaptive traffic light control in wireless sensor network-based intelligent transportation system. In *Vehicular technology conference fall (VTC 2010-Fall), 2010 IEEE 72nd* (pp. 1–5). doi: http://dx.doi.org/10.1109/VETECF.2010.5594435.

Zou, F., Yang, B., & Cao, Y. (2009). Traffic light control for a single intersection based on wireless sensor network. In *Electronic measurement instruments, 2009. ICEMI '09. 9th international conference on* (pp. 1-1040–1-1044). doi: http://dx.doi.org/10.1109/ICEMI.2009.5273994.