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A Novel Road Monitoring Approach using Wireless Sensor Networks

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Abstract— **This paper shows an innovative Wireless Sensor Network (WSN) architecture based on a flexible Quality of Service (QoS) approach for road traffic management. The aim of this work is to analyse an algorithm that dynamically enables/disables some cameras according to the real need to monitor a given area, It is based on traffic volume measured values. This approach has been developed in order to manage both network topology and workload conditions, using a fuzzy logic controller for a flexible QoS management. Performances of this approach have been evaluated using TrueTime and Simulink/Matlab.**

Keywords- Real-Time, Traffic detection, IEEE 802.15.4/ZigBee, Fuzzy Logic Controller

I. INTRODUCTION

In literature WSNs have been explored in several domains. In road monitoring, real time information are necessary to plan, for example, alternative ways in case of traffic congestion. These information may be obtained from cameras installed along roads [1], [2]. Otherwise, this is often not enough, especially when weather conditions are not good. Many works show how the use of WSNs can be a valuable support to the problem of real-time traffic monitoring [3], [4], [5]. Through WSNs, a timely service can be guaranteed in every situation. The main aim of this paper is to show a road traffic management approach that combines video-monitoring with wireless sensors to detect road traffic. The challenge is to characterize an architecture in order to:

- offer an image-based monitoring;
- produce several information, which can be processed to allow a timely interpretation of road situation.

The base idea is to integrate cameras information with parameters measured through sensors installed along roads, for example magnetometers or power sensors for traffic detection.

WSNs allow this integration and benefits of their use in this area are different:

- WSNs can continuously monitor and evaluate roads with less human work.
- WSNs can work during night and not good weather conditions (fog, rain, pollution, volcanic ash).
- WSNs are low-cost and low-power [6].
- WSNs can be used to send images [7]. This means that exhaustive information (images and traffic volume measures) can be obtained.
- WSNs can dynamically manage the number of active devices. If necessary, device number inside a monitored area may increase to produce more detailed information.

The main contribution of this work is the evaluation of a WSN for road management and data traffic acquisition, based on IEEE 802.15.4 standard protocol [8]. IEEE 802.15.4 is the most suitable protocol for this kind of approaches, because it provides a MAC layer that implements a Contention Access Period (CAP) based on CSMA/CA algorithm and a Contention Free Period (CFP) using pre-allocation of Guaranteed Time Slots (GTS). However, only seven GTS can be pre-allocated. Therefore, when the number of nodes increase, it's necessary to manage communication in CAP and avoid performances degradation against a higher workload.

This paper is organized as follow: Section II describes related works. The System Model is shown in section III, while the proposed algorithm is described in Section IV. Section V shows QoS management approach using a fuzzy logic controller. Section VI describes performance evaluation. Finally, Section VII, summarizes the paper and discusses future works.

II. RELATED WORK

Integration of WSN and monitoring through images detection has been proposed in [9], [10]. Authors proposed a system architecture in which mobile robots, together with sensor networks, are used to explore and monitor dangerous or unknown areas. The system consists of a WSN that sends signals about the way to go, to a mobile robot equipped with a drive sensor. The robot mounts also an IP camera through which it can send images of the explored zone. Another example of integration is realized in [11]. In general, the use of WSNs combines low cost, in terms of deployment and

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management, with the possibility to cover large areas like airports, train stations, subways, malls, and others. However, these works [9], [10], [11], [12] are intended only for human behavior control or monitor possible gas leaks and power management. Some recent works propose WSN applications for road monitoring and in particular for vehicular traffic evaluation. Reference [13] describes an algorithm that simply deals with traffic volume monitoring, speed detection, lane occupancy and, at least, vehicle classification, without respond to high traffic volume. Reference [14] shows an algorithm for in-network aggregation of the traffic flow-time series, which significantly reduces communication costs between sensor nodes and base station. The limits of these techniques, however, are that they do not provide a scalable methodology in order to follow topology changes. Some researchers describe a WSN-based monitoring technique [15] whose main purpose is to minimize road traffic, reducing the average waiting time on traffic lights. Sensor nodes, in this case, are involved in road parameters sensing for vehicle detection. Subsequently, data collected are sent to a coordinator for processing (adjusting traffic light durations or exchanging information with other agents for better traffic flows optimization). Otherwise, there is not a control technique for dynamic activation (or deactivation) of nodes. The approach here proposed, advances the state of art: the integration of a wireless sensor network with a monitoring system through images, allows to monitor traffic and, at the same time, dynamically manages network topology. Through a mechanism for QoS management, presented in Section IV, it's possible to manage activity changes in the monitored area and the consequent (possible) network overload.

III. SYSTEM MODEL

A WSN monitoring system based on IEEE 802.15.4 implies the coexistence of a high number of devices in order to ensure a right vehicular traffic analysis. Figure 1 represents the architecture proposed in which information detected cross the network through IEEE 802.15.4/ZigBee. It integrates sensors connected to cameras with several magnetic sensors.

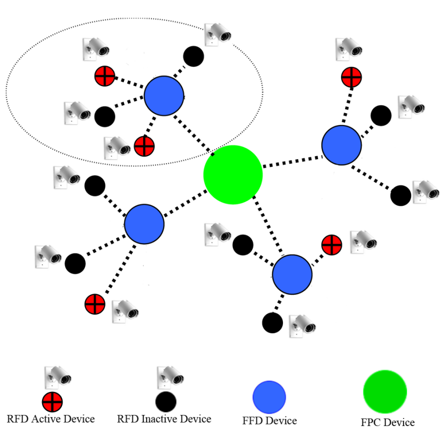

Fig. 1. System Architecture

Magnetic sensors (RFD nodes - Reduced Function Device, red and black nodes shown in Fig. 1) measure magnetic field distortion caused by the presence of ferrous objects (e.g. cars). In other words, they provide information for traffic flows estimation. Then, they send acquired data to their Full Function Device (FFD) nodes. An FFD node could be a ZigBee router [23]. It forward data received from RFD nodes to the First Pan Coordinator (FPC) which processes information and send, in case of high traffic volume observed, an activation message to "sleeping" nodes (black nodes in Fig. 1). In this way more nodes may be activated only in case of real need. Furthermore, the system provides a mechanism for QoS management in order to ensure scalability, adaptability and flexibility of the network.

A. *The Approach*

The algorithm here proposed, called Dynamic Monitoring Algorithm (DMA), allows to activate RFD devices, used for data sensing, in case of critical traffic situations detected. Furthermore, the DMA controls network workload through a fuzzy controller ensuring improved performance. The algorithm calculates the instantaneous magnetic field value through several magnetic sensors. So, traffic volume along the road, here called VT, can be evaluated. If the measured value of VT exceeds the threshold value, (queue or traffic jam detected), and additional nodes are OFF, the FPC (green node in Fig. 1) sends an activation request to FFD nodes (blue nodes in Fig. 1). Then, they forward the request to sleeping RFD nodes using the sleep/wakeup mechanism described in the IEEE 802.15.4 standard protocol [8]. The idea is to forward a request setting to 1 the bit "High Traffic" introduced in the free reserved subfield of standard MAC control field frame (Fig. 2).

Bits: 0-2	3	4	5	6	7	8	9	10-11	12-13	14-15
Frame Type	Security Enabled	Frame Pending	Add. Request	PAN ID Compress	Reserved	High Traffic	ADD Nodes Req.	Dest. Address. Mode	Frame Version	Source Address. Mode

Fig. 2. Modified MAC Control Field Frame

B. *DMA flow chart*

Flow chart in Fig. 3 shows DMA, explaining all its functions. *Threshold_inizialization()* function defines the minimum traffic density. Beyond this limit, additional controls must be activated. According to magnetic field distortion detected by RFD sensors, traffic volume trend can be analytically represented (Fig. 4). *VT_acquisition()* function acquires data collected by magnetic sensors placed along roads. *Send_request_activation()* function, sends an activation request from the First Pan Coordinator to "sleeping" RFD nodes through the FFD nodes (ZigBee routers) using 802.15.4/ZigBee standard protocol. Sleeping nodes wake up periodically, as described by standard [8], for channel control.

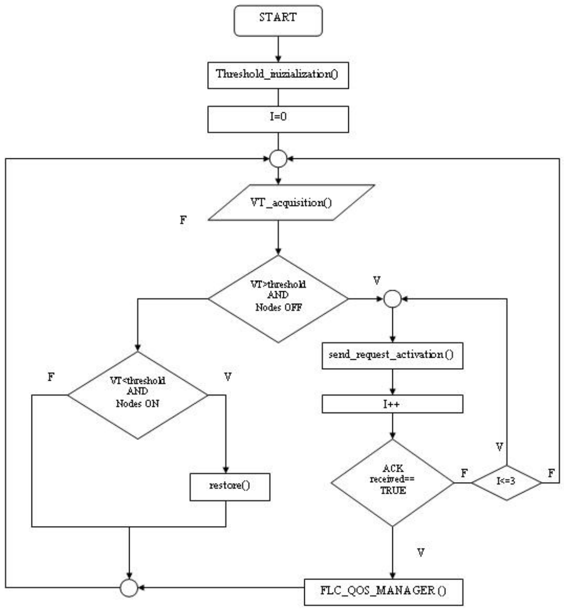

Figure 3. DMA Flow Chart

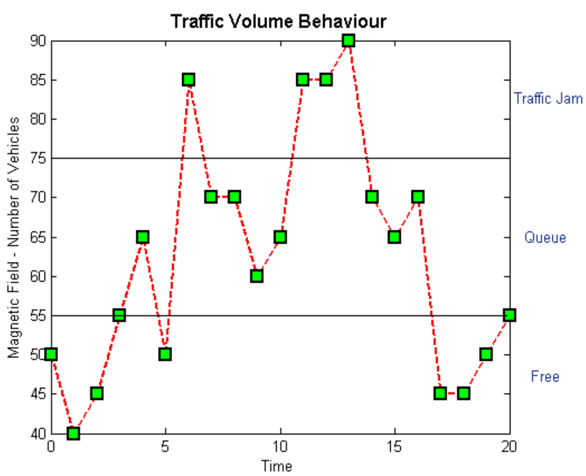

Figure 4. Traffic Volume Behaviour

If they found pending requests, they send an ACK. Otherwise, they return to "sleep mode". This mechanism provides considerable energy savings inside the WSN as described in several works [16], [17], [18], [19].

Restore() function restores network topology, disabling added nodes. This is done only when, at a given moment, measured traffic volume is less than the threshold value, and there are additional nodes activated. *FLC_QoS_Manager()* function deals with QoS dynamic management and will be described in detail in Section IV.

IV. Fuzzy Logic Controller

The fuzzy logic controller manages topology and network workload. A similar approach has been applied in a context of WSAN [20] (Wireless Sensor Actuator Network). In our case, we have designed a fuzzy controller to dynamically change the sampling period of RFD nodes. It determines the new sampling period (NST) on the basis of two input values:

- Deadline Miss Ratio Measured of packets (DMRM in fig. 5)
- Sampling Time (ST in fig. 5)

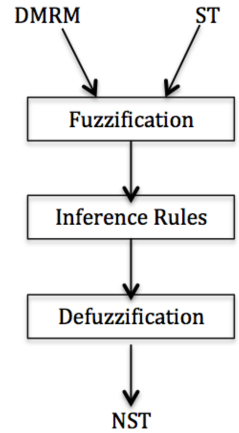

Figure 5. Fuzzy Logic Controller

Based on predetermined "membership" functions [21], inputs are converted into "language" values: Positive Big (PB), Positive Small (PS), Positive Medium (PM), Zero (ZE), Negative Small (NS), Negative Medium (NM), Negative Big (NB). Subsequently, an inference mechanism, based on several "IF-THEN" rules, determines the output linguistic value representing the new sampling time "NST" (Positive Big, Positive Small, Zero, Negative Small, Negative Big). Table I shows a generic example of inference mechanism functioning scheme. To better understand Table I, IF "CST" value is "NS" (Negative Small) and "DMRM" value is "ZE" (Zero), THEN "NST" value will be "ZE" (Zero). Finally, this value is defuzzified into a numeric value, which represents the new sampling period of RFD nodes. In our algorithm, for each variable, a range of value has been defined. Therefore the range has been divided in sub-ranges (called fuzzy sets). Established that Deadline Miss Ratio Measured (DMRM) can assume values between 0 and 1.25, this range can be divided into fuzzy sets as shown in Table II. In other words, if the value of DMRM is between 0 and 0.03, it will be fuzzyfied as "Very Low" (VL). Similarly, Current Sampling Time (CST) can assume values inside a range divided in fuzzy sets too, as shown in Table III.

TABLE I. Generic Example of Inference Rules

NST		**CST**				
		NB	**NS**	**ZE**	**PS**	**PB**
DMRM	**NB**	PB	PB	PB	PM	PS
	NS	PM	PS	PS	ZE	ZE
	ZE	PS	ZE	ZE	ZE	NS
	PS	ZE	ZE	NS	NS	NM
	PB	NS	NS	NM	NB	NB

TABLE II. DEADLINE MISS RATIO MEASURED FUZZY SETS

VL	0	0.0015	0.03
L	0.00265	0.0326	0.203
M	0.15	0.225	0.3
H	0.25	0.5	0.7
VH	0.55	1.001	1.25

TABLE III. CURRENT SAMPLING TIME FUZZY SETS

VL	0	2	4
L	0	4	8
M	4	8	12
H	8	12	16
VH	12	16	20

So, if Current Sampling Time has a value between 0 and 4, it will be fuzzyfied as Very Low (VL). As seen previously, outputs are input functions. According to fuzzy logic, these functions are expressed through IF-THEN constructs. To better understand, the following construct (1) (from Table IV) can be taken as a model:

$$\text{IF } (DMRM\_1 \text{ is } VL) \text{ THEN } (NST\_1 \text{ is } H) \qquad (1)$$

IF the DMRM value (measured by FFD node with ID number = 1) is Very Low, THEN the NST value (New Sampling Time for FFD node with ID number = 1) will be High. Table IV shows all inference rules which implement our fuzzy controller. These are combined inside the controller that will produce a single membership function that can be represented with a Gaussian function.

TABLE IV. INFERENCE RULES

1	IF *DMRM_1 is VL* THEN *NST_1 is H*
2	IF *DMRM_1 is L* THEN *NST_1 is M*
3	IF *DMRM_1* is M THEN *NST_1 is L*
4	IF *DMRM_1* is H THEN *NST_1 is VL*
5	IF *DMRM_1* is VH THEN *NST_1 is VL*
6	IF *DMRM_2 is VL* THEN *NST_2 is H*
7	IF *DMRM_2 is L* THEN *NST_2 is M*
8	IF *DMRM_2* is M THEN *NST_2 is L*
9	IF *DMRM_2* is H THEN *NST_2 is VL*
10	IF *DMRM_2* is VH THEN *NST_2 is VL*
11	IF *DMRM_3 is VL* THEN *NST_3 is H*
12	IF *DMRM_3 is L* THEN *NST_3 is M*
13	IF *DMRM_3* is M THEN *NST_3 is L*
14	IF *DMRM_3* is H THEN *NST_3 is VL*
15	IF *DMRM_3* is VH THEN *NST_3 is VL*
16	IF *DMRM_4 is VL* THEN *NST_4 is H*
17	IF *DMRM_4 is L* THEN *NST_4 is M*
18	IF *DMRM_4* is M THEN *NST_4 is L*
19	IF *DMRM_4* is H THEN *NST_4 is VL*
20	IF *DMRM_4* is VH THEN *NST_4 is VL*
21	IF *ST_1 is VL* THEN *NST_1 is VL*
22	IF *ST_1 is L* THEN *NST_1 is VL*
23	IF *ST_1 is M* THEN *NST_1 is L*
24	IF *ST_1 is H* THEN *NST_1 is M*
25	IF *ST_1 is VH* THEN *NST_1 is H*
26	IF *ST_2 is VL* THEN *NST_2 is VL*
27	IF *ST_2 is L* THEN *NST_2 is VL*
28	IF *ST_2 is M* THEN *NST_2 is L*
29	IF *CST_2 is H* THEN *NST_2 is M*
30	IF *CST_2 is VH* THEN *NST_2 is H*
31	IF *CST_3 is VL* THEN *NST_3 is VL*
32	IF *CST_3 is L* THEN *NST_3 is VL*
33	IF *CST_3 is M* THEN *NST_3 is L*
34	IF *CST_3 is H* THEN *NST_3 is M*
35	IF *CST_3 is VH* THEN *NST_3 is H*
36	IF *CST_4 is VL* THEN *NST_4 is VL*
37	IF *CST_4 is L* THEN *NST_4 is VL*
38	IF *CST_4 is M* THEN *NST_4 is L*
39	IF *CST_4 is H* THEN *NST_4 is M*
40	IF *CST_4 is VH* THEN *NST_4 is H*

V. PERFORMANCE EVALUATION

To demonstrate benefits introduced by the DMA, several simulations were carried out using:

- TrueTime [22]: it is a real-time simulation environment that allows co-simulation control tasks performed in real-time kernels.
- Simulink/Matlab has been used to test the DMA in a WSN 802.15.4 based.

The simulated network consists of a central FPC node. It covers 480 meters of road section in every direction thanks to FFD nodes located at a distance of about 50 meters from each other. Each FFD node (ZigBee router) provides a magnetic sensor, for traffic measures, and two cameras in "sleeping mode". These cameras will be activated only in case of real need. In other words, when magnetic sensors detect traffic volume increase.

The simulation campaign refers to periodic and aperiodic packets. The first concerns video monitoring traffic flows, while aperiodic packets concerns variable sent by magnetometer sensors. During simulations, have been evaluated: number of packets received and lost for image traffic and network management traffic respectively (it ensures network workload and traffic generated by magnetic sensors). Packet size considered is 18 Kb, data-rate equal to 180 Kbps, Simulation Time equal to 30s.

Figure 6 shows results obtained with fuzzy logic controller OFF while Figure 7 shows what obtained switching ON the controller. Results indicate a great improvement when the controller inside the network is ON: a higher number of image packets sent (230-270 Vs. 80-90) and, at the same time, a strong decrease of lost packets (80-120 Vs. 410-400).

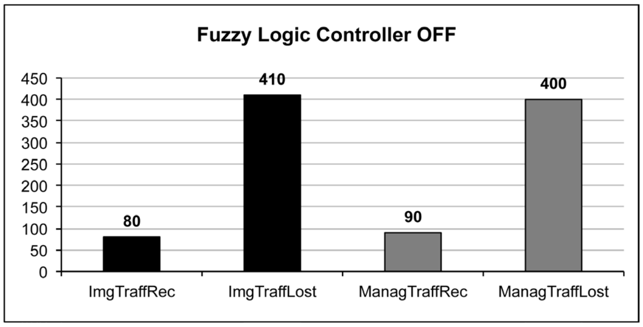

Figure 6. Packets sent and Pachets loss with fuzzy controller OFF

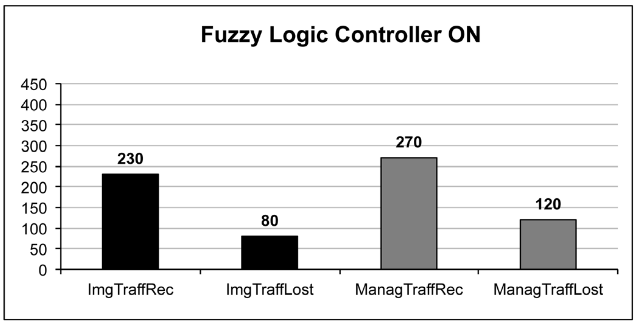

Figure 7. Packets sent and Pachets loss with fuzzy controller ON

We analyzed also network performances in terms of Throughput (Th) / Workload (Wl) (2). In other words:

$$\mathrm{TH/WL} = \frac{\text{Number of packets successfully sent and received}}{\text{Number of packets generated and transmitted}} \quad (2)$$

Figure 8, Figure 9 and Figure 10 show how the fuzzy controller reacts to network degradations.

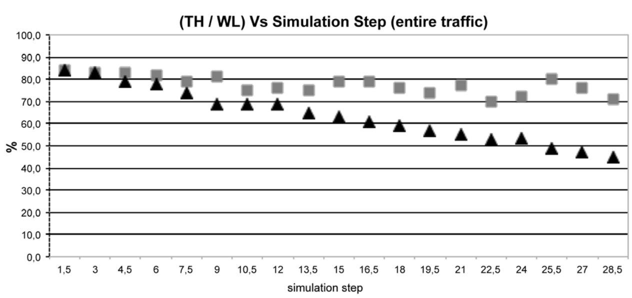

Figure 8. Th/Wl entire traffic

Figures 8,9,10 show how performances get worse when the controller is OFF. At each time window, in fact, the number of packets that correctly reach their destination, decreases till a minimum value measured of about 44% (total traffic sent), 41% (image traffic sent) and 59% (aperiodic traffic sent).

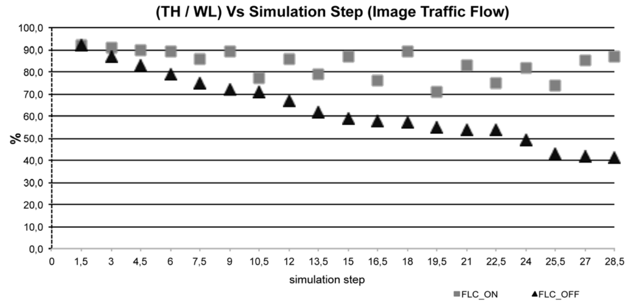

Figure 9. Th/Wl Images traffic flow

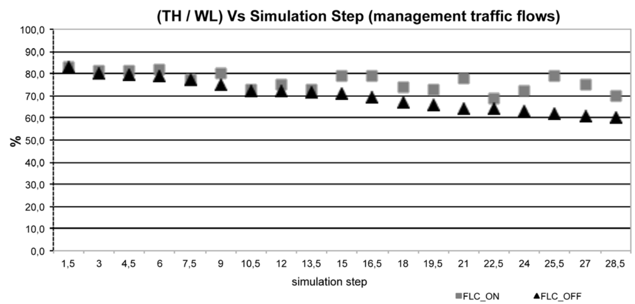

Figure 10. Th/Wl aperiodic traffic flow

Instead using the fuzzy logic controller, Th/Wl measured is equal to about 80% (total traffic sent), 76% (image traffic sent) and 82% (aperiodic traffic sent). The DMA has demonstrated that the controller dynamically responds to an overloaded scenario. It has been simulated a real situation: adding and removing stations which generate additional traffic to the network. It is able to prevent network collapse, while adding more monitoring nodes or when network conditions are close to saturation.

VI. Conclusions and Future Works

This paper discussed an algorithm to manage road traffic volume through a hybrid architecture that integrates magnetic sensors for vehicular traffic detection, with several cameras, to ensure better monitoring. The possibility to activate more devices only in case of real need, ensures energy savings. Furthermore, using a fuzzy logic controller, we can manage easily and in a better way network workload changes. The controller works dynamically, based on QoS measured parameters and results are really promising. We are currently working on the implementation of the proposed architecture using COTS devices, with panels which indicate, along the monitored road section, the presence of heavy traffic and suggesting, where possible, alternative routes or estimated time to reach the desired destination. Moreover, our research will focus on real-time scheduling algorithms having as input data acquired through WSNs for road monitoring near traffic lights. In particular we are developing a mechanism to allow dynamic management of queues at traffic lights in order to give more green time to road sections with longest queues.

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