A Wireless Sensor Network Architecture for Traffic Monitoring in a Road Network

Nouha Rida, Loubna Elhaloui and Mohammed Ouadoud

***Abstract*— Road congestion has become one of the major problems of urban cities due to the growth in the number of vehicles and the limitation of road infrastructure. The consequences of this congestion can be seen through a difficult movement of vehicles, an increase in CO2 emissions, increasing energy consumption, stress for drivers and the dismantling of road safety. Intelligent Transport Systems (ITS) based on wireless sensor networks (WSN) have emerged with new solutions and application potentials in the context of the Intelligent City. This manuscript provides an overview of WSN technology in the field of ITS It takes the advantage of small size, low power consumption, uncalled coverage and a network of intersections connected to each other to improve ITS efficiency. It provides a sensor network architecture at each three-level traffic intersection to improve the quality and methods of the traffic information collection service. A brief analysis of the important system requirements, as well as the operation of the system, is described.**

***Keywords*— Intelligent transportation systems, wireless sensor network for smart mobility, smart traffic management system, traffic light control system.**

I. Introduction

Traffic monitoring system is an essential part of the intelligent transportation systems. This system allows continuous monitoring of traffic condition by using sensors to collect traffic information, such as: number of vehicles in each road segment, waiting time, speed of a vehicle, etc. those information's are used by decision-making node in order to control the traffic in real time and optimize the urban transport network performance. figure 1 illustrates the mechanism of real-time transport network management in intelligent transportation system.

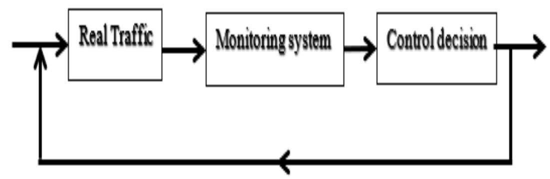

Fig. 1. ITS mechanism

Traditional monitoring systems use expensive sensors such as: radar, video camera, inductive loops. Those are based on wired communications that often transmit limited volumes of traffic data with high redundancy over expensive communication channels [1]. In addition, this type of sensors cannot be able to cover the entire road network of a city, because of their high cost of installation and maintenance.

With the appearance of a new generation of wireless sensor network (WSN), this network presents a viable alternative to traditional surveillance systems, due to their reduced costs, and their smart deployments.

In addition, it can be used as a distributed monitoring and control system for large-scale traffic [2] [3]. For the distributed control, the use of a hierarchical control structure is almost essential for system design, which combines both the advantages of localized and centralized control strategies, express the global objectives of traffic management for a city [4].

Continuous monitoring of the traffic variations for an area requires the implementation of an efficient and adapted wireless sensor network. Indeed, this network must meet the needs for the local and the global traffic monitoring objectives, by communicating in real time the data collected by the sensor nodes.

The purpose of this paper is to propose a new scheme of traffic monitoring by implementing hierarchical model of control using a three-tier architecture with a wireless sensor network. We will present in this document the adopted design methodology of this architecture with presenting certain key design factors: the nodes behavior at each level, the data types exchanged between the nodes of the network, and the energy management of the nodes.

To achieve this goal, we first define the network architecture, the chosen scenario and the network requirements. then, we present a description of the proposed model with the different possible network configurations. In a second step, we model the behavior of each sensor node according to its role in the

Manuscript received Apr. 11, 2022.

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https://doi.org/10.17758/URUAE16.AE08221004

network. Finally, we describe the organization of the data exchanged between these nodes, in order to exchange traffic data in real time.

II. Background and Literature Review

Researchers in the field of road traffic management based on sensor networks are becoming a reality. In recent years, a major research effort has been carried out by the scientific community on the following topics: the development of adaptive strategies for controlling traffic lights [20-25], the design of effective architectures of the sensor network for surveillance Small-scale traffic (the case of a road intersection) and large-scale traffic for an area or city [8], [9] [10], emergency vehicle traffic management, etc.

Indeed, very little research is proposed architectures of the wireless sensor network for traffic monitoring. Most of them are focused on two categories: the number of sensors per lane and the control strategy by type of network: local strategy for an isolated or distributed intersection and coordinated for an extended network for a city or area.

We present below the systems that we have met in the literature with examples of proposed architectures and sensors used for traffic control of road intersections:

Tubaishat et al. [19] study the influence of using a topology with one sensor per lane and another of two sensors per lane on the quality of traffic data collected, and on the efficiency of the adaptive traffic management strategy in an isolated intersection. They arrived that two sensors per lane allow better results; one sensor does not enough to specify the vehicles number, the speed of the vehicles or the number of the queue.

Subsequently they separated the two sensors of the same lane by different distances in order to study the influence of this variation on the quality of the collected data. They have arrived that the variation in distance has a negligible effect on the efficiency of the traffic control strategy in an intersection.

In the topology used, the sensors send traffic data (vehicle speed, vehicle numbers, queue length, etc.) to the intersection control agent, who chooses the traffic control strategy. intersection and dynamically controls the traffic lights in real time.

Youssef et al. [20] propose an adaptive system for controlling the traffic lights of a single and multiple intersection, the system is based on a network of wireless sensors for traffic monitoring.

They presented their system with two algorithms. The first is TSCA, an algorithm that manages communications between traffic sensor nodes installed on the roadside and the base station that executes the control algorithm. The communications between the sensor nodes and the base station are initialized by the latter during each start of the traffic light cycle, and the sensors only respond to these requests by sending the sequences of the detected physical events in a random time slot.

The authors use a star topology for the LAN of an intersection and for the WAN on multiple intersections, they did not specify the technology of communication between intersections.

The second algorithm (TSTMA) is the controller, which defines the next traffic light plan based on the data communicated to the base station by the sensor nodes. The phase selection process is based on the order of the queues, so that the one containing the maximum lengths is prioritized.

The authors present the algorithm for signal sequences in isolated and interconnected intersections. But they do not talk about security of communication or the type of sensor used (magnetic ...) or the type of data exchanged between the intersections and the frequency of these exchanges.

Zhou et al. [21] propose an adaptive traffic light management system for four-way intersection, each with two lanes (go forward and turn left).

The proposed algorithm has three steps: vehicle detection, determination of the green light sequence and determination of the green light duration. In the second step, they consider a number of traffic factors such as: queue size, waiting time, vehicle density, presence of empty spaces between vehicles, etc. In the first step of the algorithm, they used sensor nodes installed at the road pavement with two sensors per lane to detect the traffic flow in each lane.

In [22] Another version of this algorithm is proposed for multi- intersections to plan a cooperative traffic light control for several intersections in order to: reduce the stops number, increase the road network flow, and decrease the waiting time of vehicles.

The authors propose signaling management algorithms for isolated and interconnected intersections, but they do not give information on the communication scheme to be used, on the technologies of communication between intersections, distance between sensors on the same lane, or the energy management of these sensors. In addition, the sensors used are not mentioned. The integration of this traffic light system with other possible ITS or Internet systems is not discussed.

In [29,30], we have inspired the smallest job first method of task scheduling to be execute by a computer processor. They proposed the smallest phase first algorithm, which gives priority to phases with the smallest waiting line. In another study [12,39-33], the authors proposed solutions using a WSN architecture for isolated intersection.

Zou et al [23] propose a rather interesting approach to measure arrivals. They use a model incorporating only one sensor per direction (thus four sensors for an intersection) and use the realistic assumption that they are able to detect the variations of the Earth's magnetic field over five meters. Thus, by putting a sensor, at the roadside, before each traffic light of the intersection, their model is able to count the number of cars using each road. This single parameter makes it possible to establish the duration of the lights at different intervals. The authors also define a mechanism for energy saving sensors: when a direction has a green light, then the corresponding sensor goes to sleep and wakes up when the traffic light turns red to count the arrivals. Finally, the authors use data extracted directly to simulate the effectiveness of their solution.

The proposed solution is limited since the detection range of the sensors is limited for a sensor per lane, and this topology does not allow to specify the number of vehicles in each lane, the waiting time, the speed or follow a vehicle in its displacement in the intersection (because there is only one sensor for a direction).

In [5,18], the authors propose a cooperative traffic light management system for multi-intersections. This system relies on the use of a multi-intersection wireless sensor network to detect vehicle movements and synchronize traffic lights. For each intersection the wireless sensor network is organized into three levels: physical event detection sensors (electromagnetic sensors), aggregator nodes to transfer information from the sensor nodes to the master node that applies proper control strategy. Master nodes will also need to send the collected information to nearby intersections. This step is intended to estimate the time needed to move from one intersection to another. This delay will be used to configure the green light synchronization process.

The authors do not present the communication scheme between nodes of the network, and a fault tolerance strategy to reduce the loss rate as well as a strategy of energy saving. In addition, they have no security mechanism.

III. A MULTI-LEVEL MODEL OF TRAFFIC MONITORING

A. The model description

The proposed model for a traffic intersection surveillance and control system is a multi-level hierarchical and distributed system of control, based on the assumption that an effective urban traffic control system must solve problems (crossroads related) and global optimization (zones or cities) [13].

Hierarchical control can be presented as a method to solve the complexity of the control system by composing their problems into simpler subproblems and by assembling the operation of their solutions into a hierarchical structure [14].

A traffic control system relies on a hierarchical control offers two main advantages over conventional methods: First, the scalability of the system [15], which is a requirement for very complex systems, such as urban traffic; Secondly, flexibility, hierarchical control provided the fluidity to change the control application, for example by integrating other urban traffic control system with other applications, and adding or removing monitoring entities.

Figure 2 presents the proposed sensors network model for road traffic control. The nodes of this network are divided into clusters, one cluster per intersection. The local traffic data is detected and sent to the local leader node (A), that is selected in each cluster/intersection during cluster formation.

During monitoring periods, the leader node supports the reception of traffic information collected by the sensor nodes of its cluster, manages local information transmissions, receives data from other clusters, performs the local control algorithm, and transmits the data to other clusters (adjacent intersections) or to central node.

The information transmission to the central node (S) allows for in-depth information processing for various strategies and procedures for large-scale traffic control and service (city or area).

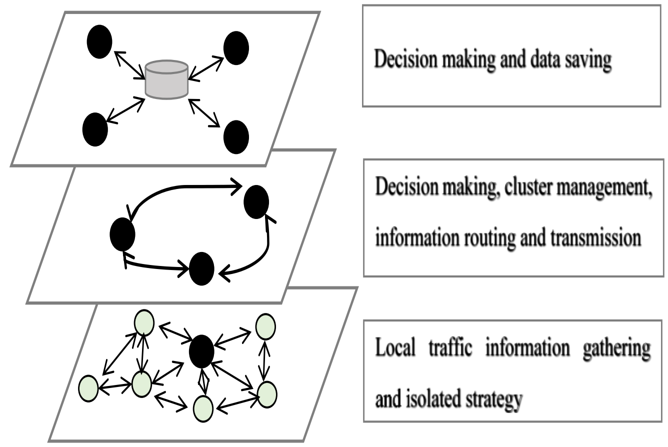

Fig. 2. The proposed network architecture

Below we describe the main characteristics of each level.

B. The model characteristics

1) First level: Network of an intersection

This level consists of sensor nodes (N) and an actuator node (A). The sensors form a cluster network to monitor the physical traffic and transmit the results to the actuator node (A). The nodes of this level form a star topology (chosen for its simplicity, adapted for small networks and its energy efficiency). The nodes are fixed, they are installed in a specific location on the road pavement because they must collect physical data on road traffic in this location. The transmission distance requirement of the sensor nodes is thus considerably reduced, to reduce their energy consumption. The number of sensors is not fixed for all intersections of the road network, it can be changed from one intersection to another according to the structure of the intersection (number of lanes and directions) and the traffic control strategy adopted.

The actuator node receives inputs from the sensor nodes of its cluster to extract information on the traffic intensity in each direction, the waiting time, the queues length, etc. The control algorithm implemented at this level of the hierarchy, executed by the actuator node, it can be an isolated signal control strategy if this intersection is not connected to other intersections. the main objective of this strategy is optimizing traffic parameters for the local intersection, based only on the data provided by the traffic sensors installed in this intersection/cluster. This control strategy may also include a "default" behavior that is executed whenever the controller or the actuator node fails to communicate with the other sensor nodes.

2) The second level: Group of intersections

This level is characterized by the communication between actuator nodes of neighboring clusters in the adjacent intersections. In order to optimize traffic in each of them according to specific actions involving congestion management, reorientation of the traffic flow, optimization of waiting time and queues length, and creating of "green waves”. The actuators nodes of this level exchange traffic information among themselves, such as traffic characteristics: waiting times, vehicle queues, and so on. It may also receive information from the base station (see next item) regarding the efficiency objective of the current traffic, e.g., to avoid long queues and minimize vehicle delays, or avoid movements arriving a certain direction. This level includes a coordinated traffic control strategy for interconnected intersections.

Those nodes (A) form a transmission and management level. As these nodes take more charge and power consumption than other members of the cluster, a battery backup or direct power cable is added to eliminate energy constraints.

In addition to a 916 MHz general radio transceiver that collects information from cluster members, an additional 2.4 GHz radio transceiver, compliant with the IEEE 802.15.4 / ZigBee protocol [16], is equipped with actuator nodes for provide reliable data. Thus, the separate communication scheme can avoid potential interference between intra-cluster and inter-cluster levels and ensure the rapid transmission of global traffic information.

3) The third Level: Network of an area or city

This last level concerns the communications between the actuator nodes and the control center of the traffic control systems of the city. The sink node presents the central node of the network which has a complete knowledge of the global network condition of an area. It can be a server that presents the traffic control center of the city. Its main functionality is the reception and processing of information from the sensors to meet the overall objectives for a specific area or for the entire city. This level includes not only traffic control assistance and transport statistics, but also dynamic dissemination of information, travel advice, provision of individual traffic control services, such as: local alerts, estimated journey time, reservation of parking spaces, etc. It responds by adjusting traffic parameters in case of unforeseen events such as street work, reducing traffic in bottling areas, car accidents, etc.

The proposed model has the advantage of providing three levels of management and two levels of data access (distributed storage): local access on the node (A) and remote access on the central node Sink. The model is based on an architecture that minimizes energy and data processing load per sensor and per level involving low overall network consumption.

IV. The Traffic Surveillance Network Design

We proposed a multi-level network that consists of three levels, characterized by distributed detection and processing capabilities. The lower level represents the collection network of traffic information. This network includes the sensor nodes (N) for detecting the arrival or departure events of vehicles. The intermediate level represents communications between the actuator nodes of adjacent clusters, in order to exchange traffic information on adjacent intersections. The last level represents the communications between the actuators (A) and the base stations (N). The leader or actuator node(A) of each intersection applies practical traffic control and service strategies using the information provided by the local sensor nodes and actuators nodes of neighboring intersections.

To develop this network for road traffic monitoring, there are different aspects to be considered. The radio component is the component that consumes the most energy in the sensor. In our study, energy conservation will mainly focus on first-level nodes as they are the most critical. For this, it is necessary to minimize their communications of events captured by time driven and not by event driven.

In our design framework, we assume that all nodes adhere to the request-driven transmission model that periodically evaluate traffic monitoring by first-level sensors. This transmission model is described in figure 4. It shows the interaction between the different levels as well as the exchange of requests for traffic information "beacon-MSG" between the actuator (A) and sensor nodes (N) in the communication chain. In order to respond to these requests that can be repeated several times in a traffic light management cycle, it is expected that the nodes (N) remain in listening mode, and upon receipt of the message’s "beacon", they must communicate their detected events.

This a mechanism allows to reduce the communication of the sensor nodes by responding to the "beacon-MSG" requests started by the actuator node(A), which will also have an impact on the energy consumption of the nodes (N).

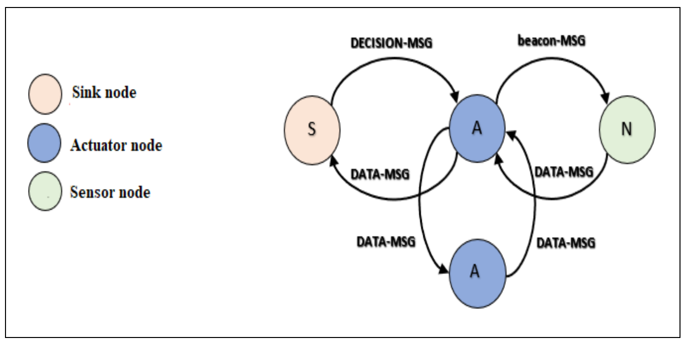

Fig. 4. Inter-sensor interaction between network levels.

In our design process, we distinguish two parts. The first part concerns the modelling of the internal behavior for each node using the States-Transitions diagram: descripts the adequate behavior of the nodes and programs the tasks to be executed in relation to the scenario of the application. The second part concerns the definition of inter-sensor communications (inter-level interactions).

A. *The network nodes Behaviors*

In our multi-level network model, we propose three distinct behaviors modelled using the States-Transitions diagram. Each behavior depends on the position and role assigned to the node, as shown in figure 4, expected functionality and node type requirements (three types of nodes considered). We describe in the following the functional states as well as the possible transitions for the different behaviors of each node, that can create a change in the overall behavior of the network.

1) *Sensor node*

The tasks of detecting and collecting physical measurements are processed by the sensor node. After receiving a "beacon-MSG" request to send the collected traffic information, the sensor node communicates the collected data directly to its actuator node.

Three states describe the behavior of this node as shown in figure 5. During state 1, the node constantly monitors and controls the value of the sensor parameters and the transmission unit is always active at all times allowing the node listen to "beacon-MSG" requests to send the collected events. The node goes to state 2 when it receives a message to communicate the traffic data by its actuator. In this state, the sensor node sends the collected data (DATA-MSG) to its actuator and waits (according to defined time delay) an acknowledgment of receipt (ACK -MSG) (state 3). If the ACK -MSG is not received, the sensor node retransmits the message. At this point, a retransmission mechanism must be considered taking into account the fixed number of retransmissions. When the ACK-MSG is received, the sensor node returns to the listening state (state 1).

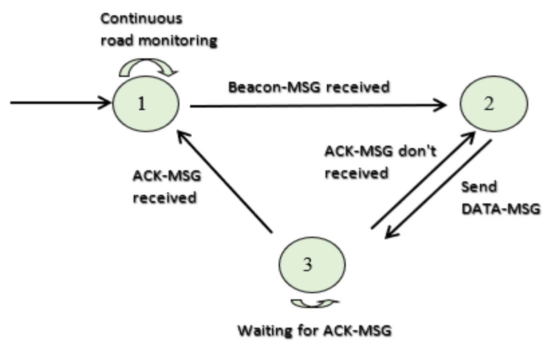

Fig. 5. The sensor node behavior

2) *Actuator node*

The actuator node is intelligent node that exploits the captured events by the sensor nodes, in the local strategy of intelligent traffic control approach. It also performs a second level of data aggregation (so that data leaves the WSN network from the local intersection to other clusters or to Sink).

As described in figure 6, in state 1, the actuator node waits the end of the current green light signal for a new operation to detect the traffic state in the intersection.

When it starts a new operation, state 2 is activated. In this state, the actuator node sends a beacon-MSG message to alert its sensor nodes of beginning the new operation, and waits (according to a defined timeout) for an acknowledgment (MSG-ACK) (state 3). If the MSG-ACK is not received, it returns to state 2. After it receives the acknowledgment, in state 3, the actuator waits the reception of the traffic data for a definite time and towards the end of this time (state 4), if the node does not receive the data it goes to state 2, and if it obtains the data it sends the appropriate acknowledgments (MSG-ACKs). In the state 5, the node processes the information for a new traffic control decision, then it can be sent or not the received data (according traffic light strategy if is it isolated or coordinated) to the neighboring intersections clusters. If it decides to do not communicate this information to other intersections, it returns to its initial state (state 1). Otherwise, it starts sending packets of the collected data to the sink node (S) and waits for an acknowledgment message by entering state 6. For a defined time if MSG-ACK is not received, the actuator node returns to state 5, otherwise it means that the node has received a MSG-ACK data from (S), it returns to the initial state 1.

We note that in states 2, 4 and 5, a selective retransmission mechanism is necessary to avoid the infinite cycle (defined delay and / or limitation of the retransmissions number).

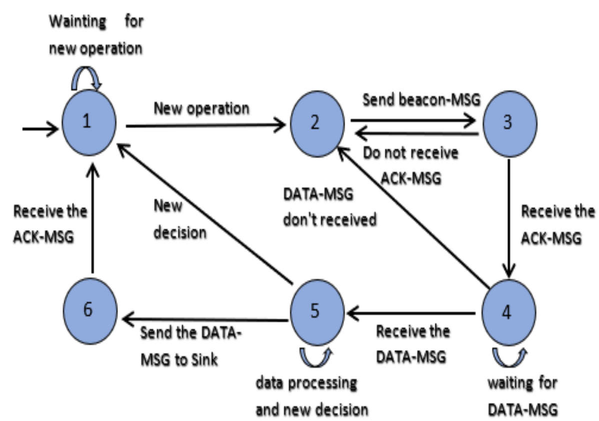

Fig. 6. The actuator node Behavior

3) *Sink or central node*

The sink node is another intelligent node in the network that exploits the captured events by the sensor nodes in the overall strategy of the intelligent road traffic management for a zone or the city.

He makes a second level of decision). As described in figure 7, in state 1, the Sink node waits for a DATA-MSG from its lower-level predecessors (the cluster actuators). When it receives the message, state 2 is activated. In this state, it sends the appropriate acknowledgments (ACKs-MSG), and state 3 processing of these data takes place.

At this point, the Sink node decides whether or not to send a new traffic management decision to the clusters (ex: A decision to avoid the paths arriving at an intersection in the case of an accident in this intersection). Depending on the selection, state 4 or state 1 takes place.

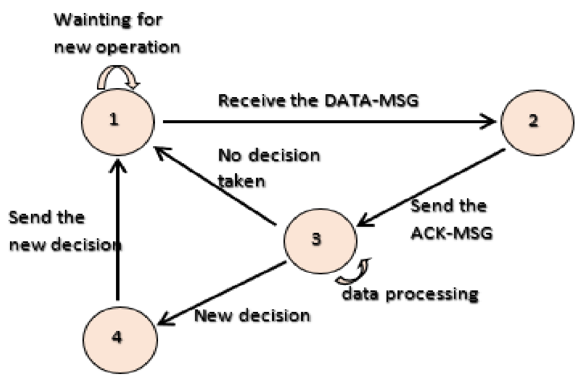

Fig. 7. The sink node behavior

V. Performance Evaluation and Analysis

There are many simulators for wireless sensor networks such as: TOSSIM [24], Opnet [25], Omnet++ [26], Glomosim [27], NS-2 [28], etc. We chose the NS-2 discrete event simulator (Network Simulator 2). This simulator offers a rich library including most of the communication protocols.

The objective of our simulations is to evaluate the performance of the hierarchical architecture chosen for our application, and specifically the first level of the solution proposed in this paper. First, we have defined the properties and important parameters to be simulated. In a second step, we analysed the results using energy consumption as a performance criterion.

The scenario is based on several fixed sensors and a actuator. Our simulations aim at evaluating the sequencing of the wake-up message exchanges between the sensors of a single intersection, from the actuator node (A) to the sensor node (N).

We considered a monitoring environment of 100 m2 (10 m by 10 m) using the parameters "length of scenario (x)" and "length of scenario (y)" with respect to the position of the nodes.

The sensor nodes detect continuously (the sensor unit remains active). Then these nodes

send the data to their actuator periodically (the transmission interval is parameterizable).

This choice is dictated by the fact that in the NS-2 simulator, it is not possible to implement an event-driven wake-up of the sensor nodes. The transmission interval of the nodes (A) has been fixed at 5 seconds with a rate of 250 kbps.

Each node has three main operating modes: detection, processing and communication (receive, transmit, idle).

To evaluate the average energy consumed by each node, we need to add up the consumptions in each mode, as described in the equation below:

$$E = \left(\sum E_{Tx} + \sum E_{Rx} + \sum E_{idle}\right) + \left(\sum E_{pr}\right) + \left(\sum E_{s}\right) \quad (1)$$

Where:

$E_X = P_X . t_X$ with: X=Tx, Rx, Idle, Pr or S

This sum depends on the power dissipated and the time elapsed in each mode: reception (PRx and tRx), Transmission (PTx and tTx), Idle (PIdle and tIdle), Processing (PPr and tPr) and Detection (Ps and tS).

We consider a typical day of operation of the system (24 hours) consisting of a sensor network with 17 communicating nodes: 16 sensor nodes communicating with 1 actuator node.

The transmission interval and the number of nodes are the important parameters of our application. The simulation aims at dimensioning them.

Figure 8 shows the average energy consumed in Joule for each group of nodes and for two transmission intervals: 5 and 20 s.

Clearly, power consumption increases with the functionality of the node. Indeed, the actuator node is the largest energy consumer: 0.36% for the 5 s interval (compared to the initial energy 16200 Joules) and 0.34% for the 20 s interval. The main reason is that this node is the one with its active radio that stays in receive mode the longest time compared to the sensor node. On the other hand, the sensor nodes are the ones that consume the least (0.24% for 5 s and 0.08% for 20 s).

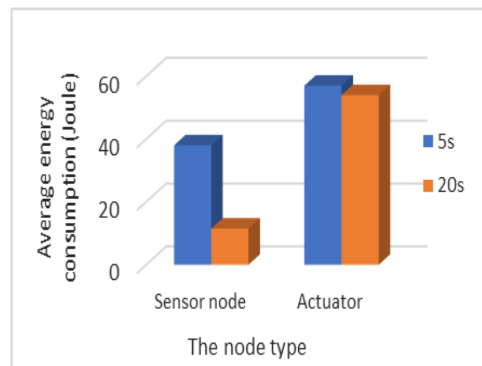

Fig. 8. The average energy consumption for the two types of sensors: sensor node and actuator node.

Nodes (N) wake up periodically to transmit their data to their actuator. Indeed, this parameter has a significant influence on their energy. Therefore, we were interested in evaluating the impact of this parameter. Figure 9 illustrates the impact of the transmission periods of the sensor nodes on their energy consumption. We observe that the energy consumption decreases as the transmission interval increases.

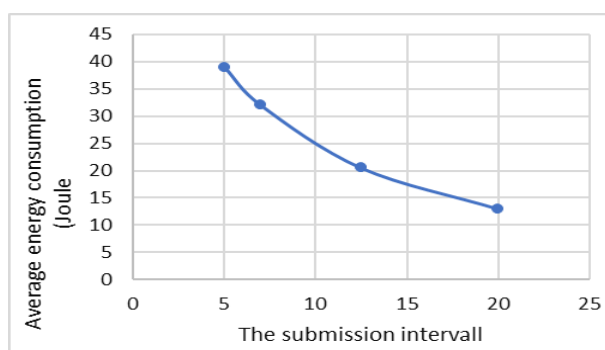

Fig. 9. The average power consumption of the sensor node as a function of the transmission interval.

The previous results give us indications on the impact of the different parameters on the performance of our network, in particular: the impact of the node functionalities (use of the components and energy resources of the sensor groups), and the impact of the transmission interval of the sensor nodes (N).

From these conclusions, we deduced the advantage of using a multi-level architecture.

VI. Conclusion

In this paper, we presented a wireless sensor network model for a traffic monitoring application at a road intersection, in order to manage traffic lights in real time. This model consists of organizing the nodes into three communicating groups according to their roles in the network. We proposed a behavior adapted to each of the nodes according to the need of the application and we organized their exchanges of data and the behaviors are modelized via the State-Transition diagram.

The originality of this model is that it is based on a multi-level architecture for a hierarchical system with multiple levels of control, which is based on the assumption that an effective urban traffic control system must solve local (intersections) and global (zones or cities) optimization, that adapts to isolated strategies (single intersection) and coordinated strategies (network of intersections connected to each other). Still based on this hypothesis, in our future work we will propose approaches to the adaptive signaling lights control for the first two levels of the proposed model.

we determine them for all phases of the intersection concerned.

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