Collision-free emission and dynamic duty cycle management to save energy without performance reduction in IoT wireless multi hop collecting network

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Abstract: This paper addresses a protocol dedicated to Internet of Things wireless collecting network. Such network collects data from large static systems such as bridges, roads, buildings or mobile like materials, products or people transport systems. The purpose of this data collection is to monitor the system in order to enhance security and maintenance procedures. Low energy consumption is required from sensor nodes due to the cost and working time to change or recharge batteries. According that data are not locally processed and for a given type of electronics and node architecture energy consumption vary with two parameters: emission duration and reception duration. The proposed TOMAC-WSN-Eco protocol reduced both parameters at the minimum values by avoiding collision and waking up receiver component just when it is needed. All operations are formally defined. Performance and energy consumption are calculated. Various simulations give also performance evaluation. The results show that the proposed TOMAC-WSN-Eco protocol is particularly sober while satisfying the imposed quality of service constraints.

Keywords: Internet of Thing; Wireless sensor network; Energy saving; WSN MAC protocol; mechanical system supervision.

1. INTRODUCTION

Monitoring a large fix or mobile system from a fixed host is a great challenge at information sensing level. Instrumentation can be designed either to monitor continuously the installation to diagnose malfunctions and to ensure its safety or to make parameters measurements. Collected data could be also used for technical verification - certification or for business to bill the use of a service or the consumption of energy or liquid. Data must be captured in many places and transmitted in long distance while sometime using a link between mobile sensors and a fixed sink. Due to this constraint or for installation facilities wireless communications are more and more used at the sensors level. Wireless sensor networks (WSNs) are well suited for rapid instrumentation even of existing installations with moving parts without expensive investments. Two categories of wireless sensor network technologies meet more or less the technical and environmental requirements: WPAN (Wireless Personal Area Network) and LPWAN (Low Power Wide Area Network). LPWAN is not chosen in this research work due to its to low bandwidth. For economic and reliability reasons the network technology must be COTS (Commercial off-the-shelf).

Among the large mobile mechanical systems, we address those moving in an invariant way over a fixed path travelled cyclically. Examples are transfer lines of products in industry, material ropeways in cement factory, chairlifts in ski resort or gondolas in leisure parks. Among fixed system we address pipes for water, gas or oil, civil structures like bridges or big buildings. This specificity is expected to optimize the sensors network topology and two essential functions: localization of the moving sensor node(s) and routing. Studies have already been carried out on the subject by some of the authors (Chafik et al. (2014)). Among others the results is a classification of monitored systems and dedicated WSN topologies for the intended application type.

The objective of the research presented in this paper is to design, verify and test a protocol using the best properties of the system to optimize performance while reducing as much as possible energy consumption and quantity of resources. The targeted wireless sensor network works in multi-hop architecture but single path to the sink. The research does not start from scratch but from a previously designed protocol called TOMAC-WSN (TOken MAC protocol for Wireless Sensor Network) (Lepage et al. (2018)). TOMAC-WSN reduce at the maximum transmission time. The new research tries to reduce receiver active time using a kind of dynamic duty cycle.

The result is a new protocol called TOMAC-WSN-Eco that is described in the rest of the paper organized as follows. Section 2 summarizes the related works. The technology, architecture and protocol operations are described in Section 3. The performance of the proposed network is evaluated by theoretical calculations and by measurements obtained by simulations. The results are reported and discussed in Section 4. A conclusion and some perspectives complete this paper.

II. RELATED WORKS

2.1 Big systems monitoring

The use of WSN for monitoring physical systems or areas is well known in several fields like military defense, environment, civil infrastructures. WSN act alone or often as an add-on on existing wired sensor networks. Integration of WSN as a connection technology of objects in the Internet of things framework enhances this approach.

A comprehensive survey addressing the use of WSN for Structural Health Monitoring has just been release in (Noel et al. (2017)). This paper provides a general overview of the different topics that are integrated from sensor characteristics, sensors placement, wireless sensor networks and data processing. It presents also laboratory testbeds and experimental work with real structures like bridges, football stadiums, buildings and wind turbines. The 64 nodes WSN deployed on the Golden Gate Bridge is a famous example (Kim et al. (2007)). Pipenet (Stoianov et al. (2007)) is a WSN based monitoring system which aims to detect, localize and quantify bursts and leaks and other anomalies in water transmission pipelines. A difficult challenge in pipe monitoring is such structure is often underground restricting signal propagation between sensor nodes (Akyildiz et al. (2009)). Monitoring scenarii with mobile nodes connected using wireless technology was targeted by Cartel project at MIT and MobEyes at UCLA using VANET (Vehicular Adhoc Network). But this monitoring is adapted to a Delay Tolerant Network with non-permanent link from a node to a sink.

Machine monitoring using WSN is often specific. A review of the industrial WSN protocols was recently published (Queiroz et al. (2017)). It described numerous improvements of standard WSN protocols to fulfil industrial requirements at physical and MAC layers. ReICOvAir E.U. project (Reicovair. (2017)) tries to rate wireless communication systems in industrial environment.

2.2. WSN MAC layer energy saving

Because each node is autonomous the search for energy efficient protocols has always been a major goal for WSN. Due to their significant share in the consumption of a node a particular focus has been made on MAC and Network layers. Clustering and routing protocols are also very important at network layer in the case of random or complex or evolving topologies. This is not the case in the studied system where a basic geographic routing protocol is suitable.

Collision free MAC protocols are well suited to avoid energy waste by additional transmission and duty cycle of radio component save energy during no communication activity. An excellent and recent review of energy efficient MAC protocols is available in (Kumar et al. (2018)). Time synchronization of all nodes is quite easy in one hop cluster but is more difficult in mesh networks. WRTP is a token ring approach which is efficient, fair and distributed. It has been improved by (Wei et al. (2012)) but its robustness must be proven. Virtual Token Passing Protocol is more robust and suitable for manufacturing environment (Ren. (2015)). The token passing concept is also used in the former proposed TOMAC-WSN protocol (Lepage et al. (2018)).

Data aggregation is a processing to reduce data quantity to transfer until sink node. But it is application specific. A simpler and application independent traffic reduction is provided by frame or packet aggregation (Razafindralambo et al. (2006), (Breck et al. (2014)). This approach is used for TOMAC-WSN.

Finally, no contribution has been found addressing especially large machines monitoring by WSN and so no adapted protocol like the proposed TOMAC-WSN.

III. TOMAC-WSN-ECO PROTOCOL

3.1 Overview

In the same way as industrial wireless network protocols like HART (Queiroz et al (2017)), TOMAC-WSN (Lepage et al. (2018)) is a MAC overlay working above the standard IEEE 802.15.4 protocol. It is dedicated to WSN topology where communications from any node to the sink take the unique multi-hop path. It exploits this topology for two purposes: to schedule the transmissions of neighbouring nodes to avoid collision and to aggregate frames when possible to reduce their number. TOMAC-WSN-Eco is an improvement significantly saving energy.

3.2 Network technology

For economic and reliability reasons the network technology is COTS (Commercial off-the-shelf). As explained in introduction LPWAN technologies are discarded because they do not meet the bandwidth requirements of the targeted applications.
WPAN technologies allow theoretical data rates up to a few hundred kb/s but in a short transmission distance, that is to say less than 100 m. This induces the need to set up routing strategies when the network is deployed in a large area. These features are compatible with the network topology and the QoS requirements of a monitoring application. Among the WPAN technologies, the IEEE 802.15.4 protocol is used in most cases and is implemented in electronics components. Moreover, it is energy efficient. So this technology is chosen for physical and MAC layers using "nonbeacon-enabled mode" in the MAC layer due to the topology.

3.3 Architecture

The system architecture includes network topology and protocols that run on it. Various topologies have been studied in previous works (Chafik et al. 2014). These studies showed that a topology with the sensor nodes placed in line or on curve so that a single path is created toward a fixed sink (Figure 1) was a simple and economical solution while providing the expected performance. The signal transmission range must be adjusted optimally: each node must be able to reach it neighbour on each side but no more nodes to limit the size of the access to the transmission channel. This topology could be used to monitor fixed systems like pipes, bridges or some

buildings or mobiles systems like ropeways or transfer lines with embedded nodes. A chairlift is used in section IV as example and a scenario to evaluate our proposal.
Based on this topology and the objective of reducing energy consumption three main ideas guided the protocol design: avoiding any collision, reducing the frames number and sleeping when not busy.
By sequentially triggering the generation of frames TOMAC-WSN eliminates concurrent access to the communication channel. The protocol uses principles from token bus and token ring protocols (Wei et al, 2012). The network is therefore an open logical loop as shown schematically in Fig. 2. The emission of the first node of the loop is time triggered at period Pf. It is the initiator node numbered 0. All other nodes are token triggered. That means that a node transmits when and only when it has received one frame from its predecessor in the open loop. Because a node receives from its two neighbours each frame must be addressed to the follower in the loop. It is simply necessary that each node knows the addresses of its neighbours in the loop, which can be done statically at configuration time of the network.
Thanks to this principle, the risk of collisions is zero if the following condition is fulfilled: each node has finished receiving from its follower before its upstream neighbour transmits a new frame. In a Pf period that means to respect the sequence format. A sequence is the set of 3 periods (Fig. 4): frame reception, emission, reception. Because a complete frame lasts 5.44 ms with interframes time, it lasts at most: 5.44 * 3 = 16.32 ms. A second condition is about Pf. A node sending N frames receives N or N-1 complete frames. So the generation period Pf frame cannot be less than N*16.32 ms. The worst case is on the penultimate node.

To reduce the number of frames, the protocol aggregates the data groups of size DG in the manner of frame aggregation (Breck et al, 2014). IEEE 802.15.4 frame has a maximum size of 127 bytes and a maximum payload of 118 bytes, with a specific field of 3 bytes, so M= Integer value (115/DG) groups of data can be aggregated in one frame.
The operations of the protocol are detailed in the following section.

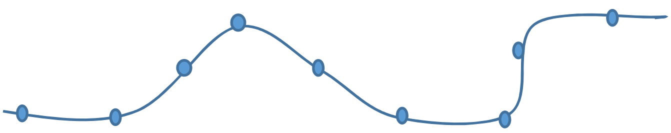

Fig. 1. Sensor nodes placement

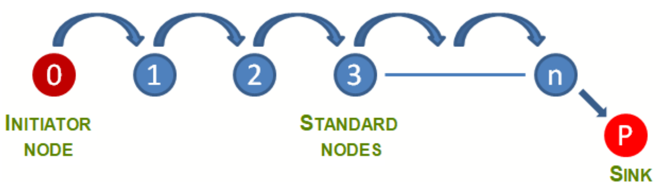

Fig. 2. The open logical loop topology.

3.4 Operational rules
TOMAC-WSN protocol works in 4 modes (Figure 3).

Mode 0: It is the bootstrap Mode, the mode when the node is turned on. All components are set with the configuration parameters and receiver is switched on. This mode ends either by receiving a Go_Mode1 binary signal, so protocol enters Mode 1, or either by receiving a correct frame, so protocol enters mode 2.

Mode 1: It is the Initiator Mode. A frame is generated at each period Pf, its payload consists of the group of data of DG bytes size from the sensors of this node. This frame is sent to the successor node (number 1) for which it is the equivalent of a token or right to transmit. When receiving a *Request_Mode1 frame* node sends a Request_Mode1-Ack, leaves Mode1 and enters Mode 2.

Mode 2: It is the Token Mode. When it receives a frame node in Mode 2 checks its Agg tag. If this frame is tagged complete, the node changes destination address and sends the frame to its follower in the loop or to the sink. If not the node tries to add its data group. If it is possible it makes it, modifies if useful its k number (in case of mobile node), tags the frame and sends it. If not it tags the frame as complete, sends it as a complete frame, waits for two slots, create a new frame loaded with its data group, modifies its k number if useful, tags the frame and sends it to its follower or to the sink. Mode 2 ends when le number k of the node become greater than kmax or by receiving a GoToSleep signal and enters Mode 3. Diagram of frames propagation in the network is provides in figure 4.

Mode 3: It is the Sleepy Mode. The receiver is switched off and the node is turned sleep mode. This mode ends by receiving a Wakeup signal acting as an interrupt on the node processor. Node sends a Request_Mode1 frame.

3.5 Frame format

The frame is structured in 5 fields (Figure 4):

- SN (sequence number): sequence number of the frame;
- Agg: bit to indicate whether the frame is tagged complete (1) or not (0);
- k: position of the node in the chain of the active nodes with respect to the initiator node (k = 0);
- node address: address of the last node having aggregated its data in the frame;
- data: application data.

8	1	7	8	n
SN	Agg	k	Node address	data

Fig. 4. Data Frame of the TOMAC-WSN protocol.

3.6 Formal modelling and verification

In order to verify the logic of its operation, each mode of the protocol has been formally modelled by finite state automata. These models were processed by UPPAAL Model Checking Tool (UPPAAL (2019)).

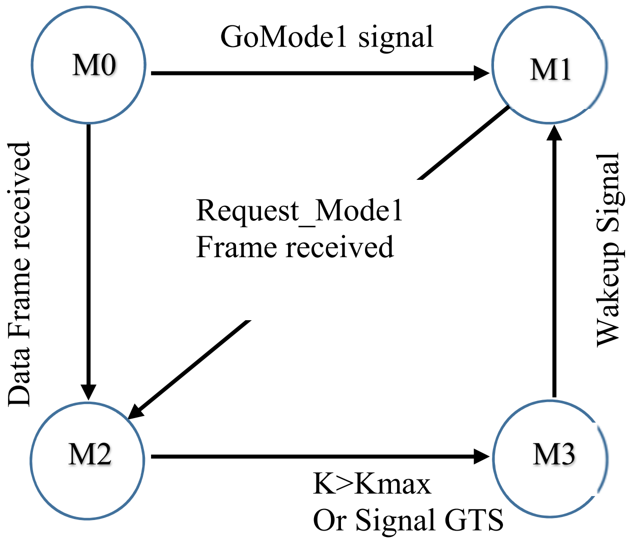

Fig. 3. Mode diagram

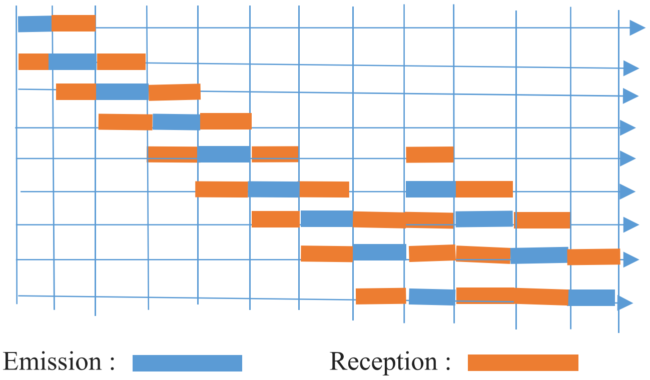

Fig. 4. Frames propagation diagram

3.7 TOMAC-WSN energy consumption

To calculate the energy dissipated in a node during T, T being large enough to include states changes, the following model is used:

$E_T = E_P + E_S + E_R + E_E$
with E_T = Total energy during T time, E_P = processor and memory energy, E_S = Sensor energy, E_R = receiver energy, E_E = emitter energy.
Considering that the power of processor Pp and sensor Ps are constant, except in Mode 3, then $E_P = Pp * T$ and $E_S = Ps * T$.
In previous TOMAC-WSN version Transmitter / Receiver or Tx / Rx component was always on. So time in reception T_R is T minus time in emission T_E and $E_R = P_R * (T - T_E)$.
Finally, with an emitter power P_E depending of the requested transmission distance and an emission duration T_E adjusted at the lowest in TOMAC-WSN, $E_E = T_E * P_E$.
Numerical examples are given in section IV.

3.8 TOMAC-WSN potential improvement

TOMAC-WSN wastes little energy at the side of transmission due to its collision free protocol and its aggregation mechanism. But it keeps always active its receiver that is a source of consumption sometimes useless. So the chosen policy is to follow the duty-cycle concept (Kumar et al. (2018)) to reduce energy consumption. Hopefully the deterministic behaviour of each node, except in case of transmission error, and the knowledge of data sizes allow to design an adaptive receiver sleeping period.

TOMAC-WSN modified by this improvement is called TOMAC-WSN-Eco. Details of this new operation are given in the following section.

3.9 Adaptive sleeping period calculation

The procedure for managing the Tx / Rx component is as follows: after sending the last frame (the one containing its data) the node can sleep the component Tx / Rx until it receives the first frame of the new period Pf. To take into account the jitter and the wakeup time, a guard period Tguard is used. Because a sequence lasts 16.32 ms (section 3.3) and if a node sends N frames, Tx/Rx active period T_A per period Pf is equal to:
T_A (ms) = N *16.32 +Tguard.
So sleeping period = Pf – T_A. Numerical values are calculated in section 4.2.2.

IV. TOMAC-WSN-ECO PERFORMANCE

4.1. Scenario for a testbed

It is impossible to evaluate performance of a WSN protocol without considering one or a few deployments and working scenarios.

Let us consider the monitoring of a chairlift with each chair equipped with sensors. These sensors can be used to record a variety of data, which are then used for routine checks, or by specialized inspectors verifying safety standards during live working. A real system, the Pré La Joux chairlift of the city of Châtel, located in Haute-Savoie (France) is chosen because its characteristics are publicly available (Pre La Joux (2019)). This system has the following characteristics:

- number of seats: 76
- spacing between each seat: 39 m
- diameter of the drive pulley: 4.76 m
- total length: 1487 m
- moving speed: 5m / s.

To be able to monitor all seats, it is necessary to use a total of 76 sensor nodes, plus one sink for data collection. A schema of the physical system is given in Fig. 5.

For simplicity reason, only the nodes of the upright seats will be activated. The nodes of the descending seats are put to sleep. A sensor at the bottom of the chairlift detects the change of direction of the seat in front of it.

The monitoring application measures amplitude and frequencies of the swinging and vibrations of seats. It requires periodic sampling of data on each seat. Let Ps be the sampling period. These samples are not always transmitted directly to each period. Local processing can extract the fundamental parameters of the signal and it is they that transmitted. For real-time monitoring, transmission of information in data frame to the central monitoring system is considered necessary for a period of frame Pf. Data produced by each node for each send are called a Data Group whose selected size is 20 bytes so 5 Data Groups could be aggregated in a frame. With a network of 38 sensor nodes, the minimum total data throughput on the network is 6080 bits/s. The rate of packet loss must be less than 2% and the maximum delivery time for each data group is limited to 1 second. All these parameters defined the requested quality of service (QoS).

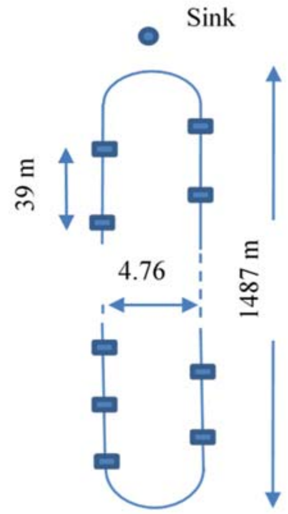

Fig. 5. Chairlift geometrical characteristics.

4.2 Theoretical performance calculation

The different parameters allow to calculate some Quality of Service attributes and energy consumption.

4.2.1. Transfer Delay TD

The data transfer delay is the time separating their availability in the node, assumed at the start time of the PF period for the considered node, and the reception in the sink. Two worst cases are considered:

- The node furthest from the sink: Transfer time TD = duration of a full frame (including interframe) x number of hops. There are 38 hops (37 + 1 towards the sink). TD is therefore: 5.44 * 38 = 206 ms.

- That of the last node: The transfer delay corresponds to the local waiting time to put the data in the frame + the transfer time of the frame. TD = duration of a sequence x 7 + duration of a frame = 16.32 * 7 +5.44 = 114 + 5 = 119 ms.

4.2.2. Energy consumption

The climb trip of a chair lasts about 5 minutes (1487 m at the speed of 5 m / s). The descent lasts the same time. The chairlift is in operation from 9 am to 5 pm so 8 hours a day. During descent Mode 3 has a negligible consumption. So the real working duration per day is 4 hours.
Let us consider power values come from Arduino and XBee data sheets (see 2.3.6) : Pp = 6.6 mW; Ps = 0.181 mW; Pr = 165 mW ; P_E = 148.5 mW.

We calculate Energy dissipated by each Node per Day: E/N/D.

- **TOMAC-WSN**

Ep + Es = 4 h * (6.6 + 0.181) =27.12 mWh

The mean emission duration per Pf is: 5.44*4 = 21.76 ms.

With a frame generation period Pf = 150 ms : during 4 h, the number of Pf is N1 = 4*3600/0,15 = 96000.

Then T_E = 0.021 * 96000 = 2088 s = 0.58 h
E_E = 148.5 * 0.58 = 86.13 mWh
T_R = 4h – TE = 3.42 h → E_R = 165 * 3.42 = 564 mWh
E/N/D = 27.12 + 86.13 + 564 = 677.25 mWh = 2438 J.

With a frame generation Pf = 1 s, the number of Pf is
N2 = 4 *3600 = 14400
Then T_E = 0.021 * 14400 = 313 s = 0.087 h
E_E = 148.5 * 0.087 = 12.9 mWh
T_R = 4h – TE = 3.91 h → E_R = 165 * 3.91 = 645.6 mWh
E/N/D = 27.12 +12.9 + 645.6= 685.6 mWh = 2468 J.

- **TOMAC-WSN-Eco**

TOMAC-WSN-Eco reduces receiver energy consumption by reducing its Tx/Rx active time.

The mean Time of Activity TA of TX/RX is:
TA = 16.32*4 +1 = 66.28 ms set to 67 ms
With a frame generation period Pf = 150 ms
TA per day= 67*96000 = 6432 s = 1.78 h
TR = TA-TE = 1.78 – 0.58 = 1.2 h
ER = 165*1.2 = 198 mWh
E/D/N = 27.12 + 86.13 + 198 = 311 mWh = 1120 J

With Pf = 1s
TA per day = 67*14400 = 965 s = 0.27 h
TR per day = TA-TE = 965 – 313 = 652 = O.181 h
ER = 165*0.181 = 30 mWh
E/N/D = 27.12 + 12.9 + 30 = 70 mWh = 252 J

Energy consumption comparison

The previous results are summarised in Table 1**.**

Protocol	Pf = 150 ms	Pf = 1 s
TOMAC WSN	2438 J	2468 J
TOMAC WSN Eco	1120 J	252 J
Energy saving (ratio)	2.1	9.8

Table 1: Energy consumption per node per day

4.3. Performance measurement by simulation

Network simulation was used to verify the smooth operation of TOMAC-WSN-Eco and to measure some performance. WSNET4 simulator developed by INRIA for wireless sensor networks was used. The disk type propagation model was chosen with a radius of 45 meters, ie a value slightly larger than the distance between two seats but less than two inter-seats distance. The network is considered as deployed in a plan. Conventional 802.15.4 is used and TOMAC-WSN-Eco is implemented over this MAC layer.

Each simulation is performed over a period of 30 minutes of network operation. Both Frame Generation Period Pf values were used: 150 ms and 1 second.

The average delay value of a packet from the farthest node to the sink is 151 ms. The packet loss rate is always zero. This is explained by the fact that the frames are never in competition for access to the medium, except Request_Mode1 frame that can compete with a data frame of the node in M1 state.

Energy consumption can be measured with this simulator. The more noticeable way to compare energy consumption is to express the battery recharge period. Let us consider a power supply of each node by 3 rechargeable batteries of 1.2 V with a capacity of 2600 mAh each, ie 3120 mWh. The total capacity is about 9 Wh = 32400 J. The recharge period given in Table 2 are obtained in two ways: calculation (Calc.) and simulation (Sim.). Results are equal for TOMAC-WSN and not very different for TOMAC WSN ECO. The energy efficiency of TOMAC-WSN-ECO increases with the Pf period duration due to the sleeping time.

Protocol	Pf = 150 ms		Pf = 1 s	
	Calc.	Sim.	Calc.	Sim.
TOMAC WSN	13	13	13	13
TOMAC WSN Eco	28	22	128	147

Table 2. Battery recharge period in days

4.4. Protocol implementation

Finally, a real node implementation has been made but not on the chairlift. Students have deployed 5 nodes in the laboratory corridors to create a 60 meters long network. The protocol has been programmed on an Arduino Mega 2560 platform equipped with a Digi Xbee wireless network module. The TOMAC-WSN-ECO protocol worked perfectly on this installation.

VI. Conclusion

A new protocol for IoT wireless multi hop collecting network has been designed to meet QoS monitoring application requirements while been very energy efficient. It could be used for a large physical system static or in cyclic mobility. It wastes no time by scheduling emission without global synchronisation and no energy by this emission triggering and by adaptive receiver duty cycling. The performance parameters calculated or obtained by simulation are those expected and outperform a previous version of this protocol. Its implementation on Arduino nodes made it possible to verify that it really works on light equipment and is easy to program. But experiments in real situation must be conducted to fully verify its robustness and measure its performance in real conditions. Moreover, the location of one or more sinks should be studied according the quality of service requirements of the monitoring application.

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