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TOMAC-WSN: A new WSN efficient protocol for monitoring big distributed mechanical systems

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Abstract: This paper addresses a wireless sensor network dedicated to monitor a large mechanical system. The chosen system for the scenario is a chairlift. In this case the wireless sensor network special feature is the mobility of nodes following an invariant path traveled repeatedly. A sensor node is put on each chair and a sink node is at ground at the upper end of the chairlift. A new protocol called TOMAC-WSN is designed in order to schedule frames transmission using token concept. This avoids collision at the medium access. The second concept used by TOMAC-WSN is frame aggregation. This new protocol has been modelled using Finite State Automata. An experimental implementation on Arduino boards shows the correct operation of the network. Network performance in terms of delivery time and packet loss rate is evaluated using simulation. The results show that the proposed TOMAC-WSN protocol delivers the appropriate quality of service for the monitoring of large physical systems.

Keywords: Wireless sensor network; MAC protocol; Internet of Things; mechanical system supervision; pipe supervision; WSN synchronized MAC protocol.

1. INTRODUCTION

Monitoring a large mobile mechanical system from a fixed host is a great challenge at information sensing level. This one must indeed capture data in many places and transmits them in long distance while using a link between mobile sensors and a fixed sink. So this one is necessarily wireless. Instrumentation can be designed either to monitor continuously the installation to diagnose malfunctions and to ensure its safety or to make measurements during a verification - certification phase. Particularly for the second purpose wireless sensor networks (WSNs) are well suited for rapid instrumentation of existing installations with moving parts without expensive investments. Each sensor can measure a parameter specific to the mobile part (e.g., vibrations, forces acting on a mechanical part) or related to environment throughout the trajectory of the mobile (e.g., wind speed, temperature) or a combination of both. 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, a chairlift in ski resort or gondola in a leisure park. The safety of such outstanding leisure equipment is mandatory. This specificity is expected to optimize the sensor 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)). They provided satisfactory results for the intended application type. However, prospects for change had been proposed to improve performance.

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 improve performance while reducing energy consumption and resources.

1.1 Scenario and assumptions

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 in live safety standards.

To give credibility to the study, it is carried out by taking a real system, the Pré La Joux chairlift of the city of Châtel, located in Haute-Savoie (France). This choice is justified by the public availability of its characteristics (Pre La Joux (2017)). 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 at least one sink for data collection. A schema of the physical system is given in Fig. 1.

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.

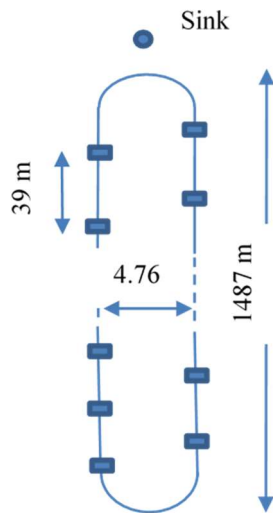


Fig. 1. Chairlift geometrical characteristics.

The monitoring application measures amplitude and frequencies of the swinging and vibrations of seats. It requires periodic sampling of data on each seat. Let P_s be the sampling period. These samples are not always transmitted directly to each period, it is not useful and it would be difficult for high frequency signals such as vibrations. Local processing can extract the fundamental parameters of the signal and it is they that are transmitted. For real-time monitoring, transmission of information in data frame to the central monitoring system is considered necessary for a period P_f of up to one second. For real-time monitoring of the considered system, information transmission to the central system must be carried out at a maximum period of one second. Data produced by each node for each send are called a group of data whose size is estimated at 12 bytes but a margin is taken for other information and the selected size is 20 bytes. With a network of 38 sensor nodes, the minimum total data throughput on the network is 6080 bits / s. The rate of packet loss should be zero if possible, but realistically it is set at a limit value of 2%, with a rate of two successive losses limited to 0.1%. The maximum delivery time for each data group is set to 1 second. All these parameters defined the requested quality of service (QoS).

1.2 Research objectives

The overall objective of our research is to design a wireless sensor network system capable of providing the requested quality of service. A specific result is a protocol called TOMAC-WSN (Token MAC protocol for Wireless Sensor Network). It will be described in the rest of the paper that is organized as follows. Section 2 summarizes the related works. The technology, architecture and protocol are described in Section 3. Details of protocol development are given in section 4. The performance of the proposed network is evaluated by simulations. The results are reported and discussed in Section 5. A conclusion and some perspectives complete this paper.

II. RELATED WORKS

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 gives first the expected output of such monitoring. It 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. Among these real structural health monitoring this based on 64 nodes WSN deployed on the Golden Gate Bridge is a famous example (Kim et al. (2007)). More similar to the targeted application is the monitoring of pipes using WSN. 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)). One example of such underground WSN is Smartpipes (Sadeghioon et al. (2014)). Each node communicates with both nodes in front and behind itself via radio frequency signals. For every 4 to less than 10 nodes there is a master node which is the gateway between the cluster and the sink collecting data.

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 does not match the studied scenario because it is adapted to a Delay Tolerant Network with non-permanent link from a node to a sink.

Machine monitoring using WSN is often specific. Some cases use the wireless capability to monitor electrical motors (Delgado Gomes et al. (2013)) but some address more global systems in order to optimize energy (Salvadori et al. (2009)) or to monitor machines-tools especially the wear of the tools. To provide the requested QoS (Quality of Service) some specific WSN dedicated to industrial automation have been developed (Christin et al. (2010)). They are based on low layers WSN protocol standards but additional higher protocols provide QoS and security. 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. The basic single channel physical layer in IEEE 802.15.4 is not resistant to multipath and interference problems. ReICOvAir E.U. project (Reicovair. (2017)) tries to rate wireless communication systems in industrial environment.

Contributions on MAC layer are also described in (Yigitel et al. (2011)). MAC add-on protocols use differentiated services or Time synchronization (Song et al. (2009)) to provide the requested time constrained access to the medium. 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

tested and proven. Some of its basic concepts are used for the design of the proposed TOMAC protocol. Some ideas coming from industrial Ethernet like Ethercat are also used and adapted to wireless constraints.

Routing protocol is needed if network topology is complex, not known at design time and changes. This is not the case in the studied system so routing protocols are not examined in this section.

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.

WSN sensor nodes defaults could occur and so affect the monitoring. The localization of the faulty sensors has been addressed by Chen et al. (2006).

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

III. TECHNOLOGY AND ARCHITECTURE

The monitoring system must perform measurements on the mobile part and send them to a fixed station for data analysis and storage. For multiple reasons, it is necessary to place the control station in a room on the ground: power supply, station environment, operator comfort. A wireless sensor network with mobile nodes seems well suited to carry out such a measurement system. It enables rapid deployment thanks to its infrastructure less and self-configuration capabilities. It can capture information in the right places, at suitable time, with sufficient precision, and transmit data to the control station in real time. But their performance is limited in terms of bit rate, reliability of communications and message delivery delay. This performance is closely related to the topology of the network, the corresponding routing protocol and the medium sharing method. This is why these essential features must be designed making best use of geometry of the mechanical system and its movement with the aim of meeting the required performance. The topology should ensure permanent connectivity between the sensor(s) and the sink. Depending of the WSN technology all nodes are or are not directly connected to the sink.

3.1 Network technology

For economic and reliability reasons, the technology used must be COTS (Commercial off-the-shelf). Two categories of wireless sensor network technologies were examined: WPAN (Wireless Personal Area Network) and LPWAN (Low Power Wide Area Network).

WPAN technologies have the following characteristics:

- theoretical data rates in the range of Kb / s to a few hundred kb / s;
- low energy consumption;
- a short transmission distance, that is to say less than 100 m;
- 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 the monitoring application.

LPWAN technologies have the following characteristics:

- theoretical data rates limited to a few Kb /s;
- very low energy consumption;
- a large transmission range, that is to say several tens of km.

There is therefore no need for routing on the wireless part of the network, all the terminal nodes are connected directly to the sink.

Current LPWAN technologies do not meet the bandwidth requirements of the application. They are therefore not chosen.

Among the WPAN technologies, the 802.15.4 protocol of the IEEE is used in most cases, is particularly known (Baronti et al., 2007) and is easy to implement. Moreover, it is energy efficient. We have therefore selected this technology in its simplest version, that is to say without additional layer since we want to design one specifically adapted to the deployed network.

3.2 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 used as routers up to the one closest to the single fixed sink was a simple and economical solution which provides often the required performance. This topology is therefore retained for the carried out study. The particularity of the chairlift is that the nodes are positioned on the seats aligned on two parallels 4.76 meters apart. As indicated in the scenario, only the nodes of the upright seats are active. The sink being placed at the top of the chairlift; the network is a chain of nodes transmitting their data always in the same direction. The network is therefore an open logical loop as shown schematically in fig. 2. The active nodes are numbered from 0 to 37. The bottom node is numbered 0 and is called the initiating node. Other mobile nodes are called standard nodes. Nodes being mobile, their situation in the loop evolves over time.

The signal transmission range can be adjusted optimally: each node must be able to reach its neighbours but no more to limit the size of the contention area of the access to the transmission channel. Concretely the transmitters are set for a range of 45 meters in free space, to adjust given the actual conditions of propagation.

The protocol must take into account the topology. As the IEEE 802.15.4 technology has been chosen for the physical layer, the topology involves choosing for the MAC layer its operation in "nonbeacon-enabled mode".

This mode corresponds to a standard CSMA/CA type medium access that is flexible but not deterministic and inefficient under heavy load. The protocol we propose at the upper level corrects this weakness. Packet routing is simple on this topology: geographic routing is natural. 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.

To reduce the number of frames, the protocol aggregates the data groups in the manner of frame aggregation (Breck et al, 2014). Because the IEEE 802.15.4 frame has a maximum size of 127 bytes and a maximum payload of 118 bytes, five groups of data can be aggregated in one frame taking into account the 3-byte header specific to our protocol. The developed protocol is detailed in the following section.

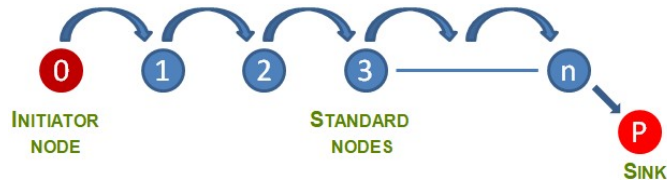


Fig. 2. Topology of the open logical loop.

IV. TOMAC-WSN PROTOCOL

4.1 Operational rules

In the same way as industrial wireless network protocols like HART (Queiroz et al (2017)), a MAC overlay is added to improve the performance of the standard IEEE 802.15.4 protocol. By sequentially triggering the generation of frames, it eliminates concurrent access to the communication channel. Triggering exploits the network topology. The new protocol uses principles from token bus and token ring protocols (Wei et al, 2012). The frame aggregation mechanism is part of this MAC overlay.

The operation of this protocol is as follows: on the initiator node (number 0), a frame is generated at each period P_f , its payload consists of the group of data of 20 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. Node 1 adds its 20-byte data group to the payload, modifies the protocol-specific field, and sends the new frame to its successor in the loop, that is, node 2. This one proceeds in the same way as the node 1: it adds its group of data in the frame and it transmits it to the node 3. Idem for the nodes 3 and 4. Node 5 receives the frame loaded with 5 groups of data so there is not enough space to aggregate its group of data. It tags this frame as complete and it generates a new one in which it places its group of data. Then it transmits successively to its successor (node 6) the complete frame and the new frame. The following nodes will receive two types of frames: one or more complete frames that they will retransmit to their successor without modification and an untagged frame. The latter is treated as in the nodes 1 to 4 if it is not complete or as in the node 5 if it is complete (in the nodes 10, 15, ...) and a new frame is generated. The last node of the loop transmits all the frames to the sink.

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 frame of the next period P_f . The worst case is on node 36. A complete frame lasts about 5 ms with interframes time. This node receives 7 complete frames and one frame with one group of data. It must therefore receive for about 40 ms, emits for about the same duration and then receives. The generation period P_f frame cannot be less than 120 ms.

4.2 Protection against the loss of the token frame

To avoid that the loss of the token frame results in the non-generation of the data frames of the nodes following the place of loss in the logic loop for the current period, a protection mechanism has been implemented. The detection of the loss is carried out by a watchdog: the non-reception of the token in a maximum period T_{Out} triggers the generation of a substitution token, i.e. a new frame which is loaded with the data group of the node for this period P_f . The value of the counter T_{Out} is calculated by adding the frame generation period P_f by the initiating node plus the time required to transfer a frame of maximum size. Formally, the value of the counter is calculated as follows:

$$T_{Out} = P_f + S_{max}/C + J$$

with P_f the frame generation period of the initiator node, S_{max} the maximum size of a frame in bits, C the theoretical bitrate and J a jitter value whose nominal value is set to 1ms. The watchdog is reset each time a token frame (not complete frame) is received.

4.3 Frame format

The frame is structured in 5 fields including:

- 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. 3. Data Frame of the TOMAC-WSN protocol.

4.4 Formal modelling and verification

In order to verify the logic of its operation, the protocol has been formally modelled. The chosen model is based on finite state automata.

At a time, T , a node is in one of the following three states: Idle state noted State 0, Initiator state noted State 1 or standard state noted State 2.

- State 0 = Idle state, described in fig. 4. This is the state in which are all the nodes on the descending seats.

The node waits for an initiating signal given by a localization sensor at the lower end of the chairlift. When it receives it, it sends a message to the neighbouring node which is in state 1 and it goes to state 1 when it receives acknowledgement message from this node.

- State 1: initiator state, described in Fig. 5. In this state, the node is at the beginning of the open logical loop, it periodically creates the data message that serves as a token for the following nodes (which are in the state 2).

It turns to state 2 on reception of the message of its idle neighbour requesting to become initiator.

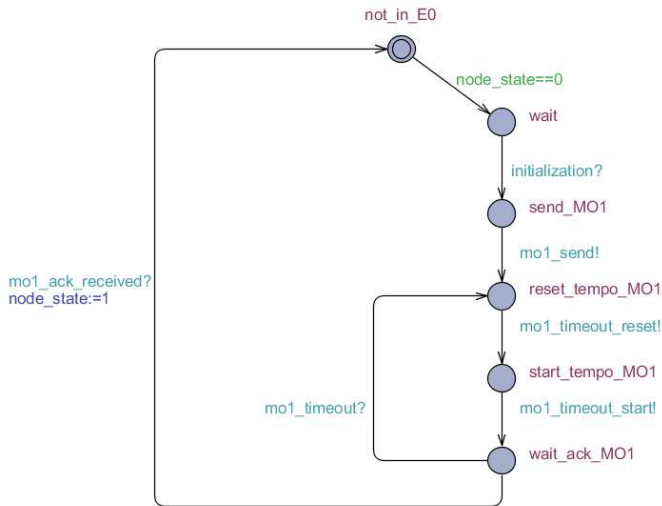


Fig. 4. Model of State 0 or Idle State.

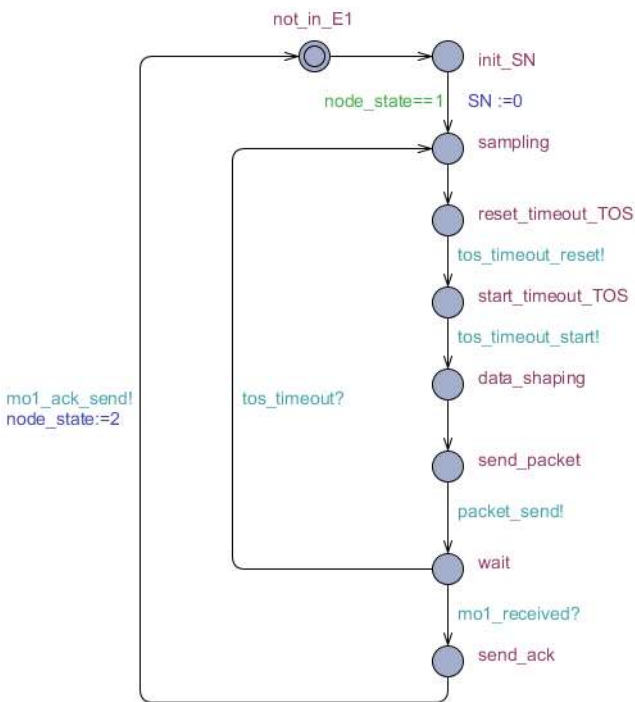


Fig. 5. Model of State 1 or Initiator State.

- State 2: Standard state, the node waits for one or more packets from its previous neighbour in the loop. On receipt, it aggregates its data in the incomplete received frame or creates a new one. Each node in the standard state carries a number k which evolves with the displacement of the seat on which it is. The rule for incrementing the value k is as follows: the node that has just passed to the initiator state inserts into the packet that it generates its value of k which is 0. The next node seeing that the value of k of the previous node is the same as its own, increments the value of k by 1. It writes it in the packet it has just received and will relay to its neighbour. In this way each next node in the chain sees that the value of k has changed and increments its number k accordingly. The node leaves the standard state to turn into the idle state when its numbering k

goes to the value 38 since the seat on which it is installed then begins the descent. The model is not provided in this paper but could be access at www.cran.univ-lorraine.fr/jean-philippe.georges/cescit/state2.pdf. To verify the proper design of the new protocol these models were introduced in Model Checking tool UPPAAL (www.uppaal.org). We were able to verify the absence of blocking and unwanted situation.

V. RESULTS

Network simulation is used to measure performance in terms of delay and packet loss. For this, we use the WSNET4 simulator developed by INRIA for wireless sensor networks. For this simulation, the disk type propagation model was chosen with a radius of 45 meters, ie a value slightly larger than the distance between two seats. The B-MAC protocol is used at the MAC level but with a duty cycle of 100% which corresponds to the operation of the conventional CSMA / CA protocol. We implemented TOMAC-WSN over this MAC layer.

Each simulation is performed over a period of 30 minutes of network operation. To simplify simulations and calculations, we take the following general assumptions:

- the topology of the network is considered as deployed in a plan, it does not take into account the irregularities of the relief;
- the propagation time of the signal is neglected;
- the theoretical bitrates are used and do not vary.

The delay values of a packet is a function of the number of hops to cross over as displayed in fig. 6. Node number 0 is the farrest from the sink and packet delay is 151 ms. Fig. 7 shows the packet loss rate as a function of the frame generation period P_f . These losses become less than 2% for a period P_f equal or greater than 130 ms. These good results meet the requirements and are in accordance with the theoretical calculation (section 4.1). They are explained by the fact that the frames are practically never sent in competition for access to the medium, except that the transition from the Idle state to the Initiator state that can compete with a data frame of the node in the state Initiator.

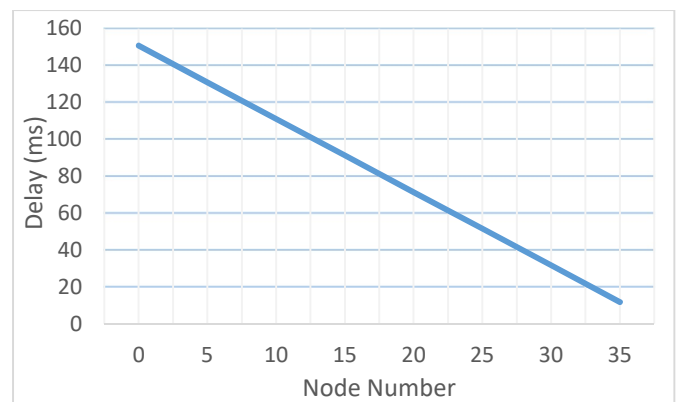


Fig. 6. Frame delay vs hop number.

Finally, a real node implementation has been made. The protocol has been programmed on an Arduino Mega 2560 platform equipped with a Digi Xbee wireless network module. 5 nodes were deployed in the laboratory corridors to create a

60 meters long network. The TOMAC-WSN protocol worked perfectly on this installation.

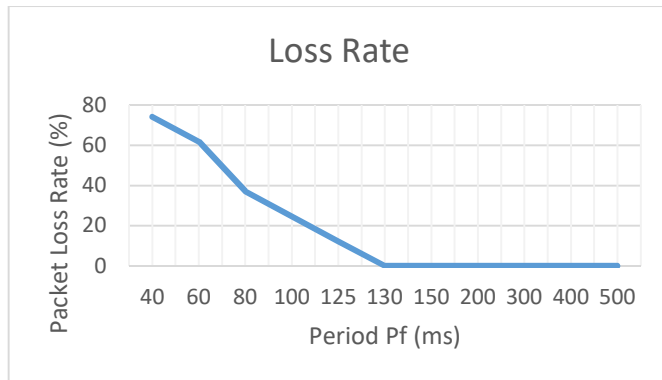


Fig. 7. Packet loss ratio vs frame period generation.

VI. CONCLUSION

A new protocol for a wireless sensor network has been designed to meet the needs of a monitoring application for a large physical system in cyclic mobility. The performance obtained by simulation shows that this protocol meets the requirements of the monitoring application for a large system such as a chairlift. Its implementation on Arduino nodes made it possible to verify that it really works on light equipment and is easy to program. It remains to install the nodes on a chairlift to fully verify its operation and measure its performance in real conditions. Adaptations can easily be made to meet other requirements of an application. For example, the monitoring of the descending seats could be done by activating the nodes on another frequency channel and adding a sink down which would allow to have two quasi-independent networks whose performances of each would be those presented in this paper. The TOMAC-WSN protocol could also be used on a WSN to monitor large fixed systems such as pipelines. The location of the sinks should be studied to meet the quality of service requirements of the monitoring application.

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