Adaptive TDMA-Based Clustering for Critical Event Detection in Wireless Sensor Networks

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Abstract—**In this paper, a novel adaptive TDMA-based clustering for critical event detection in Wireless Sensor Networks (WSN) is proposed. The aim of our adaptive approach is to detect the critical event, such a fire detection in the forest, at the required delay with minimum energy consumption. So, when an event occurs, only the sensor nodes in the detection area will be in active mode, while the others will be in sleep mode. The reaction to the event is made locally. This behavior can consume less energy. The simulation results show that our adaptive approach is better than the non-adaptive approach. We have compared our results to other works and we have proved the efficiency of our approach in terms of energy consumption.**

Keywords—Wireless sensor networks; event detection; adaptive TDMA cycle; sleep/wakeup; delay; power consumption.

I. INTRODUCTION

In recent years, Wireless Sensor Networks (WSNs) have been used in a wide variety of applications including industrial control, home automation, security and military sensing, health monitoring, intelligent agriculture and environmental sensing. In addition, WSNs are used widely for sensing various events, such as animal movements, forest fires, gas leaks, intruders, and so on. For many applications of WSN, event detection can be considered one of the major issues. So, these events may occur infrequently. Thus, the sensor nodes should use as little energy as possible, because most sensor nodes operate with batteries which are difficult to replace or recharge [1].

It exists many protocols which reduce the nodes activity (duty cycle), such as SMAC [2], T-MAC [3] and DMAC [4]. The main idea of these protocols is to allow the sensor nodes to alternate between active and sleep periods. During the listen period, all sensor nodes turn ON their radio and keep listening to communicate with their neighbors. But, when this period expires the nodes go back into a sleep state. The duty cycle is defined as the ratio between the active period and the active/sleep periods. So, the shorter duty cycle implies sleeping of the node most of the time in order to consume less energy and avoid idle listening [5]. It is important to note that a longer sleep period increases latency.

As we consider a critical events with real time constraints, we are looking for deterministic medium access protocols. Many protocols are not suitable for this context such as SMAC and DMAC. We focus on TDMA which provides a deterministic transmission with slot times allocated for each node for every cycle. At the specific slot, the node will be active and for other it can be in sleeping. It is clear that if we get a larger TDMA cycle, the node activity will be less (shorter duty cycle) which implies less energy consumption and more latency. We should get the right optimization that maximizes TDMA cycle without braking real time constraints on communication delay. To optimize TDMA according to the energy and the real time constraints, allocation should be adapted to the events occuring. For this reason, we propose an approach which deploys an adaptive TDMA cycle depending on event occurring. This adaptation is applied locally around the event and on the nodes in the event detection area. Thus, our aim is to reduce the nodes activity and to respect the delay constraint which is relative to the required detection time ($T_{Detection}$).

The rest of this paper is organized as follows: Section 2 presents a synthesis of most of the related work concerning adaptive slot assignment in WSN, particularly the On-demand Convergecast Scheduling protocol. The proposed adaptive approach is presented in section 3. Our performance evaluation is given in section 4. Finally, Section 5 concludes the paper.

II. RELATED WORK

In this section, we present the brief description of the most related work that utilizes the adaptive slot assignment depending on the traffic load in Wireless Sensor Networks, such as TA-MAC [6], P-MAC [7] and GMAC [8]. But, we interest, in particular, to the “On-demand Convergecast Scheduling” (OCS) based MAC protocol [9].

A. PMAC, TA-MAC and GMAC protocols

P-MAC [7] is the abbreviation of **P**attern-**MAC** protocol. It is proposed to save more power saving than the existing MAC protocols without compromising on the throughput. It adaptively determines the sleep-wake up schedules for a node based on its own traffic load as well as the traffic patterns of its neighbors. So, the aim of PMAC is to divide the duty cycle into n time slots and to generate a sequence of pattern bits, which indicate the tentative sleep/wakeup plan for a sensor node during the time slots, depending on the network traffic loads. While, TA-MAC [6] is the abbreviation of **T**raffic **A**daptive duty cycle **MAC** protocol for Wireless Sensor Networks. Its aim is to forward more packets in single cycle when traffic loads increase. The main idea is to add, dynamically and depending on the data quantity, an extra transmission cycle in the original basic cycle.

Finally, the G-MAC [8] is the abbreviation of Gateway-MAC protocol. It is an energy-efficient sensor MAC protocol which coordinates transmissions within a cluster and obtains significant energy savings by allowing associated cluster nodes to sleep for extended periods of time. The aim of this protocol is to define a node acting as a gateway for a certain time, and then rotates nodes so as to balance the load among them.

B. OCS

OCS [9] is the abbreviation of **O**n-demand **C**onvergecast **S**cheduling based MAC protocol. It is a centralized and adaptive multi-hop scheduling based TDMA protocol which supports convergecast applications in the event-driven WSNs with the objective of energy efficiency and delay guarantees. Its main idea is to allow nodes to sleep most of the time then wake-up at specific time slots to send and/or relay requests for slot assignment to the sink. In addition, the mechanism of the slot assignment in OCS protocol is different from many proposed TDMA-based protocols because the time slots are only assigned to nodes that are sources or relays of traffic. These slots are assigned by the sink for the requesting and relaying nodes. It must be noted that when there is no traffic received, for a certain time period, from the source nodes, the sink node removes those nodes from the last slot assignment. The operation of the OCS protocol is based on two phases which are setup phase (called SP) and steady-state phase (called SSP). During the SP, the sensors determine the presence of neighboring nodes in their area and relay this information to the sink node. The latter use this information during the creation of the multi-hop schedule. The construction of the topology is based on the PROGRESSIVE protocol [10] which conserves energy by controlling the use of CSMA while collecting network connectivity information. The nodes undiscovered enter into the sleep mode while the nodes which have one or more scheduled neighbor wake up at a specific time period in order to send their connectivity information to the sink node. Using this technique, the PROGRESSIVE protocol will progressively collect topology information at the sink node with less energy consumption.

When an event occurs, the OCS approach does not take into account the required detection time to transmit data from the sensor nodes to the sink node. So, this can be a major drawback of OCS because the non-respect of this time can be a problem in the critical applications. In this paper, we try to resolve this problem by the deployment of the adaptive TDMA approach based on the required detection time. This solution will be detailed in the next section.

III. OUR ADAPTIVE APPROACH FOR CRITICAL EVENT DETECTION

In this section, we will describe the principle of our adaptive approach in order to detect the event at the required delay and with a reduction of energy. It should be mention that our network topology is a tree and the TDMA cycle is applied on the nodes with the same parent node (i.e in the same cluster) (see Fig. 3) [11] [12].

A. Principle and Problematic

In our work, we try to find a solution that can respond to the following problem :

"*How the sensor nodes can detect the critical event and inform the Sink node at the required delay with minimum energy consumption?*"

To response for this question, we have proposed an approach which consumes less energy by reducing the activity since the sensors react locally when the event appears. It means that, only the sensor nodes in the same detection area will be in active state, while the others will be in the sleep state. This solution offers a better compromise between the energy consumption and the event transmission in time. This compromise is done by adapting the cycle TDMA in each detection area, depending on the traffic load. So, when a sensor node detects an event, it must transmit this information immediately. The proposed approach is based on two phases. During the first phase, the sensor node must ensure that an event was occurred. This phase is necessary in order to protect the other nodes against the destruction, especially if the event is the fire. During the second phase, the sensor nodes must transmit the information of the detected event to the Sink node at the required delay. In fact, when the event occurs, the sensor node can have many states depending on its location in the detection area. These states help the neighbor nodes, in the same detection area, to know if an event is detected or not yet.

For example, when there is not activity (low activity), the sensor node will be in the Normal State (called N_S). This state is present since there are no events to detect. It becomes in the Suspect State (called S_S), if there are no HELLO messages exchanged between the sensor node and other nodes in the network. It should be mentioned that the HELLO messages are used to maintain the good operation of the network. The sensor node becomes in the Failed State (called F_S) or in the Set_On_Fire State (SOF_S), if there is a problem in the detection. It means, when there is no Hello messages during a *timeout*, the sensor node will be in the F_S. Whereas, it will be in the SOF_S when the fire destroys its components before that the event is detected (see Fig. 1).

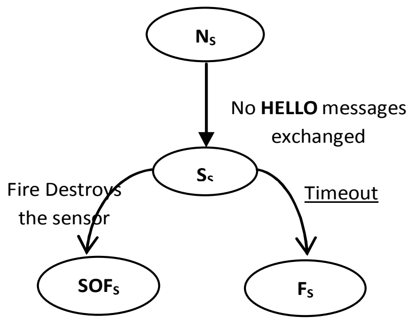

Fig. 1. The different states of the sensor node during the event detection

It must be noted that each event has a velocity in the sensor network. This velocity presents a critical parameter to ensure the detection and the transmission of events before that the sensor node will be destroyed. Indeed, we define the sensing area (S_A) as the area where the sensor nodes can sense the event. While, the detection area (D_A) represents the area where the sensor nodes can detect the event (see Fig. 2).

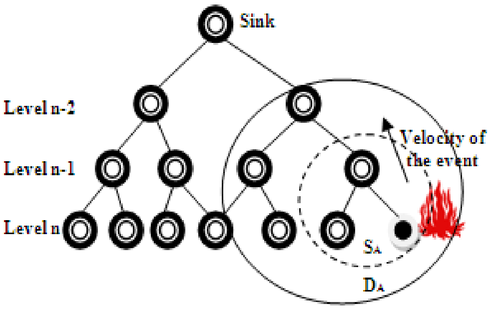

Fig. 2. Propagation of the fire in the detection area

B. Analysis of the propagation time and the duty cycle

In this sub-section, we analyze, on the hand, the propagation time needed before the event detection. On the other hand, we analyze the duty cycle. The aim of these variations is to demonstrate how the duty cycle can affects the propagation time. It is important to note that, the duty cycle represents an important parameter to prove the efficiency of our approach in terms of energy consumption and the delay.

1) Hypothesis

We have taken the following assumptions in our simulations.

- All sensors have the same characteristics (energy level, memory capacity, etc.), except the sensor node.
- Sensors are randomly distributed across the whole sensing area.
- Each sensor has a Sensing Area, called S_A (t), to detect the event.
- We consider the fire as an example of event in WSN.
- The event velocity is uniform (computed in the worst case).

2) Analysis of the propagation Time

The forest fires, known as wild fires, are uncontrolled fires occurring in wild areas and cause significant damage to natural and human resources. For that, it must analysis the necessary propagation time in order to inform all sensor nodes that the fire is happening before the detection time ($T_{Detection}$) destruction of the sink node. In addition, it is important to mention that the sensor nodes can detect either one or more than one event at the same time. For that, we have divided our sensor network into two types of activity areas; the Low Activity Area (called LAA) and the High Activity Area (called HAA).

In the following sub-sections, we will give an analysis of the propagation time, called T_{Hello}, in the two types.

a) Low Activity Area

Before the analysis of the propagation time, we define the transmission time of **HELLO** message (called T_{Hello}) as the time used in order to maintain the state of the neighbor nodes especially used to inform about fire detection. This time must be strictly lower than the time of the event detection (see equation1). This condition must be satisfied in order to avoid the destruction of nodes.

$$T_{Hello} < T_{Detection} \quad (1)$$

Since, the event has a propagation velocity, thus at the **n hop** and for a coverage radius R, we have:

$$V = \frac{n*R}{T_{Detection}} \quad (2)$$

Thus, the time of event detection is expressed as in (3).

$$T_{Detection} = \frac{n*R}{V} \quad (3)$$

According to (1), the time of **HELLO** message must satisfy the following condition:

$$T_{Hello} < \frac{n*R}{V} \quad (4)$$

Where '*n*' is the hop count, '*R*' is the coverage radius and '*V*' is the velocity of the event propagation.

It should be noted that, in the case of low activity area, the transmission time of **HELLO** message must be strictly greater than the TDMA cycle. This condition is defined as in (5).

$$Cycle_{TDMA} < T_{Hello} \quad (5)$$

b) High Activity Area

In the case of High Activity Area (HAA), the sensor node must detect the event at the required delay ($T_{Detection}$). So, all its neighbors will be in the wakeup state and inform the sink in time. In fact, the necessary time to inform all the neighbors, using the **HELLO** message, must satisfy the following condition:

$$T_{Hello} \leq T'_{Detection} \quad (6)$$

The detection time (called $T'_{Detection}$) is defined as the ratio between the detection area and the velocity (7):

$$T'_{Detection} = \frac{Detection_{Area}}{V} \quad (7)$$

Thus, the transmission time of **HELLO** message must be less than the detection time (8):

$$T_{Hello} \leq \frac{Detection_{Area}}{V} \quad (8)$$

3) Analysis of Duty Cycle

In this sub-section, we will determine the Duty Cycle in the two types of activities; HAA and LAA. In our work, we define the duty cycle as the ratio between active period and all active/sleep periods which represent the activity period of TDMA Cycle. During the active period, each sensor network can have the possibility either to gather the data received from its neighbors and retransmit it with its data, or transmit just its data without gathering since it has not data generated from its neighbors. Thus, in the first case, we represent the transmission with gathering, while in the second case we represent the transmission without gathering. These cases are applied in the two types of activities HAA and LAA.

a) Duty Cycle with data gathering

In this case, our adaptive approach is deployed when there are a data gathering before the transmission. The aim of data gathering is to transmit data that has been collected by the sensor nodes, in the same cluster, to the sink node. Thus the idea is to combine the data coming from different sources and route it further after eliminating redundancy. Each node will transmit within its TDMA cluster cycle (see Fig. 3) [11] [12]. Indeed, each sensor node with the same parent will have the possibility to transmit data with a definite size. Thus, the duty cycle can be expressed as in (9):

$$Duty_{Cycle} = \frac{|C_i|*T_s*g_i}{Cycle_{TDMA}} = \frac{|C_i|*T_s*g_i}{T_{Hello}} \quad (9)$$

Where, g_i, represents the packet generation rate for each sensor node, $|C_i|$ is the cluster size (i.e. the number of nodes in the cluster), T_s is the duration of the time slot and T_{Hello} is the propagation time of HELLO messages.

For example, we consider the Fig. 3, when the parent node "2" has a time slot greater than the parent node "1". This is due because the parent node "2" aggregates its own data with the data received from its neighbors (nodes 3 and 4) before transmitting them to the sink node. Indeed, the duration of the time slots allocated to the parent nodes having data for gathering, will be greater compared to the other parent nodes.

b) Duty Cycle without data gathering

In this case, we deploy our adaptive approach when there aren't a data gathering before the transmission. Each parent node will transmit, on different measures, its own data (g_i) and the data of its children nodes (f_i). For that, we define the Duty Cycle as in (10).

$$Duty_{cycle} = \frac{\sum_{i=1}^{|C_k|}(g_i+f_i)*T_s}{Cycle_{TDMA}} \quad (10)$$

Where, f_i, is the data generation rate received from the children nodes and $|C_k|$ is the cluster size.

It is important to mention that the difference between the LAA and HAA is in the formula of the duty cycle. This timer will be divided, in the HAA case, by the time of information (called T_{info}) instead of the Hello time (called T_{Hello}) in the LAA case.

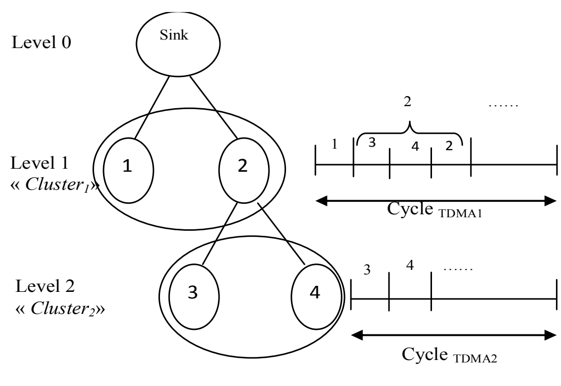

Fig. 3. Example of the slot time allocation with/without data gathering

IV. PERFORMANCE EVALUATION

In this section, we evaluate the proposed solution and we give, on the hand, a comparison with the duty cycle value when we use the adaptive approach and, in the opposite case, when we use the non-adaptive approach. On the other hand, we compare our results to the OCS work [9]. The performance evaluation is discussed when the network size is varied in [1-10] nodes per cluster for three levels, the packet generation rate is 0.03 pkt/sec, the time slot is equal to 2ms, the hop count is varied in [2-5], the coverage radius R is 50m and the detection time is 5sec. The duty cycle and the delay are taken as a performance metric. The first parameter has an effect on the energy consumption and the delay since it evaluates the active period when the sensor nodes wakeup to detect the event. We run simulations by varying the number of nodes either in each cluster or in the whole of the sensor network. Simultaneously, we have varied also other parameters for each simulation. In the Fig. 4, we varied the number of nodes per cluster to determine the duty cycle. The results show that, the adaptation of the TDMA cycle minimizes the nodes activities (minimum duty cycle) compared to the non-adaptive approach. It means that the sensor nodes will consume less energy since the active period is not important. We take, for example, the case of a wireless sensor networks when the nodes per cluster is equal to 5. From the Fig. 4, we observe that, in the case of a non-adaptive approach, the duty cycle reaches a value of 0.1%. While, when our adaptive approach is deployed, the duty cycle will have a lower value which is equal to 0.05%. This prove that our approach is more efficient in terms of energy minimization compared to the non-adaptive approaches.

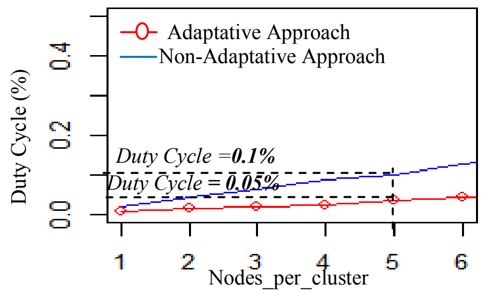

Fig. 4. Variation of the duty cycle vs. Nodes per cluster

In the Fig. 5, we made a variation of the detection area diameter and we determine the communication delay. It is clear that the delay increases when the detection area increases. This behavior is normal since the sensor nodes will spend more time to detect the event when it is occurs in a wide area. The Fig. 5 shows an example, when two events occur in two detection areas with different diameters. In this case, the first event is occured in a detection area with a diameter equal to 70m, and the second event is occurred in a detection area with a diameter equal to 100m. For these two detection areas, the sensor nodes must detect the first event within a period not exceeding 28secondes whereas 40secondes for the second event. It must be noted that the diameter of the detection area has an effect on the number of active nodes in this area. For that, we present the variation of the duty cycle based on the number of nodes per cluster (see Fig. 6). This variation was obtained for two different diameters of the detection area (70m and 100m). From the results, depicted in Fig.6, we observe that when the detection area becomes wider, the duty cycle decreases. In other words, the nodes activities decrease when the detection area becomes wider. Subsequently, the power consumption in these nodes will be decreased.

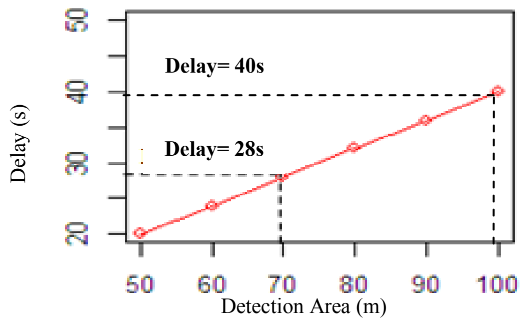

Fig. 5. Variation of the delay vs. Detection Area

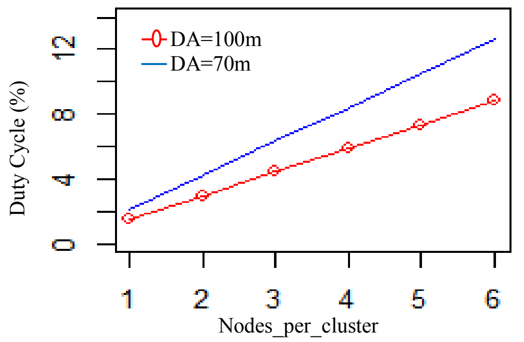

Fig. 6. Variation of the duty cycle vs. number of nodes per cluster

Finally, we compare our adaptive approach to the OCS approach (see Fig.7). Our aim is to evaluate the performance of our adaptive approach in terms of energy consumption in the sensor nodes. For that, we calculate the duty cycle depending on the number of active nodes in the entire of the sensor network. From the results, we observe that our approach is better than the OCS approach [9] in terms of energy consumption because the duty cycle (active period) is lower than them. For example, when the active nodes in the sensor networks achieves the value 10, the duty cycle calculated using our adaptive approach is equal to 30%, whereas it is equal to 32% using the OCS approach. These results prove that when we deploy our adaptive approach, the sensor nodes consume less energy compared to the OCS approach.

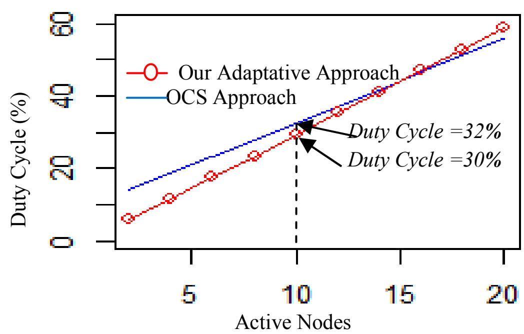

Fig. 7. Variation of the duty cycle vs. active nodes

V. CONCLUSION

In this paper, we have presented the most important WSN MAC protocols which deploy the adaptive TDMA technique. After that, we have proposed an adaptive approach based on the adaptation of the TDMA cycle depending on the event detection and its propagation in the network. Our aim is to optimize the TDMA cycle to reduce the activity period of sensor networks. This optimization is applied locally and on the sensor nodes in the same detection area. We have compared our results to the non-adaptive approaches. Indeed, we have proved the efficiency of our approach in terms of energy consumption compared to the OCS approach. The adaptation of the TDMA cycle has shown that our approach is better than the others (non-adaptive and OCS) since, on the hand, the adaptive TDMA cycle represents a good distribution of the activity and the inactivity periods for the sensor nodes. On the other hand, this cycle is adjusted to respect the delay constraint relative to the required detection time.

REFERENCES

[1] Zhiping, L., Q. Huibin, et al. (2006). “The design of wireless sensor networks for forest fire monitoring system”. School of Electronics and Information, Hangzhou Dianzi University, White Paper.

[2] W. Ye, J. Heidemann, D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks”, IEEE/ACM Transactions on Networking 12 (3) (2004) 493 – 506.

[3] T. van Dam., K. Langendoen, “An adaptive energy-efficient MAC protocol for wireless sensor networks”, in Proc. 1st International Conference on Embedded Networked Sensor Systems, pp. 171 – 180, 2003.

[4] G. Lu, B. Krishnamachari, C. S. Raghavendr, “An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks”, in 18th International Parallel and Distributed Processing Symposium, pp. 224, 2004.

[5] S. Gherairi, S. Ouni and F. Kamoun, “Sleep/Wakeup and TDMA scheduling access protocols in sensor networks : A survey”, in the International Conference on Wireless Networks (ICWN’09), Las Vegas, Nevada, USA, Vol. 2, pp. 625—631, July 13-16, 2009.

[6] H. Chen, “Traffic adaptive duty cycle MAC protocol for wireless sensor networks”, The 4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '08), pp. 1-4, 2008.

[7] Tao Zheng, Sridhar Radhakrishnan and Venkatesh Sarangan, “PMAC: an adaptive energy-efficient MAC protocol for wireless sensor networks”, in: Proc. 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS 2005), Denver, CO, 18 April 2005.

[8] I. Brownfield, Kaveh Mehrjoo, Almohonad S. Fayez, and Nathaniel J. Davis IV, “Wireless sensor network energy-adaptive MAC protocol”, IEEE CCNC’06 proceedings, pp.778-782, 2006.

[9] Y. Barnawi Abdulaziz, “Adaptive TDMA slot assignment using request aggregation in wireless sensor networks”, in the 3rd International Conference on Ambient Systems, Networks and Technologies (ANT), Procedia Computer Science Vol. 10, pp 78 – 85, 2012.

[10] A. Barnawi, R. Hafez, “Progressive: a topology discovery and scheduling protocol for wireless sensor networks”, In: Proc. of the 12th ACM international Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM’09, pp 325-328, 2009.

[11] S. Gherairi, S. Ouni and F. Kamoun, “Optimized TDMA multi-frequency scheduling access protocols for sensor networks”, International Conference on Communications, Computing and Control Applications (CCCA), Hammamet, Tunisia , ISBN. 978-1-4244-9795-9, pp 1-6, 3-5 March 2011.

[12] Sofiane Ouni, Salsabil Gherairi, Farouk Kamoun, “Data-Aggregation and Pipelining Scheduling Protocols for Real-Time Wireless Sensor Networks”, Accepted in International Journal of Ad Hoc and Ubiquitous Computing, INDERSCIENCE Publishers, Vol.12, Issue 1, pp.56-64, January 2013.