A pollution monitoring system based on an energy-efficient Wireless Sensor Networks architecture

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***Abstract*— A wireless pollution analysis system based on an energy-efficient, scalable and robust architecture for wireless sensor networks is presented in this paper. This architecture called EDETA (Energy-efficient aDaptive hiErarchical and robusT Architecture) has been optimized to save node's power, being scalable and suitable for heterogeneous and homogeneous wireless sensor networks, supports single or multiple sinks, and also provides features increasely-demanded in the current applications such as fault tolerance and bounded-time response communications. All these features make EDETA suitable for the implementation of applications where the consumption and the network duration (in time) is a key factor, such as the proposed application. A wireless pollution monitoring system based on EDETA has been implemented. From the chemical point of view, the parameters to be controlled and their acceptable levels are based on the current legislation. As for the methods of analysis for the detection of pollutants, well-known electrochemical methods are proposed. Very satisfactory results about the energy consumption and reliability have been obtained, the implemented system based on EDETA reduces the energy consumption in a factor of 8x compared with most popular power-aware protocols. Furthermore, EDETA multiplies the lifetime of the sensor network while providing, in addition, extra-features such as low response time and fault-tolerant mechanisms.

***Keywords*— Wireless sensor networks, routing protocols, distributed in-line analysis, pollution monitoring.**

I. Introduction

Important advances have also been obtained in the field of transductors, which allows for the development of new devices for the detection and measurement of chemical and physical properties in an easy, inexpensive way. Therefore, they replace the traditional techniques since they are usually slower, more expensive, and more difficult to be automated. These new transductors, mainly in solid state (ion selective electrodes, ISE [1]) have provided important advantages such as easiness, lower size, precision, easy automation, and low cost. ISEs are membrane electrodes that respond selectively to ions in solution in the presence of others. The nature of the membrane determines the selectivity of the electrode. Several types of sensing electrodes are commercially available. They are classified by the nature of the membrane material used to construct the electrode. In the case of water pollution analysis, the following types are to be remarked:

a) Polymer Membrane Electrodes (Organic Ion Exchangers and Chelating Agents) -- Polymer membrane electrodes consist of various ion-exchange materials incorporated into an inert matrix such as PVC, polyethylene or silicone rubber. After the membrane is formed, it is sealed to the end of a PVC tube. The potential developed at the membrane surface is related to the concentration of the species of interest. Electrodes of this type include chloride, nitrate, and water hardness.

b) Solid State Electrodes (Insoluble Conductive Inorganic Salts) -- Solid state electrodes utilize relatively insoluble inorganic salts in a membrane. Solid state electrodes exist in homogeneous or heterogeneous forms. In both types, potentials are developed at the membrane surface due to the ion-exchange process. Examples include lead, copper (II), cyanide, chloride and fluoride.

In this work, we analyze chloride, nitrate and ammonium concentration using the corresponding ion selective electrodes placed in situ in a suitable analysis device. Chloride is one of the major inorganic anions in water and wastewater. A higher value of chloride may indicate the inflow of wastewater or industrial effluents into the river. The chloride concentration is higher in wastewater than in raw water because sodium chloride is a common constituent of the diet and passes unchanged through the digestive system [2]. Nitrate and ammonium are important because they are the major forms of nitrogen which are directly assimilated by plants and organisms the former being one of the most common contaminants of groundwater, originating mainly from agricultural fertilizer application and release of sewage.

On the other hand, huge advances have taken place in the field of electronic circuits, as well as in that of wireless communications [3]. They have opened an interesting research line with the development of low-consumption, low-cost electronic devices that are able to carry out data acquisition tasks; these data are then processed and the results transmitted to a process center for their storage and further study. This research field is the so-called Wireless Sensor Networks (WSN) [3][4], which makes low consumption prevail over bandwidth and coverage, hence achieving to cover long distances thanks to the application of multi-hop communications. Moreover, these networks offer a greater fault tolerance and provide interesting features in terms of real time, composability, and scalability [5].

There are a lot of routing protocols for WSN [4]. The main problem of these protocols and other recent approaches [6,7,8,9] is the assumption that all nodes can reach the sink among others. In practice, with a network of some square kilometers this assumption is not valid. Moreover, the transmission power grows with a cost $O(d^4)$ with the distance. So the farther a node wants to transmit, the more energy it will consume.

In this paper a new architecture with a far better treatment of these inconveniences, which also presents new necessary and very important features for the pollution monitoring system implementation, not allowed with other approaches, such as fault tolerance and bounded time communications, is presented.

II. ENERGY-EFFICIENT ADAPTIVE HIERARCHICAL AND ROBUST ARCHITECTURE

EDETA is a new protocol based on two levels, the first formed by clusters and the second formed by a dynamic tree. It elects its clusters randomly and recalculates the achieved network structure after certain number of rounds.

Between CHs, a tree structure, with the sink as the root, is build to allow data communication to the sink.

The protocol supports more than one sink in order to provide more scalability and some fault tolerant mechanisms.

The CH election is based on a random number that must be lower than a calculated threshold given by (1):

$$T(n) = \frac{c}{|N|-2c} \times t,\ n \in N \quad (1)$$

Where c is the number of clusters that we want in the network, N is a set with the nodes in the network and t is a parameter and its value will depend on the time in which the equation is computed.

At the beginning of the network configuration, the above equation will be computed, assuming $t=1$. During the network configuration, it will also be evaluated if there is any CH that needs some normal nodes to become CH to avoid being isolated. In this case t has to be greater than one to increase the node's probability to become CH.

If the number randomly generated is lower than the calculated threshold, a node can become a CH only if its remaining energy is greater than (2).

$$E(n) = \frac{3}{4} E_T,\ n \in N \quad (2)$$

Where E_T is a mean of the remaining energy of other possible CH's that are around the node.

EDETA is a time constrained protocol. As will be discussed later, EDETA's operation is divided into phases. The duration of this phases are time constrained. This way, EDETA can be used in applications in which time it is an important variable.

A. *Operation*

EDETA is divided into two phases, the initialization phase and the normal operation phase. There are two variables that limit the phases' duration. The TIME_CONFIG variable limits the initialization phase and the TIME_SUPERFRAME variable limits one round of the normal operation phase. The normal operation phase has a limited number of rounds defined by the parameter MAX_INTRAROUNDS. So, the normal operation phase lasts, at most, $MAX\_INTRAROUNDS \times TIME\_SUPERFRAME$.

B. *Protocol phases*

As has been explained, EDETA operation is divided in two phases. First of all, the network initialization is performed. This phase lasts a maximum of two TIME_CONFIG. In it, nodes elect their CHs and a tree is build between CHs to send the collected data to de sink. When the network is build, the normal operation phase begins. This phase takes a configurable number of TIME_SUPERFRAME intervals. It depends on the rounds that CHs have to operate before the network structure is considered obsolete, and then recalculated. In this phase, CHs collect data from their nodes at defined intervals, and they send them to their fathers in the tree in order to reach the sink. After certain number of rounds, all this network structure must be dissolved and the process begins again.

Initialization phase.

In this phase the network structure is built and it consists in three sub-phases.

On the first part, with duration of a half TIME_CONFIG, each node decides on his own if it is going to be a CH, based on the above explained procedure.

When a node decides to be a CH it sends HEAD messages to announce its role to the rest. At the same time, a CH starts receiving HEAD messages from the others and decides which CH joins in order to send its data to the sink.

This decision is based only on the distance between CHs. But a CH will only try to join another CH if this one has established a path to the sink. That is, it can communicate with a CHs that can reach the sink directly or through others CHs.

Meanwhile, nodes which have decide to be leaf nodes start receiving HEAD messages too. They store them to decide which CH to join on the second part of this phase. The selection of the CH for these nodes follows the same criteria than previous selection of parent CH.

If a CH doesn't receive any HEAD message, it sends a NEED_CH message. When a normal node receives it, reruns the procedure to decide whether is going to be a CH or not, but with an increased value of *t*. When *t* is increased the probability of a node to become a CH increases too. In this case, we have to increase the probability because we need the network to be built as fast as possible.

This mechanism along with the first random distribution of CHs allows the protocol to adapt rapidly the CH's population to the needs of the network.

At the end of this sub-phase, the tree structure is build and normal nodes have the necessary information to decided which cluster are going to join in.

On the second sub-phase, with duration of a half TIME_CONFIG, normal nodes start to join their selected clusters and the CH sends, in the response message, the time schedule in which each node has to send its data. After that the normal nodes enter in the sleep state.

A CH can only allow a limited number of nodes to join in. This number is given by the parameters *MaxSoft* and *MaxHard*. A CH accepts all the join request petitions until it reaches its *MaxSoft*. After that, it will only accept join petitions that have activated a last resort bit. When a CH reaches the *MaxHard* threshold, it will no longer allow new joins.

Finally, on the third sub-phase, with a duration of one TIME_CONFIG, each leaf CH in the tree sends to its father the amount of time needed to have all the data recollected from his nodes. The father collects all this information and decides the time schedule in which its sons can send him the data. After that, the father repeats the process with its own father, sending the amount of time needed to collect all the data from its nodes and its sons; then, the grandfather decides the time schedule in which its sons have to send it the data. This process continues until the entire tree schedule is done.

Normal operation phase

At this moment, the network structure is done and every node must send its data to the CH at the scheduled time, and during the remaining time the nodes enter in the sleep state. When a CH has received the data from all its nodes, it aggregates it and sends it to his father at the established time.

As has been said, the father of a cluster informs in which time its sons have to send their data. Sons will send their data when they receive a POLL message. This allows the father to decide exactly when the data will be sent. This make applicable some fault tolerant mechanisms, as discussed later, without inquiring collision of messages. Moreover, this polling mechanism allows timing synchronization between all the CHs in the tree.

This phase is performed during some amount of rounds, with duration TIME_SUPERFRAME, defined by the parameter MAX_INTRAROUNDS. After that, the network structure is considered obsolete and every node restarts from the beginning at the initialization phase.

III. Wireless Pollution Monitoring System

The system architecture consists of three major subsystems:

a) Data acquisition subsystem. It is formed by a set of transductors that are in charge of getting information on the different parameters to be analyzed.

b) Control and communication subsystem. It is the sensor network itself, which controls the chemical analysis subsystem, collects the information that it provides, and carries it to the data management subsystem.

c) Data management subsystem. It is in charge of receiving the information from the control and communication subsystem, which is then handled and stored. This information can be accessed through the Internet, and it can generate the appropriate warnings

A. *Data acquisition subsystem*

Nitrate, ammonium/ammonia, and chloride are monitored in-line. They are measured using three ISEs incorporated in the Sensor Node [10]. The probe ammonium ISE makes use of a silver/silver chloride wire electrode in a custom filling solution. A nonactin membrane separates the internal solution from the sample medium and this membrane selectively interacts with NH4+ ions. The probe chloride ISE utilizes a solid state membrane attached to a conductive wire. The probe nitrate ISE consists of a silver/silver chloride wire electrode in a custom filling solution. The internal solution is separated from the sample medium by a polymer membrane, which selectively interacts with NO3- ions. For these three selective electrodes, when the probe is immersed in water, a potential is established across the membrane that depends on the relative amounts of the analyte (ammonium, chloride, and nitrate ions, respectively) in the water and the internal filling solution. This potential is read relative to the pH reference electrode of the probe.

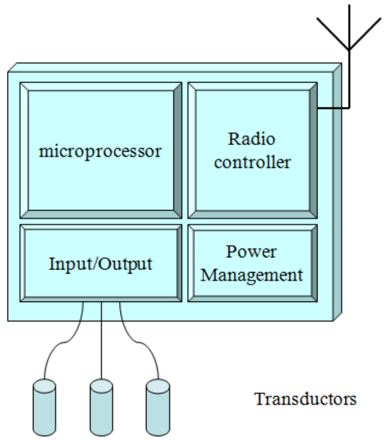

Fig. 1. Sensor node structure.

It should be remarked that the control of all transductors is carried out through the microcontroller node itself, their tension values being measured through analog inputs; the acquired value is then interpreted and so are the suitable calibration mechanisms.

B. *Control and communication subsystem*

This subsystem is formed by a set of sensor nodes and a sink node, all of them interconnected by means of a private wireless network. On the other hand, the sink node is communicated with the data management system through a public network.

Sensor node: As Figure 1 shows, each sensor node is based on a microcontroller that (a) controls the different aforementioned transductors, and (b) has a communication module and a power mode. Everything is located inside a small-size, low-cost buoy.

We have chosen the CC1110 microcontroller system (compatible with MC 8051) due to their excellent features for WSN implementation, namely: low cost and consumption, and the availability of a chip-integrated radio circuit for communications in the ISM 800/900 MHz band, as well as a suitable number of I/O lines for the interconnection of the utilized transductors.

Sink node: This node is in charge of receiving data from all the sensors nodes of the network, performing an intelligent processing of them, and resending them to the data management subsystem. Furthermore, it carries out key tasks in the wireless network management, such as the creation of its topology, the diagnosis on the status of the sensor nodes, and the recovery mechanisms in case of malfunctions. Finally, from the point of view of the data, it is an interesting passing route between local and remote communications, since it can carry out different treatments (filtration, compression, summary, and aggregation) on the data received before resending them.

An ARM9 microcontroller has been used for its implementation, to which the following devices have been connected:

- An RF module in the ISM 800/900 MHz band: it is based on a CC1101 chip, and connected by SPI.
- A GSM/GPRS communication module based on an integrated TELIT GM 862 connected to the microcontroller by means of an RS232 link. Nowadays, a new WiMax communication system is being set up to replace the GSM/GPRS, which will provide a communication system without any cost for amount of data nor for connection time.
- A supply module, capable of getting the energy from either the mains supply or solar panels (when the former is not available).

This sink node is located in a small hut securely anchored on the floor and suitably protected against vandalism.

C. Data management subsystem

The data management subsystem is based on a server with a PC-architecture equipped with an uninterruptible power supply (UPS), and is located at our university (Polytechnic University of Valencia, Valencia, Spain) and connected to the Internet. This computer runs a web server (Apache), a database manager system (MySQL) that contains all acquired data recorded so far, and a program of management and supervision of the information.

D. System operation

In order to carry out the distributed analysis of pollutants, the system periodically takes samples at the different points where the sensor nodes are located, this information being led to the sink node, which introduces it in the remote database. The different data can then be consulted in real time as well as those coming from previous times.

TABLE 1: RESULTS OBTAINED FOR NITRATE, AMMONIUM, AND CHLORIDE, IN DIFFERENT NODES.

Node	$[NO_3^-]$, mg L^{-1}			$[NH_4^+]$, mg L^{-1}			$[Cl^-]$, mg L^{-1}		
	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.
1	102.8	99.3	100.5	1.3	0.2	0.4	202.8	170.4	180.6
2	117.6	115.3	115.8	0.8	0.1	0.5	206.4	162.7	174.8
3	127.3	120.0	125.0	2.4	2.0	2.1	223.3	179.9	185.1
4	122.6	110.9	131.5	1.3	0.0	0.5	184.4	118.3	159.0
5	147.7	130.7	132.3	1.1	0.2	0.4	207.7	145.5	166.0
6	136.4	125.5	130.9	0.6	0.0	0.1	186.0	160.2	173.2
7	134.8	128.5	130.1	0.2	0.0	0.0	198.9	170.1	183.2
8	134.9	130.4	131.2	1.0	0.3	0.7	205.2	198.8	203.8
9	135.1	115.6	120.4	0.4	0.0	0.1	156.8	130.6	137.2
10	120.7	112.6	117.4	0.4	0.0	0.2	179.5	148.8	168.0
11	126.4	98.4	105.0	0.3	0.0	0.1	202.9	179.4	194.1
12	125.5	100.8	114.4	2.9	1.8	2.3	200.7	170.6	190.3
13	127.5	121.1	126.3	3.7	1.9	2.5	203.6	196.2	201.1
14	139.0	127.2	133.8	3.5	2.2	2.4	162.2	147.2	154.7

IV. CONCLUSIONS

In this work, a wireless pollution monitoring system based on a new power-aware and robust architecture for wireless sensor networks has been proposed. The experimentation demonstrates that the techniques implemented in EDETA are effective in reducing energy consumption from a global perspective and enhancing system lifetime. Our experiments show that EDETA can achieve as much as a factor of 8 decrease in energy consumption compared with most popular power-aware protocols. Furthermore, EDETA multiplies the lifetime of the sensor network. Moreover, it allows the coverage of greater areas, while providing some fault-tolerant mechanisms that allow the network to deal with the malfunction of one or more nodes. What's more, as the protocol phases are time-bounded, it is suitable to develop time constrained applications. In addition, the support for multiple sinks and the tree structure build between the CHs, allows great scalability and the deployment of WSN for a wide range of applications.

The results obtained in the in-line continuous monitoring of nitrate, ammonium, and chloride are summarized in Table I. On the other hand, the wireless sensor network with EDETA has shown a correct behavior regarding the supply system as well as the electrode control system and the wireless transmission of the results. The consumption and reliability observed in the system can be considered as excellent.

ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support from the CICYT (research project DPI2007-66796-C03-01).

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