Environmental Monitoring Using Wireless Sensor Networks

Christos G. Panayiotou[*] Despo Fatta[†] Michalis P. Michaelides[§]

***Abstract*— This paper provides a brief overview of the wireless sensor networks technology for environmental monitoring applications. The paper discusses a number of open research issues in designing such applications. Emphasis is given to issues relating to data analysis specifically handling the potentially huge volume of sensor measurements. Furthermore, we address the problem of area coverage to minimize the probabilities of undetected events or false alarms.**

I. INTRODUCTION

The diversity and quantity of chemicals released into the environment has risen dramatically in recent years. These emissions and their impacts are varied and usually complex. This causes serious concerns about their adverse effects on the ecosystem and on human health. The legacy of land and groundwater contaminated by human activities affects quality of life. Increasing regulatory and economic requirements to monitor and treat pollution in the environment have created a pressing need for reliable, cost-effective monitoring of contaminating compounds in water, soil and sediments. For example, the Integrated Prevention and Pollution Control (IPPC) Directive, 1996; the Landfill Directive, 1999; the Water Framework Directive, 2000 etc. New low-cost effective tools are needed for monitoring pollution and detecting trends over time.

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances. These tiny and generally simple sensor nodes consist of sensing units, data processing, and communicating components [1], [2], [3]. A large number of such nodes deployed over large areas can collaborate with each other to monitor the impacts of urban and agricultural land use on water, soils and sediments to support risk assessment and environmental sustainability. They can be deployed to provide *in situ*, real-time data about the state of the environment, including bioavailability and mobility. For example, they can be used to identify trends of pollution and to control the efficiency of remediation and natural attenuation processes. Currently, a number of environmental monitoring programs are under way, see for example [4], [5], [6], [7], [8], [9].

Even though sensor networking technologies have come a long way, a number of issues are still open and deserve further investigation. Sensor technologies have the potential to measure a number of parameters however, due to the diversity and quantity of possible pollutants, sensors with more sensing capabilities are required and this is an area where the field of nanotechnology is expected to have a significant impact. Furthermore, biosensor technologies and biomimetic (mimicking) systems can be used to assess the ecotoxicological risks of pollutant cocktails.

Clearly, the large amount of sensors involved can produce a lot of data which should be converted into meaningful information. To achieve this, one needs to answer a number of questions such as what needs to be sensed, who should sense, whom the data must be passed on to, how are the data routed to the destination etc. On top of these, to answer these questions one needs to take into consideration several constraints like the limited power of each sensor node, its low processing power and bandwidth, the dynamic nature of the sensor field (nodes may move or die due to energy depletion). Finally, the answers to these questions need not be stationary (they may change dynamically).

Collaborative Signal Information Processing (CSIP) [10] is an effort to deal with the energy constrained dynamic sensor collaboration. Zhao et al. [11], [12] have addressed the problem of dynamically querying sensors and routing data in the network so information gain is maximized while latency and band-

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[*] Dept. of Electrical and Computer Eng., University of Cyprus, Nicosia, Cyprus, `christosp@ucy.ac.cy`

[†] Dept. of Civil and Environmental Eng., University of Cyprus, Nicosia, Cyprus, `dfatta@ucy.ac.cy`

[§] Dept. of Electrical and Computer Eng., University of Cyprus, Nicosia, Cyprus, `eep4mm1@ucy.ac.cy`

width consumption is minimized. In the context of tracking contaminant transport, they concentrate on selecting the next best sensor for a vehicle tracking application and updating the belief state in order to maximize information content. For this problem, other approaches including least squares estimation and triangulation [13] have been proposed. Though successful in dealing with the specific problems they address, these approaches are still limited in scope.

Due to the large number of distributed sensors which are densely deployed in the area under observation, it is bound that there will be significant redundancy among the collected data. Sending all these data to the sink (where processing will take place) wastes both energy and bandwidth. Therefore, it is desired to find efficient ways where "neighboring" nodes may collaborate to send the relevant data only once. In addition, it is desired to have intermediate nodes (that act as routers) process and/or aggregate the data they collect from upstream nodes and send only the relevant result downstream towards the sink. On one hand, we look for ways of aggregating data and reduce the communication cost from sensing nodes to the sink, but on the other hand, we also need ways to *guarantee* that the sink has received at least a copy of the relevant data. Towards this end, the standard Transport Control Protocol (TCP) is inappropriate since the sink would be required to send acknowledgements to *all* sensors that may have detected something.

A possible approach for dealing with the complexity of a huge sensor network is the grouping of several nodes into *clusters*, where nodes within a cluster will collaborate with each other in order to process the collected data and possibly limit the data that need to be communicated to the sink, thus improve the monitoring capability and at the same time save both energy and bandwidth. LEACH [14] is a clustering proposal for extending the life of the network. The questions that are still open here is how to *dynamically* form clusters to achieve various objectives.

The remaining of this paper is organized as follows. Section II briefly describes the wireless sensor network technology and outlines some open research issues associated with them. Section III presents some case studies for environmental and habitat monitoring and describes some open research issues in the field. The paper concludes with Section IV.

II. SENSOR NETWORKS

Sensor networks is a technology that gained momentum over the recent years and it is very promising in making the vision of Mark Weiser a reality: "Conceive a new way of thinking about computers in the world, one that takes into account the natural human environment and allows computers themselves to vanish into the background" [15]. Fortunately for researchers, this new technology brings up a wealth of research problems that need to be solved. Such networks are considerably different from the traditional computer networks we have been building over the past years, and thus they may have different requirements and/or constraints in each of the seven OSI layers [2]. Some of these problems are briefly described next.

When reading research papers relating to sensor networks, overwhelmingly, there are two main issues that rightly get great attention and differentiate sensor networks from the networks we know and understand. These are the *limited power* and the potential of deploying networks with *huge number of sensor nodes*. Depending on the application, the power constraint is really critical. For example, as described in the next section, at the Great Duck Island [16] sensors are installed during the off-season and it is important that there is no human intervention during breeding season (7-9 months). As a result, the nodes should conserve energy so that the network as a whole will perform its tasks over that period. This is a significant constraint which affects the sensing, processing and communication capabilities of the sensor nodes as well as the protocols used to for coordination.

The other important issue associated with sensor networks, the huge number of sensor nodes that will be involved, is important because it is no longer possible to have a unique identifier for each sensor (e.g., an IP address). The addressing issue has implications to the media access control (MAC) protocols, routing protocols as well as reliable communication. Furthermore, the huge number of sensors have the potential of generating a vast amount of measurement data and therefore we need efficient algorithms for "making sense" out of the raw data, and turn them into useful information that humans can use. Measurements from sensor nodes capture the spatial and temporal state of the field. Thus, it is desirable to find ways of correlating the data and draw inferences that can improve the decision making process.

Up to now, traditional computer network architectures were layered and (to some extent) have followed the principles of the OSI 7-layer architecture. Amazingly enough, the overwhelming majority of networks converge to the TCP/IP layers (for transport and network layers). Due to the significant differences between sensor networks and "traditional" networks (as described above) it is doubtful whether a TCP/IP-based architecture will be appropriate for sensor networks. In the TCP/IP layered architecture, in order to increase generality and accommodate any application, each layer provides a wealth of services to the layers above, making it fairly complex and inappropriate for the simple sensor nodes. In addition, the addressing is unlikely to include an IP address, and data routing will be done to either minimize the energy expenditure or extend the life and connectivity of the network. Furthermore, due to possible redundancy between different sensor measurements, end-to-end reliable communication will no longer require that every packet is individually acknowledged. Acknowledging every individual packet will cause "unnecessary" traffic and waste energy. Unlike "traditional" networks, sensor network require simple layers which may be application specific. One may design sensor network applications where intermediate nodes will analyze incoming sensor measurements (from neighboring nodes) and communicate to the sink *only* a "summary" report which will be adequate for the decision making process. We expect that data aggregation and sensor fusion approaches will play an important role in the architecture of successful wireless sensor network applications. Furthermore, transport layers for sensor networks will be designed to maximize the probability of event detection, minimize the probabilities of false alarms or misses, minimize classification and tracking errors.

Despite the wealth of research problems, the field of sensor networks would not have gained such popularity if it wasn't for its potential contribution in addressing some difficult problems effectively and economically. Sensor networks have been proposed for various applications including environmental and habitat monitoring, military sensing, industrial monitoring, building monitoring, etc. In the next section we present some projects that deal with environmental and habitat monitoring and address some open issues that we believe need to be resolved.

III. ENVIRONMENTAL AND HABITAT MONITORING

Over the past few years, a number of environmental and habitat monitoring projects have emerged which have attracted the attention of many researchers worldwide. These projects include (but are not limited to) the Great Duck Island, the North Temperate Lakes and the vine monitoring in Pickberry Vineyard.

1) Great Duck Island [17]: The Intel Research Laboratory at Berkeley in collaboration with the College of the Atlantic in Bar Harbor and the University of California at Berkeley have developed habitat monitoring wireless sensor network that enables researchers worldwide to engage in the *non-intrusive* and *non-disruptive* monitoring of sensitive wildlife and habitats. The network was first deployed on Great Duck Island, Maine in Spring of 2002. This network consisted of 32 motes and monitors the microclimate in and around nesting burrows. Each mote had sensors for temperature, humidity, barometric pressure, and mid-range infrared. Motes periodically sample and relay their sensor readings to computer base stations on the island which then make them available to researchers world-wide over the internet. In June 2003, a second generation network with 56 nodes was deployed which was then augmented with 49 additional nodes in July 2003 and with 60 more burrow nodes and 25 new weather station nodes in August 2003. The main project requirements as well as the network architecture are presented in [16]. Among the main requirements is that there should be no human presence on the island for the approximately 9 month breeding season, thus each node should conserve its energy to last until the end of the monitoring period.

2) North Temperate Lakes: The North Temperate Lakes project [18] is another example of sensor networks for environmental monitoring. The main goal of the project is to "develop an intelligent environmental sensing network for detecting 'episodic environmental events and understanding their consequences to lake dynamics". The network is collecting measurements of the overnight Dissolve Oxygen (DO) level from the sensors and its aim is to understand the interactions among the processes (physical, chemical, and biological) that along with external drivers result in the long-term dynamics within the lake. The proposed embedded sensor network needs to have an intelligent command control system to implement adaptive sampling and query the sensors for more information in case of an event.

3) Pickberry Vineyards: An example of precise farming are the wireless mesh networked sensors placed by Accenture Technology Labs [19] in Pickberry Vineyards, a 30-acre premium grape grower in California, USA. In the Pickberry project, collected data from electronic sensors (measuring soil moisture, leaf moisture and air temperature) are sent over the mesh network at the vineyard and then via a cellular network to a server at the Accenture Technology Labs. The objective is to turn the measurements into useful information that could eventually help the vineyard increase yields, cut costs, reduce dependence on chemicals and save on labor. The most important challenge of the Accenture team is to build the right inside applications needed to make the data useful for decision making.

4) Syracuse Project [20]: By summer 2005, Syracuse University researchers will have installed a dozen robotic sensors (RUSS system – Remote Underwater Sampling Stations) to form an underwater monitoring system to safeguard drinking water. The 12 robots will cover (in almost real-time) part of the Seneca River and five connected lakes that provide drinking water for more than 500,000 people in central New York. Such a robot network can automate the process of water testing making it significantly easier and faster. Similar underwater environmental monitoring programs are under way in Minnesota, Washington, Nevada and North Carolina. In this system, each robot is equipped with temperature, oxygen, turbidity, light and salt content sensors. As the robots move in the lake, they record measurements every 10 minutes and send them to a central location using mobile phone technologies.

A. Monitoring the Impacts of Urban and Agricultural Land Use

Monitoring the impacts of urban and agricultural land use on Water, soils and sediments is another potential application for wireless sensor networks. As mentioned earlier, the diversity and quantity of chemicals released into the environment has risen dramatically in recent years which causes serious concerns about their adverse effects on the ecosystem and on human health. As a result, new low-cost effective tools are needed for monitoring pollution, detecting trends over time and ultimately controlling pollution.

Sensor networks can capture the spatial and temporal state of the environment and thus constitute a valuable tool that can be used to determine the best available technologies in support of risk assessment and environmental sustainability. An important application of the sensors is to assess the impact of agricultural and urban land use, on water, sediment and soil quality. While the focus is on water quality, we have to consider soil and sediments aspects as well, as repository of diffused- and point-sourced pollutants. In terms of catchments water quality the focus could be on carbonaceous materials (BOD), turbidity, biological indicators (macro invertebrates and other indicators as well indicators of microbial contamination (faecal, streptococcus counts, E. Coli, possibly cryptosporidium). This should help assess the causes of ecological water status degradation. In the past the focus in terms of water ecology has been on phosphorus and nitrogen. The emphasis is now shifting towards a wider approach, as turbidity and inputs of carbonaceous material is more important, particularly in running waters. Sensors could also be applied for the identification of herbicides, pesticides and PCBs in the systems of soil-water-sediment [21].

Pollution monitoring in soils, sediments and water often requires measurement of nitrates and nitrites. According to Article 8 of the WFD Directive (2000/60/EC), EU member states must ensure the establishment of programs for the monitoring of surface water status in order to establish a coherent and comprehensive overview within each river basin district. The monitoring program, which must evaluate the ecological and chemical status of water, must include among others information on nutrients conditions. In addition, according to the Nitrates EU Directive (91/676/EEC), the areas with significant contribution to N pollution at watershed level must be continuously monitored. Nitrates as well as phosphates are the key nutrients needed for growth. They are necessary in small quantities, but in water excess nutrients promote the excessive growth of algae. Large inputs of nutrients arising from human activities (e.g. fertilizers, sewage disposal, manure storage) into rivers can lead to eutrophication, adversely affecting the ecology and limiting the use of rivers for drinking water abstraction and recreation. High nitrate levels in rivers can increase degrading habitat for fish, other aquatic organisms, and wildlife. Nitrate contamination in drinking water can cause methemoglobinemia, which is especially detrimental to infants and nursing mothers represent an environmental problem of global significance. Nitrate is usually the end product of the nitrogen system in an oxygenated environment. Many monitoring programs monitor the ammonia and nitrite stages that precede nitrates, but since nitrates are the end product, for simplicity, monitoring nitrates is more practical, [9].

Whether you are monitoring seabirds on the Great Duck Island, North Temperate Lakes for pollution, or vines in Pickberry Vineyard environmental monitoring using sensor networks shares some common issues and important challenges that researchers are faced with today. In our view, the most important challenges include

1) Taking the vast amount of data produced by the thousands of sensor nodes deployed and turning them into something useful that the final user can benefit from. This process implies that spatial and temporal infield data must be compressed to remove redundancy and exploit correlations, e.g., use situation-aware adaptive sampling. Furthermore, the data processing may be done in a *decentralized* fashion by employing data-centric communication.
2) Detection of driving events by observing readings of many different sensors and using in-field power-aware decision fusion. This also raises the issue of area coverage such that the “miss” and “false alarm” probabilities are minimized.

To address these challenges (within the sensor power and processing constraints) one needs to find ways for information management (sensor data collection, storage, quality control, applications for querying and analyzing data).

B. All These Data...

As technology advances, it may be feasible to install a number of sensors on every vine of a vineyard. The problem is to figure out what to do with the huge volume of data produced by the sensors. In order to build the right applications that will benefit the final user one has to spend the time to *get to know the user needs*. Such an approach is shown in [22]. Using ethnographic research methods, the authors studied the structure of the needs and priorities of people working in a vineyard to gain a better understanding of the potential for sensor networks in agriculture. Agriculturists want data that recommends a course of action, something that will save them time rather than create additional work. The authors of [22] used interviews, site tours, and observational work to broadly understand the work activities and priorities of the various roles working in the vineyard. Pervasive computing technologies such as sensor network systems- give us new capabilities for sensing and gathering data about the environment and new ways to manage the data digitally. These capabilities pose several questions in the application space:

1) What data should we gather and how often?
2) What level of computational interpretation should we apply to the data?
3) How should we present the data to the user?
4) When should the system act on data and when should action be left to the user?

Furthermore, these questions should be answered given the following three constraints.

1) Equipment capabilities: battery-life limits, processor power, types of available sensors, memory, sensor accuracy, and transmission range.
2) Environmental conditions: variability of conditions (i.e. more variation in daytime)
3) User needs: limit on what should be measured and how often.

Some of the solution methodologies may be application specific and can include various strategies.

1) Explore Available Data:: Looking at available data before sensor deployment and analyzing them for spatial-temporal patterns can provide important information for designing predictive models and optimal sensor placement. For example, the authors of [6] try to couple knowledge discovery in large environmental databases with biological and chemical sensor networks in order to improve drinking water quality and security decision making. The approach adopted is that of spatial-temporal data mining. The ultimate goal is to develop new data-mining techniques for knowledge discovery in water quality databases and the design of an implementation strategy for using this knowledge discovery, related watershed and water distribution models, and a decision framework, to inform the development and placement of in situ sensor networks.

2) Processing The Sensor Data: Processing the sensor data to find temporal patterns and exploit spatial correlations is a difficult problem addressed by many research groups today. Monitoring thousands of data streams online poses a challenge for data-centric applications like sensor networks. Stream mining techniques have to be efficient in terms of space-usage and per-item processing time, while providing a high quality of answers to similarity queries such as detecting correlations and finding similar patterns. The authors of [23] propose a new approach for summarizing a set of data streams and constructing a composite index structure to answer similarity queries. The goal of sensor networks is to detect and report the temporal and spatial dynamics of the environment and to run unattended for several months. The authors of [24] propose that each node compresses its gathered data locally, transmitting a burst of data when communication conditions are good. The protocol adapts the data reporting demands of its environment dynamics to the communication capacity of the environment. In [25] the authors propose a way of removing data redundancy due to high spatial density in a completely distributed manner- i.e. without the sensors needing to talk to one another.

C. *Data-Centric Communication*

As already mentioned, power saving (depending on the application) is a significant constraint. Given that the communication process consumes significantly more power compared to processing, it may not be feasible to send all obtained data from each sensor to the sink using a multi-hop sensor network. In fact, it may be significantly cheaper to have intermediate nodes use data aggregation or data fusion approaches before they relay incoming information towards the sink [26], [27]. In this context, intermediate nodes may buffer and delay an incoming measurement until more measurements become available. Subsequently, the node forms a single packet with all available data (or with processed data) which is then forwarded to the sink. Exactly how the data aggregation or fusion will be done is still a topic of open research. Since data aggregation or data fusion will be performed at intermediate nodes, the approach used will also affect the routing algorithm used as well as the overall network architecture. Note that a node will be able to perform the data aggregation only if it understands the application data communicated between sensor and sink. Given that the capabilities of each sensor node are limited, it may be beneficial to form clusters of nodes [14] which will be able to collaboratively process the data and relay information downstream.

D. *How Many Sensors?*

In general, environmental monitoring applications involve large areas of the order of several hundreds of square kilometers. To achieve good coverage (with good detection probabilities and low miss and false alarm probabilities) it may be necessary to install a large number of sensors. In fact, this number with today's technology may be too expensive to implement. For example, in [28] the objective is to estimate the position of a point source that emits some substance in the sensor field. Fig. 1 shows some simulation results for a fairly small sensor field (1Km×1Km) with 100 sensors. In this experiment, we fixed the sensor field and vary the position of the source and record the sensor measurements for different noise variance. As seen from the figure, about 7% of the sources remained completely undetected. Furthermore, for about 5% of the experiments only one sensor detected the existence of the substance and for 8% of the experiments only two sensors. Since, triangulation requires at least three sensor measurements to estimate the location of a source, we see that even for this simple example, 20% of the experiments either totally miss the existence of the source or cannot compute its location. This is a fairly high percentage for an admittedly small sensor field. One would expect that achieving a good coverage of a large area (e.g., a forest) will require a huge number of sensors. Even though in the sensor networks literature the concept of a sensor network suggests the existence of a huge number of nodes, in practice, large scale sensor networks are not yet available. To resolve this problem, it may be necessary to also complement the network operation with some mobile nodes which will move around and complete possible missing information. Of course in this case, an interesting problem is to design the paths of the mobile nodes in order to maximize the coverage area with the smallest possible number of sensors.

IV. CONCLUSIONS

Sensor networks have two significant differences from traditional networks, namely nodes have limited processing capability and power and a sensor network may consists of a huge number of nodes. As a result, the traditional layer architecture may not be appropriate since it is designed to support generality, rather than simplicity. As a result, a new architecture is needed which will also help us handle the huge volume of measurement data that the network can generate. Furthermore, it is necessary to find efficient ways of processing the data (preferably in a decentralized manner) and turn them into meaningful information that the user can benefit from.

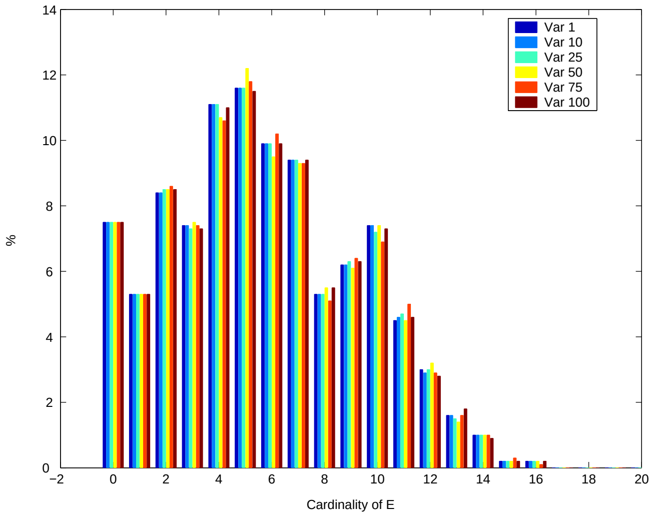

Fig. 1. Number of sensors that detect the existence of the substance

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