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A Survey of Applying Ad Hoc Wireless Sensor Actuator Networks to Enhance Context-Awareness in Environmental Management Systems

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Keywords

ad hoc wireless sensor actuator network, wireless technology, energy management system

Disciplines

Computer and Systems Architecture | Digital Communications and Networking | Hardware Systems | Systems and Communications

Comments

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A Survey of Applying Ad Hoc Wireless Sensor Actuator Networks to Enhance Context-Awareness in Environmental Management Systems

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Abstract

Sensor mesh networking is set to be one of the key tools for the future of *Ambient Intelligence* (*AmI*) due to new emerging technologies in *Ad hoc Wireless Sensor Networks* (*AWSNs*). AWSNs symbolize the new generation of sensor networks with many promising advantages applicable to most networked environments. Unfortunately, however, these practical technologies have some technical problems and, as a consequence, this fascinating field has created novel and interesting challenges, which in turn, have inspired many ongoing research projects and more are likely to follow. Almost certainly, there will be notable improvements in the management of control/actuator networks as a consequence of enhancing the sensitivity capabilities of systems. With an emphasis on *Ad hoc Wireless Sensor Actuator Networks* (*AWSANs*) this study presents a systematic analysis of the different existing techniques to improve such systems. It also discusses, analyzes and summarizes the advantages these technologies offer in certain applications and presents a generic solution, in the form of a case study, for an AmI system to enhance the overall environmental management of a campus based on a hierarchical network using an AWSAN.

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1. Introduction

Technological advances such as pervasive computing, sensing technologies etc. improve the *Ambient Intelligence* (*AmI*) paradigm by providing smart environments to help humans in their everyday jobs in a non-intrusive way (Akyildiz, 2004; Rezgui, 2007 and Sgroi *et al.*, 2005). These innovations are leading to the appearance of *Ad hoc Wireless Sensor Actuator Networks* (*AWSANs*), which were originally implemented for military purposes (e.g. battlefield surveillance, reconnaissance etc.). However, it is now common to observe these technologies applied in specific civilians applications including home automation, smart office, traffic control, warehouse and supply chain, natural environment, healthcare applications and so on (Romer, 2004 and Hadim, 2006). Based on a mesh network topology, AWSANs are constituted of clusters of devices such as microscopic sensors (also called "motes") and actuators deployed over a precise region in order to either monitor or control the environment. The size and the complexity of the AWSANs vary depending on the environment being observed.

Each AWSAN includes a number of sensor nodes (either stationary or mobile) interconnected with each other over wireless links; the sensors support a multi-hop routing algorithm which means that they are able to forward data to another node. They are able to sense environmental changes or phenomena (sensors) gathering enough data to help the system to better control the environment (actuators) (Akyildiz, 2004). AWSANs are complex as they include "a data acquisition network and a data distribution network, monitored and controlled by a management centre" (Lewis, 2004). Each node of the mesh network is equipped with a radio transceiver, a small microcontroller and a battery. According to the definition made by Sgroi et al (2005), these sensors are small, low-cost and low-power components that measure the state of the environment whereas actuators have better communication and processing capabilities, a longer battery life and set the state of the environment.

In order for this technology to be efficient, there are various requirements that AWSANs have: the ability to expand the network without difficulty (*scalability*), the ability to ensure reliable data transmission (*reliability*), the ability to quickly adapt itself to the changes in topology (*responsiveness*), the ability to handle mobile nodes (*mobility*) and the ability to operate at low power levels (*power efficiency*). In the last decade, wireless sensor networks have attracted a lot of attention (Lansford, 2000 and Haartsen, 2000) due to an increasing demand for ubiquitous connectivity and several high profile applications for wireless sensor networks have been proposed (Tennenhouse, 2000 and Estrin, 2000). In this paper, we look at the role of ASWANs in energy consumption monitoring. Such an infrastructure could be employed to obtain figures of daily, weekly and monthly usage of energy in homes, buildings etc. so costs and energy consumption can be quickly analysed. Thanks to the easy installation of AWSANs and easy maintenance, money can be saved by taking timely measures to improve energy efficiency. This kind of solution can greatly help industrial engineers to monitor the cost of utilities such as gas, water, electricity, steam etc. (Expert Monitoring, 2008).

In the future, we expect that sensor networks will grow in size due to new improvements which are lowering the cost and creating better communication protocols (Shwiebert, 2005). Even though wireless sensor networks have prospects fpor a bright future, a lot of research remains to be conducted. Many concerns arise (ScienceDaily, 2006 and Shwiebert, 2005) such as energy-efficiency apprehension (e.g. in a network of hundreds of sensors, we do not expect to have to change batteries all the time so even better energy efficiency is required) or security, privacy and misuse issues. Hopefully, improvements will address all these matters and the new sensors will be cheaper, smaller, low-power and maybe will even have the ability to be powered by ambient energy.

2. Related work in optimizing ad-hoc wireless sensor networks to enhance context-awareness

AWSNs are a reality thanks to the latest improvements in micro sensors, low power communications and processing; ideally the exploitation of ad hoc wireless sensor networks will play an important role in the future of AmI systems. The continuous improvements in this field are increasing their suitability for more applications where their characteristics have proved to be relevant. Even though the nodes utilized in these networks are limited, generally with few capabilities, they are still expected to accomplish multifaceted tasks working as a whole and with the rest of the networked devices. In view of the fact that they introduce a new networking concept, it can be assumed that many new different methods to enhance their performance are going to emerge. In order to manage properly an ad hoc wireless sensor network, possibly comprissing thousands of nodes, it is necessary to apply realistic and appropriate solutions to deal with routing, deployment, area of coverage, energy consumption, node-location awareness and node information querying.

Optimized use of energy consumption in ad hoc wireless sensor networks is one of the major enhancements AWSNs offer in environmental management compared to other techniques in this field. Bearing in mind that many sensor nodes could be placed in barely accessible places, physically examining a single node may not be possible. Besides, a sensor network is usually expected to last several months without recharging (Kumar et al., 2004; Wu et al., 2004) sometimes even several years considering the trends of the newest technologies in ad hoc wireless sensor networks. The lifetime of a node may be determined by the battery life, thereby requiring the minimization of energy expenditure; this can be achieved by activating only the necessary number of sensor nodes at any particular moment to save energy. There are different methods to accomplish this goal, for example Slijepcevic and Potkonjak (2001) use a heuristic to select mutually exclusive sets of sensor nodes, where the members of each of those sets together completely cover the monitored area. In their approach the intervals of activity are the same for all sets, and only one of the sets is active at any time. Finding the most appropriate scheduling techniques is the most common practice to extend the lifetime of wireless ad hoc sensor networks. Sometimes the use of simple timers may help as well (Deng et al., 2004; Kumar et al., 2004) or applying duty rotation among cluster heads. Using a different method, Hou et al. (2005) take advantage of the possibilities to efficiently use directional antennas to save energy and consequently extend the network lifetime. Another approach more based on the network's topology was expressed by Li et al. (2002) to demonstrate that the initial placement of the nodes may lead to an important energy saving as well.

Another related flourishing area of research is related to algorithm refinement with the purpose of establishing an accurate initial deployment of sensor nodes for a better overall network performance . Given that sensor networks have many sensor nodes, nodes need to be deployed in clusters, where the location of each particular node cannot be defined a priori. Many researchers have focused their work on the placement of the nodes and attaining the best coverage area with the allocated resources. Some examples are those carried out by Lieska et al. (1998) and Molina et al. (1999); they analyze the optimum number of base stations required by a system. The research of Haas (1997) is also relevant; however, in this case, the network coverage is improved by a multi-hop routing which features and optimizes the coverage constraint and studies the effect of limiting the path length on the network performance. Other techniques focus on the placement of gateway nodes such as the polynomial time near-optimal algorithm which recursively computes minimum weighted Dominating Sets (DS), while consistently preserving QoS requirements across iterations (Aoun et al., 2006). However, even the best positioning algorithms can be restricted by other factors independent to the AWSN itself like structural characteristics (e.g. material compositions) or contents (e.g. mobile , temporal, variable items) , etc) of the environment,

Routing information has always been a vital topic in networking; the apparition of new paradigms of wireless networking requires “path finding” improvements (Morgan & Grout, 2007) for the network. These improvements are key factors in AWSNs since the constituent meshes are often prone to suffer link changes; given the large number of nodes generally included in these networks it is required that the network will be able to self-organize because some nodes may stop working, others may be faulty and there might be new ones being added to the network. As a result the network must be able to periodically reconfigure itself so that it can continue to function properly being able to send data to the proper targets. Additionally AWSNs have to properly distribute data to the desired end users without making routing mistakes and in some specific cases, facing quite strict time requirements when they have to update data in risk-preventing systems. Due to their particular characteristics AWSNs require specific routing techniques that differ from the ones used in conventional networks.

A common practice to find routing solutions is the use of adapted mathematical algorithms to finds the minimal exposure paths like the one developed by Meguerdician et al. (2001) which calculates it for any give distribution and characteristics of sensor networks. Numerous works study multipath routing in wireless ad hoc networks using directional antennas (Tang el al., 2005; Li and Man, 2004; Roy et al., 2003). Although since there are many kinds of routing protocols for ad hoc wireless sensor networks and not all of them use directional antennas we will limit ourselves to mention the major ones. There are two common routing techniques: **proactive** (Perkins and Bhagwat, 1994;Murphy and Garcia, 1996; Chiang et al.,1997; Aron and Gupta, 1999; Zygmunt et al., 2002) and **reactive** (Broch et al., 1996; Park and Corson, 1998; Perkins and Royer, 1999; Toh, 1999; Aggelou and Tafazolli, 1999; Lee and Riley, 2005). In proactive techniques, nodes try to find the right path by themselves while in the reactive ones the networks actually contains the information to tell the node which root to take. There are other more specific techniques related to the two main ones**:** **flow oriented** which is an adapted reactive technique (reactive (Manoj et al., 2001); **hybrid** which conbines both proactive and reactive techniques (Pandey et al., 2006) and **hierarchical** which permits the network to choose which technique to use (Eriksson et al., 2004). Some studies have demonstrated that reactive protocols are often better than proactive protocols because it takes more resources to find new routes rather than check the pre-established ones. However reactive routing may be more sensitive to topology changes (Broch et al., 1998; Johansson et al. 1999).

Finally, it is important not to forget to mention other not less important techniques. For example there are techniques about finding the location of nodes (Koushanfar et al., 2002) or querying information from nodes (Carzaniga and Wolf, 2001; Zhou and Singh, 2000) for either a single node or a group of nodes. The goal of location discovery is to establish as accurately as possible the position of each node given partial information about location of a subset of nodes and distances between pairs of nodes (Meguerdichian et al., 2001).

3. Managing the actuator network

An ad hoc sensor network without actuators is usually limited to environment monitoring and data logging. They can still be quite useful but only in certain situations where there are no available actions to be taken. At the time a sensor network is combined with an actuator network the number of applications increases noticeably. Some application examples could be controlling heaters, curtains, solar panels, doors, windows, lights, taps, fans, video cameras, sprinklers, etc. The use of actuators tend to appear with the use of sensors (Kumar et al., 2004; Li, 2006; Rezgui and Eltoweissy, 2007; Koerber et al., 2007), nowadays most of the ad hoc wireless sensor networks are meant to gather data to be used not only for monitoring but to help to make accurate control decisions over the network. An example is the strategy developed by Wan and Lemmon (2007) where they use smart sensors to control water flow in metropolitan sewers; the combinational formulas used in their system represent advancement in comparison with the barely automated sewer systems in the U.S. which have already faced considerable flood disasters in the last century.

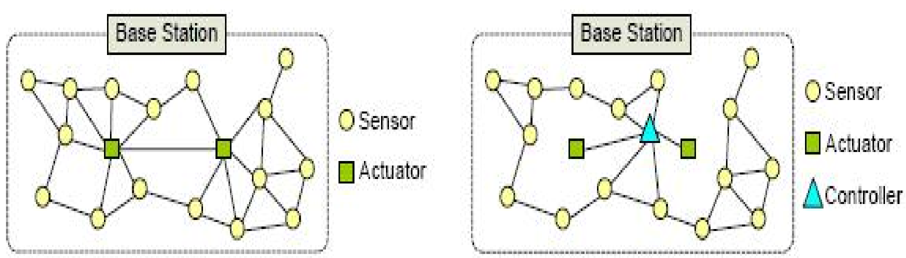

Figure 1: Automated and semi-automated architectures (*Akyildiz, 2004*)

Initially it is recommended to use a similar approach for both the sensor network and the actuator network; it will be optimal to use wireless low-power/low-cost technologies as in an AWSAN. This approach will permit the use of similar routing protocols for all devices and will make the network more scalable helping the management of the control points. However some control data may be heavier than the information sent by the sensors requiring more bandwidth, this is common when the use of audio/video streams is involved. If necessary some wired networks can be used (Bertsekas and Tsitsiklis, 1996; Ogata, 2001) such as Ethernet or Power Line Communications if preferred where the deployment of more cable is not a feasible option. Actuator nodes typically have stronger computation and communication powers and a larger energy budget that allows longer battery life (Melodia et al., 2007). The choice of control points placement in AWSANs also affects the network properties and the choice of the routing protocol; for example, Figure 1 shows two different approaches combining sensor nodes with the actuator ones, one including controllers:

The first approach (left) shows an automated base station where the smart sensors are connected to the actuators, within the same network, and the actuators perform actions depending on the data gathered by the sensors without going through any controllers; the solution developed by Wan and Lemmon (2007) will fit into this approach. In the second case (right) there are controllers capable of making control decisions to manage the actuators and, actuators can be part of the sensor mesh or form an independent one; in addition, they might be controlled manually by an administrator. In the first case, decision-making algorithms will be the main motor of the success of the network while in the second one they will be determined by the capacity of the software to monitor and administrate the heterogeneous mesh's main features automatically or involving minimum effort to the user; including: analysis of events, precise automated control, data logging/storage, analysis of historical data, accurate notifications/alerts, automatic detection of new devices, export data, robust middleware and secured communications.

4. A case study: the Ecological Campus

By now a few universities have decided to apply changes to the campus's management with the intention of saving energy and money. For instance, the Green Campus Initiative in Chicago seeks to restrict the environmental impact along with resource savings. They encourage practices such as energy efficiency, waste reduction and improved recycling (Green Campus Initiative, 2008). Another example, the EcoCampus, uses an AWSAN to analyse and take action on their energy consumption (EcoCampus®, 2008). Following these examples we decided to define another approeach for a system to manage a University's resources based in a hierarchical mesh distribution controlled by a centralized intelligent core stablishing 2-way communications with the control points to share metadata (XML) about status and control each mesh. The resulted organized environmental data communications will help decrease the waste of energy and other resources.

As shown, a large number of sensor nodes are deployed over a wide area in order to sense environmental phenomena (e.g. temperature, lighting, humidity, motion, equipment status, presence etc.), communicate wirelessly with nearby sensor nodes and then broadcast data to the gateway sensor of the mesh network. All the clusters within a determined area are connected with a control station . Control stations will communicate with the core management via XML messaging which will provide a standardized, scalable and reliable data handling. Control stations will gather and handle data, like link status (Riggio et al. 2007), locally and will perform actions in the following ways: an automatic response, an automatic response with notification or a notification to help further semi-automated/manual responses. The core management will store and analyse the data coming from all control stations to provide support with more advanced features (normally requiring higher security, processing and storage levels) and to apply more complex and generalized management decisions in the campus.

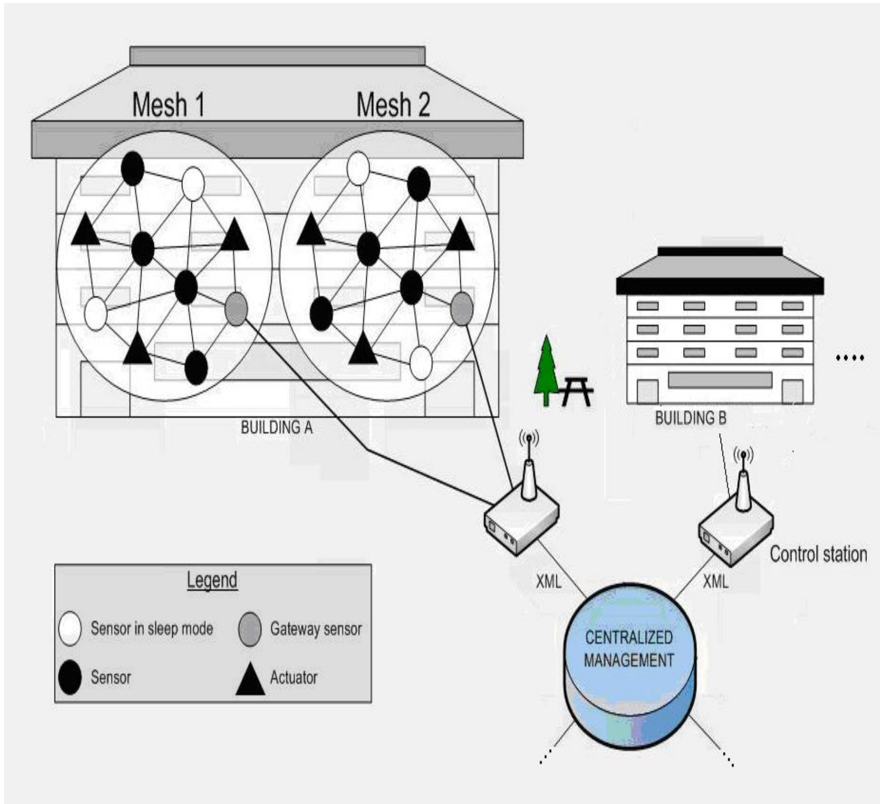

Figure 2: The Ecological Campus

As a result the system will rely partially in the core management which may be an issue as Wan and Lemmon (2007) say because centralized approaches may cause the network to cause bottlenecks in the transmissions; however the hierarchical structure and the use of organized Service Oriented Architectures metadata for messaging will be an answer to overcome an excess of centralization. For example, one type of mesh status message can be sent periodically by each control point to the core management (using different timings) to update a centralized Database, the update message sent to the core management can be as follows:

```
  <?xml version="1.0" ?>
- <sysmessage>
  - <eventdescrp>
      <eventID>04</eventID>
      <eventype name="statusupd">1</eventype>
      <ctrlpointID name="mathematics1">06</ctrlpointID>
      <MeshID>02</MeshID>
      <Meshtype>1</Meshtype>
      <messageID>0A</messageID>
      <time>wed feb 11 14:18:43 2008</time>
    </eventdescrp>
  - <eventparams>
    - <statuschg>
        <newstatus>true</newstatus>
        <totalchg>3</totalchg>
      - <stschg id="01" type="mode">
          <seqnum>0</seqnum>
          <sensorID>0CC</sensorID>
          <sensortype>routing</sensortype>
          <status>ON</status>
          <mode>pasive</mode>
          <battery>yes</battery>
          <source>ec-a0-b9-dc-76-c5</source>
        </stschg>
      - <stschg id="02" type="status">
          <seqnum>1</seqnum>
          <sensorID>1C6</sensorID>
          <sensortype>routing</sensortype>
          <status>OFF</status>
        - <linkcache>
          - <linkchg id="bbc2" sensor1="1C6" sensor2="015">
              <state>down</state>
              <type>3</type>
            </linkchg>
          - <linkchg id="bbdd" sensor1="1C6" sensor2="0a2">
              <state>down</state>
              <type>3</type>
            </linkchg>
          </linkcache>
          <mode>pasive</mode>
          <battery>no</battery>
          <MAC>02-a4-a9-bc-66-c1</MAC>
        </stschg>
      </statuschg>
    - <bodychg>
        <newbody>true</newbody>
        <totalchg>1</totalchg>
      - <bdychg id="01" type="newnode">
          <seqnum>0</seqnum>
          <sensorID>009</sensorID>
          <sensortype>leaf</sensortype>
          <status>ON</status>
        - <linkcache>
          - <linkchg id="01c2" sensor1="009" sensor2="345">
              <state>up</state>
              <type>3</type>
            </linkchg>
          </linkcache>
          <mode>pasive</mode>
          <battery>no</battery>
          <MAC>ec-aa-00-dc-7a-b5</MAC>
        </bdychg>
      </bodychg>
    </eventparams>
  </sysmessage>
```

Apart from the mesh status, other types of messages can be sent to provide the controls points or the core management with enough information to take the right actions in the environment. If some predetermined conditions occur the core application can activate services or advise properly the control stations with the possible actions to take. As a consequence, appropriate measures are taken to save resources, apply security and assure the quality standards of the facilities. Using AWSANs for context-awareness in a university will help to increase the sensitivity of the system consequently helping to perform correct action-taking bringing the following advantages:

- Lighting: lights will be switched off or dimmed if no presence detected. Campus outdoors (e.g. sport fields) illumination will be managed as well.
- Electricity: electrical devices will not be let on standby if not used.
- Water: taps will be turned off if no presence detected or if there are floods. The football field and grass will be watered if the level of humidity is low.
- Scheduling: some manual maintenance activities (cleaning, closing or opening doors and windows, etc) will be automated.
- Heating & cooling: temperature can be set depending either if it is winter or summer. Heating will not be on in unused rooms. Thermostats can be regulated automatically.
- Hazards: responses against fire, flood, structural damage, etc.
- Security: detect and prevent intrusion.

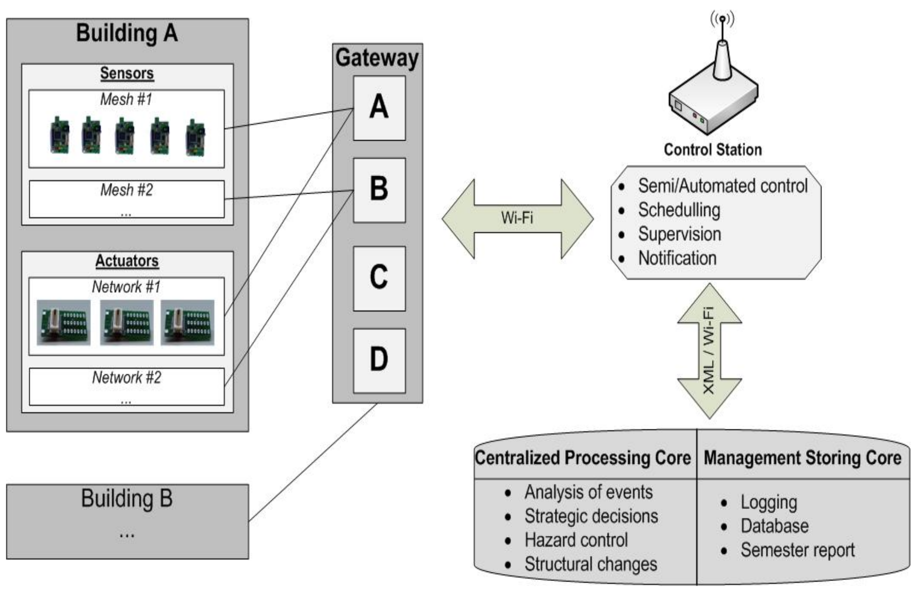

Figure 3: Systems logical architecture

These clusters of sensors give a considerable amount of data in real-time and energy consumption could be significantly reduced. The University of Berkeley (Chicago) is a good illustration of the benefits from installing AWSANs as they were able to reduce 50,000 to 80,000 watts of power in one building for the duration of a practice trial (Ainsworth, 2001). One of the professors of the electrical engineering and computer sciences, Kris Pister, said that "We would see savings of about $900,000 a year on the Berkeley campus if all of the buildings were outfitted with these sensor networks. The network would pay for itself in a year." (Ainsworth, 2001)

5. Conclusion

With the new era of ubiquitous computing, wireless sensor technologies have shown that they can be a great potential in opening a world of sensing applications. Corke *et al.* (2006) see them as "the new instruments for observing our world" as they offer a wide range of monitoring and data-gathering applications (health care, habitat monitoring, forecasting, traffic control etc.). In this paper, we focussed principally in the context of energy-efficiency where numerous sensors are set up to monitor the energy consumption of an area and take appropriate actions in order to save on energy utility bills. However sensor technology is not perfect yet: there are concerns about interference, motes positioning, battery-life of the sensors, coverage problems etc. But with enough time, technological development will improve wireless sensor networks.

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