AQUA-NET: A FLEXIBLE ARCHITECTURAL FRAMEWORK FOR WATER MANAGEMENT BASED ON WIRELESS SENSOR NETWORKS

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ABSTRACT

Traditional techniques and technologies for water management will no longer be cost effective or efficient in meeting the demands and challenges of the coming years. In this paper we describe Aqua-Net, a wireless sensor networks (WSNs)-based architectural framework for an efficient and reliable water management application. We identify areas of research that we are currently engaged in. The proposed framework is a flexible and multi-tiered hybrid network architecture that consists of a large number of autonomous single-hop "sensor communities", a traveling backbone network, and a data depot. The key elements of the proposed architecture are reconfigurability, fault-tolerance and modularity. The architecture also addresses practical considerations in operating such monitoring networks during floods and other natural disasters.

Index Terms— Water Management, Wireless Sensor Networks, Pervasive Computing, Fault Tolerant, Reliability, Distributed Consensus, Context-Awareness.

1. INTRODUCTION

A recent report by the World Bank on Water Management estimates that by the year 2025, more than four billion people will be living under severe water stress. Water impacts many aspects of our lives, and forms an essential link between our well-being and our ability to harness the resources of this planet. Water is used for drinking, washing, irrigation, energy generation and transportation to name a few. It allows bio-diversity to exist and provides many with their daily livelihood. As a valuable resource it is also a source of bitter disputes between peoples and nations.

In a recent report [1] the World Water Commission has put forth a very sobering assessment on the availability of water resources in the world. According to the report, water consumption has increased twice as fast as the population growth over the past century. It also predicts that water usage will increase by about 50% over the next 30 years. It is estimated that agriculture by far consumes most (60-70%) of the fresh water resources in the world [3].

Efficiency of water usage has become a crucial issue. Currently it is estimated that the water efficiency for agriculture water usage is less than 30% [3]. To achieve higher levels of sustainable water utilization, systematic monitoring of the soil and water quality is required. Based on these readings, watering of the fields can be adjusted to provide the optimum yield with minimum water wastage. Because of real-time monitoring of soil quality and water discharge to the fields, community based management schemes could also be implemented resulting in fairness, trust, and policing within the community.

Monitoring of agriculture fields has been going for as long as agriculture has existed. However, the collection of data and its interpretation has been mostly based on knowledge that was passed down from one generation to another. This modus operandi is neither precise nor scalable. Recently, standalone sensors have been employed to collect information. Information from these sensors is either collected manually or transmitted via telemetric signals using the mobile phone network. These solutions are cumbersome and expensive to operate.

Neither is fault tolerance one of the key attributes of these networks nor are these networks configurable in a way to allow substitution of functional units during natural or manmade disasters. Recent floods in Pakistan were a testament of the need for such a network. Areas under flood were completely cut off from the rest of the country and it was very difficult to get information about the current state of the water quality and level of flooding in the villages around the Indus river delta.

With recent advances in VLSI circuit and fabrication technology, smaller and sophisticated devices such as micro-sensors, may provide the necessary hardware infrastructure required for creating sensor networks. These devices are smaller, have better processing capacity, are more energy efficient and, increasingly, have the ability to be powered by alternative in-situ sources of energy. These standalone sensors are composed of a processing unit, a sensing unit and a radio transceiver, and connected to one another via a wireless network [2]. Sensor nodes in the network collect data and communicate the observed data with one another using short haul radio links with limited range and bandwidth in order to conserve energy. Sensors and sensor networks equipped with appropriate monitoring and sensing capabilities can play crucial role in regulating and monitoring water usage and water quality in rural and urban areas. These monitoring systems can help farmers regulate water supply to the fields based on soil conditions, or help predict breaks in urban water distribution networks. Apart from monitoring and regulating water, sensors can also be used to provide near-real time information about the water quality during floods and other natural disasters. An overview of WSNs technology in the field of agriculture and food can be found in Ruiz-Garcia *et al.* [5].

In this paper, we propose an architecture that addresses the challenges faced in deploying and managing a wireless sensor network with particular focus on rural and agricultural settings. In discussing this architecture, we also identify areas of further research which we have embarked upon.

The rest of the paper is organized as follows. In Section 2, we briefly describe the challenges of developing and deploying wireless sensor network for water management and the key attributes required to make such a network successful. In Section 3, we provide a summary of what already has been proposed and in Section 4 we present our architecture. Finally, in Section 5 we conclude this paper.

2. CHALLENGES AND PROBLEM STATEMENT

A comprehensive information collection and dissemination system for water management will consist of a framework and tools that facilitate the collection of different types of parameters of interest (soil moisture, rainfall, underground water, water quality, sunlight, etc.) from the field. Information is then delievered to a "HOST" node where it can be processed. The network should also be able to receive commands from the host node, recalibrate based on the information received, and provide different quality of service (QoS) for different types of messages. Although the need for real-time delivery of information is not a requirement for water management, the network does need to support near-real time delivery with bounded delay.

Unlike other application settings in the home, office or industrial plants, water management requires large swaths of land to be monitored and regulated. Often these areas are isolated and may not have access to cheap means of communication. As such continuous connectivity with the host would not be possible. It would also be impractical to assume that all parts of the network would simultaneously be connected to one another or to hosts whenever the communication link/means is available. That is, it would be fair to assume that some parts of the overall network will be connected while others may not.

The network also needs to be up and running for long periods of time without supervision and should be resilient to node failures, node tampering etc. Repairing failed sensor nodes in the field is often infeasible and in most cases would require a trip by a technician out to the field.

Furthermore, the sensor network has to be reconfigurable and resilient to natural or manmade disasters. Lastly the sensor network has to be cost effective to compete with traditional methods. The ideal wireless sensor to serve such a purpose should have the following attributes:

1. Should support multiple levels of QoS for near-real time as well as non-critical information.
2. Should be scalable and operate over large area often with poor connectivity.
3. Should be able to reconfigure and re-organize, based on instruction received from an authorized host.
4. Should be resilient and fault tolerant.
5. Should be able to collect varied types of information (water table, water quality, soil salinity, water flow, discharge, water leakage) and transport it to data processing centers/hosts.
6. Should be cost effective.

The requirements and desired attributes as listed above necessitate a new approach to architecting the wireless sensor networks for water management. For example, the ability to operate in a loosely connected fashion both in time and space needs to be incorporated in the design. Similarly, fault tolerance and resiliency in the face of natural or manmade disasters also needs to be taken in to account right from the beginning as it impacts not only the architecture but protocols and applications as well.

3. RELATED WORK

Aqua-Net combines the successes of projects that may be seen as falling into one of two categories.

The first of these categories consist of existing wireless networks designed to monitor agricultural settings. Among projects in advanced stages are the joint India-Swiss COMMON-Sense Net [3,4], and Australia's CSIRO Project [6,7]. These projects have demonstrated success in terms of monitoring, communication, and deployment. However, their designs are such that the network is a vast array of sensing devices, where readings from each device are relayed back to a central portal. Aqua-Net aims to expand on the successes of projects such as these by implementing autonomous communities of sensors that can properly capitalize on limited communication opportunities.

The second of these categories consists of efforts to link people in disconnected regions. KioskNet [9] at the University of Waterloo is one such example. It is among the earliest efforts to connect remote communities of people to the Internet by using routers attached to motorized vehicles. It is from these 'people-oriented' networks we draw the inspiration to connect communities of sensing devices. This enables Aqua-Net to reduce the costs of physical deployment and add levels of fault-tolerance and flexibility.

In the remaining sections we describe the Aqua-Net architecture and the benefits of its design.

4. PROPOSED ARCHITECTURE

In order to address the challenges and desired attributes listed in Section 2 we propose Aqua-Net, a hybrid multi-tiered network architecture as shown in Figure 1. The network that we envision is loosely connected in time and space, and should be able to operate autonomously; if not the whole network then at least parts of it. It should be resilient to natural and manmade disasters. We define resiliency in the true sense of the word, that is, the network should be able to bypass node failures, adapt to different communications mechanisms and degrade gracefully.

Before we present the details of our architecture in the following sub-sections, first we would like to define the terminology used:

1. Sensing Agent: These are sensing nodes responsible for gathering information. Sensing agent may be stationary or mobile.
2. Collection Agent: These nodes collect and store information from sensing agents. They reside in all nodes in the network and can operate in both pull or push modes depending on an application.
3. Relay Agent: A relay agent transport information from one location to another. They are the carriers of information. Relay Agents have also been defined as Data MULEs in the literature [8]. A relay agent could be a human carrier, an animal, a motorized vehicle, a wireless access point or a telecom gateway. We envision multiple relay agents operating simultaneously in the network.
4. Data Depot: A data depot is the portal to and from the wired network and ultimately to the host. It is where messages from the wireless sensor nodes are stored for onward delivery to the respective hosts and also from the host(s) to the sensor nodes. Messages from the host(s) to sensor nodes may like to wait for an appropriate relay agent so as to conform to an application needs.

4.1 Transparency and Substitution

By defining network members and functions in an abstract manner as above, we gain the flexibility to substitute underlying physical nodes/agents as needed, and suitable to conditions. For example, the one relay agent can be substituted for another as long as they perform the same function. In one instance, the relay agent could be a motorized vehicle and in another it could be a human riding a bicycle. This flexibility also makes the network resilient to failures or breakdown due to natural or manmade disasters because relay agents can be substituted. During the recent floods in Pakistan, most of the flooded areas became inaccessible by road and communication (both wireless and wireline) removing the ability to gather data and affect change. Ground-based relay agents would not have worked either. However, if the network could allow substitution of relay agents then airborne relay agents could have been used to collect information from the sensor nodes.

4.2 Headless Autonomous Communities

There are consequences to a flexible substitution system. For example, different relay agents will have different communication constraints. To address this variability we introduce the concept of *headless autonomous sensor communities*. A sensor community is created based on the geographical and communication proximity of the sensors as well as the type of function performed by them. The design of Aqua-Net avoids multi-hop sensor communities by allowing each community to schedule individual node communication. The comparatively long 'idle' periods between visits from relay nodes enable communities to establish communication schedules among community members.

Therefore in a community, each sensor has similar privileges. During the idle period between visits, a decentralized decision-making system empowers sensor nodes to be able to update the information that they would like to send to the host through mobile relay agent. The data collection times can be unpredictable and the relay agent may only have a limited opportunity to communicate with the sensor community before moving on. As such it would be best if each sensor node is responsible for deciding what it needs to report. This complexity is made tractable by removing multi-hop communication requirements within each sensing community.

In our environment the traditional cluster head approach where the cluster head is endowed with special capabilities and collects all the information from the sensor nodes before transmitting them to the relay agent would not work, as it does not give individual sensors the option to update the information if the need so arises.

Besides, having a centralized approach does not lend itself very well to robustness and resiliency. Sensor nodes within the sensor community arbitrate to establish the data transmission schedule and as soon as the community comes in contact with the Relay agent, each sensor node transmits data according to an agreed upon schedule. Details of this decentralized protocol will be reported elsewhere due to space constraints.

4.3 Travelling Backbone

Sensor communities are connected to one another and to the Data Depot via a travelling backbone network. Multiple Relay agents traverse the sensor communities along specific paths. These paths are not disjoint and intersect at multiple places. As such a message traversing from the sensor node to the Data depot has multiple opportunities to hop from one route to another. Inter-change stations are setup at points where message routes intersect. Interchange stations also have waiting stations where message consolidation and application specific processing is done. These waiting stations act as store and forward routers. Messages are stored if the Relay agent on the other path is delayed. Getting the message from the sensor node to the Data Depot, is similar to the minimum cost and delay mobile element scheduling problem[10], however, with slight differences. For one, we introduce the concept of waiting stations in this architecture and secondly the data transfer phase is initiated by the Relay agents when they come in contact with the sensor community. An authentication protocol is envisioned to authenticate both the sensor community as well as the Relay agent before any transfer of information takes place.

Messages from the sensor communities reach the Data Depot and are forwarded to the host(s). Messages from the host(s) destined for sensor nodes and communities wait at the Data Depot for the right Relay agent to hitch the ride on.

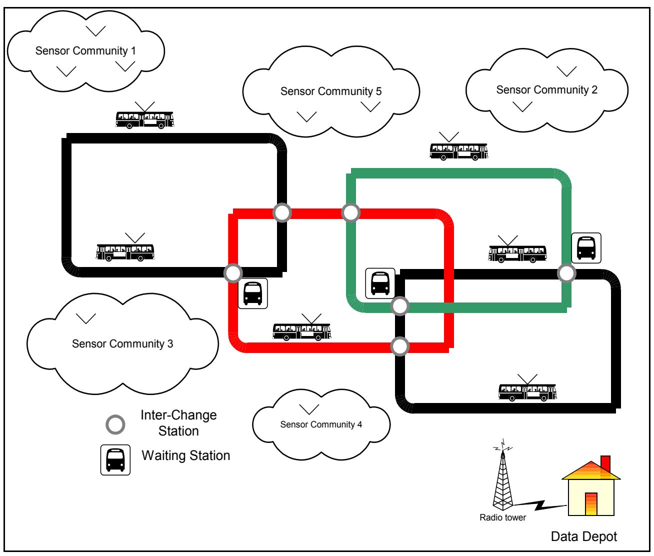

Figure 1. Aqua-Net: A Multi-tiered Hybrid Architectural Framework for Water Management Application.

5. CONCLUSION AND FUTURE DIRECTIONS

In this paper, we highlight the need for water management given the current assessment from different organizations around the world. Wireless sensor networks can play a very important role in helping to reduce water wastage, increase water efficiency, and utility. Building such a wireless sensor network for water management presents many challenges which are different from those of other applications. In this paper, we discussed some of the challenges and proposed an architectural framework to address those challenges. The framework allows for substitution of the mechanics of transport for information, thereby increasing fault tolerance and resiliency during natural or manmade disasters.

Furthermore, we introduced the concept of single-hop autonomous sensor communities and a decentralized arbitration mechanism within the sensor communities to empower the sensor nodes to make priority decisions. Our approach provides greater fault tolerance as it does not require cluster heads. All nodes have similar capabilities which are optimized for collection and transmission of data. As such failed nodes can be replaced by others in the community.

We are currently working on multiple areas of research based on the architecture presented in this paper. These include distributed MAC layer issues, application level protocols and Relay agent scheduling and routing issues. Our findings and proposals on the above will be presented in subsequent future conferences.

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