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Using Feedback for Single Type Relays in a Wireless Sensor Networks Environment for Water Management

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***Abstract*— This paper proposes feedback control architecture model for Water Management using Wireless Sensor Networks (WSNs). The proposed model uses classical control theoretic techniques to design the controllers to improve the performance of WSNs. Controllers are used to tune the dispatching rate of *relay agents* (also referred to as mules). Relay agents dispatching rate depends on the severity of the water condition messages sent by the sensors in a WSN environment through the relay agents back to the host. Priorities fields in the messages sent reflect the message severity. Results show that feedback controllers improved the performance by 13% compared with WSNs that do not use feedback controllers for water management.**

***Index Terms*— Sensor Networks, Water Management, Reliability, Fault Tolerance; Quality of Service, Feedback Control.**

I. INTRODUCTION

Smart environments represent the next evolutionary development stage in building various entities such as utilities, industries, homes, electronic boards, and automatic systems. Smart environments have the following characteristics (1) Rely on sensory data from the real world. Sensory data comes from multiple sensors of different sources in distributed locations. (2) Need information about their surroundings as well as about its internal systems. (3) Have the ability to detect the relevant quantities, monitor and collect data, assess and evaluate the information, formulate meaningful user displays and perform decision making and alarm functions.

The study of Wireless Sensor Networks (WSN) is challenging since it requires a diversity of knowledge in many fields. Sensor networks are the key to gathering the information needed by smart environments, whether in buildings, utilities, industrial, home, shipboard, transportation systems automation, or elsewhere. WSNs satisfy these requirements since sensor nodes are easy to install, self-identification, self-diagnosis, reliability, time awareness for coordination with other nodes, and use standard control protocols.

The information needed by smart environments is provided by distributed WSNs. WSNs are used to collect data from the environment. WSNs consist of large number of sensor nodes and one or more base stations. The nodes in the network are connected via wireless communication channels. Each sensor node in the environment has the capability to sense data, process the data and send it to rest of the nodes. Relay agents (also called mules) transports data periodically to base stations [11].

Each sensor node contains a computational module which provides computation ability, storage, and bidirectional communication with other nodes in the network. The transit network can consist of a single hop link or a series of networked wireless nodes. Each transit network design has different characteristics such as robustness, bandwidth, energy efficiency, cost, manageability [7].

Water utilization is considered a crucial issue. Currently, it is estimated that water efficiency for agriculture water usage is less than 25% [1][2]. To achieve higher water utilization, monitoring of the soil and water quality is required. Based on the readings watering of the fields can be tuned to provide the maximum water utilization. Since real time monitoring of soil quality and water discharge to the fields, cluster based management schemes are implemented to ensure fairness, trust and policies within the cluster.

Monitoring of agriculture fields is an ongoing process for a long time. But, the collection of data and its interpretation has been an ongoing process through knowledge and experience inherited from generation to generation. This process is always inaccurate and not scalable. Recently, standalone sensors were deployed to collect data from the field. This data is either collected manually or transported via radio signals. This solution is considered an expensive solution and not flexible.

In this paper we propose a new architecture that addresses the challenges in the process of gathering information from the sensor nodes to the base stations. In the proposed model, relay agents are used to carry the information from the sensor nodes

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to the base stations. The paper proposes architecture that controls the dispatching rate of the relay agents.

The rest of the paper is organized as follows. Section II. discusses the related work for using WSN to manage water management. Section III discusses the feedback control approach used and the proposed architecture. Section IV discusses feedback control theoretic techniques for the proposed architecture. Section 5 discuses the simulation testbed and the simulation results. Section VI discusses the paper's conclusion and future work.

II. RELATED WORK

The work in this paper combines the strengths of the work which falls in three directions. The first direction consists of existing wireless networks designed to monitor water settings in agricultural fields. Examples for projects in this direction are (1) India-Swiss COMMON-Sense Net [9] and (2) Australia's CSIRO Project [4][5]. Both projects focus on monitoring, communication, and development. These designs assume network as an array of sensing devises, where readings from each device are relayed back to a data depot.

The work by Wark et al. [4] studies the challenges in the agriculture field using WSNs. Challenges studied include climate change, water shortages, and labor shortage due to an aging urbanized population, and increased societal concern about issues such as animal welfare, food safety and environmental impacts.

The project by Corke et al. [5] deals with monitoring lake water quality. The work in [5] is concerned with large scale environmental monitoring. Authors in [5] used real examples to illustrate the technological difficulties and challenges that are entailed in meeting end user requirement for information gathering systems. Authors in [5] studied application such as the cattle monitoring, ground water quality monitoring, virtual fencing, lake water quality monitoring and rainforest monitoring. Authors in [5] also studied the salinity, water table level, and water extraction rate.

The second direction is the KioskNet project [14] that aims to link people in disconnected regions. KioskNet is an effort to connect remote clusters of people to the Internet by using routers attached to motorized vehicles. KioskNet project's goal is to provide very low cost Internet access to rural villages in developing countries. This is achieved based on the concept of delay tolerant networking. It uses vehicles, such as buses, to transport data between village structure and gateways in the neighbourhood areas.

The third direction is the work proposed by Shah el al [13]. The work in [13] describes the Aqua-Net model that introduced the concept of single-hop autonomous sensor communities and a decentralized arbitration mechanism within the sensor communities.

To the best of our knowledge, there is no work is performed concerning applying feedback control theoretic approaches for water management using WSNs. Steine et al [19] and Zimmer [22] use feedback control mechanism for balancing multiple conflicting network quality metrics, such as power consumption and end to end packet latency for heterogeneous wireless sensor network operating in a dynamic context.

Work done by Abdelzaher et al [20], is concerned with data communication and aggregation to maintain specified acceptable latency bounds on data delivery while attempting to minimize energy consumption. The work did not deal with the dispatching rate of the relay agents in different message levels.

Previous work [4][5][6][9][10][14][24][25] for water management have the following drawbacks (1) Not fault tolerance (2) Not configurable to allow substitution of functional units during natural or artificial disasters. Work proposed in [13] claim long idle times between visits from relay nodes and hence enables communication schedules among community members, but if the delay was not long enough, this would affect dramatically the accuracy of the data sent in the communication schedule. This paper proposes an architecture that handles these issues.

III. PROPOSED ARCHITECTURE

The proposed architecture added a feedback module at the data depot module on the top of the Aqua-Net architecture [13]. The proposed network framework architecture is composed of the following modules as shown in Fig. 1:

1. **Sensing Modules:** Sensing nodes responsible for gathering information. Sensing nodes maybe stationary or moving. Sensing modules are deployed.

2. **Collecting Module:** Collects and store information from sensing modules. Reside in all nodes in the network. Can operate in both sending and receiving fashion depending on the application. Collecting modules are setup at points where messages are gathered and consolidated. Collecting modules have buffers to store the received messages and forward it to the transportation module.

3. **Relay Agent Transporting Module:** Carries information from one location to another. The carriers are also referred to as *mules* in literature. Could be human carrier, animal, or a motorized vehicle, etc.

4. **Data Reservoir Module:** Stores messages from wireless sensor nodes to be delivered to the respective hosts and back.

5. **Feedback Controller Module:** It is responsible for compute the dispatching rate of the relay agent in order to collect information from the sensor nodes based on control law.

The proposed architecture in this paper is built on the top of the architecture proposed in [18]. The proposed architecture introduces a feedback control approach to tune the dispatching rate of relay agents based on the severity of the message information from the sensors in a WSN environment

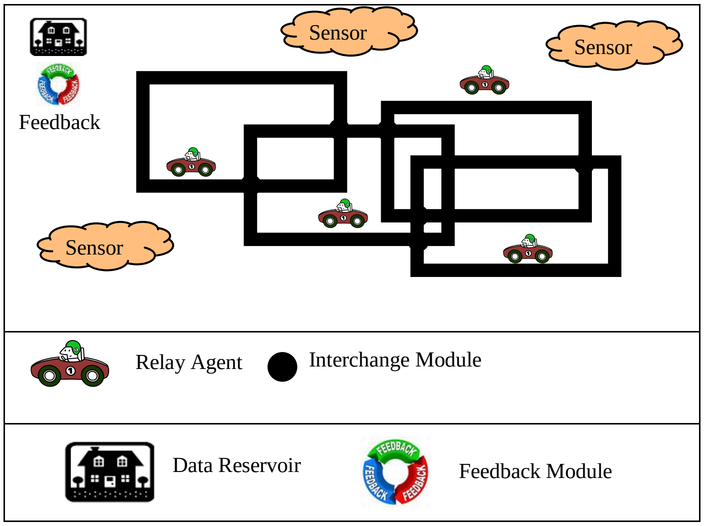

Fig. 1. The Proposed block diagram Architecture for Feedback Water Management built on top of Aqua-Net Architecture [13]

This paper proposes closed loop feedback architecture for water management architecture using wireless sensor network. The framework aims to manage the message passing communication in a wireless sensor network for water management. This has an effect on the amount of water saved in order to maximize the overall water gain. The proposed framework is flexible as it consists of a large number of autonomous averaged single hop sensor clusters, travelling backbone network, and a data reservoir. It is also a fault tolerant and reconfigurable architecture. This model abstraction adds flexibility to substitute any module with another that performs the same functions without major changes.

Each relay agent is responsible of carrying information periodically from the sensor nodes based on its priority. The relay agent dispatch rate is tuned based on the severity of the information gathered from the sensor environment. The relay agent dispatching rate is tuned based on the controller's control law (discussed in details in section IV).

Fig. 1 shows the feedback control system proposed. The message controller module regulated the dispatching rate of the relay agents to collect the information from the sensor nodes back to the data reservoir. Messages that are transferred by the sensor nodes are assumed to have a priority field to indicate severity of the field situation

IV. CLASSICAL CONTROL THEORY FOR THE PROPOSED ARCHITECTURE

Control systems are everywhere around us and within us. Many complex control systems are included among the functions of the human body. Control systems regulate temperature in homes, schools, and buildings of all types. They also affect the production of goods and services by ensuring the purity and uniformity of the food we eat and maintaining the quality of products from paper mills, steel mills, chemical plants, refineries, and other types of manufacturing plants. Control systems help protect the environment by minimizing waste material that must be discarded, thus reducing manufacturing costs and minimizing the waste disposal problem.

To the best of our knowledge, there is no work is performed concerning applying feedback control theoretic approaches for water management using WSNs. The monitored information is referred to as *feedback*. An attribute of system behaviour is referred to as a *controlled output parameter*. The feedback is used to adjust the system's tuning parameters that impact the system behaviour as represented by one or more controlled output parameters. Possible tuning parameters include the Possible controlled output parameters include the soil moisture, rainfall, underground water, water supply, sunlight, water table, water quality, soil salinity, water flow, discharge, and water leakage.

Instead of using first principles, empirical approach could be used for system identification. In this paper, *empirical approach* is used for WSN network system identification. Input and output parameters need to be identified based on autoregressive moving average (ARMA) model parameters. This approach treats the system as a black box and thus is not affected by the system complexity or lack of expert knowledge. Challenges in the target system can be accommodated by re-estimating model parameters

A. *Closed-loop Control Systems*

In this section the structure of a single-loop closed-loop control system is given. The required components of the system are defined, and the functions of these components are discussed as well. A typical classical controller design consists of two phases: (1*) System identification phase*. In the System identification phase construction of the transfer functions that relates the past and the present input values to past and present output values. The transfer function constitutes a model of the system. (2) *Controller design phase*. The controller design phase is based on the properties of the transfer function and the desired objectives; a particular *control law* is used. Techniques from control theory are used to predict how the system behaves once the chosen controller is used.

B. *System Identification Phase through Transfer Functions*

Controllers use defined relationships between inputs and outputs that are defined mathematically. To relate inputs and outputs, this work uses the autoregressive, moving average (ARMA) model which is an example of an empirical approach. The relationships described in this section are similar to those derived in discrete time is assumed with uniform interval sizes. The general form of the ARMA model is given by:

$$y(t) = \sum_{i=1}^{n} a_i y(t-i) + \sum_{j=0}^{m} b_j x(t-j) \tag{1}$$

The input x(t) of the ARMA model represents a tuning parameter and the output, y(t), represents a controlled output parameter. The parameters *n* and *m* are the "*order of the model*", and the a_i, b_j are constants that are estimated from data using least squares regression. By identifying the values for *n*, *m*, a_i, b_j, the transfer function can be derived. The ARMA model is used to relate the output of the model to the input and also to the history of the output.

ARMA models are in the discrete time domain. Control theory techniques are usually based on frequency domains. Thus, transfer functions should be converted from time to frequency domain. The frequency domain is referred to as the z-domain. The following formula is applied:

$$Y(z) = \sum_{t=0}^{\infty} y(t) z^{-t} \tag{2}$$

This is known as the z-transform, where z is a complex number and y(t) is the output in the time domain. This allows for the use of existing control theory principles that are usually based on frequency domains. Note that in the time domain, lower case is used (e.g., y(t)) and in the frequency domain uppercase is used (e.g., Y(z)).

By applying the z-transform given in equation (2) and applying it to the ARMA model in the time domain given in (1), a general formula in the z-domain can be derived:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{\sum_{j=0}^{m} b_j z^{n-j}}{z^n - \sum_{i=1}^{n} a_i z^{n-i}} \tag{3}$$

Extensive experimentation showed that the ARMA model is a good fit for WSN network wsn(t), if we set y(t)=cop(t), x(t)=tp(t) and n = 1, m=0. That is,

$$WSN(z) = \frac{COP(z)}{TP(z)} = \frac{zb_0}{z - a_1} \tag{4}$$

Least squares regression was used to estimate the values of the parameters of the ARMA model b_0 and a_1. It was found that the R^2 that measures the goodness of the model is no lower than 87% for the model.

The most important characteristic of a component is the relationship between the input signal and the output signal. This relationship is expressed by the *transfer function* of the component, which is defined as the ratio of the output signal divided by the input signal using z-transform.

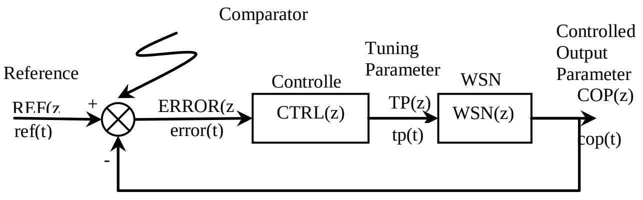

Fig. 2: A closed-loop mathematical control system

Using the properties of the transfer functions and applying them to Fig. 2, we get the following: the overall closed loop system transfer function can be given by:

$$\frac{COP(z)}{REF(z)} = \frac{CTRL(z).WSN(z)}{1 + CTRL(z).WSN(z)} \tag{5}$$

In general, the closed-loop transfer function represents the path between the input and the output without having a feedback loop, and a transfer function in a feedback loop, with subscripts as needed.

Controller Design

As shown in Fig. 2, integral controller is used in the proposed architecture. Designing the controller is finding the appropriate values for its gain K.

A *control law* describes how the controller changes the value of its output. Due to its simplicity and efficiency, an *integral control law* is used. The integral controller produces a control action that continues to increase its corrective effect as long as the error persists. If the error is small, the integral controller increases the correction slowly. If the error is large, the integral action increases the correction more rapidly.

The integral controller has the following general time domain formula:

$$tp(t)=tp(t-1)+K.error(t) \tag{6}$$

where tp(t) is the controller's output which changes over time, K is the integral controller gain. The integral controller gain (K) is designed using root locus which is a classical control theory technique.

The control law used for the controller is the maximum number of requests allowed to be served concurrently at the server; this value is to be adjusted dynamically based on the previous values of COP.

Using z-transform properties, the z-transform of u (t) and u(t-1) is TP(z) and (1/z).TP(z) respectively. Thus, the application of the z-transform presented in (2) to the general form in (3) results in the following:

$$TP(z) = \frac{1}{z}TP(z) + K.ERROR(z) \qquad (7)$$

Therefore,

$$\frac{COP(z)}{REF(z)} = \frac{K.z(z.b_0)}{(z-1)(z-a_1) + K.z(z.b_0)} \qquad (8)$$

A classical control theory technique called *root locus* can be applied to calculate the value of K. Software packages such as Matlab perform the *root locus* technique [21]. This technique studies the poles and the zeros of closed loop transfer functions such as the ones presented in equation (8) as the gain increases from 0 to infinity.

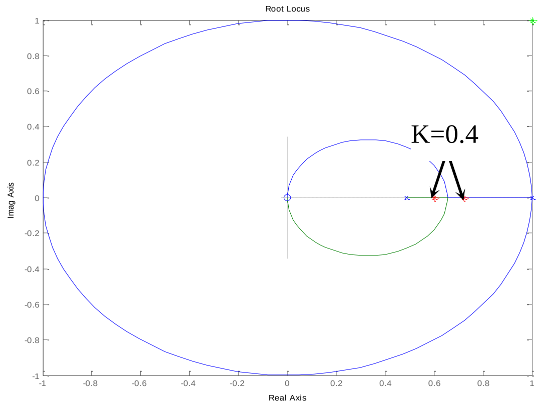

Fig. 3: Root Locus Plot for the tuning parameter controller at K=0.4

The roots of the numerator are called its zeros and the roots of the denominator are its poles. For equation (8), the zeros are the values of z where COP(z) = 0 (thus COP(z)/REF(z)=0) and the poles are where REF(z)=0 (thus COP(z)/REF(z)= ∞). If any of the poles of COP(z)/REF(z) lies outside the unit circle, then COP(z)/REF(z) is said to be unstable. The gain value associated with a pole that lies outside of the unit circle is not considered. Appropriate root values are those values that have a magnitude less than one, and also on the real axis to minimize oscillations. Root locus plot of the model is shown in Fig. 3. The horizontal axis of the plot corresponds to the real part of z (Re(z)) and the vertical axis is the imaginary axis of z (Im(z)). A gain K of 0.4 is chosen to satisfy stability and less oscillation conditions.

V. SIMULATION SETUP AND RESULTS

This section discusses the simulation setup followed by the experimental results. NS-3 simulator is used for simulation [18]. The requests used have the following properties: Arrival data rate from sensor nodes are following Pareto distribution. Requests are of three levels of priorities (Gold, silver and bronze). Machines used for the simulation are 3.4 GHz Sun-Blade (UltraSPARC) with 4 GB memory running SunOS. Matlab is used for the controller design [21]. This is an ongoing research, as of yet experiments show very promising results

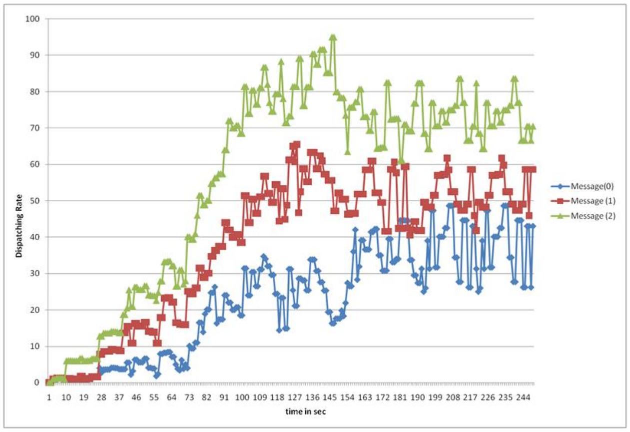

Fig. 4: Computed Dispatching Rate

As shown in Fig. 4, the relay agent dispatching rates are complying with the severity of the messages sent from the sensor nodes towards the base station through the relay agents. The base station reads those messages and reacts according to the severity of the message with the appropriate relay agent dispatching rate. Three levels of message severity are supported in the proposed model. The base station reacts by dispatching more relay agents in the case of message of high priority to react accordingly.

In the proposed architecture the three levels of severity are assumed to be around 85% for the highest message severity (alarming messages that need highest dispatching rates), 60% for the middle class messages and 30% for the least severe messages.

Fig. 4 shows the high compliance of the dispatching rate towards message severity obtained from the field.

VI. CONCLUSION

In this paper a new architecture is proposed. The architecture proposes a feedback control theoretic mechanisms to control the dispatching rates of the relay agents. Dispatching rates depend on message severity sent from the sensor nodes to the base stations. Three message priorities are assumed in the proposed model. Base stations respond to the message severity coming from the sensor nodes, by dispatching relay agents according to the message severity level.

To use classical control theory to obtain the desired rate in a dynamic fashion, two steps were required to achieve the controller design. First step is the identification phase that included describing the WSN system in terms of mathematical transfer functions. The second step was to design the controllers, by determining the gains. Techniques from control theory were used for the design. Results show very promising results. The dispatching rate is complying with the desired values of the reference values according to the message severity. Results are compared with architecture that is not using feedback controllers and the proposed architecture outperformed the non-feedback model by 13%.

Concerning the future work of this work, it is an ongoing research. In this work, it is assumed that three levels of message severity are sent from the sensor nodes to the base station. This could be generalized to n levels. Differentiated services could also be tested to include relay agents that have different priorities using more than one type of relay agents..

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