A Self-Powered Adaptive Wireless Sensor Network for Wastewater Treatment Plants

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Abstract- **Efficient monitoring and control of wastewater treatment plants (WWTPs) has become an important public issue as the cost of electricity continues to grow and the quality requirements of processed water tightens. However, the development, deployment, and maintenance of highly efficient monitors and controllers for wastewater processing tanks are significantly challenging. Self-powered, wireless sensor networks (WSNs) are an ideal candidate for this application, since their deployment would have the least impact on the existing infrastructure. A novel wireless sensor network is presented in this paper that integrates microbial fuel cells (MFCs), field-programmable analog arrays (FPAAs), and low-power networking protocols into the sensors to make them self-powered, highly flexible, and adaptive. MFCs convert chemicals in the waste water into electrical energy, while FPAAs provide a means of performing ultra-low-power, real-time, and adaptive processing of the sensor signals. This design achieves sustainable monitoring and control of wastewater treatment with minimal impact to existing infrastructure.**

Keywords: Self-Power, Wireless Sensor Networks, Field-Programmable Analog Array, Microbial Fuel Cells.

I. Introduction

Wastewater treatment is a critical part of environmental protection, but Wastewater Treatment Plants (WWTPs) are one of the most energy consuming industrial facilities. In the United States, nearly 3% of the total electricity supply is consumed by WWTPs [10], [11], and approximately 30% of WWTP operating budgets are dedicated to electricity [3]. In addition, the demand for electricity at WWTPs is expected to grow by 20% over the next 15 years because of population expansion and increases in water quality standards [3]. As such, energy conservation has become increasingly important to WWTPs. Studies of energy efficiency optimization in both design and operation of WWTPs have been conducted over the past two decades [7], [10].

Any energy conservative industrial design needs to assess and address certain questions [10], such as:

- Does all of the equipment need to run all of the time?
- Is it feasible to run the equipment only when necessary?
- Can the processing be scheduled to avoid peak energy consumption hours (reduces energy costs)?

Essentially, real time accurate monitoring and adaptive control are required to address the above questions, but the implementation of such systems also needs attention. Updating or replacing the existing infrastructure would be prohibitively difficult and costly to support a wired network of sensors. Wireless sensor networks (WSNs) are more suitable for deployment in WWTPs to monitor the status of wastewater [5]. However, battery powered sensor networks are undesirable, as these sensors are located in inconvenient environments for regular human maintenance. Instead, periodic battery replacement can be avoided if the sensor system is self-powered. Such a sensor system would provide a maintenance free network for many years.

To meet these challenges, a self-powered, adaptive, wireless sensor network for WWTPs is proposed in this paper. Our sensor nodes integrate microbial fuel cells (MFCs), field-programmable analog arrays (FPAAs), and low-power networking protocols. The abundance of bacteria and chemical ingredients in wastewater processing tanks provides materials for MFCs to convert chemical energy into electrical energy.

Using FPAAs for the sensor signal processing has three main advantages: 1) ultra-low power consumption, 2) highly parallelized computation, and 3) greater flexibility. Self-powered systems are always constrained by the energy harvesting mechanism and thus require efficient signal processing. Analog signal processing techniques have been demonstrated [4] in which the power consumption is two to four orders of magnitude less than equivalent digital signal processing hardware.

Computations in FPAAs are inherently parallel, since there is no central processor. Multiple sensor inputs can be processed simultaneously and in real time using independently configured/programmed circuitry within the FPAA, since these devices are composed of large arrays of interconnected components, similar to FPGAs. The programmable and reconfigurable nature of these devices also leads to their high level of flexibility, since they can be configured to interface with and process a wide variety of sensors.

The status of wastewater tanks can be monitored effectively by deploying a WSN that consists of such new sensor nodes. Using this sensor data, optimized controllers can reduce the costs associated with wastewater treatment while simultaneously improving the resulting water quality, which improves environmental protection. This WSN can also be utilized in remote areas for environmental monitoring where it is infeasible to extend the power grid.

Although WWTP monitoring is selected as our prototype application, this novel WSN can be deployed in any body of water or remote region in which conventional WSNs are not practical. For example, our WSNs can be installed in the cooling water of nuclear reactors, where it is too dangerous for humans to enter while operating. Polluted rivers are an example of a region that is too vast to deploy wired sensors, and battery-powered WSNs require maintenance too often.

The rest of this paper is organized as follows. Section II provides a brief introduction to the background work utilized in the proposed sensor network. The architecture and rationale of our sensor node design are presented in Section III, and Section IV concludes this paper with our ongoing work.

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II. Background Knowledge

This section presents background knowledge in three areas that are closely related to our self-powered adaptive sensor nodes: the technologies for energy harvesting sensor systems, the current status of microbial fuel cells research, and an introduction to FPAA devices.

A. Energy Harvesting in Sensor Systems

Achieving longer lifetimes of battery-powered sensor nodes is a hot topic in the WSN research community, which has resulted in many proposed protocols that avoid unnecessary energy consumption. These approaches include sleep/active scheduling, energy-efficient routing, energy-aware MAC protocols, and others [9]. However, these have all focused on minimizing communication energy and have not addressed the sustainability of the integrated system.

Energy harvesting provides the possibility of very long sensor node life-times. Based on the energy harvesting architecture, sensor nodes can be placed into one of two categories [9]: 1) Harvest-Use, in which the energy is consumed immediately while being harvested; and 2) Harvest-Store-Use, in which the harvested energy is stored and may be used later. The advantage of the Harvest-Store-Use architecture is that it is much more tolerant of intermittent energy use, which leads to a more efficient overall design.

Energy harvesting systems can also be categorized according to the energy source, such as solar, wind, water, motion, and pressure. Considering the properties of the energy source and conversion mechanisms, they can be further sub-categorized into: 1) controllable and therefore predictable, 2) uncontrollable but predictable, 3) uncontrollable and unpredictable [9].

Although there is a plethora of energy harvesting efforts for sensor systems, none of them are feasible for sensors that are submerged in wastewater processing tanks. Fortunately, recent research achievements in the area of MFCs have provided a possible solution when combined with low-power processing and communications.

B. Microbial Fuel Cells (MFCs)

The unique working environment in wastewater processing tanks makes MFCs a feasible energy source. Research on MFCs has been conducted for more than four decades, and a lot of designs have been reported. In fact, researchers have suggested applying MFCs to provide electricity for a wide range of applications, from small portable electronic devices to robots. However, none of them has been implemented successfully in practice to date [8].

The recently reported Granular Activated Carbon Single Chamber Microbial Fuel Cells (GAC-SCMFCs) [6] is promising to satisfy our requirements. The GAC-SCMFCs was proposed for large-scale electricity generation using wastewater treatment processes. Actually, its capacity is far behind this ambitious goal, and it will not likely be able to make a significant breakthrough in the short term. However, the power density of 7 W/m^2 with an internal resistance around 100 Ω makes it an ideal candidate for self-powered, low-energy consuming systems.

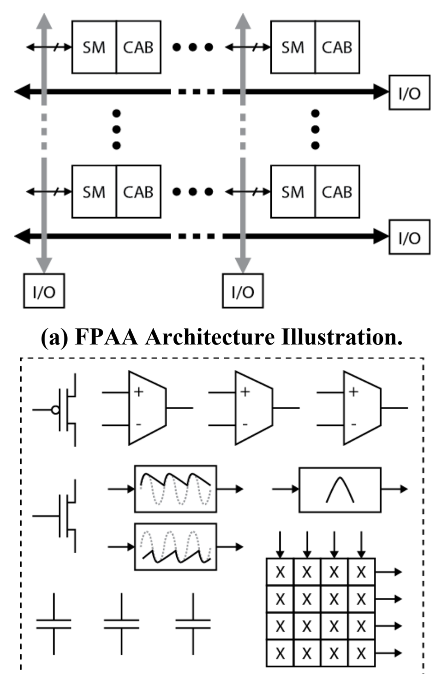
The energy generated by the GAC-SCMFCs is still limited. It is critical to ensure that the sensor nodes are energy efficient. The most energy expensive operations of a sensor node are the data processing and sending/receiving of packets. While exploring energy conservative communication schemes is important, novel low-power computations must also be considered, which has led to the incorporation of FPAAs into our sensor nodes.

C. Introduction to FPAA Devices

FPAAs are analog parallels of FPGAs, and they have been attracting a lot of recent attention from industry [1] and academic research [2], [4]. They are comprised of a large array of analog components interconnected through a fabric of programmable switches. This large array of components enables highly parallel operations and significant flexibility of functions that can be performed. Non-volatile memories within the FPAAs allow them to be reprogrammed thousands or millions of times, while also ensuring that these devices will operate properly during intermittent power losses.

Unlike FPGAs, FPAAs have programmable power consumption, which allows their power efficiency to be comparable to custom application specific integrated circuits (ASICs) designed to perform optimized processing tasks. This means that FPAAs can deliver nearly the same performance as ASICs through rapidly synthesized circuits as opposed to custom manufacturing. This can shave months if not years off the development cycle.

Figure 1 shows an example of a FPAA. The architecture of the FPAA, Figure 1(a), is composed of a two-dimensional



(a) FPAA Architecture Illustration.

(b) Example CAB Components.

Figure 1. Introduction to FPAA Structures.

array of computational analog blocks (CABs). Connected to each CAB is a local switch matrix (SM) that provides interconnectivity between the various analog components contained within the CAB. Global vertical and horizontal routing connects to the local switch matrices and provides access to the input/output (I/O) pins.

Each CAB contains a number of analog components, such as those depicted in Fig. 1(b). Fine-grain components such as transistors and capacitors provide maximum flexibility in FPAAs. Almost anything can be constructed using these fine-grain primitives. Medium-grain components, such as operational amplifiers, are included to provide increased performance while maintaining a high level of flexibility. The majority of CAB components fall within the medium-grain complexity, since they provide a good balance between performance and reconfigurability.

Course-grain components are also included within some of these CABs. Special-purpose devices, such as vector-matrix multipliers and programmable bandpass filters, provide complex functionality, high performance, and minimized area overhead. However, these devices are not as general purpose as medium-grain or fine-grain components, and therefore are not as abundant across the IC.

III. Self-Powered Adaptive Sensor Nodes

This section presents the architecture of the sensor nodes, a discussion of the energy harvesting/storage scheme, and the functionality and flexibility of FPAA devices.

A. Sensor Node Architecture

Figure 2 shows the block diagram of the sensor nodes, which consists of four subsystems:

- Energy harvesting subsystem. This subsystem consists of two main functional units, electricity generation and energy storage.
- Sensing subsystem. This part conducts the detection and monitoring tasks of the wastewater processing tanks and the quality of the reclaimed water.
- Control/computing subsystem. An FPAA and a low-power microcontroller have been selected for this subsystem, which monitors and processes the data collected by the sensing subsystem.
- Communication subsystem. This system addresses network level issues that include routing, data collection/forwarding, security of information, and network infrastructure.

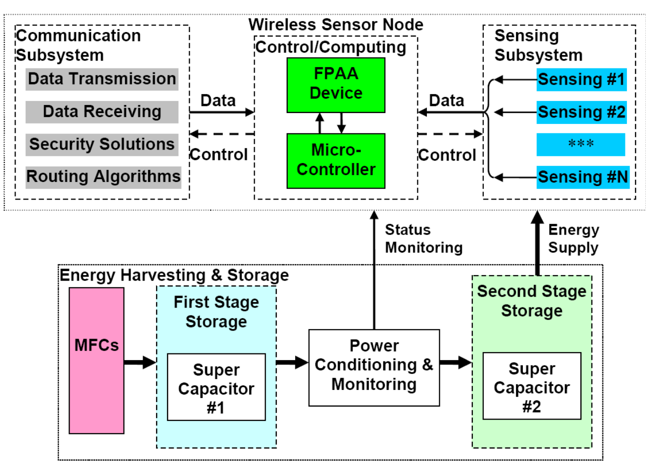


Figure 2. Sensor Node's Block Diagram.

The sensing subsystem collects data that represents the status of the wastewater processing tanks. For instance, the wastewater level, flow speed, temperature, and density of certain chemical ingredients and/or density of certain bacteria in the tank can be measured. A few issues depend on the specific application of the system, such as exactly how many sensing units are required, what kind of chemical reactions are monitored, etc.

The communication subsystem addresses design issues at both the node and network levels. It requires further development and optimization given the integration with the FPAA and MFC. Each sensor node needs to adjust its behavior according to its energy level and those of its neighbors. Typically, the duty cycle, transmit power, transmission scheduling, routing strategy, etc. can be adjusted. On the network level, security and robustness are the two major concerns.

Among the four subsystems, the most challenging tasks lie in the energy harvesting and the control/computing subsystem. Our major original contributions are also made in these two parts. More details are discussed in the two following subsections.

B. Energy Harvesting and Storage

As discussed previously in Section II, MFCs are adopted as the energy source of our sensor network. Although earlier research has shown promise [6], it is nontrivial to harvest electricity efficiently and reliably enough to meet the instantaneous power requirements of sensor nodes. Therefore, a well designed energy harvesting and storage system is necessary.

It is a challenge to provide a stable, continuous power supply for a long period of time using MFCs. However, MFCs can be used to partially recharge or supplement batteries, thus extending their lifetime significantly, but the batteries eventually wear out. It is infeasible to replace batteries embedded in sensor nodes that are submerged in wastewater processing tanks. On the other hand, the theoretical lifetime of capacitors and super capacitors is orders of magnitude longer than batteries. Therefore, capacitors are an integral part of the proposed harvesting and storage scheme, which minimizes sensor node maintenance.

The architecture of our two-stage energy harvesting and storage system is shown in Figure 2. Super capacitors are used as the energy storage device in each stage. As shown in the figure, super capacitor #1 is charged by the MFCs directly. The Power Conditioning and Monitoring (PCM) utilizes efficient power electronics to condition the power from the first capacitor for use by the sensing, processing, and communication subsystems. In this manner, the system supply is buffered through the PCM and super capacitor #2 from any fluctuations resulting from the MFC energy harvesting. In addition to simple power conditioning, the PCM also monitors the output power levels in case a power loss becomes imminent. At such times, the PCM can signal the microcontroller and FPAA to take action to conserve additional energy or signal a power failure to a central monitoring station.

C. Control/Computing using FPAA

The flexibility of FPAAs enables a wide range of integrated sensor processing, signal classification, and control possibilities. An example of this is illustrated in Figure 3, in which an array of sensors, S_1 through S_M, is connected to the FPAA. Each sensor can have independent signal conditioning and feedback control using the analog components to form any number of transfer functions, such as the second-order filters depicted in Figure 3.

Sensor data can also be combined through numerous operations, including multiple input versions of the transfer functions as well as vector-matrix multiplications, such as that depicted in Figure 3. In this case, the filtered sensor signals form a vector of inputs that are multiplied by a matrix of weights, W, and are summed along the columns of W. These signals can be further processed and refined by normalization and classification circuits to detect various events, which are used to determine the optimal control signals to send to the equipment through the microcontroller and wireless network. This entire processing chain operates simultaneously using continuous-time circuits, which enables highly parallel and very low-power operations.

A significant advantage of using FPAAs for analog signal processing in this manner is the ability to reconfigure or reprogram the device to adapt to changing conditions, add new sensor inputs, alter the processing chains, or update detected events. Since these devices can be programmed in the field, updates can be applied without significantly disturbing the hardware or the wastewater treatment systems. Initial installation and maintenance costs can also be minimized, since the same hardware can be reconfigured to support many different types of sensors and processing needs as they are updated or changed over time.

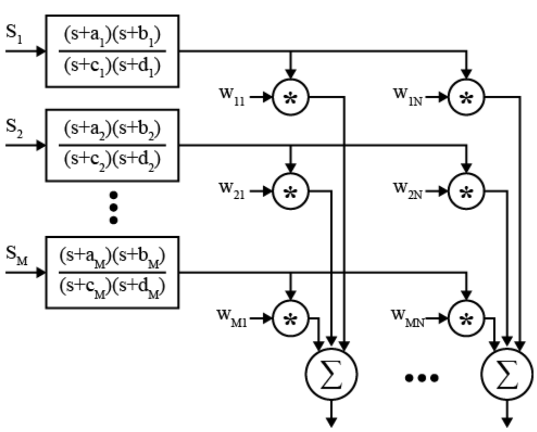


Figure 3. Calculations on FPAA.

IV. Conclusions

In this paper, we presented a novel self-powered, adaptive, wireless sensor network for wastewater treatment plant monitoring. Taking advantage of microbial fuel cells for energy harvesting and field-programmable analog arrays for very low-power signal processing, the sensor nodes can not only work for years without hardware maintenance, but they can also be adaptive to changes in the working environment to achieve higher performance.

The designs proposed within this position paper are very preliminary, but progress is being made toward verification of these ideas. A team of experts from each of the necessary fields has been formed to collaborate with a wastewater treatment plant in Philadelphia. Proof of concept experiments with this new design are being constructed for testing in the near future.

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