Architecture of Wireless Sensor Nodes for Water Monitoring Applications: From Microcontroller-based System to SoC Solutions

Fatma Karray*, Wassim M. Jmal*, Mohamed Abid and Dhouha Houssaini*
Abdulfattah M. Obeid†, Syed Manzoor Qasim† and Mohammed S. BenSaleh†
*Computer and Embedded Systems laboratory, National Engineering School of Sfax,
University of Sfax, Sfax, Tunisia
†National Electronics and Photonics Technology Center,
King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia
Email: {obeid,mqasim,mbensaleh}@kacst.edu.sa,
{karray.fatma.enis,wassim.jmal}@gmail.com, mohamed.abid_ces@yahoo.fr

***Abstract*—A significant amount of research and development work has been initiated by several research groups in the recent years to tackle the issue of water monitoring. Wireless sensor network (WSN) is predominantly used for water monitoring application. Depending on the application constraints and performance required, different implementations are considered for the development of wireless sensor nodes for water monitoring applications. Some are based on microcontroller, digital signal processor (DSP), application-specific integrated circuit (ASIC), field programmable gate array (FPGA), system-on-chip (SoC), programmable system-on-chip (PSoC) or a combination of these technologies. This paper presents a survey of state-of-the-art research on sensor node technologies used for water monitoring which includes pipeline monitoring, fresh water monitoring for quality and composition. The relative strengths and weaknesses of microcontroller, DSP, ASIC and FPGA-based wireless sensor nodes for water monitoring applications are presented. Finally, a fully-integrated energy aware SoC solution using reconfigurable hardware is proposed to achieve optimal results.**

***Index Terms*—ASIC, FPGA, microcontroller, SoC, wireless sensor node, water monitoring.**

I. Introduction

Water is the symbol of life on the earth and important to sustain all forms of life. It can be transported using pipelines or found in natural resources as rivers, streams, lakes, groundwater, ponds, wetlands, springs and floodplains. These resources have been reduced and polluted. Many factors can cause pollution as sewer's water, industrial offal, etc. Hence, water preservation and water quality monitoring is required in order to protect human lives and to monitor our environment [1]. Traditional monitoring methods are inefficient in terms of cost, technology and requirement of human intervention.

On the other hand, wireless sensor network (WSN) has emerged as an efficient method for water monitoring due to its flexibility, mobility, cost, wireless communication, etc. It comprises of large number of autonomous sensor nodes deployed spatially to collect and transmit data. Due to the recent technological and architectural advancements, a variety of platforms have been explored for wireless sensor node design [2]. Traditionally, a sensor node has been generally designed based on microcontroller platform. However, in modern applications, such as water monitoring, stringent requirements in terms of real-time, low-cost and low-energy forced researchers to think about high performance platforms after analyzing the different system aspects. Other alternative architectures (Fig. 1) which show great potential are Digital signal processors (DSPs), application-specific integrated circuit (ASIC), field programmable gate array (FPGA) and system-on-chip (SoC) [3].

Fig. 1. Architecture choices for wireless sensor node.

In fact, microcontrollers show poor execution time and energy efficiency in many complex computational cases. In many cases a DSP is an optimal solution for some but not all of the functions required of an application. The ASIC on the other hand is more energy efficient and less flexible since they are application-specific. This can be compensated by the use of new architectures such as FPGA and SoC.

The architecture of sensor nodes has evolved during the recent years. However, such technologies cannot always meet real time constraints and low-power consumption constraints. Research in WSN aims to find a tradeoff between the different constraints by using or/and introducing novel WSN node architectures. In this paper, several architectures and technologies are reviewed and presented.

The rest of the paper is organized as follows: Section II presents the use of WSN for water monitoring. Section III and IV presents the details of sensor nodes based on a microcontroller/DSP and ASIC/FPGA technologies, respectively. New architectures based on SoC will be further discussed in section V. Finally, we present concluding remarks and some recommendations for future work in section VI.

II. WSN for Water Monitoring Applications

Many traditional techniques have been employed for water monitoring including pipeline infrastructure monitoring and water quality monitoring [4]. Among these techniques, there are acoustic measurements, pressure analysis, visual inspection and ground penetrating radar (GPR) based systems.

Acoustic measurement is a non-destructive monitoring method which utilizes acoustic sensors to trace the physically anomalies of the system. This technique is not suitable for underground inspection due to the difficulties of deployment. Moreover, they have less sensitivity as compared to other techniques [4]. Visual inspection is the oldest and widely used method. It utilizes image and video sensors for the detection of leakage in aboveground pipelines and monitoring fresh water. This technique provides real-time detection. However, it cannot be used for underground inspection [5].

GPR is a non-destructive and non-invasive technique used to detect underground pipeline leaks. It transmits electromagnetic radiation and radar pulses and measures a reflected signal. This method has been widely employed due to its high resolution data and three dimensional visualization capabilities. However, it doesn't provide real time inspection capabilities [6]. These techniques employ wired networks. Wired networks present several drawbacks including high maintenance cost, installation, repairing, etc. In fact, the damage to any part of the wire can decrease the performance of the network or damage the entire network. Furthermore, repairing or maintaining underground wires from damage is difficult, time consuming and costly.

However, WSN seems to be a reliable and novel method to overcome the challenge of terrestrial water monitoring such as leaks in water pipeline, quality of water, pH level, nitrate, water pollution, etc. In fact, researchers have highlighted the potentials and the feasibility of WSN for water monitoring [7]. Comparing the traditional methods, WSN seems efficient in terms of performance, low-cost and ease of deployment.

Several WSN researches for water monitoring have been described in the literature [7]. They have been used to detect and localize leaks in pipeline, control the water flow rate or for natural water to monitor the water quality and composition. Moreover, these networks can be employed even in aboveground (terrestrial WSN), underground (WUSN) and underwater (UWSN). WUSN and UWSN are more complex and difficult to operate than aboveground systems. In fact, the maintenance cost is high, supplying power is hard and the communication mode is inefficient. The challenge is to support the soil and underwater characteristics and dynamics [2]. In the following sections we present the relative strengths and weaknesses of microcontroller, DSP, ASIC and FPGA-based wireless sensor nodes for water monitoring applications and then we propose a fully integrated SoC solution to achieve optimal results.

III. Sensor Nodes Based on Microcontroller/DSP

Microcontrollers have been widely utilized for a range of applications. The advancement in microcontroller technology provided users with an easy option to realize the WSN in hardware. Most of the earlier WSN platforms use a microcontroller as the main controller to perform multiple tasks of sensor data processing and management of power consumption. For example, Mica family of sensor nodes is equipped with 8-bit Atmel microcontroller, a programmable flash and a transceiver. Several other motes are manufactured by different companies such as iMote, TelosB, TMote and Waspmote [8]–[11].

For water pipeline monitoring, SPAMMS [12], a novel, autonomous and cost effective system that permits corrective monitoring, localization and maintenance of the pipeline by combining static sensors, mobile sensors and robot technology is used. It uses different kinds of inspection methods using charge-coupled device (CCD) sensors, chemical sensors, pressure sensors and sonar sensors. The prototype consists of Mica1 mobile sensor mote, an EM4001 ISO-based RFID system and a robot agent. Mica1 consists of an ATMega103 microcontroller, a 128 Kb Flash memory, a 512 EEPROM and a 4 Kb RAM. It consumes 27 mW in active mode.

Moreover, TriopusNet [13] is a mobile autonomous wireless sensor water pipeline monitoring network. It consists of a Kmote, a motor, a spherical case and other sensors (Intersema MS5541C water pressure sensor, gyroscope sensor) used for node localization. The Kmote is wireless sensor mote which consists of MSP430 microcontroller and CC2420 radio transceiver. The deployment and the maintenance of the WSNs are automated to overcome the battery short life time constraint of the node. This work focuses on the automatic replacement of the failed nodes and employs a replacement algorithm.

For underwater monitoring, Bondarenko et al. presented a WSN implementation for real-time sea water temperature monitoring in the marine environment [14]. The purpose was to control the high frequency changes of sea temperature and its effect in Nelly Bay, Magnetic Island, Australia. The sensor mote was a µNode mote and was connected to DS18B20 temperature sensors. The µNode consisted of a MSP430 microcontroller (48 KB of Flash Memory, 10 KB of RAM) and a Zigbee transceiver. Furthermore, for fresh water monitoring, the authors in [15] presented a wireless sensor node for river monitoring. The sensor node consisted of MSP430 microcontroller, 2.4 GHz 802.15.4 transceiver, GPS module, USB interface, ultrasonic module, pressure transducer and energy harvesting module based on solar cells and ultra-capacitors to recharge the battery.

DSP is the second choice after microcontrollers for water monitoring applications. Several implementations have been realized using DSP in WSN specially for water monitoring. For example, Yifan et al. [16] presented a WSN for above-ground water monitoring in lakes, wetlands and rivers to measure temperature, pH, turbidity, electrical conductivity and dissolved oxygen. The sensor node consisted of an ARM AT91 microprocessor, a TMS320 DSP, a CCD camera, a CC2420 transceiver and a CPLD. The DSP was used to perform compression of the images acquired by the CCD camera. Furthermore, Macias et al. in [17] proposed a multimedia distributed underwater monitoring system for UWSNs using acoustic communications. The system consists of CCD camera for recording special underwater events, three different antennas (Zigbee, acoustic and microwave antennas), DSP, memory, low cost acoustic modem and a Zigbee or a Wifi wireless network card interface for video streaming. Despite the evolution of DSPs, it cannot usually meet the high processing capabilities, high performance and low-power consumption requirements of sensor node.

IV. Sensor Nodes based on ASIC/FPGA

To the best of our knowledge, ASIC/FPGA technologies have not been extensively used for the development of sensor node for water monitoring applications. There exist very few papers where ASIC was directly/indirectly used in some form, one of them being PipeNet, a WSN-based water pipeline monitoring system. The sensor node of this system consists of an Intel mote, a sensor board which supports up to eight analog channels, a complex programmable logic device (CPLD) and an analog-to-digital converter (ADC). For the measurement of pressure, a modified OEM piezoresistive silicon sensor that includes an ASIC compensation-based technology to achieve accuracy better than ±0.2% is used [18]. In [19], an analog ion sensitive field effect transistor (ISFET)-based CMOS ASIC is used to implement a readout circuitry for low-cost system for water quality monitoring in urban areas or rivers.

FPGAs have emerged as a platform of choice for faster realization of compute-intensive applications. It provides hardware speed, software flexibility and price/performance ratio much more favorable than ASICs [20]. It also allows the system to be reconfigured even after the deployment in the field which is suitable for WSN nodes [21]. FPGAs have been used for the development of sensor systems for different applications as discussed in [22]–[26].

In [24], an FPGA-based data acquisition system is used for ground water monitoring application. The system consists of pressure sensor, an analog-to-digital converter (ADC) and FPGA. An FPGA chip is used for the implementation of smart water metering system in [25]. It is used to realize a signal generator, detection circuit, data encoder and serial port for the transmission of data. Saving energy is of prime importance for battery-operated WSN nodes deployed for monitoring applications. With the recent advancement and availability of ultra-low power FPGAs, it is now possible to develop ultra-low energy WSN nodes. This is explored in [26], where ultra-low power FPGAs are used to realize wake-up radios.

In [27], [28], the authors propose a water quality sensor calibration system that includes a set of water quality sensors for (conductivity, pH and turbidity), a Compact RIO real-time embedded controller and a FPGA. FPGA allows parallel processing which results in shorter processing time. The design of ASIC/FPGA-based sensor node for water monitoring application will result in an energy efficient and flexible solution. However, these solutions don't provide full integration and autonomy to wireless sensor nodes. A single-chip fully-integrated autonomous SoC based wireless sensor node which can provide low-power and low-cost solution is required.

V. Towards SoC Based Solutions

Energy consumption is a critical issue for WSN because of the deployment of large number of energy-constrained sensor nodes in unattended environment for monitoring applications. Therefore, performance evaluation is very important, especially at early stages of the design flow. For example, in [29], authors present the modeling, simulation and estimation of power consumption of nodes composed of SoC for WSN applications using SystemC/TLM. The SoC contains a MIPS-based processor, a memory, a bus, a timer, a transceiver and a battery. The model is intended to allow power estimation in WSN simulation. Although, WiseNET was the first wireless sensor node SoC, it required external components such as power source, RF antenna, passive devices and sensors [30]. A complete standalone SoC was attempted by the Smart Dust team but it still required additional off-chip components [31].

Regan et al. [32] presented a real-time water quality (pH, temperature, conductivity, turbidity and dissolved oxygen) monitoring system for rivers. The sensor node architecture is based on IEEE 1451 standard. To overcome the drawbacks associated with the presented solutions, we propose a wireless sensor node SoC as shown in Fig. 2 which will consist of a sensor interface, ADC, processor, memory along with some hardware accelerator (using ultra-low power FPGA), a radio transceiver, a power supply and management unit. For instance, a variety of temperature, pressure, flow and pH sensors may be attached to the node for efficient monitoring of water pipeline for detection of anomalies (leakage, rupture, bursts, etc.) and water quality respectively. The sensor node is energy constrained and mostly relies on battery or alternative energy sources to provide continuous power in difficult terrains. Because battery energy is limited, it is recommended to employ low power components and techniques to save energy for the sensor nodes. Since the processors used in SoC contributes to major power consumption even while executing simple operations, it is therefore required to delegate the compute-intensive task to hardware accelerator [33].

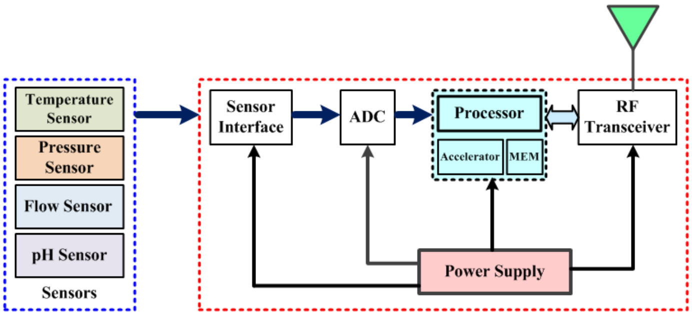

Fig. 2. Architecture of proposed wireless sensor node SoC.

VI. Conclusions and Future Perspectives

A large number of techniques have been proposed for water monitoring. These techniques are mostly related to pipeline monitoring and fresh water (quality and composition) monitoring. Architecture of the wireless sensor node has evolved from the standard RF-frontend plus microcontroller to a fully-integrated autonomous SoC including hardware accelerators, dedicated intellectual properties (IPs) for managing the communication protocols, etc.

For high-performance monitoring application, a massive paradigm shift towards multicore architectures is taking place called multiprocessor SoC (MPSoC). A wide range of MPSoC architectures may be studied. Integrating multiple cores on a single chip leads to a significant performance improvement without increasing the clock frequency. Multicore architectures offer a better performance/Watt ratio than single core architectures with similar performance.

In fact, future advancement in WSN technology requires further studies and advanced research to overcome the limitations posed by current architectures/techniques, mainly, real time execution and energy efficiency. In this context, we anticipate to develop an energy aware reconfigurable wireless sensor node for water monitoring applications.

VII. Acknowledgment

This work was supported by King Abdulaziz City for Science and Technology under Iktissab project (IRU No. 35/1012).

References

[1] B. Z. Shakhashiri, D. L. Sedlak and J. L. Schnoor, *ACS global water initiative: The grand challenge of water,* ACS, vol. 91, No. 20, May 2013, pp. 37

[2] J. Yick, B. Mukherjee and D. Ghosal, *Wireless sensor network survey,* Computer Networks, Vol. 52, No. 12, Aug. 2008, pp. 2292-2330

[3] F. Karray, M. W. Jmal, A. M. Obeid, M. Abid and M. S. BenSaleh, *A Review on Wireless Sensor Node Architectures,* in Proc. 6th IEEE Int. Workshop on Reconfigurable Communication-centric Systems-on-Chip (ReCoSoC'2014), May 2014

[4] Z. Liu and Y. Kleiner, *State of the art review of inspection technologies for condition assessment of water pipes,* Measurement, Vol. 46, No. 1, Jan. 2013, pp. 1-15.

[5] M. S. BenSaleh, S. M. Qasim, A. M. Obeid and A. Garcia-Ortiz, *A review on wireless sensor network for water pipeline monitoring applications,* in Proc. of IEEE Int. Conf. on Collaboration Technologies and Systems (CTS'2013), pp. 128-131, May 2013.

[6] A. Novo, Good Practice in Archaeological Diagnostics, Natural Science in Archaeology, pp. 165-176, Springer 2013.

[7] Y. Jin and A. Eydgahi, *Monitoring of distributed pipeline systems by wireless sensor networks,* in Proc. of 2008 IAJC-IJME Int. Conf., 2008.

[8] http://www.memsic.com/products/wireless-sensor-networks/development-kits.html (Accessed on 20 May 2014).

[9] http://www.xbow.com/pdf/ClassroomKits_press_release.pdf (Accessed on 20 May 2014).

[10] http://www.pervcomconsulting.com/wsn.html (Accessed on 20 May 2014).

[11] http://www.libelium.com/products/waspmote (Accessed on 20 May 2014).

[12] J. Kim, G. Sharma, N. Boudriga, and S. S. Iyengar, *SPAMMS: A sensor-based pipeline autonomous monitoring and maintenance system,* in Proc. of 2nd Int. Conf. on Communication Systems and Networks (COMSNETS'10), pp.1-10, Jan. 2010.

[13] T. T. Lai, W. Chen, K. H. Li, P. Huang, and H. H. Chu, *TriopusNet: Automating wireless sensor network deployment and replacement in pipeline monitoring,* in Proc. of 11th Int. Conf. on Information Processing in Sensor Networks (IPSN'12), pp.61-71, April 2012,

[14] O. Bondarenko, S. Kininmonth and M. Kingsford, *Underwater sensor networks, oceanography and plankton assemblages,* in Proc. of the Int. Conf. on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), pp. 657-662, 2007.

[15] L. B. Hormann, P. M. Glatz, C. Steger and R. Weiss, *A wireless sensor node for river monitoring using MSP430 and energy harvesting,* in Proc. of the 4th European Education and Research Conf. (EDERC), pp. 140-144, Dec. 2010.

[16] K. Yifan and J. Peng, *Development of data video base station in water environment monitoring oriented wireless sensor networks,* in Proc. of IEEE Int. Conf. Embedded Software and Systems Symposia (ICESS), pp. 281-286, July 2008.

[17] E. Macias, A. Suarez, F. Chiti, A. Sacco and R. Fantacci, *A hierarchical communication architecture for oceanic surveillance applications,* Sensors, Vol. 11, No. 12, 2011, pp. 11343-11356.

[18] I. Stoianov, L. Nachman, S. Madden and T. Tokmouline, *PIPENET: A wireless sensor network for pipeline monitoring,* in Proc. of the 6th IEEE Int. Symp. on Information Processing in Sensor Networks (IPSN), pp. 264-273, April 2007.

[19] P. Whig and S. N. Ahmad, *Development of economical ASIC for PCS for water quality monitoring*, J. Circuit Syst. Comp., Vol. 23, No. 6, 2014, pp. 1450079-1-1450079-13.

[20] S. M. Qasim, A. A. Telba and A. Y. AlMazroo, *FPGA design and implementation of matrix multiplier architectures for image and signal processing applications,* Int. J. of Comp. Sci. and Network Security, Vol. 10, No. 2, Feb. 2010, pp. 168-176.

[21] Y. E. Krasteva, J. Portilla, E. de la Torre and T. Riesgo, *Embedded runtime reconfigurable nodes for wireless sensor networks applications,* IEEE Sensors J., Vol. 11, No. 9, Sep. 2011, pp.1800-1810.

[22] A. D. L. Piedra, A. Braeken and A. Touhafi, *Sensor systems based on FPGAs and their applications: A survey,* Sensors, Vol. 12, No. 9, 2012, pp. 12235-12264.

[23] G. J. Garcia, C. A. Jara, J. Pomares, A. Alabdo, L. M. Poggi and F. Torres, *A survey on FPGA based sensor systems: Towards intelligent and reconfigurable low power sensors for computer vision, control and signal processing,* Sensors, Vol. 14, No. 4, 2014, pp. 6247-6278.

[24] S. Anumalla, B. Ramamurthy, D. C. Gosselin and M. Burbach, *Ground water monitoring using smart sensors,* in Proc. of IEEE Int. Conf. on Electro Inf. Tech., pp. 1-6, May 2005.

[25] S. -C. Hsia, S. -W. Hsu and Y. -J. Chang, *Remote monitoring and smart sensing for water meter system and leakage detection,* IET Wireless Sensor Syst., Vol. 2, No. 4, Dec. 2012, pp. 402-408.

[26] V. Rosello, J. Portilla and T. Riesgo, *Ultra low power FPGA-based architecture for wake-up radio in wireless sensor networks,* in Proc. of 37th Annual Conf. on IEEE Industrial Electronics Society (IECON), pp. 3826-3831, Nov. 2011.

[27] O. Postolache, P. S. Girão, J. M. Dias Pereira and H. Ramos, *Water quality sensors calibration system based on reconfigurable FPGA technology,* in Proc. of XVIII IMEKO World Congress, pp. 1-5, Sept. 2006.

[28] O. Postolache, J. M. D. Pereira and P. Silva Girão, *Real-time sensing channel modelling based on an FPGA and real-time controller,* in Proc. of Instrument and Measurement Technology Conference (IMTC), pp.557-562, April 2006.

[29] H. M. G. Madureira, J. E. G. de Medeiros, J. C. da Costa and G. S. Beserra, *System-level power consumption modeling of a SoC for WSN applications,* in Proc. of 2nd IEEE Int. Conf. on Networked Embedded Systems for Enterprise Applications (NESEA), pp. 1-6, Dec. 2011.

[30] C. C. Enz, A. El-Hoiydi, J. -D. Decotignie and V. Peiris, *WiseNET: An Ultra low-power Wireless Sensor Network Solution,* IEEE Computer, Vol. 37, No. 8, Aug. 2004, pp. 62-70.

[31] B. W. Cook, S. Lanzisera and K. S. J. Pister, *SoC Issues for RF Smart Dust,* Proc. of the IEEE, Vol. 94, No. 6, Jun. 2006, pp. 1177-1196.

[32] F. Regan, A. Lawlor, B. O. Flynn, J. Torres, R. M. -Catala, C. O'Mathuna and J. Wallace, *A demonstration of wireless sensing for long term monitoring of water quality,* in Proc. of Int. Conf. on Local Computer Networks (LCN), pp. 819-825, Oct. 2009.

[33] M. D. Hempstead, Accelerator-Based Architectures for Wireless Sensor Network Applications, Ph.D. Thesis, Harvard University, Cambridge, Massachusetts, May 2009.