High-performance Wireless Sensor Node Design for Water Pipeline Monitoring

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***Abstract*—Water utilities owners are facing critical challenges in repairing and maintaining pipeline infrastructure. Leakages in water pipeline infrastructure cost millions of dollars every year. The need for a reliable, continuous and efficient system for pipeline monitoring becomes crucial. Wireless Sensor Network (WSN) is a very promising technology to detect leaks in an autonomous way. In this paper, we present a WSN system for water pipeline monitoring. A wireless sensor node based on Zynq System on Chip is developed and simulated. A leak detection algorithm based on Kalman filter is also implemented and accelerated using the Zynq platform. The experimental results show that the usage of high-performance platforms is suitable only if the power management techniques are employed or for video applications.**

Keywords–Wireless sensor network; Water pipeline monitoring; Leak detection; node design; Zynq platform; Kalman Filter.

I. Introduction

With the rapid evolution of embedded systems, Wireless Sensor Networks (WSNs) have invaded our daily life in the last years. One of the most important applications of WSNs is Water Pipeline Monitoring (WPM). In fact, a large amount of water is wasted daily due to leakages in pipelines. This is aggravated by the lack of automatic systems [1]. Hence, WSN could play a primordial role in such application by decreasing the human intervention and providing continuous monitoring. WSN is composed of a large number of nodes that are widely deployed to inspect physical phenomena (pipeline leakages in our case) in a cooperative way.

The node, which is the main component of the network, integrates four units: sensing unit, treatment unit, communication unit and power unit [2]. The node is generally powered by a battery, which makes the node power considered as a major constraint. The main goal of the node design is to preserve energy consumption and extend the lifetime of the battery. Therefore, the majority of nodes used for WSN are based in general on ”limited resources” microcontrollers (MCUs), which make some processing tasks difficult or impossible in some cases [3].

An investigation on high-performance platforms becomes essential. In that line, we aim in this paper to design a robust WPM system using WSN. For this purpose, we propose a leak detection algorithm using a modified Kalman filter (KF) for accurate inspection. Moreover, we suggest a wireless sensor node platform based on a high-performance Zync system on chip (SoC).

The paper is organized as follows: In section II, we review the leak detection methods existing in the literature. Section III also reviews the WSN node platforms used for WPM from MCUs to FPGAs (Field-Programmable Gate Array). In section IV, we detail our proposal in terms of leak detection algorithm and wireless sensor node platform. Section V shows and discusses the experimental results. We finish this work with conclusion and perspectives in section VI.

II. Leak Detection Methods

Pipeline infrastructure could be threaten by several factors. This, in fact, affects the fresh water quality in pipes. It begets also economical losses and countless damages such as leaks, obstruction, corrosion, etc [4]. In this context, preserving the pipeline infrastructure is crucial. This could be accomplished by using and automating pipeline inspection. In this work, we are interested in leak detection methods.

Plenty of leak detection techniques exist in the literature [5]. These methods depend on the instrument used or the inspected physical parameter. The shared principle of these techniques is the exploitation of the pipeline material’s physical properties and/or the water flow’s characteristics to detect damages and abnormalities. From these methods, we could cite:

A. Visual Inspection Techniques

These methods are the oldest ones that employ video or image sensors to inspect leaks in pipes. Depending on the instrument used for inspection, many techniques are proposed for this method like the laser scan and the Closed-Circuit Television (CCTV) inspection [4]. The CCTV technique is composed of a robot with a camera traveling inside the pipe to inspect the pipe. We should mention that the visual methods are not based on the same idea. Laser scan technique employs laser and could be used inside or outside the pipeline. Pulse-based, phase-based and triangulation are techniques based on scanning [4]. Visual inspection techniques are used in WSNs by attaching Charge-Coupled Device (CCD) or CMOS image sensors to the computing unit in the sensor node. The captured images and/or videos are streamed to the base station for analysis [6].

B. Acoustic Techniques

Several acoustic techniques exist for leak detection. These techniques are widely used, especially for small leaks. They are

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non-destructive. In WSN, some sensors are used such as hydrophones, piezoelectric sensor, accelerometers and vibration sensor and deployed inside and/or outside the pipeline. The principle of this technique is the detection of acoustic waves or noise caused by escaped liquid when a leak occurs. This escaped liquid flows turbulently and causes acoustic signals [7]. For instance, the authors in [8] propose a leak detection method for pressurized pipeline using acoustic emissions. Another work [9] exploits acoustic signals to inspect leaks in underground pipes. The authors in [10] tested the feasibility of acoustic emission for pressurized pipe using R15a acoustic sensor. The acoustic signals are very weak and operate in noisy environments. Almost all the time, the distinction of these signals is very difficult. Pre-amplifiers as well as filters are required to avoid noise. This technique is not very adequate for underground pipes due to the deployment difficulties [11].

C. Ultrasound Techniques

The ultrasound techniques are based on ultrasound waves detection. These waves are in general of mechanical vibrations. They propagate along the pipe and are reflected then. This allows leaks detection and measuring pipeline wall thickness. The ultrasonic sensors could be used inside or outside the pipe. Many ultrasound techniques exist, such as discrete ultrasound, immersion testing, straight beam, phased array, etc [12]. The guided wave technique could be defined as ultrasound wave traveling in delimited pipes. For this reason, this technique is widely used for an economical and easy inspection [13]. The authors in [14] prove the effectiveness of ultrasonic guided waves for high temperature pipes. Jeffrey et al. propose a pipeline monitoring system that exploits ultrasound guided waves for corrosion detection. The sensors are placed outside of pipeline [15]. Another work suggests a modular WSN system to monitor the pipeline wall thickness using the ultrasound method [16]. Despite the effectiveness of the ultrasound techniques, they should be employed jointly with other technique to enhance the accuracy of the detection and avoid false alarms. Moreover, these techniques suffer from high power consumption.

D. Electromagnetic Techniques

The electromagnetic methods are based on the principle of measuring variations in the electrical properties of a subsurface. From the electromagnetic methods used for leak detection in water pipelines, we could mention: Ground-penetrating radar (GPR), Magnetic flux leakage (MFL), Ultra-wideband (UWB) pulsed radar system (P-Scan) [4].

E. Computational Pipeline Monitoring (CPM) Techniques

CPM methods exploit internal pipeline parameters like pressure, flow, temperature with algorithmic tools to monitor and detect leaks. The data is collected using pressure sensors or other sensors and then analyzed mathematically or statistically to provide an alarm. From the CPM techniques, we can cite the Mass Balance and the Real Time Transient Modelling (RTTM) [17]. The Mass Balance method is based on mass conservation. The leak in such method is detected when the difference between the upstream and the downstream flow exceeds a given threshold. Although this method is simple, cost effective and easy, it suffers from false detection [18]. RTTM analyzes the pipeline hydraulic behavior to predict the existence of leaks. It is based on the resolution of momentum calculations and numerous flow equations to detect and also localize leaks. The main drawback of this method is the computational complexity [19].

CPM methods are exploited in WSN. The use of WSN enhances the accuracy and the autonomy of such system. WSN is considered as a hybrid method that combines different kinds of sensors and algorithms to get precise, easy and early information about the leak. From the WSN projects, PipeNet [20] is a well-known project that adopts acoustic, pressure and vibration sensors for leak detection and localization. The sensor node is based on Intel mote. MISE-PIPE [21] employs soil properties, pressure and acoustic sensors. Furthermore, SmartPipe [22] uses soil properties and pressure sensors for underground pipeline inspection and monitoring. These two methods are coupled to improve the system accuracy. WSN seems a promising leak detection and localization tool. It enhances the performance by improving algorithms or combining methods by using more than one kind of sensors. However, there is no attention given to architecture of nodes [3]. Almost all WSN platforms for pipeline monitoring are based on simple MCUs. In the following, node platforms used for WPM are presented.

III. WSN Node Platforms for Water Pipeline Monitoring

Some researches on pipeline monitoring focus on improving the leak detection techniques. Others are working on the placement and replacement of nodes while some others try to improve the network communication especially for underground pipelines. Insignificant interest is devoted to the nodes architecture and design. A typical WSN node consists mainly of a processor, a radio transceiver, memories, an antenna, sensors and a battery. Commercial motes based on MCUs are the most used in WPM applications. Other technologies and platforms are not widely investigated. Few works describing alternatives to MCUs such as DSPs, ASICs (Application-specific integrated circuit) and FPGAs for WPM are presented.

A. Nodes based on MCU

MCU is an integrated circuit that includes a microprocessor, memories and input/output peripherals. It is characterized by its low cost and its low power consumption. For this reason, it is exploited in many WSN projects like [3][20][21][23][22], etc. In fact, advances in MCU technology allow easy and low cost implementations. It permits also data processing. The MCU allows also to manage the communication and the power consumption of the node. Various WSN projects that employ MCUs exist in the literature [24].

For example, PipeNet [20] is a WPM project that allows leaks detection and localization. Many signal processing algorithms have been implemented such as WT, cross-correlation algorithm, pattern recognition algorithms and other algorithms. The sensor node is based on Intel mote, which consists of an ARM7 core, a 64KB RAM, a 512 KB Flash, and a Bluetooth communication.

PipeProbe [25] is designed for pipeline monitoring. The PipeProbe node has a hydro molecule form. It consists of a EcoMote and a MS5541C pressure sensor, nRF24E1 transceiver, an antenna, a 32 KB external EEPROM, a flex-PCB expansion port and a battery.

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SPAMMS [6] is another WSN system for WPM. It is an autonomous and cost effective system for leak control, localization and maintenance of the pipeline by using static and mobile sensors and a robot. Different kinds of sensors are used like CCD, chemical, pressure and sonar sensors. This high number of sensors leads to high processing requirements. The sensor node is composed of MiCA1 mote (mobile sensor), an EM4001 ISO RFID system and a robot agent. Mica1 is a mote that contains a ATMega103 MCU, a 4 Kb of RAM, a 512 Kb of EEPROM and a 128 Kb of Flash memory.

SmartPipe [22] is also a WSN for underground pipeline monitoring. It is a non-invasive solution that employs force sensitive resistor sensors and sol proprieties sensors. The sensor node contains a PIC16LF1827 MCU, an eRA400TRS radio transceiver, two temperature sensors and one FSR based pressure sensor.

Another work, TriopusNet [23] is a mobile WSN for pipeline monitoring. The node encompasses a Kmote, a spherical case, a motor, a MS5541C pressure sensor and gyro-scope sensor. The Kmote is composed of a MSP430 MCU and a CC2420 transceiver. This work aims to automatically place or replace failed nodes using a replacement algorithm.

MCUs are widely exploited in WPM application thanks to their low cost, their low power and their flexibility. However, they have some drawbacks such as the limited processing capabilities and the small memory size. Other alternatives to MCUs are cited in this paper.

B. Sensor nodes based on DSP

General purpose processors are not usually adequate for some specific applications like Fourier transforms, filtering, signal processing and image processing algorithms. The DSP (Digital Signal Processor) is a microprocessor optimized for real time digital signal processing applications. It allows high speed streaming and processing data thanks to its specific architecture comparing MCUs. Despite the advantages of DSPs, only few implementations are dedicated for WSN-WPM application. For instance, the authors in [26] suggest an implementation on DSP of a leak detection algorithm based on FFT correlation of sound sensor data for underground pipeline monitoring. Zhang et al. employ a DSP to process acoustic signals with correlation function for leak detection [27].

DSPs are efficient for signal processing algorithms. However, they are power consuming processors. That is why, they are not largely used for WSN-WPM application.

C. Sensor Nodes based on FPGA/ASIC

ASIC/FPGA technologies are not broadly used for node design in monitoring applications. To the best of our knowledge, few works use FPGA or ASIC directly or indirectly. The sensor node, suggested in [20], is composed of a OEM piezoresistive silicon sensor. This sensor includes an ASIC compensation-based technology, which allows to achieve an accuracy better than 0.2%. FPGA is used, in general, as prototyping platform to achieve faster calculation of complex applications. It offers hardware and software high speed and flexibility. Moreover, the price and the performance is more favorable than an ASIC [28]. It permits also system reconfiguration after a field deployment [29]. For instance, the authors in [27] propose a FPGA system for data acquisition. This FPGA is employed as co-processor with a DSP for leak detection and localization using acoustic sensors. The system is composed of a FPGA, DSP, acoustic sensors, a LCD, a wireless module and an ADC. Another work suggests a leak detection method based on magnetic flux for pipeline inspection. The node prototype is implemented on Altera Cyclone FPGA [30].

The design of a sensor node based on ASIC or FPGA for the WPM application could offer an efficient and a flexible system. However, it can also result in high power consumption. Hence, saving energy and power consumption is a crucial issue for WSN nodes design. Moreover, many challenges should be satisfied for WSN-WPM. In fact, it is crucial to find a trade-off between the energy, the performance, the small size, the low cost, the time-to-market and the security [31]. For this purpose, we aim to design an efficient sensor node using a high performance platform and a reliable algorithm.

IV. Proposed Leak Detection System using WSN

WSNs face several challenges in WPM applications [32] in terms of reliable inspection, external analyses, a non-real time processing and high false alarm rates. Therefore, a novel WSN system that gets over the limitation of this technique and enhances the performance of the sensor node is essential. For this purpose, a novel KF leak detection method has been implemented and accelerated using Zynq platform.

A. Leak detection algorithm

KF is a recursive data processing algorithm proposed by Kalman in 1960 [33]. It is largely explored in WSNs due to its low requirements of memory, its low complexity and its ability to predict data. We implement a modified KF to filter noise and to detect and locate leaks. Various works that use KF exist for WPM application. For example, the authors in [34] suggest a linear KF for detecting leaks using the hydraulic measurements and the linearity of data within one week. The authors in [35] propose an Extended KF for pipeline monitoring. Torres [36] has employed an extended KF and a set of observers to detect and locate leaks in water pipes. To the best of our knowledge, this work is the first that explores KF for WSN and WPM at the same time. Our approach is applied to long distance above ground pressurized pipelines. We detail briefly the algorithm steps [33]. The KF is based on two steps: the prediction and the correction. In the first step, the estimated state x, which is a vector of the pressure and the flow in this case, at time k is elaborated from the updated state at k-1. In the first step, the prediction of the current state and the covariance matrix is given by:

$$\hat{x}_k^- = A.\hat{x}_{k-1} + B.u_k \tag{1}$$

where A is the transition matrix, B is the transition matrix of inputs; u_k is the input vector;

$$P_k^- = A.P_{k-1}.A^T + Q_k \tag{2}$$

The second step is the correction step. This step aims to get an improved estimate by incorporating new measurements into the predicted estimate using the Kalman gain (K_k).

$$K_k = P_k^-.H^T.(H.P_k^-.H^T + R_k)^{-1} \tag{3}$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \tag{4}$$

$$P_k = (I - K_k H)P_k^- \tag{5}$$

KF estimates pressure and flow variations caused by leaks using the innovation variation. When the variation exceeds a threshold, this indicates the existence of leaks.

B. Sensor nodes design and SW/HW implementation

After implementing the algorithm, we need to focus on improving the performance of the node. We should mention again that little interest is given to the sensor node architecture in WPM applications. For this purpose, testing and evaluating a high performance platform is essential. A high-performance sensor node allows in-node processing, real time and quick response. It provides also satisfaction of the application's requirements. It decreases the human intervention and facilitates pipeline monitoring.

1) Node design and implementation: A SoC technology has been chosen for this work. It is an innovative platform that allows to perform complex computational tasks, to reuse Intellectual Properties (IPs) and to miniaturize devices by integrating the greater part of the components in a single chip [1]. In this context, we implement a SoC using Zybo board.

This board is built around the Xilinx Zynq-7000 family; the Z-7010. The Z-7010 incorporates a dual core ARM Cortex-A9 processor and Xilinx programmable logic equivalent to Artix-7 FPGA in a single device. It includes also a DDR3 memory controller with 8 DMA channels, an Advanced Microcontroller Bus Architecture (AMBA) Interconnect and I/O peripherals (USB (Universal Serial Bus), SPI (Serial Peripheral Interface), UART(Universal Asynchronous Receiver Transmitter), I2C(Inter-Integrated Circuit), etc). The Programmable logic block consists of 4,400 logic slices, 240 KB of block RAM, 80 DSP slices, Internal clock speeds exceeding 450MHz, analog-to-digital converter (XADC), etc. The first basic built architecture contains the ARM Cortex-A9 processor, an AXI GPIO, a memory controller and the AXI interconnect, as shown in Figure 1.

2) Leak Detection Algorithm Implementation: The application detailed in the subsection IV-A is implemented in C. We introduce also a new function Prodmatrix, which affects the matrix multiplication. Hence, the steps of the algorithm will include the following function:

- Xestimate, Pestimate and Prodmatrix for the prediction step.
- KGain, Xupdate, Pupdate and Prodmatrix for the correction step.
- other code for the leak calculation.

The application and the hardware are performed using Vivado 14.4 and the Software Development Kit (SDK) provided by Xilinx. In fact, after generating the bit stream of the design, the project is exported in the SDK to run the leak detection algorithm and to program the board. SDK offers also the possibility of application profiling as it integrates the GNU gprof. The GNU gprof is composed of the gcc compiler and the gprof. In fact, profiling allows the application's performance analysis. The goal of this task is to select the complex function (in the algorithm), which is the most time consuming for hardware implementation. This part is very important since it requires a careful selection of the right function needed to be transformed into a hardware accelerator to speed up the application and to enhance the performance of the system. However, this is not always possible as it depends on many other parameters. Hence, a compromise between time, energy and area is crucial. Profiling has provided us statistics about the execution time and the number of calls. After profiling the leak detection algorithm a gmon.out file is generated.

Table I gives the execution time of each function in the leak detection algorithm for one iteration. The Prodmatrix is the most time consuming function in the algorithm. It is characterized also by a high number of call. Thus, we choose to implement it into hardware.

TABLE I. Execution Time of the Algorithm functions

Function	Cycles	Time
Xestimate	159	0.35
Pestimate	860	0.75
Xupdate	180	0.5
Pupdate	566	1.25
KGain	249	0.75
Prodmatrix	522	1.75

C. Hardware Accelerator Implementation

Hardware acceleration is used to make some tasks more efficient than in software implementation and to speed up the execution time of the system. Two methods are adopted to implement the Prodmatrix hardware module: with Vivado High-Level Synthesis (HLS) and manually. Vivado HLS is a tool provided by Xilinx to accelerate the creation of IPs. It allows to rapidly transform a C code to a RTL description. It permits also resource allocation and partitioning and IP module generation. We have used also Pragma directives to optimize the hardware IP like INTERFACE directive, as shown in Figure 4.

The hardware accelerator aims to speed up the execution time by transforming a software function or algorithm executed by the processor into a hardware block attached in our case to the "AXI-lite" bus. In this step, the choice of the connection mode and the register number is necessary. The register number depends on the Input/Output number of the accelerator. Then, the Prodmatrix hardware accelerator appears in the IP catalog to be integrated with the architecture, as shown in Figure 2. The bitstream is then generated and exported to the SDK to test the accelerator results. After that, we implement the all KF into a hardware block, as given in Figure 3.

The two accelerators are generated manually (VHDL programming) and with Vivado HLS. The different results of the implementations will be detailed in the next section.

V. Results and discussion

In this section, we compare the results to decide the best architectural design selection. The metrics that we have used are time, power and space. As explained before, the Zybo board is used to perform the previous implementations. All the results are given for one iteration.

A. Execution Time

The execution time is essential to test the efficiency of the application. It influences also the power consumption of the node. It is evaluated using profiling technique in the all cases,

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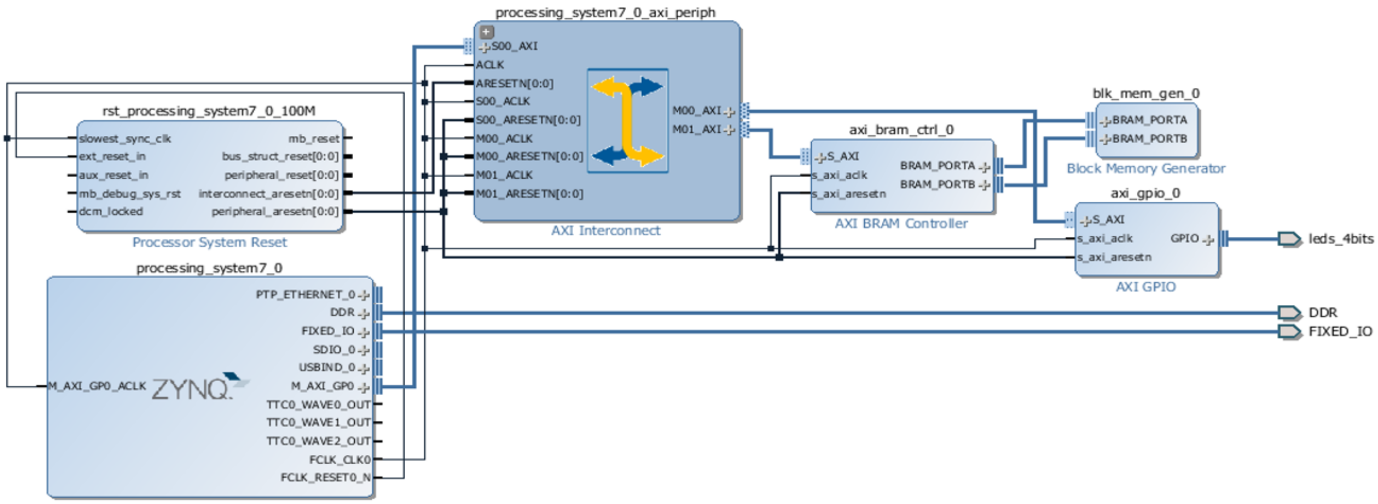

Figure 1. Proposed Sensor Node Implementation

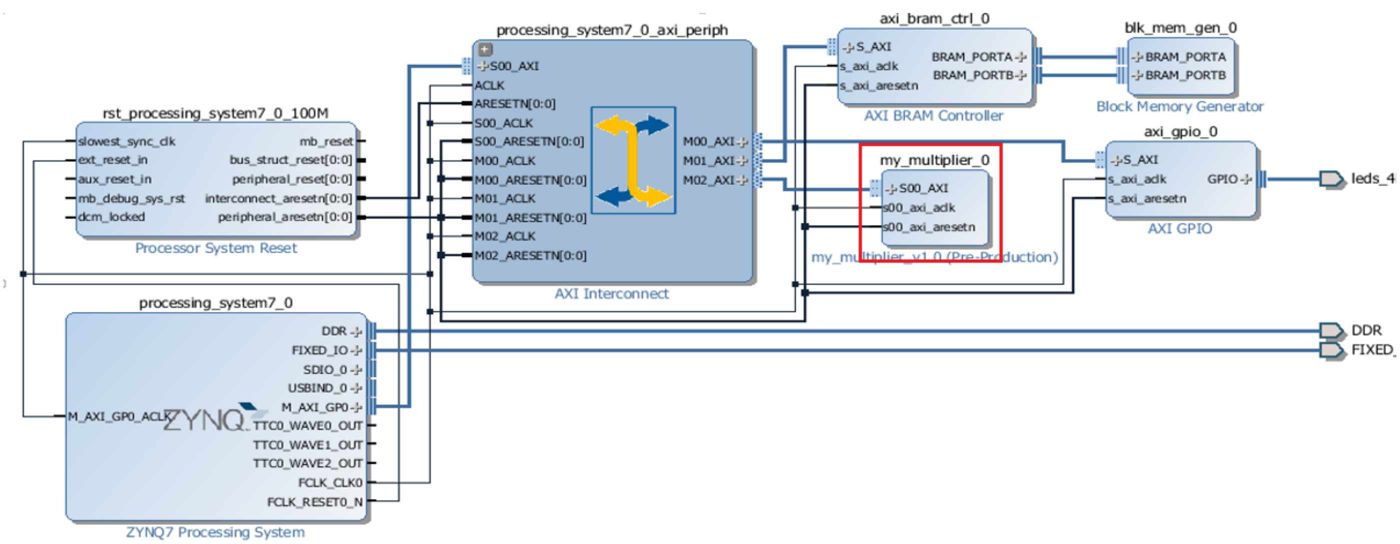

Figure 2. Hardware Acceleration and Integration of the Prodmatrix

```
double kalman_filter(double A[2][2],double H[1][2],double R,
{
#pragma HLS INTERFACE s_axilite port=return bundle=CTRL_BUS
#pragma HLS INTERFACE s_axilite port=innova bundle=CTRL_BUS
#pragma HLS INTERFACE bram port=HH
#pragma HLS INTERFACE bram port=AA
#pragma HLS INTERFACE bram port=id
#pragma HLS INTERFACE bram port=X_estimat
#pragma HLS INTERFACE bram port=X_updat
#pragma HLS INTERFACE bram port=P_estimate
#pragma HLS INTERFACE bram port=P_update
#pragma HLS INTERFACE s_axilite port=e bundle=CTRL_BUS
#pragma HLS INTERFACE bram port=Q
#pragma HLS INTERFACE s_axilite port=R bundle=CTRL_BUS
#pragma HLS INTERFACE bram port=H
#pragma HLS INTERFACE bram port=A
```

Figure 4. Pragma directives

as shown in the Figure 5. In the software implementation, the execution time is very low compared to the hardware accelerator, which is slightly abnormal. However, this could be explained by the high frequency of the processor and the difference of frequencies between the processor and the FPGA. Another reason is the usage of AXI-lite. The AXI4-Stream could maybe enhance the results.

B. Resource Utilization

Resources utilization is an important metric in SoC design. In fact, optimal resources allow optimal area, which could save energy and miniaturize node platform. We present the resources of all five implementations. Table II shows the different area occupancy including the look up tables (LUTs), Random Access Memory blocks (BRAMs), Flip Flops (FF) and Digital Signal Processing (DSP) blocks in the programmable device. These values are calculated using Vivado tool. The implementations of Vivado HLS are not optimal, a lot of resources are used. These implementations exploit DSP blocks more than other implementations.

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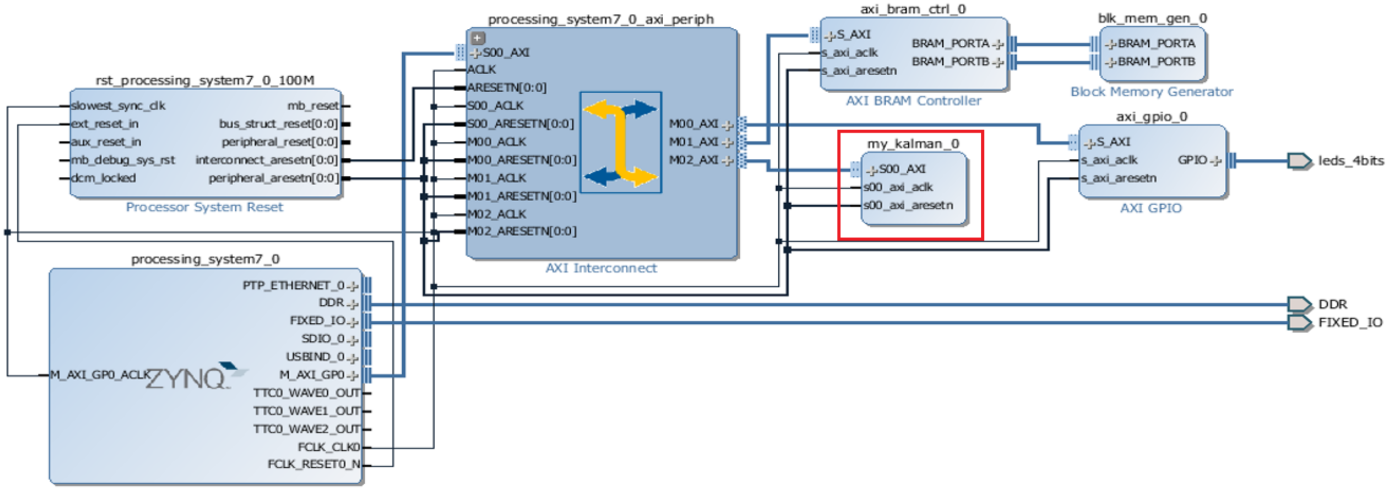

Figure 3. Hardware Acceleration and Integration of the KF

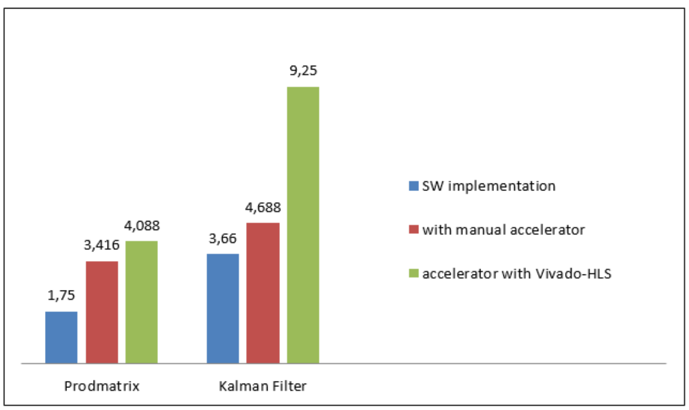

Figure 5. Execution Time of different implementations (μs)

TABLE II. Resource utilization (%)

Resources	SW	Prodmatrix		Kalman Filter	
		M	Vivado HLS	M	Vivado HLS
LUT	8.4	13.84	16.33	17.9	72.99
BRAM	26.67	3.3	10	3.33	50
FF	14.78	7.32	9.05	9.01	40.47
DSP48	0	10	17.5	0	62.5

C. Power Consumption

The power consumption of the node is a crucial criterion. In this work, we measured the power consumption of the five architectures using Vivado power report. This report details the static and the dynamic powers related to intrinsic leakage, design, inputs data patterns, etc. The total on-chip power for the software implementation was 1.484 W while the power of the Prodmatrix HW accelerator is 1.487 W for the manual implementation and 1.485 W for the Vivado HLS implementation. KF HW accelerator has as power consumption 1.726 W with manual implementation and about 2 W for the Vivado HLS implementation. As we remark, the power consumption is very high in all implementations. This again is related to the high frequency and performance of the cortex-A9 processor.

VI. Conclusion

We have detailed in this paper a WSN node platform design for water pipeline monitoring. A leak detection algorithm based on KF is implemented and accelerated using Zybo board. Five designs have been implemented for the node and compared using Xilinx Electronic Design Automation tools. The evaluation is based on three metrics: the execution time, the resource utilization, and the power consumption.

The results were not promising. This is due to several factors. First of all, the frequency of the processor is very high. In general, a high frequency processor will result in a high power dissipation. Moreover, the difference of frequency between the processor (650Mhz) and the programmable logic block (450Mhz) may decrease the performance of the accelerators and the communication between these two components. Furthermore, the usage of AXI-lite was also not very promising. In fact, this bus is characterized by its small logic footprint, a light-weight and single transaction memory mapped interface. We note also that the built accelerator using Vivado HLS is not optimized compared to the manual accelerator.

As future work, to reduce the power consumption of the node, many techniques should be implemented. On one hand, we could adjust the frequency of the processor and decrease it to meet the frequency of the FPGA and to save power. Moreover, the AXI4-Stream with the usage of a Direct Memory Access (DMA) may enhance the performance and accelerated the data reading. In fact, the AXI4-Stream offers a high-speed streaming data. On the other hand, the usage of power management techniques like wake up receiver, dynamic voltage and frequency scaling will be explored in the future. Finally, other processors with moderate frequency and features like ARM cortex M3 will be investigated.

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