A High-Performance Wireless Sensor Network Platform Design for Water Pipeline Monitoring

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Abstract
Water utilities owners are facing critical challenges in repairing and maintaining cost of pipeline infrastructure. Leakages in water pipelines cost millions of dollars every year. The need of reliable, continuous and efficient system for pipeline monitoring becomes crucial. WSN is a very promising technology to overcome the pipeline leak detection in an autonomous way. We present in this paper, a WSN system for water pipeline monitoring. A wireless sensor node based on Zynq SoC 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.

1. Introduction

With the rapid evolution of the embedded systems, Wireless Sensor Network (WSN) has emerged our daily life in last years. One of the most important applications of WSN is the Water Pipeline Monitoring (WPM). In fact, large amount of water is daily wasted due to leakages in pipelines. This is boosted 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 and cooperate to inspect physical phenomena (pipeline leakages in our case). 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 in the node design is to preserve energy consumption and enlarge the lifetime of the battery. That is why, almost of the node 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 a high performance platforms becomes essential. Hence, 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 a high-performance Zync system on chip (SoC). The paper is organized as follows: In section II, we reviews the leak detection methods existing in the literature. Section III reviews also the WSN node platforms used for WPM from MCUs to FPGAs. In section IV, we details our proposal in term 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.

2. 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 essential and crucial. This could be accomplished by using and automating pipeline inspection. In this work, we are interested on leak detection methods. Plenty of leak detection techniques exist in the literature [5]. These methods depends 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

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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]. This technique is 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 non-destructive. In WSN, some sensors are used like hy-drophones, piezoelectric sensor, accelerometers and vibration sensor and deployed inside and/or outside the pipeline. The principal 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 an 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. In almost of 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 purpose, 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. pro-pose 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 alarm. Moreover, these techniques suffer from high power consumption.

D. Electromagnetic Techniques

The electromagnetic methods are based on the principal of measuring variations in the electrical properties of a subsur-face. 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 CPMs, we could cite the Mass Balance and the Real Time Transient Modelling (RTTM) [17]. Mass Balance method is based on mass conservation. The leak in such method is detected when the difference between the upstream and the down stream flow exceed a given threshold. Although this method is simple, cost effective and easy, it suffers from false detection [18]. RTTM analyzes the the pipeline hydraulic behavior to predict the existence of leak. It 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].

These methods are exploited in WSN. The use of WSN enhance the accuracy and the autonomy of such system. WSN is considered as a hybrid method that combines different kind 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] em-ploys soil property, pressure and acoustic sensors. furthermore, SmartPipe [22] uses soil property 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 en-hances 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 of WSN platforms for pipeline monitoring are based on simple MCUs. In the following, node platforms used for WPM are presented.

3. WSN Node Platforms for Water Pipeline Monitoring

The research for pipeline monitoring focuses on improv-ing the leak detection techniques. Some other works were working the placement and replacement of nodes while some others try to improve the network communication specially for underground pipelines. Insignificant interest is consecrated to the nodes architecture and design. A typical WSN node consists mainly of a processor, a radio transceiver, a memories, an antenna, sensors and a battery as shown in figure 1. 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 and FPGAs for WPM are presented.

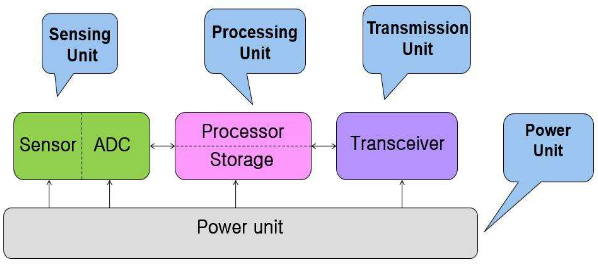


Figure 1. A typical architecture of a sensor node

A. Nodes based on MCU

MCU is an integrated circuit that includes a microproces-sor, memories and input/output peripherals. It is characterized by its low cost and low power consumption. For this reason, it is exploited in many WSN projects like in [20], [23], [22], [3], [21], etc. In fact, advances in MCU technology allows easy software implementations and with low cost. It permits data processing. These data are collected by sensors to make decision about the leak existence. The MCU allows also to manage the communication and the power consumption of the node. Many WSN projects that employ MCUs exist in the literature [24]. For example, PipeNet [20] is a WPM project that allows leak detection and localization. It permits also other complex problems in the pipeline infrastructure. Many signal processing algorithms have been implemented such as WT, cross-correlation function, 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. Another work named, PipeProbe [25] is designed for pipeline monitoring. The PipeProbe node has hydro molecule form. It consists of a EcoMote and a MS5541C pressure sensor, nRF24E1 transceiver, an antenna, a 32KB external EEPROM, a flex-PCB expansion port and a battery. 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 kind of sensors are used like CCD, chemical, pressure and sonar sensors. These large amount of sensors will lead 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 4Kb of RAM, a 512Kb of EEPROM and a 128Kb 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 propriety 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 the automatically place or replace failed nodes using a replacement algorithm.

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

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 is a microprocessor optimized for real time digital signal process-ing applications. It allows high speed streaming and processing data thanks to its specific architecture comparing to 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 de-sign 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 and to achieve faster calculation of complex applications. It offers hardware and software high speed and flexibility. Moreover, the ratio of price and performance is more favorable than ASICs [28]. It also permits system reconfiguration after field deployment [29]. For instance, the authors in [27] propose a FPGA system for data acquisition. This FPGA is employed as Coprocessor 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].

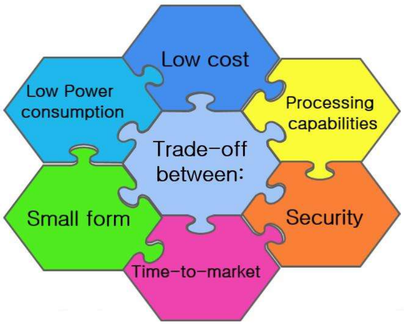


Figure 2. Node design challenges

The design of ASIC or FPGA-based sensor node for the WPM application could offer an efficient and flexible system. However, it could result also high power consumption. Hence, saving energy and power consumption is a crucial issue for WSN nodes design. Moreover, many challenges are also needed for WSN-WPM. From these challenges, it is crucial to find a trade-off between energy, performance, small size, low cost, time-to-market and security [31] (figure 2). For this purpose, we aim to design a high performance sensor node using high performance platform and reliable algorithm.

4. Proposed Leak Detection System using WSN

WSN faces several challenges in WPM applications [32] in terms of reliable inspection, external analyses, a non-real time processing and a high false alarm rate. Therefore, a novel WSN system that enhances the limitation of this technique and 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, low complexity and its ability to predict data. We implement a modified KF to filter noise and to detect and locate leaks. Many works that use KF exist for WPM application. For example, the authors in [34] suggest a linear KF for detecting leaks using hydraulic measurements and linearity of data within one week. The authors in [35] propose an Extended KF for pipeline monitoring. After several years, Torres [36] has used 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 explore KF for WSN and WPM in the same time. Our work is dedicated for long distance above ground pressurized pipelines. We detail briefly the algorithm steps. The KF is based on two steps:the prediction and the correction. In the first step, the estimated state x, which is 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 covariance matrix is given by:

$$X_p(\mathrm{k}) = \mathrm{AX}(\mathrm{k}-1) + \mathrm{BU}(\mathrm{k}) + \tag{1}$$

where A is the transition matrix, B is transition matrix of inputs; $U_{(k)}$ is the input vector;

$$P_P(\mathrm{k}) = \mathrm{AP}(\mathrm{k}-1)A^T + \mathrm{Q}(\mathrm{k}) \tag{2}$$

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

$$K = \frac{P_P(k)H^T}{HP_p(k)H^T + R} \tag{3}$$

$$\mathrm{X}(\mathrm{k}) = X_P(k) + K(\mathrm{Z}(\mathrm{k}) - \mathrm{H}X_P(k)) \tag{4}$$

$$\mathrm{P}(\mathrm{k}) = (\mathrm{I} - \mathrm{KH})P_P(k) \tag{5}$$

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

B. Sensor nodes design and SW/HW implementation

After designing our software and as described on section 3, it is essential to design our node to improve the performance of the all solution. We should re-mention that a few interest is given to the sensor node architecture in WPM application. For this purpose, testing and evaluating high performance platform is essential. A high-performance sensor node allows real time processing, in-node processing and quick response. It permits also to satisfy all the application requirements. It decrease the human intervention and facilitate 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 almost of the components in a single chip [1]. In this context, we implement a SoC using Zybo board 3. 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, SPI, UART, I2C, 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 4.

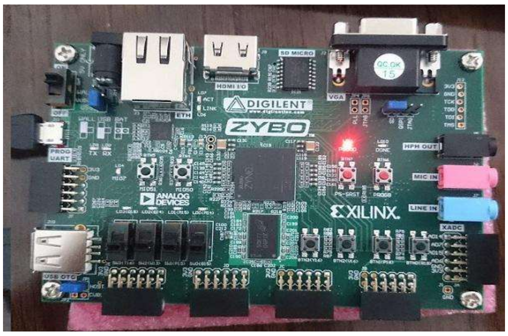


Figure 3. Zybo board

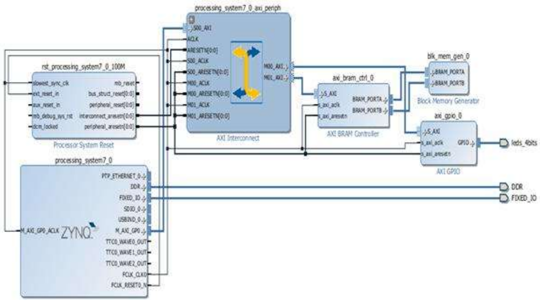


Figure 4. Proposed Sensor Node Implementation

2) Leak Detection Algorithm Implementation: The appli-cation detailed in section 4 is implemented in C. We introduce also a new function Prodmatrix which effects the matrix multiplication. Hence, the steps of algorithm will include the following function:

Xestimate, Pestimate and Prodmatrix for the predic-tion 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 need a careful selection of the right candidate for hardware acceleration to speed up the application and enhance the performance of the system. However, this not always possible as it depends on many other parameters. Hence, a compromise between time, energy and area is very crucial. Profiling has provided us statistics about the execution time and the number of calls. After ofiling the leak detection algorithm a gmon.out file is generated. The 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. 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

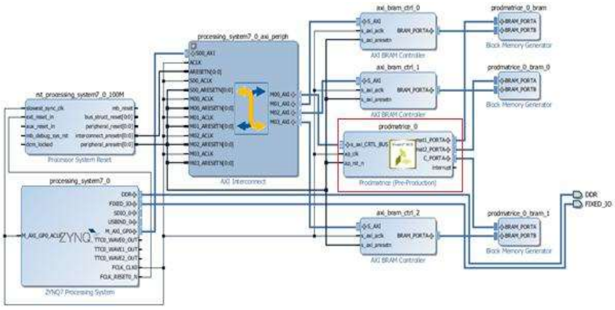


Figure 5. Hardware Acceleration and Integration of the Prodmatrix

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 7. 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. After this, the Prodmatrix hardware accelerator appears in the IP catalog to be integrated to the architecture as show in Figure 5. The bitstream is then generated and exported to the SDK

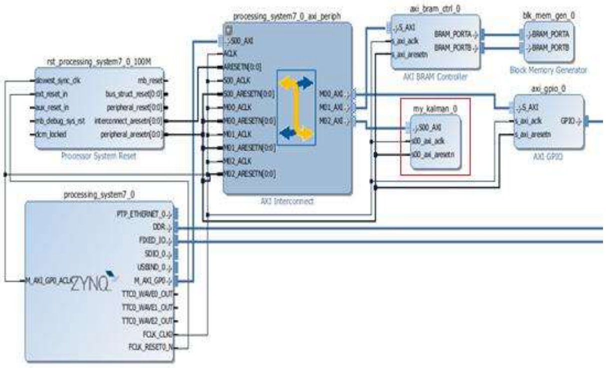
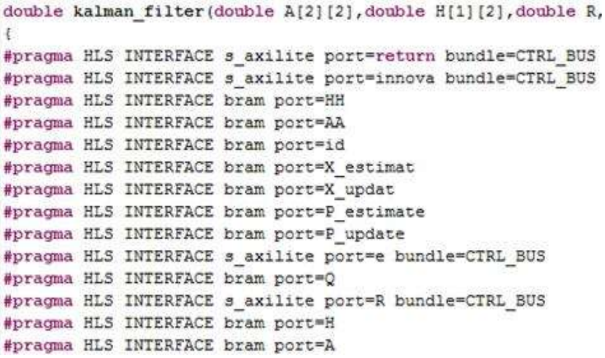


Figure 6. Hardware Acceleration and Integration of the KF



```
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 7. Pragma directives

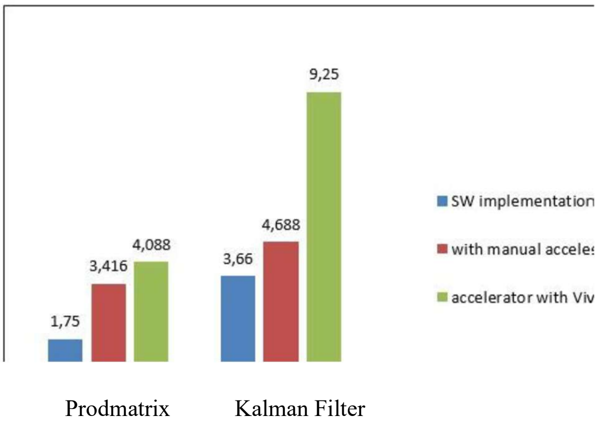


Figure 8. Execution Time of different implementations results

4. Results and Discussion

In this Section, we compare the results to help us 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 implementation.

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

B. Resource Utilization

The Resources utilization is an important metric in SoC design. In fact, optimal resources allows optimal area which could save energy and miniaturize node platform. We present the resources of the 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 pro-grammable 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 the DSP blocks more than other implementations.

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 implemen-tation. 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.

5. 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 due to the high frequency of the processor. Moreover, the difference of frequency between the processor and the programmable logic block may speed down the performance of the accelerators and the communication between these two components. The usage of AXI-lite was not also very promising.

Hence, to reduce the power consumption of the node, many techniques should be implemented in the future. 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 may enhance the performance and accelerated the data reading. On the other hand, the usage of power management techniques like wake up receiver will be explored in the future.

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