FPGA implementation of r-FIFO-based high-speed data acquisition IOT architecture model

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Abstract

To enhance the utilization efficiency of Internet of Things (IoT) and cyber-physical system technologies, more collaboration in data transmission is recommended. These applications receive data from multiple sensors; hence, addition of efficient data acquisition system becomes mandatory. Past research works report use of data sharing among the tasks; however, this is only possible as long as the data meets the time-sensitive requirements of the tasks. To have an efficient communication between the different nodes of the IoT applications, this research work proposes use of reconfigurable first-in, first-out (r-FIFO) design to acquire data. This would not only reduce total sensing time but also the energy consumption, which is a conspicuous concernment in IoT systems for the offline scenarios. This paper first provides an optimal algorithm for FIFO tasks in the offline case, and later the r-FIFO architecture is synthesized on the FPGA board using ZYBO (zynq-7000). Further, the design is being implemented in SCL 180 nm CMOS ASIC technology. Performance measurement is performed by evaluating the frequency, total power, and the energy per bit of the design.

Keywords Internet of things · Data sharing · Algorithms

1 Introduction

With the advent of pervasive computing in 'Industry 4.0' [1, 2], the evolution of myriad Internet of Things (IoT) technologies applications [3, 4] has emerged significantly. In an IoT set-up, a number of sensors as data supplier and a central platform as the coordinator are customarily employed. Multiple applications apply their data requests to the platform. These requests need to be stored before the consent of the sensed data is transmitted through the required platform. These distinct applications require big data acquisition system, analysis and display of global sensor data. For this connectivity of intelligent instruments to evaluate strategic decisions have become inevitable [5]. The incoming data in the existing IoT applications subsist in two categories (1) databases (2) sensing instruments,

viz. sensors and computers. Currently, with different data types, access methods and communication protocols from various data sources, development of IoT set-up to handle this input data becomes immensely complex. With mismatch in communication clock frequencies of various nodes, it is obvious that the set-up may not be able to fully exploit efficiency of sensors, energy, data, etc. This may impact overall efficiency of the system as it is incredible to have a different data format and uniform communication protocol for various instrument manufacturers.

For an IoT set-up design, various research works have been reported. Most of the studies in past have focused on the overall application design [6–8] and communication protocol [9–11] in IoT systems. There is no much research on handling variable big data at different clock frequencies. Tavakoli [12] proposes a data sharing algorithm for

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wireless sensor networks to minimize the complete sampling time. Here, the application used requests the need for discrete sample data at some point intervals, finally this data could be shared via multiple requests. Tavakoli [12] work was further improved by Fang et al. [13] by considering a continuous interval of sampling data by sending continuous sampling requests. In order to reduce the overall sampling time, an offline algorithm was developed. Also the overlapping of the data intervals could be shared by the other vacant requests. Zhao et al. [14] optimized the aggregate of min–max sensing time thus making fairness among the available sensors. Besides, this sufficient research has been made in the data acquisition system by implementing varied types of architectures. Kovac [15] proposed an interface between the general purpose interface bus and virtual instrument technology. This methodology provides comfort to access the available sensing instruments. Qiu et al. [16] proposed a data acquisition algorithm. Dynamic delay characteristics are analysed with the help of this algorithm. But this is appropriate for some specific sensing applications only and is not considerable for myriad data sources. The Open GIS (Geospatial) Consortium (OGC) [17] proposes a method for automatic integration of physical instruments. This is done with the use of Programmable Underwater Connector with Knowledge (PUCK) protocol. Although, many problems are solved with this development, but it also increases the cost of instrument manufactures. Zhu et al. [18] proposed sleep scheduling schemes for network systems to minimize energy consumption. But this work was not able to derive the complete benefit in terms of data sharing in the united/collaborative sensing process. In brief, none of the aforementioned solutions can resolve comprehensively the issues with data acquisition of IoT systems.

This paper focuses on the need of some generic solutions to overcome the frequency mismatch between the different nodes. These nodes in the data transmission work at the different operating frequencies and are further dependent on the application they are employed in. Here, the IoT fog computing architecture is adopted, with three subsets (1) IoT nodes (2) the cloud (3) Gateway layer (WAN-GSM, UMTS, MQTT, LTE, LTE-A; WiFi, Ethernet, Gateway control) [19–21]. The IoT node constitutes a group of sensors data providers that can be designated as a central platform to perform IoT operations. The IoT gateways deployed works as message exchange between IoT nodes and cloud. The solution proposed in this paper uses high-speed data acquisition (HSDA) algorithm for IoT. Along with this a reconfigurable first-in, first-out (r-FIFO) design module is being implemented in the fog layer, keeping energy constraints as the main requisite. The r-FIFO module is further implemented on SCL 180 nm CMOS ASIC technology. This block could be used to stack the sensor

data, and as a result, communication could be done in an efficient manner between the different nodes of the IoT architecture.

In summary, the major contributions of this paper are as follows: (a) *In the IoT application scenario, HSDA parallel data acquisition technique is employed*: Here, the global network of IoT, sensors and actuators are considered to be the main source of data. The massive, time-sensitive and heterogeneous nature of data accounts for myriad real-time challenges in decision-making scenarios. Thus, for any IoT-based management system, the need of HSDA acquisition algorithm becomes requisite. (b) *FPGA implementation of r-FIFO*: The raw events of multiple sensors need to be aligned in time, so as to get high quality results. This growing number of various connected sensor devices makes the energy saving data acquisition process strenuous for any IoT application. Hence, a FIFO interface is proposed to store the multiple data samples, thus relaxing its timing constraints issues. (c) *SCL 180 nm CMOS ASIC technology implementation*: This is done to verify real-time processing of the device that is mandatory, to be designed for various existing and necessary applications. The purpose of this research work is to reduce the development cost and improve the data acquisition efficiency, as data could be measured in the parallel manner with the use of r-FIFO. Rest of the paper is arranged as follows: Sect. 2 provides information about the HSDA and the reconfigurable FIFO design. System architecture for the IoT applications is being proposed. Experimental results of the design r-FIFO for both the FPGA and ASIC implementation are given in Sect. 3. Section 4 provides the power result analysis of the design. Finally, Sect. 5 concludes the paper.

2 Proposed system architecture for IoT applications

The IoT applications have emerged in myriad sectors [3, 4]. This research work employs a three-layered IoT architecture and proposes the use of r-FIFO design for low power and high latency communication. This proposal with various IoT applications enables the exchange of data from the sensor nodes to control nodes through r-FIFO. This r-FIFO as a part of the fog computing layer communicates with multiple sensor nodes and gateway node. The employed sensor nodes are used to capture the relevant data from the environment, and later, these data are being used for further processing. The data are acquired using high-speed data acquisition (HSDA) [19]. The data acquired from sensor nodes are converted to digital format using analog-to-digital converters (ADCs). Further, the data as per the requirement can be compressed/filtered using data computation algorithms.

Figure 1 illustrates the complete proposed set-up. Here, the perception layer constitutes a group of sensors data providers that can be designated as a central platform to perform IoT operations. It is flowed by HSDA to convert the physical sensor data to digital numeric value by sampling process. The data can be further stored in r-FIFO and process accordingly by management layer. Here, the gate way layer is present to communicate through a network to an enterprise back-end server that is running an IoT platform. This helps to integrate the IoT information into an existing enterprise and lastly the application layer provides the services requested by the customers.

The r-FIFO holds the final data acquired and can work in both the synchronous and asynchronous manner according to the application they are employed. The design of reconfigurable FIFO is inevitable as one requires the same clock frequency for local synchronization of the components present on the same chip module. In the case of inter-island communication (between the different chips), use of asynchronous mode in FIFO becomes necessary. The r-FIFO module mainly works as data storage and processing unit in the proposed design. Here, size of the FIFO is defined as depth X depending on number of input bits, where the input bits are equal to the multiple data sample inputs from the various sensors. The data rate can be defined in terms of number of data inputs and time period of input data signal and the depth X can be defined as Eq. (1):

$$\text{Depth } X = \frac{\text{Difference (clk data rate)}}{\text{High frequency time period}} \quad (1)$$

Difference = Data rate of Fast clk ($writeclk$) – Data rate of Slow clk ($readclk$). The output of this block is fed to the microcontroller for further processing. This is the control node, which acts as a link between the gateway nodes, where the data are being put on the cloud for client's usage. The next subsections discuss in detail about the (A) HSDA (B) r-FIFO design

A. High-speed data acquisition (HSDA)

The parallel data acquisition is done using HSDA technique [16] in which measured sensor data are converted into digital numeric values as illustrated in Fig. 2. According to the

Fig. 2 HSDA architecture for parallel data acquisition

Fig. 1 The proposed IoT architecture model

characteristics of different sensor data and data interface, the mapping relationship is established between sensor data and data interfaces which improves the data acquisition efficiency of IoT. Data acquisition between different sensor data is independent of each other; hence, we can perform them in parallel.

Let I_i denote interface information, where the index of interface and the sensor data information is denoted as D_j . Here ' j ' is the index of sensor data for each interface connection. The number of sensors connected to the I_i interface is ' j ' = 1, 2, ..., n . As different data interfaces are independent from each other, we divide the data acquisition into j rounds. And for each round, we acquire data from a data source on ' i ' interfaces. There is a possible situation where no data source corresponds to the elements of matrix M_{ij} . This represents the data source information of each accessed interface, so we set that value '0'. The output of the algorithm is acquired sensor data and acquisition time with matrix M_{ij} form the sensor data. This describes all the information of the data sources that are accessed as input.

Algorithm for HSDA

1. To acquire data for round $j = 1$ to n from sensor data source, *do*
2. for each interface $i = 1$ to m *do*
3. if M_{ij} is not zero, then acquisition main program sends the list to the acquisition module correspond to sensor data M_{ij}
4. end
5. To obtain acquisition time for interface $i = 1$ to m *do*
6. if M_{ij} is not zero then acquisition modules collect data according to the communication protocol and record the time t_{ij} required for the data acquisition
7. if $M_{ij}=0$ then time required is zero
8. end

According to the obtained acquisition time $t_{m \times n}$, we can calculate the time required to complete one round of data acquisition. The time required for each round of data acquisition is the maximum value of each column of matrix, namely $t_j = \max T_{ij}$. The time t required to complete a complete data acquisition is $\max T_{ij}$ for all sensor data. The time t_1 of the serial data acquisition is sum of T_{ij} for ' j ' sensor data and ' i ' interface. Obviously, $t \leq t_1$, and the efficiency of data acquisition is improved significantly with the increasing number of data sources.

B. Reconfigurable FIFO design

Local data synchronization is handled by clock, whereas asynchronous methodology is required for inter-island communication. The synchronization of different islands operating with different frequencies is inevitable with the

use of synchronous FIFO module. However, these FIFO are required for the switches that are working in same clock domain. Distribution of single global clock is one of the major bottlenecks in today's high-performance VLSI system. This is mainly due to the multi-cycle cross-chip signalling, process variability and power dissipation. Hence, for local data synchronization clock is required to be synchronous in nature while data are required to be handled asynchronously for the inter-island communication. There requires the need for the reconfigurable FIFO (r-FIFO) that could be used for both the purposes. Hence, here an r-FIFO design is being implemented using gray encoding technique, in which gray code is passed from the read domain to write domain. The model has an advantage over a conventional FIFO module because it could be operated in both synchronous and asynchronous modes at a particular instant of time as per the requirement of the application [20].

The operation designed could be done via sync/bi-sync signal connected to both write and read modules. In synchronous mode, read and write operation is performed on the same clock frequency and in asynchronous mode read and write operation is performed on different clock frequency. (In this case, write operation is done at 40 MHz clock frequency and read operation at 50 MHz clock frequency.) This model has great relevance in terms of the proposed IoT design application, as FIFO states that the earlier arrival tasks will have the earlier deadlines. Figure 3 gives the brief architecture design of the reconfigurable FIFO.

Here, the FIFO memory block is a dual port RAM that is accessed by both the read and write clock domains. The sync_r2w is the synchronizer that is used to synchronize read to the write pointer, and sync_w2r also acts similarly with vice-a-versa synchronization. The FIFO $wptr$ and full module are synchronous to the write clock domain, whereas $rptr$ and the empty module are synchronous to read clock domain. Beside this, the working of each port is clearly explained in Table 1. The further analysis of the designed architecture is provided in the next sections.

3 Design analysis of the reconfigurable FIFO

This design of reconfigurable FIFO is being simulated using the Vivado tool version 2018.2. The verification of the designed RTL code is done on the FPGA board using ZYBO (zynq- 7000). The simulated code is finally synthesized using Synopsys Design Compiler [21], where the timing and power constraints are checked at the synthesis level only. Later on, the design is physically designed using Synopsys IC Compiler tool. This is an ASIC designer tool where a small chip for the reconfigurable FIFO is being designed. It is being done so that this small unit could also

Port	Direction	No of bits	Importance
writein	In	8	8-bit data written into the FIFO
readout	Out	8	8-bit data read from the FIFO
empty	Out	1	Represents empty state condition of the FIFO
full	Out	1	Indicates no further data could be written in the FIFO, as the memory block is full
writeclk	In	1	Write clock for the FIFO write operation
readclk	In	1	Read clock for the FIFO read operation
wrst	In	1	Reset signal used to rest the write operation of the FIFO
rrst	In	1	This is used to reset the read operation of the FIFO
Sync/Bi-Sync	In	1	This signal decides that whether FIFO works in the synchronous mode or asynchronous mode. If the signal is high, it works in a synchronous mode and vice-a-versa in a low state

FIFO design is done on Xilinx zynq Z-7000 series AP SoC/ FPGA board. Here, for testing the design of the reconfigurable FIFO frequency match between the LEDs of the I/O port and VGA (Video Graphics Array) port is done. The input is given by the push buttons, the control signal is provided by the switches, and the flag signal response is indicated by the LEDs present on the board. Initially, when the write operation is performed, led indicates that FIFO is empty. At this stage, data storage is done in the FIFO memory block with the use of a different combination of push buttons. When FIFO is in full state, then read operation is performed. To visibly see the stored data in the FIFO block, data are taken out from the unit designed using the VGA port present on the ZYBO (zynq-7000) board. Once the testing is compiled, further analysis of the designed

As already explained in this paper, we have implemented the design of a dual port reconfigurable FIFO. The simulation result of the designed FIFO is provided in Fig. 4. It works on two different modes that are asynchronous and synchronous. The aided verification of the reconfigurable

Fig. 4 **a** FIFO in synchronous mode **b** FIFO in asynchronous mode

Table 2 Design summary

Name	Slice LUTs (17600)	Slice registers (35200)	F7 Muxes (8800)	Slice (4400)	LUT as logic (17600)
FIFO (top)	34	40	2	14	26
fifomem	8	8	0	3	0
rprr_ empty	13	8	1	7	13
sync_r2w	0	8	0	4	0
sync_w2r	0	8	0	4	0
wptr_full	13	8	1	5	13

architecture is done. The lookup table (LUT) model provided by the design summary is shown as Table 2.

Figure 4a shows the synchronous mode of the FIFO in which write clock (*wclk*) and read clock (*rclk*) frequency are kept equal at 40 MHz. Whereas in Fig. 4b, asynchronous mode of FIFO is shown in which *wclk* is kept at 40 MHz

frequency and *rclk* is at 50 MHz frequency. Here, the data in and out are represented by *writein* and *readout* signal, respectively.

B. ASIC implementation results

This physical designing process is done using the SCL (Semiconductor Laboratory) physical design kit. The environment of the tool could be set for three cases slow–slow (having the maximum transition time and delays), fast–fast (with minimum transition time and delays) and the typical condition. Here, the whole experimentation is being performed for the slow–slow corner set libraries, as this is the worst-case timing set. Then, the major concern of giving the design constraints to the reconfigurable FIFO is given by setting the operating frequency of the two different clock nets at 50 MHz for *readclk* and 40 MHz for *writeclk*, respectively.

Table 3 Standard cell count

Module	Cell count	Area (mm ²)	NAND GEs
<i>Reconfigurable FIFO</i>			
Write full module	46	0.0106	845
Read empty module	46		
Sync write to read	8		
Sync read to write	8		
FIFO memory	219		
Top level	2		

Table 4 Power analysis

Constraints	Value (μ W)
Cell internal power	257.196
Switching power	53.842
Leakage power	0.155
Total power	311.039

Here during the P&R flow, core size and die size of the designed chip are taken to be the integer multiple of the tile width and tile height that are of 0.56 and 5.6 micron, respectively, of the standard cells available in the library. Besides, this special care is being taken, in order to meet the required timing and power constraints of the design. It is an iterative process and continues until the required voltage (IR) drop, and electromigration of the design analysis is met, according to the foundry specifications [23]. The design is analysed at both the post-synthesis and post-layout level, where it meets all the violators. The standard cell count of the design summary could be clearly seen with the help of the provided Table 3.

Also, the slack that is the difference between the arrival time and the required time of the different clock nets is

met [24]. The slack for the designed circuit is 2.98 and 3.57 for *readclk* and *writclk*, respectively. Then, after performing the clock tree synthesis operation, the *readclk* takes 2 buffer levels, and *writclk* acquires 3 buffer levels to meet the skew in the implemented design. The power analysis of the reconfigurable FIFO design is given in Table 4. The complete routed chip view of the design could be seen in Fig. 5.

4 Results and discussions

The architecture of reconfigurable FIFO was modelled in VHDL, and its simulation was performed on the Vivado software. The design is evaluated in terms of many parameters like area, slice count, timing, and power [25]. The synthesis of the design and its required ASIC flow is done, providing the proof of its verification. The post-synthesis power versus frequency curve when both the clocks operate in the synchronous mode is being illustrated in Fig. 6. The figure clearly explains that there is an increase in power with increase in the device frequency of the designed FIFO. This is because that with an increase in operating frequency there will be more switching in the

Fig. 5 Chip View of the Designed FIFO

Fig. 6 Power versus frequency curve

device, thus affecting the efficiency of the power module. Hence, an appropriate frequency is chosen, according to the requirement of the application for the designed r-FIFO.

5 Conclusion

In this paper, we have investigated the data communication problem between the different nodes (working at different frequencies) of the IoT architecture. The low latency is the main stumbling block for IoT cloud computing applications. This implies the usage of front-end data calculation as in case of IoT-based fog computing architecture. Further to address issues of frequency mismatch of various front-end devices or serially connected terminal devices and for the better collaboration between the platforms of the various IoT applications, an idea of using the reconfigurable FIFO as a stack module is being proposed. The design of the FIFO module is being simulated, and its verification is done on the FPGA board using ZYBO. Besides this, the ASIC implementation of the block unit is also done, along with its power and timing consideration. This r-FIFO block has a total power dissipation of 311.09 μ W and it could also be used as a custom chip on large platforms. The energy per bit data for different clock domains of the designed reconfigurable FIFO is 0.777 pJ/bit and 0.971 pJ/bit for *readclk* and *writeclk*, respectively. In summary, the proposal can provide an optimum solution in fog computing to handle frequency inconsistency in various nodes.

Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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