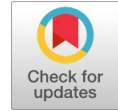


FPGA Implementation of RECTANGLE Block Cipher Architectures



Nivedita Shrivastava, Bibhudendra Acharya

Abstract: In recent time, various lightweight algorithms have been proposed to provide security in a constrained resource environment. With so many algorithms and their different implementations, it is hard to choose the appropriate security primitive for an application. In this work, various hardware implementations of lightweight block cipher RECTANGLE is proposed like Iterative design, 16-bits architecture, Reduced Substitution box design, RAM-based design and Iterative design with Partial loop unrolled. These designs provide aid in overcoming the problem of security in a constrained resource environment. Architectures are designed and implemented in various FPGA platforms. Results are extensively evaluated and compared on the basis of throughput, throughput/slice, area utilization, energy requirement and power consumption for their implementation in different FPGA platforms. Best trade-off among throughput and area is given by Iterative design with partial loop unrolling. It also gave best energy consumption values for all FPGAs. Ram-based design utilized least number of registers for its implementation.

Keywords: BRAM, FPGA, lightweight cryptography, Security, RECTANGLE Cipher, Hardware architecture.

I. INTRODUCTION

With the advancement in technology, there is a huge development in various ubiquitous computing devices like smart cards, Radio-frequency Identification tags (RFID), smartphones etc. Ubiquitous computing among various devices puts a major effect in real life environment [1]. With the growing use of these devices and rapid growth of Internet of things (IoT), there is a constant threat to security and privacy of the information. These small devices are equipped with slow oscillators and low-end microcontrollers, which have small word length [2]. There are also limited power generation resources available. As a result, performance enhancement is achieved by using various power optimization techniques [3], novel transmission techniques [4] or by using energy harvesting technique [5]. One of the widely used techniques to safeguard data is by using Data Encryption [6]. Many ciphers are introduced to combat the issue of security and privacy. For example, some traditional ciphers like advanced encryption standards (AES)

[7] and Data encryption standard (DES) [8] are proposed. In the field of lightweight cryptography also many ciphers are introduced in order to deal with security concerns in the field of constrained resource environment. Lightweight ciphers are mainly divided as Substitution-permutation network (SPN) based ciphers and Feistel network based ciphers. In SPN based ciphers confusion and diffusion of bits is performed. Some of the popular SPN based ciphers are PRESENT [9], RECTANGLE [10], KLEIN [11], Light encryption device (LED) [12], mCrypton [13] etc. Another category of lightweight ciphers is Feistel cipher. In these ciphers encryption is performed on half of the data, thus they require more number of rounds in order to provide proper security. Some of the famous Feistel ciphers are CLEFIA [14], SIMON and SPECK [15], PICCOLO [16], TWINE [17], LBLOCK [18] etc. To make our day-to-day life simpler, IoT is inherently applied in all domains [19]. Security, performance, and availability are the major challenges, which are observed in the IoT environment [20]. For IoT based applications, hardware-based solutions are considered ideal in order to provide security [21]. Various optimization techniques are proposed by several authors. With optimization, these ciphers become more suitable for resource scarce lightweight applications. Lightweight algorithms have been implemented in application specific integrated circuits (ASIC). Due to feature of non-recurring engineering (NRE), implementation cost in ASIC is very high and they also require long manufacturing time, that makes ASICs undesirable for low volume products. For the production of the devices like RFIDs, sensor nodes etc., low-cost and low-power Field programmable gate array (FPGA) [22] are preferred, as they possess low or zero NRE cost along with reconfigurable nature with reduced time to market [23]. Reconfigurable nature of FPGA allows easy upgrades at low cost [24]. Also with the usage of FPGA, we can reduce hardware resources [25]. As the nature of security protocols are rapidly evolving, there is a need for reconfigurable devices [26]. Another advantage of FPGA is in-built Block Random access memory (BRAM) [27]. In random access memory (RAM) based architecture BRAM is utilized for implementation of hardware architecture, leaving registers free to be used for any other purpose.

A. Contribution

In the proposed work different hardware architecture of RECTANGLE block cipher is proposed for FPGA implementation. These architectures have different resource and power consumption. According to the requirement, these architectures can be used by users. The main contribution of the paper is as follows:

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- Iterative Architecture for both 80-bits and 128-bits key schedule along with a finite state machine (FSM), which is used to control the circuit. Reduced S-box architecture with 80-bits key generation mechanism is also proposed.
- 16-bits architecture with key scheduling of both 80-bits and 128-bits key length are proposed. These architectures have a reduction in datapath width from 64-bits to 16-bits.
- Two RAM based designs are proposed which aims in reducing area consumption of the architecture. In this architecture, BRAM of FPGA is used for storing an intermediate state of the design. In the first work, S-box is implemented using slices available in FPGA. In other design S-box is implemented in BRAM itself.
- Iterative design with partial Loop Unrolling is proposed. Five rounds of RECTANGLE cipher are unrolled and connected serially with each other. ROM based key retrieval mechanism is used.
- Evaluation of different works is done on the basis of area requirement, power consumption, energy requirement, latency, throughput, and throughput/slice. Evaluation of all the architectures is done in four different FPGA platforms.

B. Organization of paper

The paper is divided into six sections. Section 2 comprises of basic description of RECTANGLE cipher algorithm. Section 3 describes the proposed hardware architectures of the RECTANGLE block cipher for FPGA implementation. Section 4 comprises of metrics and methodology used for performing the work. Section 5 illustrates results obtained for different designs. It also includes discussion, evaluation and comparison of the obtained results. Finally, Section 6 presents the final conclusion.

II. THE RECTANGLE CIPHER: ALGORITHM

The RECTANGLE block cipher is a hardware-friendly lightweight cipher. This is an SPN based cipher and comprises of 25 rounds of encryption. This cipher can work with the key schedule of both 80-bits and 128-bits. Selection of key schedule depends on the requirement of user i.e. whether high security or less resource consumption is desired. Cipher architecture consists of data scheduling and key scheduling part. Data scheduling part consists of three basic operations, which are performed in each round of encryption.

These operations are described as follow:

- **AddRoundKey Operation:** Simple XOR operation between 64-bits of round subkey and intermediate data is performed during the encryption process.
- **Substitution Layer:** This operation performs substitution of 64-bits, through a set of 16 Boolean S-boxes. S-box accepts input of 4-bits and produces output of 4-bits. There are various methods available to design S-box like Boolean logic based S-box, RAM-based S-box, look-up table (LUT) based S-box etc.
- **Permutation Layer:** This layer performs permutation in 64-bits of data. Data is divided in the set of 16-bits, and rotation is performed in each bit set. In each of the 16-bits, rotation offset of 0, 1, 12, and 13 is used

respectively.

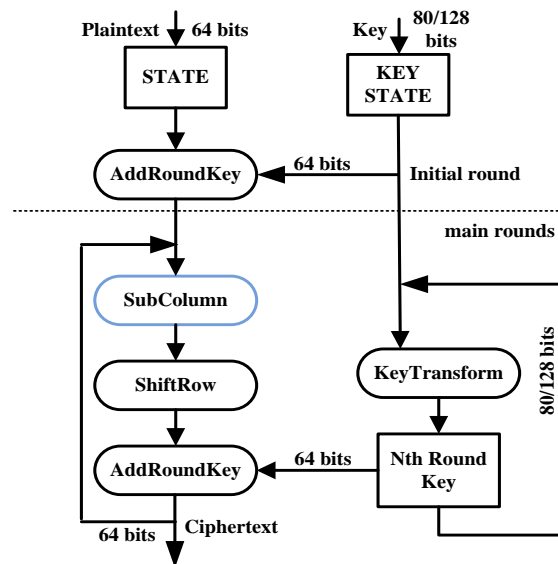


Fig. 1. Encryption Process of RECTANGLE cipher. Plaintext is encrypted through various rounds of encryption and round subkey is generated simultaneously through the key scheduling part

In Fig. 1, the basic algorithm of RECTANGLE is shown. The ciphertext is achieved after completion of all the rounds and an additional AddRoundKey operation. For each round, a subkey is generated using key scheduling mechanism. This mechanism comprises of substitution operation followed by generalized Feistel transformation. Thereafter, XOR operation with round constant is performed. It is generated through a linear feedback shift register (LFSR) of 5-bits.

III. HARDWARE ARCHITECTURE OF RECTANGLE BLOCK CIPHER

A. Reduced S-Box Architecture

RECTANGLE cipher has a block size of 64-bits. For storing data and key, 64-bits and 80-bits registers are used respectively. Authors used 16 S-boxes to design the substitution layer of the RECTANGLE cipher [10]. In the proposed architecture, number of S-boxes in the data scheduling part is reduced from 16 to just two.

It is observed that S-boxes and registers require maximum area for their implementation. Reduction in the number of S-boxes results in the reduction of area. But there are two disadvantages of this architecture. First is to process 64-bits, 8 extra clock cycles are required. This results in increase of latency. Another disadvantage is as the datapath width is varied, so extra circuitry is required to synchronize the design. As a result, there is an introduction of extra area overhead. Two clock cycles are required to take the input and to process the output. For processing all rounds, 192 clock cycles are required. This leads to latency of 194 clock cycles. This architecture requires 149 flip-flops, 10 S-boxes and 1 permutation layer.

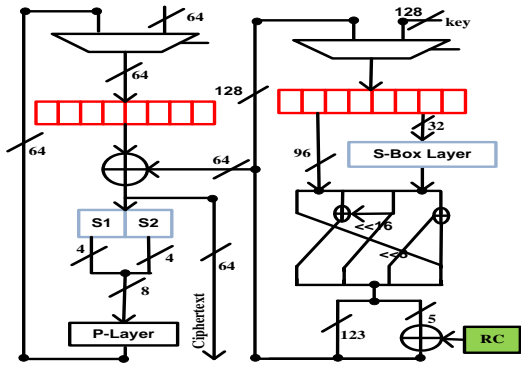


Fig. 2. Hardware Architecture of RECTANGLE block cipher. The main characteristic of this design is the reduced number of S-boxes

B. Iterative Architecture

In this architecture, 8-bits I/O ports are used for data and key. For storing data, a 64-bits register is used while for key 80-bits register is used. As shown in Fig. 3, 8-bits XOR gate is used to perform initial AddRoundKey operation. As it uses a key size of 128-bits, this architecture is preferred when there is a need for higher security.

For synchronizing and controlling the circuit FSM is used, which is shown in Fig. 4. As the circuit is reset, it enters in initial ‘BOOT’ state. Then directly goes to ‘IDLE’ state. When the user gives ‘en’ signal data loading begins. For the first eight cycles, both data and key register are loaded and FSM stays in ‘LD0’ state. As the counter reaches count of seven, it gets reset and FSM reaches ‘LD1’ state. Key is loaded in the key register for the next eight clock cycles. When the counter reaches seven, loading is completed. The counter resets again and FSM reaches ‘ENC’ state. In this state in a single clock cycle, one round of encryption is performed. After completion of all the rounds, data is unloaded in ‘ULD’ state for the next 8 cycles. At last FSM reaches ‘BOOT’ state and the device is ready to be used again.

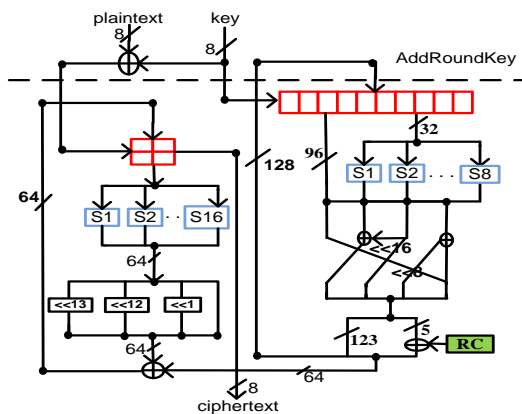


Fig. 3. Iterative Architecture of RECTANGLE block cipher with 128-bits key Schedule. This architecture closely follows the basic specification of RECTANGLE cipher with 128-bits key schedule

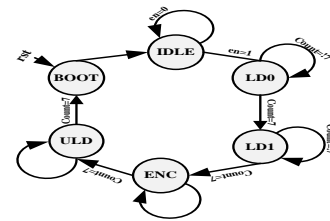


Fig. 4. Six stages finite state machine for Iterative Architecture of RECTANGLE block cipher with 128-bits key Schedule. FSM generates required control signals to control the working of circuitry

For the design with 80-bits key schedule, FSM is same as 128-bits architecture. The only difference is change from ‘LD1’ to ‘ENC’ state happens when the counter reaches 2. 8 cycles are required to store data and two extra cycles are required to store the key. 8 clock-cycles are required for generating output. So latency of the architecture comes out to be 42. In this work 149 flop-flops, 20 Boolean S-box and one Permutation layer (P-layer) is used.

C. 16-bits Architecture with Key Scheduling

In this work, I/O port of 16-bits is used. Datapath width of the architecture is reduced from 64 to 16-bits. Conventionally to optimize architecture, datapath width is varied. This requires large area overhead, as to transfer data from small to a wider word or vice versa requires extra registers for storing data, which leads to the increased area [28]. For data scheduling part, four 16-bits shift registers are required to store the plaintext. These registers are designed to provide serial and parallel, input-output operations. The idea for implementing registers with both shift and parallel access is taken from work done in [29]. Another feature of this design is the reduction in the number of S-boxes from 20 to just 8. Permutation is performed with the help of parallel operation of the 16-bits shift register. So no extra P-layer is needed to perform diffusion of bits. Architecture is designed for the key schedule of both 80-bits and 128-bits key length. Fig. 6 and Fig. 7 shows the architecture of the same.

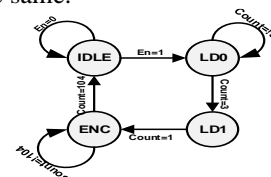


Fig. 5. Finite State Machine for 16-bits architecture with 80-bits key Scheduling. This FSM generates control signals for the architecture.

- **80-bits Key Schedule:** The 80-bits key is divided in set of 16-bits words and stored in five 16-bits shift registers. These registers can perform parallel and serial, input-output operations. Five 16-bits multiplexers are used to aid key scheduling. Leftmost 4-bits from first four registers are taken to generate 16-bit round subkey. Another feature of this design is that number of S-boxes is reduced from 20 to just 8.

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Fig. 5 shows FSM designed to control the working of the architecture. When the device is reset it enters in the 'IDLE' state then on applying 'en' signal, FSM enters into 'LD0' state. In this state, data is loaded in both key and data register. As the counter reaches 3, FSM enters into 'LD1' state. In this state remaining bit of key is loaded in key register. When loading is completed, FSM reaches 'ENC' encryption state. For completing all the rounds of encryption, 100 clock cycles are needed. Four additional cycles are required to obtain the output. As the counter reaches a count of 104, encryption is completed. Thereafter, FSM enters into 'IDLE' state, indicating the device is ready to be used again.

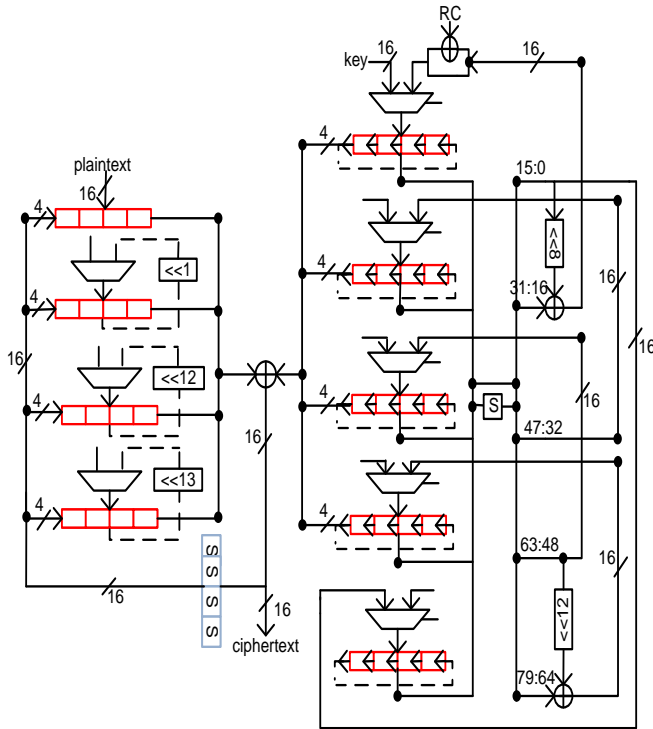


Fig. 6. 16-bit Architecture of RECTANGLE block cipher with 80-bit key Scheduling. Datapath width is reduced to 16-bits.

- **128-bits Key Schedule:** If enhanced security is desired, architecture with key size of 128-bits is preferred. 128-bits key is divided into a set of eight 16-bit words. Each 16-bit word is divided into a set of 4-bit words and stored in a 16-bit shift register. 4 clock cycles are required to feed data serially into the circuitry. Extra 4 clock cycles are needed to feed remaining 64-bits of key. Registers numbered from 0 to 7 stores key from the least significant bit (LSB) side to most significant bit (MSB) side. Leftmost 4-bits from each even-numbered register are taken and concatenated to generate 16-bit subkey.

Here, number of S-boxes is reduced from 24 to 12. FSM used is same as the one used in 80-bit architecture. The only difference, when the count reaches the value of three then only FSM changes its state from 'LD1' to 'ENC'. To complete a single round of encryption, architecture takes 4 clock cycles. For producing output also, 4 clock cycles are required. This leads to a total latency of 108.

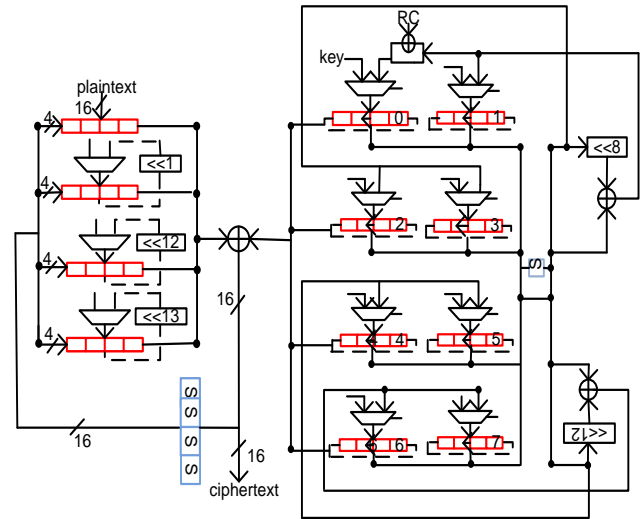


Fig. 7. 16-bit architecture with 128-bit key Scheduling. Datapath width is reduced to 16-bits. Shift registers are used to perform permutation

D. RAM-based Architecture

In this section, two RAM-based architectures are proposed. BRAM is used to store data and to generate S-boxes as a result registers, slices, and LUTs in the FPGA are free to be used for any other purpose.

- **Using RAM based S-Box:** In this architecture, BRAM is used to store data, key and to implement S-box. Two multiplexers are used to decide whether the user given input or processed intermediate data should be the input of BRAM. As shown in Fig. 8 in Data scheduling part of the architecture output of the BRAM is fed to a 64-bit XOR gate. Thereafter this output of XOR goes to another BRAM. Output of this BRAM is actually the value which should come after performing substitution in the given data. Then this output is permuted through hard-wired P-layer. As mentioned in [7], for silicon technology shifts and permutation do not require any cost for implementation.

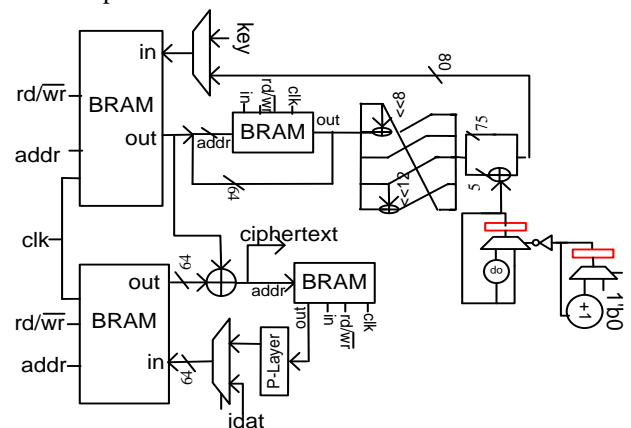


Fig. 8. RAM-based Architecture of RECTANGLE cipher with RAM-based S-box. BRAM is used to store key, data and to generate S-box as well.

The output from P-layer gets stored in BRAM via a multiplexer. In key scheduling part of the design, rightmost 16-bits from the output of the BRAM are sent to S-box layer, which is stored in another BRAM module. Rest of the 64-bits is not processed. Thereafter generalized Feistel transformation is performed on the resultant 80-bits.

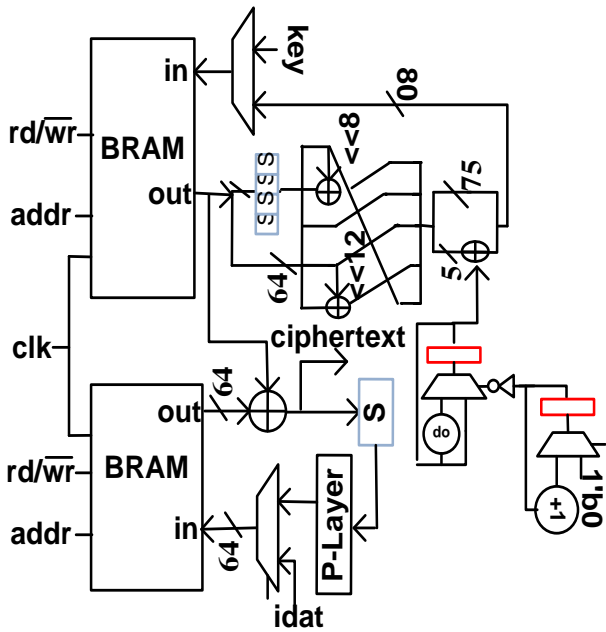


Fig. 9. RAM-based Architecture of RECTANGLE block cipher with Boolean S-box. BRAM is used to store key and data.

- **Using Boolean S-Box:** As shown in Fig. 9, only processed data and key are stored in BRAM. For storing data and key, BRAM of 64-bits and 80-bits are used respectively. S-boxes are not implemented using BRAM but by using slices and LUTs. Optimization in BRAM based S-box is difficult due to the rigid nature of the design [30]. In this work, Boolean logic is used to implement S-boxes. One clock cycle is required to take the input and another to generate output. Additional 2 clock cycles are required to complete a single round of encryption. This leads to a total latency of 50 clock cycles.

E. Iterative design with partial loop unrolling

In this work, 5 rounds of RECTANGLE cipher are unrolled and chained together with no registers in between. Data is passed serially through the five rounds. As shown in Fig. 10, a common 64-bits register is used to hold the input and intermediate data. To complete the encryption, iterations are repeated five times. The objective behind this work is to obtain an optimum trade-off between area and performance. Round subkeys are pre-generated and stored in a ROM module. Keys are retrieved from ROM, according to the round. This design can be implemented through pipeline as well, with the introduction of registers. A similar approach is reported by the authors in [31]. But the introduction of registers will increase area a lot. Disadvantage of this design is that architecture is vulnerable to side channel attack.

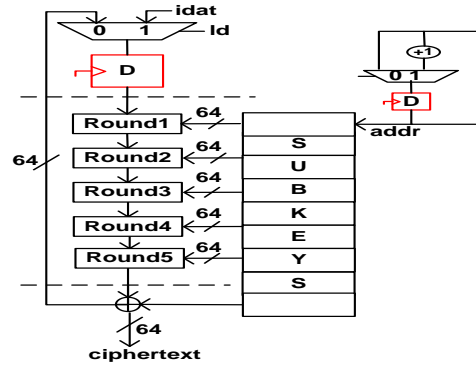


Fig. 10. Iterative Architecture with Partially loop unrolled

IV. SIMULATION PLATFORM

A. Environment

All the RECTANGLE architectures were modeled using Verilog and synthesized for Xilinx FPGAs using ISE design suite 14.6. Different FPGA platforms are used to implement, compare and evaluate the architectures. For implementation in LUT-4 FPGA, Spartan-3(xc3s4000l-4fg900) and Virtex-4 (xc4vlx25-12ff668) were considered. For implementation in LUT-6 FPGA, Spartan-6 (xc6slx16-3csg324) and Virtex-5 (xc5vlx50t-3ff1136) platforms were considered. For performing power analysis Xilinx tool XPower Analyzer is used. In evaluation newer 7 series FPGA are not considered as their configurable logic block (CLB) is very similar to 6 series FPGA leading to replication of implementation results [35].

B. Configuration

Source code for implementation of RECTANGLE block cipher round based architecture is provided by the authors in [8]. Source files are synthesized and implemented in different FPGA platforms to obtain the results. Design environment is kept constant while implementing the architectures so as to provide a fair comparison between all the architectures. All the designs are implemented with the same synthesis parameters and implementation criteria. Different configurations along with their key sizes are shown in Table I.

C. Metrics

In this work, for evaluation of architecture various metrics are considered. For resource estimation, Slices, Flip-flops and number of LUTs are taken into account. Resource usage for each design is estimated through implementation report generated by ISE design tool 14.6. All these metrics vary according to the type of FPGA used. Power consumption is calculated using the Xilinx XPower analyzer tool. It provides values of static, dynamic and total power consumed by the architecture. Analysis is done using user-defined operational frequency at default operation temperature. For all the studies operational frequency of 13.56 MHz is considered. Reason for this is low power devices do not work on maximum operational frequency but are limited to lower frequency. For example, in case of RFID tags, operational frequency is taken to be of 13.56MHz [36].



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Table- I: Different configurations of the RECTANGLE cipher

Architecture	Key Size	Conf.
Iterative Architecture	80	A1
Iterative Architecture	128	A2
16-bits Serial with key scheduling	80	A3
16-bits Serial with key scheduling	128	A4
RAM-based Architecture(on Slice)	80	A5
RAM-based Architecture(on RAM)	80	A6
Iterative design with partial loop unrolled	80/128	A7*
Base Architecture[8]	80	A8

* Results same for 80/128 bits architecture

Energy spent by the architecture to process a single block of data, for the frequency of 13.56 MHz is calculated according to (1):

$$\text{Energy} = \text{Total Power} \times \text{latency} / 13.56 \text{ MHz} \quad (1)$$

Energy will directly be affected by the latency of design if constant operational frequency is taken for all the architectures. For performance evaluation, both latency and throughput of the design is considered. Throughput is calculated according to (2) and (3):

$$\text{Thr.} = \text{Block Size} \times \text{FMax} / \text{Latency} \quad (2)$$

$$\text{Thr.*} = \text{Block Size} \times 13.56 \text{ MHz} / \text{Latency} \quad (3)$$

Table- II: Presents resource usage and power consumption results for the architectures for different computing platforms

Conf.	Key (bit)	Latency (Cycles)	Slice	LUT	Flip Flop	FMax (MHz)	Static Pow(mW)	Dynamic Pow(mW)	Total Pow(mW)	Thr (Mbps)	Thr* (Mbps)	ENE* (μJ)	Thr*/slc (mbps/slc)
<i>xc6slx16-3csg324 (Spartan-6)</i>													
A1	80	42	58	202	158	168.327	19.91	1.46	21.37	256.496	20.66	.066	.356
A2	128	48	85	300	203	172.391	19.91	1.80	21.71	229.797	18.08	.076	.212
A3	80	105	55	198	153	166.615	19.94	4.25	24.19	101.555	8.035	.187	.144
A4	128	108	80	275	203	164.206	19.92	2.90	22.82	93.827	7.961	.181	.096
A5	80	50	61	160	6	180.209	20.08	18.72	38.80	230.667	17.356	.143	.279
A6	80	50	83	110	6	135.022	20.10	20.46	40.56	172.829	17.356	.149	.184
A7	80/128	5	139	472	67	61.758	20.31	41.82	62.13	838.298	173.56	.022	.933
A8	80	26	76	272	149	286.111	20.29	39.09	59.37	704.273	33.37	.113	.514
<i>xc5vlx50t-3ff1136 (Virtex-5)</i>													
A1	80	42	72	231	158	410.590	562.96	2.92	562.96	626.252	20.66	1.74	.317
A2	128	48	117	313	203	388.188	560.07	5.90	565.97	517.454	18.08	1.99	.194
A3	80	105	67	226	153	338.146	560.06	5.18	565.24	206.107	8.035	4.37	.118
A4	128	108	103	301	203	338.391	560.08	7.58	567.67	193.356	7.961	4.52	.078
A5	80	50	113	224	6	286.246	560.42	41.55	601.97	366.394	17.356	2.219	.158
A6	80	50	146	212	6	175.568	560.20	19.31	579.52	224.692	17.356	2.136	.098
A7	80/128	5	221	573	67	146.638	560.44	43.29	603.72	1876.96	173.56	.222	.784
A8	80	26	101	278	149	501.655	560.37	36.75	597.12	1234.54	33.37	1.144	.596
<i>xc3s4000l-4fg900 (Spartan-3)</i>													
A1	80	42	174	312	158	102.554	268.29	6.68	274.97	156.217	20.66	.849	.118
A2	128	48	212	377	203	108.510	268.27	5.68	273.94	144.643	18.08	.967	.085
A3	80	105	186	350	153	93.519	268.16	1.58	269.73	57	8.035	2.088	.042
A4	128	108	252	365	203	94.917	268.14	1.14	269.28	54.235	7.961	2.144	.031
A5	80	50	173	262	6	141.253	268.54	15.80	284.34	181.149	17.356	1.048	.100
A6	80	50	166	218	6	141.123	268.84	26.90	295.74	180.637	17.356	1.090	.104
A7	80/128	5	361	624	67	37.046	268.71	58.68	328.39	474.188	173.56	.024	.476
A8	80	26	180	300	149	179.791	268.69	57.72	327.40	442.46	33.37	.627	.185
<i>xc4vlx25-12ff668 (Virtex-4)</i>													
A1	80	42	173	311	158	247.391	233.03	16.36	249.39	376.974	20.66	.770	.119
A2	128	48	212	377	203	261.897	233.06	17.51	250.57	349.108	18.08	.884	.085
A3	80	105	186	350	153	224.558	232.89	8.71	241.60	136.872	8.035	1.87	.042
A4	128	108	253	365	203	222.620	232.99	14.22	247.21	127.205	7.961	1.97	.031
A5	80	50	170	261	6	261.219	233.66	49.31	282.97	334.360	17.356	1.043	.100
A6	80	50	166	217	6	167.794	233.61	46.65	280.26	214.7763	17.356	1.033	.104
A7	80/128	5	361	624	67	99.698	233.79	56.21	290	1276.134	173.56	.022	.480



A8	80	26	180	300	149	494.035	233.59	45.68	279.45	1215.82	33.37	.535	.185
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Here, Throughput (thr) is maximum throughput of the design and depends on the maximum operational frequency and latency of the architecture. Throughput*(Thr*) is calculated using an operational frequency of 13.56 MHz.

Throughput/slice (thr*/slc) is a derived metric. It is estimated to study how efficient a design is when trade-off between implementation size and performance is desired [2].

It is simply calculated by dividing throughput obtained at a frequency of 13.56 MHz. with the number of slices utilized in the implementation of the architecture.

V. RESULTS AND DISCUSSION

Table II illustrates resource requirement, performance, energy utilization and power consumption for all the implementations. Results are evaluated and compared for all the four FPGAs.

Performance parameter and resource consumption changes according to the type of FPGA used for implementation of the architecture. Fig. 11 shows a graphical representation of resource consumption for all the FPGA platforms. It is observed, for both LUT-4 FPGA resource utilization remains nearly constant.

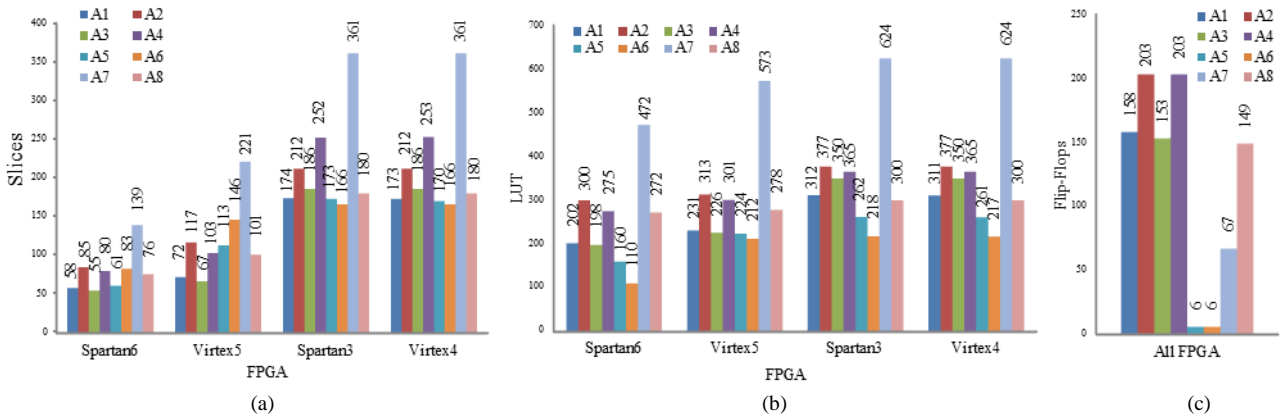


Fig. 11. Resource consumption for all the architectures (a) Slices (b) LUTs (c) Flip-Flops

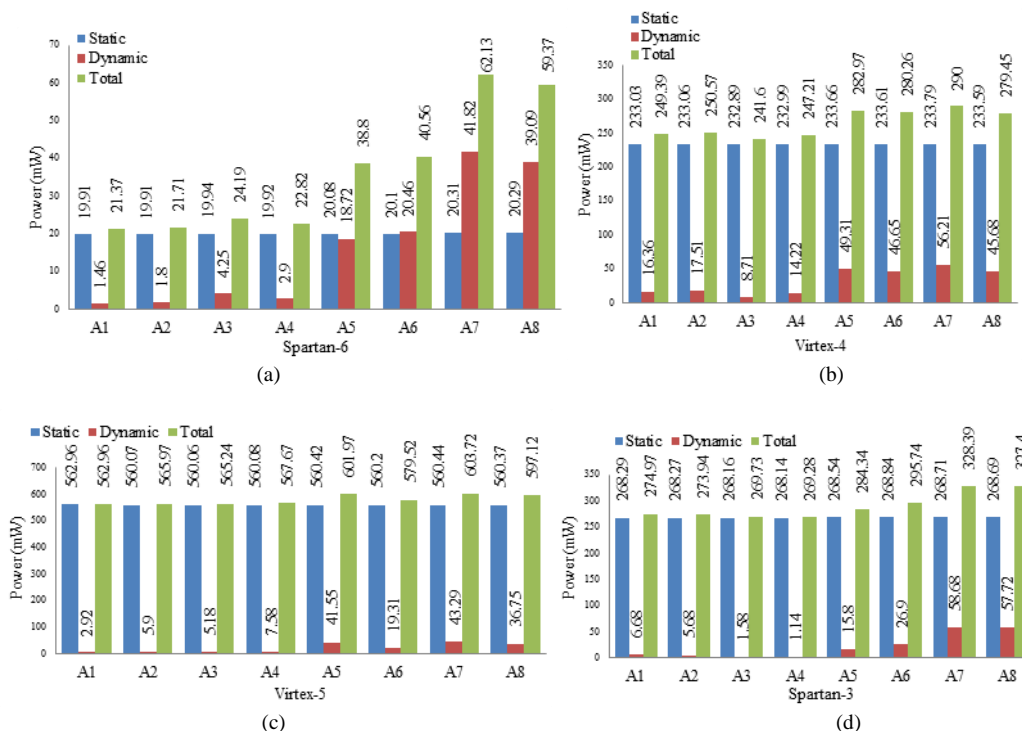


Fig. 12. Power consumption for all the architectures in different platforms (a) Spartan-6 (b) Virtex-4 (c) Virtex-5 (d) Spartan-3

FPGA Implementation of RECTANGLE Block Cipher Architectures

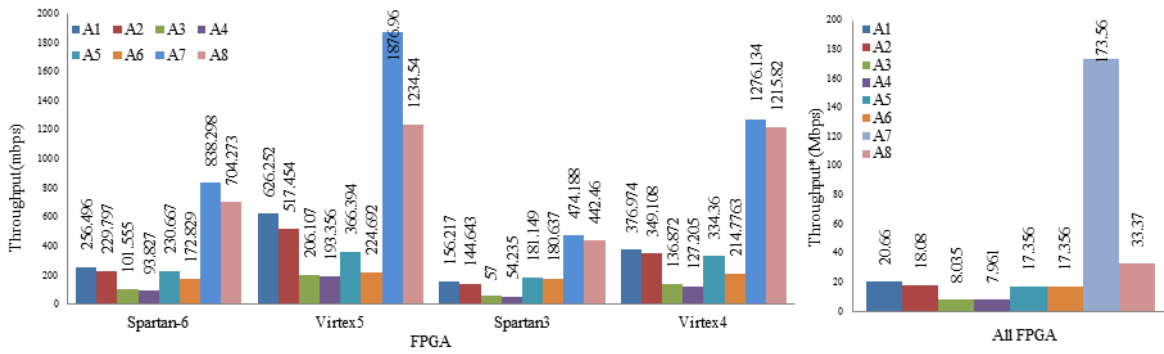


Fig. 13. Throughput obtained for all the architectures using different platforms at (a) Maximum operational frequency (b) Frequency of 13.56 MHz

While for LUT-6 FPGA, there is variation in resource consumption. Spartan-6 uses less number of slices for implementation as compared to Virtex-5. This is due to variation in architecture design of the slices in the FPGA. The best result for resource consumption is given by Spartan-6 FPGA. The number of flip-flops utilized by any architecture remains consistent for all the platforms.

Number of flip-flops used is least for BRAM based architecture (A5/A6) followed by Iterative design with partial loop unrolling (A7). Least number of slices is used by 16-bit architecture with 80-bits key scheduling (A3) for Spartan-6 FPGA, with reduction of 38.18% as compared to base architecture (A8). Iterative design (A1) gives 55.03% reduction in the number of flip-flops and 34.65% reduction in the number of LUTs as compared to A8. In RAM based Architecture (A5/A6), the number of flip-flops needed for implementation is reduced by 96.07% as compared to 16-bits architecture with 80-bit key scheduling (A3). This reduction in number of flip-flops remains the same for all four FPGAs. Remaining unused flip-flops are free to be used for any other purpose. On implementing S-box in BRAM (A6), resource consumption is reduced further. For Spartan-6, number of LUTs in A6 is reduced by 41.17% as compared to A8.

Fig. 12 illustrates power consumption for all designs. It is observed that static power remains nearly constant for all the architectures. Dynamic power changes due to switching activity of the FPGA. Power analysis shows variation based on the type of FPGA used for the implementation of the architecture. Implementation in Virtex-5 FPGA requires less dynamic power and more static power as compared to Virtex-4. It is observed any architecture implemented in Spartan-6 FPGA requires relatively less power consumption than any other FPGA. Iterative designs (A1/A2) required less power consumption for their implementation in LUT-6 FPGA. While for LUT-4 FPGA RAM based designs require less power.

Fig. 13 provides an illustration of throughput obtained for all the designs. It is seen that the best throughput results for maximum operational frequency as well as for frequency of 13.56 MHz are given by A7. In this design, latency is also less than other architectures. As compared to A8, latency of A7 is decreased by 80.76%. Throughput (Thr*) of A7 is 5.20 times that of A8. Best value of throughput at maximum operational frequency is given for Virtex-5 platform. For this FPGA, throughput is increased by 52.03% as compared to

A8. Throughput of designs at a frequency of 13.56 MHz remains same for all the FPGA platforms.

Fig. 14 shows the graphical representation of throughput per slice obtained for different FPGA platforms. The advantage of A7 is that it requires just five clock cycles for generating the result. So, it gives good throughput for all four FPGA platforms. A7 gives best trade-off between resource consumption and throughput. Best value for throughput per slice is given for Spartan-6 platform. For LUT-4 FPGA, throughput per slice of A7 becomes nearly 2.6 times that of A8.

Least energy consumption is taken by A7 in all the four platforms. Energy requirement in A7 is reduced by nearly 80% as compared to A8 for all FPGA. However, while comparing architectures with ROM based key schedule (A7) with other designs, security concerns due to side channel attack should be kept in mind.

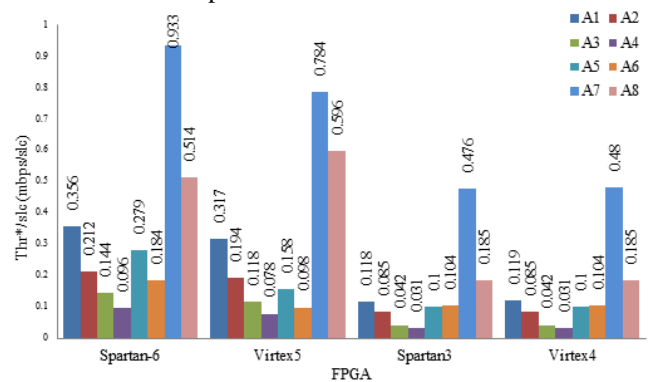


Fig. 14. Throughput/Slice for all configurations for different FPGA

VI. CONCLUSION

In this work evaluation and comparison of different hardware architectures of RECTANGLE block cipher is presented. All the architectures are implemented in four different FPGA platforms. Results are evaluated with similar implementation tools and design environment. This leads to a fair evaluation of all the designs in a given FPGA platform.

It is observed that Spartan-6 FPGA provides the least resource and power consumption among all other FPGAs.

16-bit architecture with the 80-bits key schedule (A3) is a good alternative if area/security trade-off is required. If the requirement is of higher security, architecture with 128-bits key schedule (A2/A4) is desirable. Iterative architecture (A1) is providing a good trade-off between throughput per slice and energy requirement. RAM-based architecture (A5/A6) needs the least number of registers for its implementation. Best trade-off among throughput and area is given by Iterated design with partial loop unrolling (A7). It also gave the best energy consumption results for all four FPGA platforms.

All the architectures have different power consumption and have different requirement of resources for their implementation in different FPGA platforms. According to the requirement, appropriate architecture can be selected for an application.

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