



NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS

DEPARTMENT OF INFORMATICS AND TELECOMMUNICATIONS

THESIS

**FPGA Implementation using VHDL of the AES-GCM 256-bit
Authenticated Encryption Algorithm**

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Supervisor: Antonis Paschalis, Professor

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

**ΣΧΟΛΗ ΘΕΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
ΤΜΗΜΑ ΠΛΗΡΟΦΟΡΙΚΗΣ ΚΑΙ ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ**

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**Υλοποίηση σε FPGA με τη Χρήση VHDL του Αλγόριθμου
Κρυπτογράφησης με Πιστοποίηση Αυθεντικότητας
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ABSTRACT

Achieving high-speed network performance along with data integrity and security was always a challenge. The necessity to communicate through public channels securely led to the use of asymmetric key cryptography algorithms that commonly use a “handshake” mechanism allowing the implementation of a “trust” system that could quarantine the security of the transaction and the integrity of the data as long as the algorithm could provide strong resistance to cryptographic attacks. Although, there is no mathematical proof that these algorithms are invulnerable to attacks there is strong indication that they are highly resistant to most of them, making brute force the only attack that can have a 100% success rate which is countered by the huge computational power someone needs to succeed.

While asymmetric key cryptography algorithms were the solution to public communication, the ongoing demand for higher bandwidth made the use of them inefficient, because the complexity of the algorithms demanded a processing cost that were creating latency gaps. A solution to this problem was the use of symmetric key algorithms for data transactions where the processing cost is much lower, so that the transaction security was intact but the bottleneck on the encryption/decryption speed limit was increased.

The analysis in symmetric cryptographic algorithms resulted in the creation of the Advanced Encryption Standard (AES) published by NIST in 2001. Also the need of authentication and integrity of information transmitted, resulted in the creation of the AES-GCM mode which can authenticate a stream of data (up to 68Gb) with reliable and efficient way. Both algorithms have the advantage to be easily implemented in both software and hardware. With the demand of high speed interaction between networks and systems, it became clear that hardware solutions were the leading option to cover this demand. FPGA-based IP cores can implement those algorithms, with the use of hardware description language like VHDL, and provide accurate, reliable and high speed data process.

In this thesis, we have designed in VHDL and implemented in Xilinx Virtex-5 FPGA technology an AES-GCM algorithm that performs authenticated encryption with an encryption key of 256 bits. Our AES-GCM implementation utilizes a non-pipelined version of the AES core and needs 15 cycles to encrypt 128-bits of plaintext, which is the minimum encryption duration supported without pipelining. Concerning the authentication process, our IP core can complete the authenticate process in 16 cycles. Our implementation of the AES-GCM algorithm with AES key = 256 bit, initialization vector (IV) vector = 96 bit, and a full parallel GHASH multiplier on a Xilinx's Virtex-5 XC5VFX130T FPGA that is pin-to-pin compatible with the Space-grade Xilinx's Virtex-5QV FPGA requires 5% of slices and 1% of BRAMs. The maximum achievable clock frequency is 227.690 MHz.

SUBJECT AREA: Embedded Systems

KEYWORDS: AES, encryption, GCM, authentication, FPGA, VHDL, block cipher, MAC

ΠΕΡΙΛΗΨΗ

Η επίτευξη υψηλών ταχυτήτων μετάδοσης δεδομένων στα τηλεπικοινωνιακά δίκτυα μαζί με την ανάγκη για αξιόπιστη και ασφαλή μετάδοση των πληροφοριών ήταν πάντα μια πρόκληση. Η ανάγκη για επικοινωνία μέσω δημόσιων δικτύων με ασφαλή τρόπο, οδήγησε στην χρήση αλγόριθμων κρυπτογράφηση ασύμμετρου κλειδιού, όπου ένας μηχανισμός «χειραψίας» εξασφαλίζει την ασφαλή μετάδοση δεδομένων και την ακεραιότητα αυτών. Παρόλο που μαθηματικά δεν έχει αποδειχτεί ότι αυτοί οι αλγόριθμοι είναι άτρωτοι σε κρυπτογραφικές επιθέσεις, υπάρχουν ισχυρές ενδείξεις ότι είναι ανθεκτικοί στις περισσότερες κάνοντας την επίθεση ωμής βίας (bruteforce) την μόνη που έχει 100% πιθανότητα επιτυχίας δεδομένης τεράστιας υπολογιστικής ισχύος.

Ενώ οι αλγόριθμοι ασύμμετρου κλειδιού ήταν η λύση για τις δημόσιες επικοινωνίες, η συνεχής απαίτηση για μεγαλύτερο εύρος ζώνης, έκανε την χρήση τους μη αποδοτική λόγω του υψηλού κόστους που απαιτούν σε υπολογιστική ισχύ. Η λύση στο πρόβλημα ήρθε με την υβριδική χρήση αλγορίθμων συμμετρικού και ασύμμετρου κλειδιού, έτσι ώστε να διατηρείτε ασφαλή μεταφορά δεδομένων αλλά η ταχύτητα επεξεργασίας των δεδομένων να αυξηθεί σημαντικά.

Η ανάλυση στους συμμετρικούς αλγόριθμους οδήγησε στην δημιουργία του αλγορίθμου κρυπτογράφησης Advanced Encryption Standard (AES) που δημοσιεύτηκε από τον οργανισμό NIST το 2001, ως διάδοχο του DES. Η ανάγκη για αυθεντικοποίηση των δεδομένων οδήγησε στην δημιουργία του αλγορίθμου GCM όπου μπορεί να αυθεντικοποιήσει μια ροή δεδομένων με αξιόπιστο και αποδοτικό τρόπο. Και οι δύο αλγόριθμοι έχουν το πλεονέκτημα ότι μπορεί να υλοποιηθούν εύκολα τόσο σε λογισμικό όσο και σε υλικό. Με την ζήτηση για υψηλές ταχύτητες να είναι μεγάλη, η υλοποίηση σε υλικό γίνεται μια όλο και πιο ελκυστική επιλογή. Οι πυρήνες IP με βάση την τεχνολογία FPGA μπορούν να υλοποιήσουν αυτούς τους αλγόριθμους με την χρήση γλωσσών περιγραφής υλικού όπως η VHDL, και να προσφέρουν αξιόπιστη και υψηλών ταχυτήτων επεξεργασία δεδομένων.

Σε αυτή την εργασία σχεδιάσαμε χρησιμοποιώντας την γλώσσα VHDL και υλοποιήσαμε στο FPGA Virtex 5 XC5VFX130T της Xilinx, τον αλγόριθμο κρυπτογράφησης AES με το πρωτόκολλο αυθεντικοποίησης GCM, με μέγεθος κλειδιού στα 256 bits. Η υλοποίηση μας βασίζεται σε μια μη σωληνομένη εκδοχή του αλγορίθμου AES που μπορεί να κρυπτογραφήσει ένα μπλοκ 128 bits σε 15 κύκλους. Η αυθεντικοποίηση του μηνύματος μπορεί να επιτευχθεί σε 16 κύκλους. Η υλοποίηση μας με $IV = 96$ bits και παράλληλο πολλαπλασιαστή χρειάζεται 5% από τα slices και 1% από τα BRAMs του Virtex-5 XC5VFX130T FPGA. Η μέγιστη δυνατή συχνότητα είναι 227.690 MHz.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Ενσωματωμένα Συστήματα

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: AES, κρυπτογράφηση, GCM, αυθεντικοποίηση, VHDL, FPGA, μπλοκ κρυπτογράμματος, MAC

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1. INTRODUCTION

Embedded systems are a common solution to cryptographic algorithms for network communication uses. They can provide high bandwidth, maximizing throughput and reliability. The rising trend on embedded systems is the FPGA. Field Programmable Gate Arrays (FPGAs) are semiconductor devices based around a matrix of configurable logic blocks (CLBs) connected via programmable interconnects. FPGAs are reconfigurable devices that can implement any desired application or functionality requirements after manufacturing. This feature distinguishes FPGAs from Application Specific Integrated Circuits (ASICs), which are custom manufactured for specific design tasks. While FPGA are inferior to ASIC in matter of processing power, low cost and design flexibility make FPGA a fitting solution to certain applications like network communications and aerospace applications.

With data encryption, the need for authentication required the use of specific operation modes that made the computational processes more demanding. The need for minimum latency led to the creation of algorithms that could be parallel processed and implemented in both software and hardware. The Galois/Counter Mode is an authentication mode used along with the AES algorithm as an expansion. Meeting the required criteria, GCM is an efficient authentication algorithm that can be parallelized, making its computational cycle needs in a range of 128 cycles to 1 cycle, with cost on chipset area coverage.

In this thesis, we are going to implement the encryption part of a symmetric key cryptographic algorithm, the AES, along with the authentication mode GCM, using VHDL. The system will be implemented in an FPGA device, with main objective the maximum throughput possible which translates to minimum clock cycles needed for completion of operation. With these goals in mind we are going to analyze the core functions of the algorithm, following by performance analysis and hardware limitations.

In Chapter 2 we are going to discuss the background theory necessary to understand how AES-GCM works. In chapter 2.1 we present a reference to the AES and in chapter 2.2 a reference to GCM. Chapter 3 refers to the mathematical components of the algorithms, were in chapter 3.1 we present some basic mathematic notations that we are going to use during our analysis and implementation, in 3.2 we present the AES components and in 3.3 the GCM components. In chapter 4 we make a performance analysis and we structure the basic design that we are going to use in chapter 5 were we implement and simulate the design in a FPGA.

The software we used for this thesis was:

- Xilinx *ISE 14.7 WebPack* edition for implementation of the code in VHDL
- Xilinx *Isim* for test bench simulation and validation

The hardware we used to use for this thesis was:

- Virtex 5 XC5VLX50T with package FF1136 of Xilinx FPGA family.

2. CRYPTOGRAPHY

In this chapter we are going to present the theoretical background that is required to understand the key points of the encryption and authentication mechanism of AES-GCM. In chapter 2.1 we discuss the AES algorithm in a simplified manner so that we can understand the importance of the algorithm and why is one of the most powerful symmetric key cryptographic algorithms. In chapter 2.2 we analyze the authentication modes that were proposed from NIST and why GCM is our choice of authentication.

2.1 AES - (Advanced Encryption Standard)

AES is a symmetric block cipher algorithm used to protect classified information from being compromised by a not authorized user. The encryption mechanism allows only those that have access to the key used for the encryption to have access to the information. Also known as Rijndael cipher algorithm, AES was proposed by two Belgian cryptographers, Joan Daemen and Vincent Rijmen, who submitted it to NIST during the AES selection process. The need of increased security, flexibility in implementation and high performance led Rijndael to be the winning candidate of the competition, making it a security standard by NIST, replacing 3DES and becoming the recommended option for sensitive data transactions.

The basic criteria AES needed to meet were:

- It can handle 128-bit data size blocks.
- Accepts key size blocks of 128, 192 and 256 bits.
- Has no academic weakness worse than exhaustive key search.
- It should be as fast as 3DES.

The criteria were met and the standard was established by NIST in 2001.

AES encryption mechanism, as all block cipher algorithms, consists of a key and data for encryption. The data are separated in a number of static size blocks with upper ceiling logic, and then each block is encrypted to what is known as cipher block. Then the cipher information can only be decrypted by the same key use for encryption synthesizing each block to the original data. Both in encryption and decryption the number of operations is the same but the operations are reversed. While the key block size is unlimited, the data block size can be a maximum of 256 bits. For purposes of performance and optimization the most common values for the key block size are 128, 192 and 256 bits, and a fixed value for the data block size of 128 bits. AES design is based on a substitution-permutation network (SPN), combination of substitution and permutation operations on the block of data and the key given.

The resistance of AES towards differential and linear cryptanalysis comes from an “avalanche effect” created during the algorithm operations, meaning that a bit flip quickly propagates to the complete internal state. This effect is granted by a number of operations which is applied to both data and the key in repetitive process that is called “rounds”. At each round the algorithm uses 4 key operations which scramble the data and prepare it as input for the next round creating a chaining process. In every round,

with the exception of the final round, these operations apply on a fixed 128-bit block and the key given after it has been expanded. Those operations are: SubBytes, ShiftRows, MixColumns, and AddRoundKey.

The key expansion is a basic operation that expands the initial key input into separate round keys. Each round key is the one that is used at each round making it different from the others. This operation is the one that dictates how many rounds each data block will be processed before becoming the output, according with the key block size given.

The algorithm describing AES with 128-bit data block size given by FIPS is the following:

```
Cipher (byte in [4*Nb], byte out[4*Nb], word w[Nb*(Nr+1)])
begin
  Bytestate [4,Nb]
    state = in
    AddRoundKey (state, w[0, Nb-1])
    for round = 1 step 1 to Nr-1
      SubBytes(state)
      ShiftRows(state)
      MixColumns(state)
      AddRoundKey(state, w[round*Nb, (round+1)*Nb-1])
    end for
    SubBytes(state)
    ShiftRows(state)
    AddRoundKey(state, w[Nr*Nb, (Nr+1)*Nb-1])
  out = state
end
```

Where Nb is the number of words (4 bytes) the block has. This number is defined as 4 because we need $4 * 4 \text{ bytes} = 32 \text{ bits} * 4$ to have a 128-bit block. Nr is the number of rounds. The functions describing the algorithm we be presented in chapter 3.1

2.2 GCM - (The Galois/Counter Mode)

An authentication algorithm must quarantine that the data send are authentic and that their source is a user who has access to the encryption key. From 2001 till now, NIST has published a total of 4 recommendations for the block cipher mode of operations SP800-38A, SP800-38B, SP800-38C and SP800-38D.

In SP800-38A there are 5 modes of operation recommended from NIST

- Electronic Codebook (ECB) mode
- Cipher Block Chaining (CBC) mode,
- CipherFeedback (CFB) mode,
- Output Feedback (OFB) mode, and
- Counter (CTR) mode

ECB and CTR are non-feedback modes, while CBC, CFB and OFB are feedback modes. Feedback mode means that the result of the current executing step of the algorithm is depended from the previous step. Feedback operations need iterative architecture meaning low performance purposes. For that reason, ECB and CTR are preferred.

In SP800-38B NIST suggested a message authentication code (MAC) based on the cipher block. This cipher-based MAC is called CMAC or Cipher Block Chaining MAC

(CBC-MAC). In SP800-38C NIST introduced a mode of operation called CCM based on symmetric key block cipher where block size is 128 bits. CCM provides the confidentiality and authenticity needed by combining CTR mode and CBC-MAC.

The throughput given by CTR mode is greater than that of CBC-MAC, because in the case of CTR the implementation can be done with pipeline techniques. CBC-MAC implementation cannot be parallelized. Until this point there was no efficient solution for high speed networking.

The fourth and last article covers that gap. In SP800-38D NIST the *Galois/Counter Mode of Operation (GCM)* is provided with minimum latency and minimum operation overhead as key advantages. This can be achieved because the algorithm can be parallelized, making the multiplication process, which is the most demanding, completed in one single clock cycle. One core advantage is that the system is "online" meaning that while you need the length of the message as information for the authentication, this is calculated during the processing of data. Also the initialization vector and all others no-authenticated components can be initialized. GCM provides a strong authentication algorithm which transcends a no-cryptographic check sum or an error detection system.

The GCM authentication mechanism consists of a hashing function, also known as GHASH, where the data to be encrypted and all the additional authentication data are used to create a unique 128-bit block of data known as "tag". The tag is send along with the encrypted data, and then is used to ensure that the encrypted data belong to someone who has access to the key. A wrong tag will result in a fail indication from the system meaning that the data or a part of them are not authentic.

3. MATHEMATICAL COMPONENTS OF AES-GCM

In this chapter we are going to describe the mathematical components that we are going to use in our implementation, as long as the notation referring to them. In chapter 3.1 we present some basic function that are needed for our system. In chapter 3.2 we present the core functions of AES and the steps that are necessary for each operation. In chapter 3.3 we analyze the key components of GCM and the additional steps needed.

3.1 Basic functions

The following symbols are the mathematical and operational components we going to need to described the main operation of both AES and GCM algorithms.

- Ceiling function - $\lceil x \rceil$: Returns the smallest integer number which is not smaller than x .

Example: $\lceil 4.7 \rceil = 5$

- Concatenation - \parallel : is the operation in which two bit string are combined as one.

Example: $0001 \parallel 1001 = 00011001$

- Special power notation - 0^s : Refers to a bit string with s zeros (0).

Example: $0^7 = 0000000$

- Exclusive OR (XOR) - \oplus : Given two bit strings with the same length, it applies the XOR operation. The XOR operation is described by the following table

x	y	$x \text{ XOR } y$
0	0	0
0	1	1
1	0	1
1	1	0

Example: $0011 \oplus 1001 = 1010$

- Length function - $len(x)$: Returns the length in decimal, of a bit string.

Example: $len(001) = 3$, $len(001||0^3) = 6$

- Least/Most significant bits - $LSB_s(x), MSB_s(x)$: Given a bit string x and an integer s with $s \leq len(x)$, both functions return s bits from x with $MSB_s(x)$ returning leftmost bits and $LSB_s(x)$ rightmost bits.

Example: $LSB_5(0001001110011) = 10011$, $MSB_4(0001001110011) = 0001$

- Shift operation - $x \gg s, x \ll s$: Given a bit string x and an integer s it shifts s bits from x to right (\gg) or left (\ll). Those operations do not apply on signed or negative numbers.

Example: $0001100110111 \gg 4 = 000000110011$, $101011 \ll 2 = 101100$

3.2 AES functions

The basic structure of the AES decomposes the data block following a number of rounds of substitutions and permutations which will lead to the final product in the last round. The number of rounds is associated with the size of the key we are using (Figure 1).

	Key Length (32-bit word)	Block Size (32-bit word)	Number of Rounds
AES-128	4	4	10
AES-192	6	4	12
AES-256	8	4	14

Figure 1: AES number of rounds

The block is decomposed in 16 bytes which are considered as an array of 4x4 bytes also known as State array. The State array is filled in columns with first 8-MSB is placed in first position of the first column second 8-MSB at second position of the first column etc. Each byte is marked as $S(i, j)$ with $0 \leq i, j \leq 4$ and constitutes of the finite field $GF(2^8)$ with the irreducible polynomial $p(x) = x^8 + x^4 + x^3 + x + 1$ be the one used in the AES.

Data block conversion to State array (128-bit input) (Figure 2)

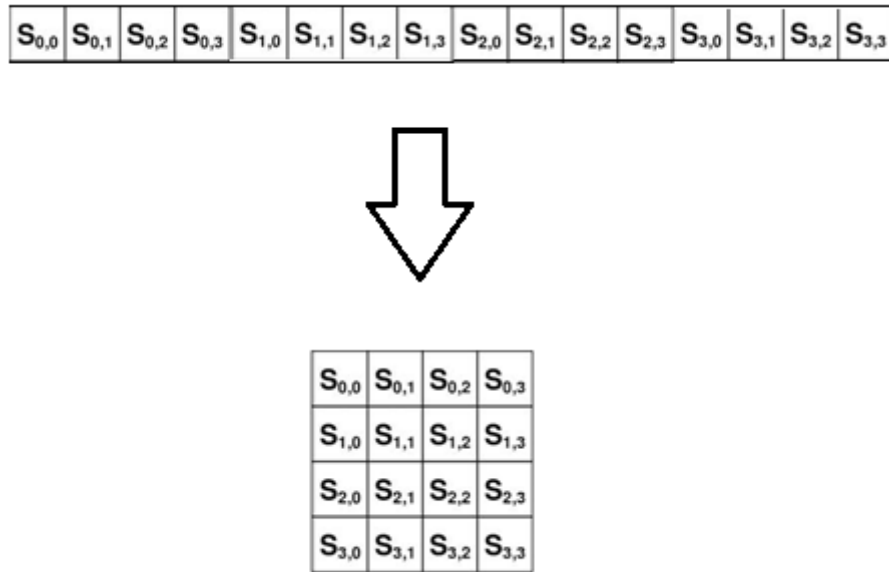


Figure 2: State array 128-bit

At each round substitutions and permutations are applied to the State array until the final round. These calculations use the following algorithms:

- **SubBytes:** A Non-Linear Transformation where each byte is substituted with a substitution array (S-box).
- **ShiftRows:** A row is transferred with cyclic model for a number of steps to a new position.
- **MixColumns:** A Linear Transformation is applied at each column based in the 4 bytes of the column.
- **AddRoundKey:** Each byte of the State array is combined with a byte of the round key as it has been formed from the key expansion algorithm.

SubBytes Transformation

In this step a Non-Linear Transformation is applied on each byte with each byte from the S-box. The S-box is a look-up-table (LUT) created by a reversible array 16x16 with the 4 leftmost bits from each byte being used as row index and the 4 rightmost bits as column index.

The S-box used in the AES is illustrated in Figure 3

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
A	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
B	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
E	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

Figure 3: AES S-box

ShiftRows Transformation

In this step each row of the State array is modified with the following pattern. The first row doesn't change at all. The second row is modified with each element i (byte) being moved to the position $i+1$ and for $i=3$ then move to $i=0$.

Example: $S(1,1) \rightarrow S(1,2)$

The third row is modified with each element i (byte) being moved to the position $i+2$

The fourth row is modified with each element i (byte) being moved to the position $i+3$

Figure 4 shows the algorithm

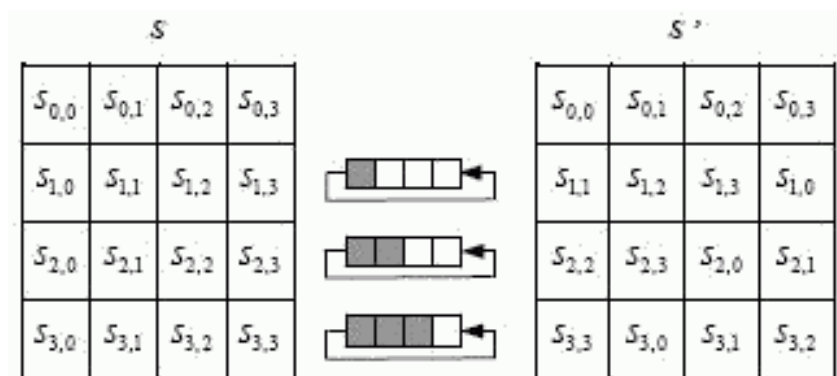


Figure 4: ShiftRows illustration

MixColumns Transformation

In this step we consider each column as polynomial over $GF(2^8)$ and is then multiplied modulo $x^4 + 1$ with a fixed polynomial : $a(x) = 3x^3 + x^2 + x + 2$.

This results in a fixed array that each column is multiplied with to give the new column (figure 5).

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

Figure 5: MixColumns illustration 1

Figure 6 shows this method on the State array for the second column.

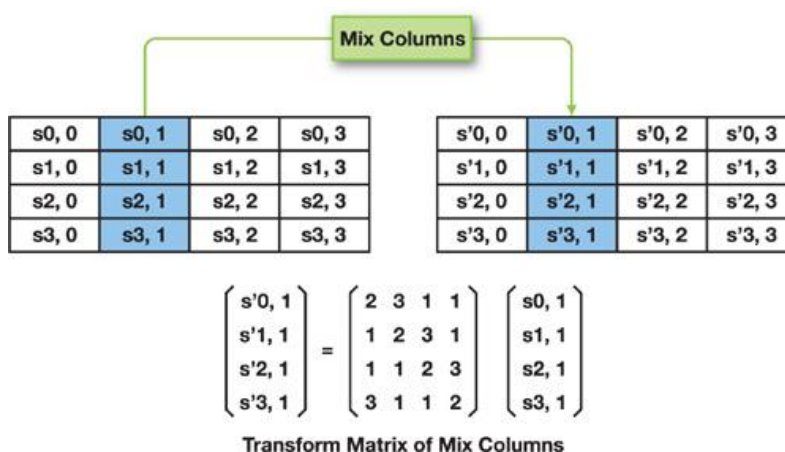


Figure 6: MixColumns illustration 2

AddRoundKey Transformation

Followed by the three previous steps in this step we apply a XOR operation over the 128 bits of the State array and 4×32 bit words from the round key. This is the only step where the key is used to encrypt the data.

Key Expansion

This algorithm expands the initial key so that a different round key is used in each round. The total number of keys produced is different for the 192-bit and 256 bit versions. We need $x \times \text{round keys} + 1$ and we split each key to 4 32-bit words.

For the first round the round key is the original key meaning the first 4 words $w[0]$, $w[1]$, $w[2]$, $w[3]$. For the next rounds each word $w[i]$ is constructed from the $w[i-1]$ and the $w[i-4]$ with a simple XOR between them. But for every $w[i]$ with $i \bmod 4 = 0$ there is an extra calculation.

For every $w[i]$ with $i \bmod 4 = 0$:

$$w[i] = ((w[i-4]) \text{ S-box (RotWord}(w[i-1])))) \text{ XOR (Rcon)}$$

-RotWord : Rotates a word transferring byte in position 0 to 4 and moving all other bytes a step left ($\text{RotWord}(w[0],w[1],w[2],w[3]) = w[1],w[2],w[3],w[0]$)

-SubWord: Substitutes each byte from $w[i-4]$ to each byte from $\text{RotWord}(w[i-1])$.

-Rcon: Rcon stands for round constant and it's a constant with 3 rightmost bits always 0.

3.3 GCM functions

GHASH

The GHASH function is defined by $GHASH(H, A, C) = X_{m+n+1}$ where H is the Hash key, A is ADD which are not encrypted and C is the cipher text. The variable X_{m+n+1} is defined as:

$$X_i = \begin{cases} 0 & \text{for } i = 0 \\ (X_{i-1} \oplus A_i) \cdot H & \text{for } i = 1, \dots, m - 1 \\ (X_{m-1} \oplus (A_m^* \parallel 0^{128-v})) \cdot H & \text{for } i = m \\ (X_{i-1} \oplus C_{i-m}) \cdot H & \text{for } i = m + 1, \dots, m + n - 1 \\ (X_{m+n-1} \oplus (C_n^* \parallel 0^{128-u})) \cdot H & \text{for } i = m + n \\ (X_{m+n} \oplus (\text{len}(A) \parallel \text{len}(C))) \cdot H & \text{for } i = m + n + 1 \end{cases}$$

where m is the number of 128 bit blocks in A , n is the number of 128 bit blocks in C , v is the bit length of final block of A and u is the bit length of final block of C. This is an iterative algorithm where each X_i depends on X_{i-1} and the final X_i is the output.

Multiplication ($X \cdot Y$)

The \cdot operation on (pairs of) the 2^{128} possible blocks corresponds to the multiplication operation for the binary Galois (finite) field of 2^{128} elements. The $GF(2^{128})$ field used is defined by the polynomial $x^{128} + x^7 + x^2 + x + 1$. The following algorithm is defined by NIST SP-800-38D for the multiplication process.

Algorithm: $X \cdot Y$

Input:

Block X, Y.

Output:

Block $X \cdot Y$.

Steps:

1. Let $x_0x_1x_2\dots x_{127}$ denote the sequence of bits in X .

2. Let $Z_0 = 0^{128}$ and $Y_0 = Y$.

3. For $i = 0$ to 127, calculate blocks Z_{i+1} and V_{i+1} as follows:

$$Z_{i+1} = \begin{cases} Z_i & \text{if } x_i = 0 \\ Z_i \oplus V_i & \text{if } x_i = 1 \end{cases}$$

$$V_{i+1} = \begin{cases} V_i \gg 1 & \text{if } LSB_1(V_i) = 0 \\ ((V_i \gg 1) \oplus R) & \text{if } LSB_1(V_i) = 1 \end{cases}$$

Return Z^{128} .

4. DESIGN OF AES-GCM-256

In this chapter, we analyze the algorithm steps and the limitations we have on a hardware implementation for the encryption process. In AES-GCM algorithm, AES core and GHASH core are the basic modules which are responsible for confidentiality and authentication, respectively. In chapter 4.1 we present the AES module and its parameters; in chapter 4.2 we present the GHASH module. The hardware implementation is presented in chapter 4.

4.1 AES Module

The AES module implements the AES algorithm for encryption at 256 bits. The signals inputs are a 256-bit key that is used for encryption, the data to be encrypted at 128 bits and the function control signal including a clock signal, a reset button and a start button. The output signals are the data ciphered at 128 bits, same as data input, and a done button that indicates the completion of the process.

4.1.1 Key Scheduler Module

The key scheduler module has the following inputs. A 256-bit key, 2 control buttons, a round indicator control button, a clock signal and a reset signal. For output we have the round key. As explained in the mathematical section each round key is used in a sequence of computational actions to produce the final product cipher.

Each round starts by splitting the 256 key into 8 x 32 bit registers. Each register result is used in a XOR operation with the result from the Rcon output. The Rcon module is a round variable creator which constructs a unique value for each round in a repetitive process. For each round Rcon sets the following values:

Round	Value	Round	Value
1	00000001	8	00001000
2	00000001	9	00010000
3	00000010	10	00010000
4	00000010	11	00100000
5	00000100	12	00100000
6	00000100	13	01000000
7	00001000	14	01000000

Figure 7: Rcon rounds

Those values are expanded with the 24 left most bits of value “0”. The result is used to a XOR operation with the result from the S-Box. This output is used in a XOR operation with the first register feedback output following the second register which uses the result of the first register etc. creating a chain of sequential calculations.

The output of the algorithm is a 128-bit round key which is used in a XOR operation with the plain text to produce the round cipher. The round cipher is then used as input for the next round. For the round key we use the first 4 registers for odd number of rounds and the last 4 registers for even number of rounds, meaning that we use a feedback mechanism for the 256-bit key.

4.1.2 Control Unit

The control module for AES is a state machine that consists of 6 control indicators as output and 1 control as input. The process consists of a reset round “RST” , 14 operation rounds from R1 to R14 and one competition round R15. The “start” control button is an external signal that initializes the encryption operation at the current data and key input. “control_1” signal indicates the input for the module, where in R1 is the data entry and from R2 to R15 is the feedback. “control_2” indicates the last data entry for the last round. “key_control_1” refers to the key scheduler module and its valid input which is represented as “1”. “key_control_2” dictates which part of the expanded key is to be used for the encryption. Since we have a 256-bit key, the expanded keys are also 256 bits. So we use half of each expanded key at each round and “key_control_2” represent first half, 128 MSB, with the value “0” and second half, 128 LSB, with value “1”. In reality we expand the key 7 times and multiplied by 2 we get the 14 rounds.

The following state machine diagram illustrates the states involved in the AES control unit. The signal h_k stands for the “key_control_2” signal.

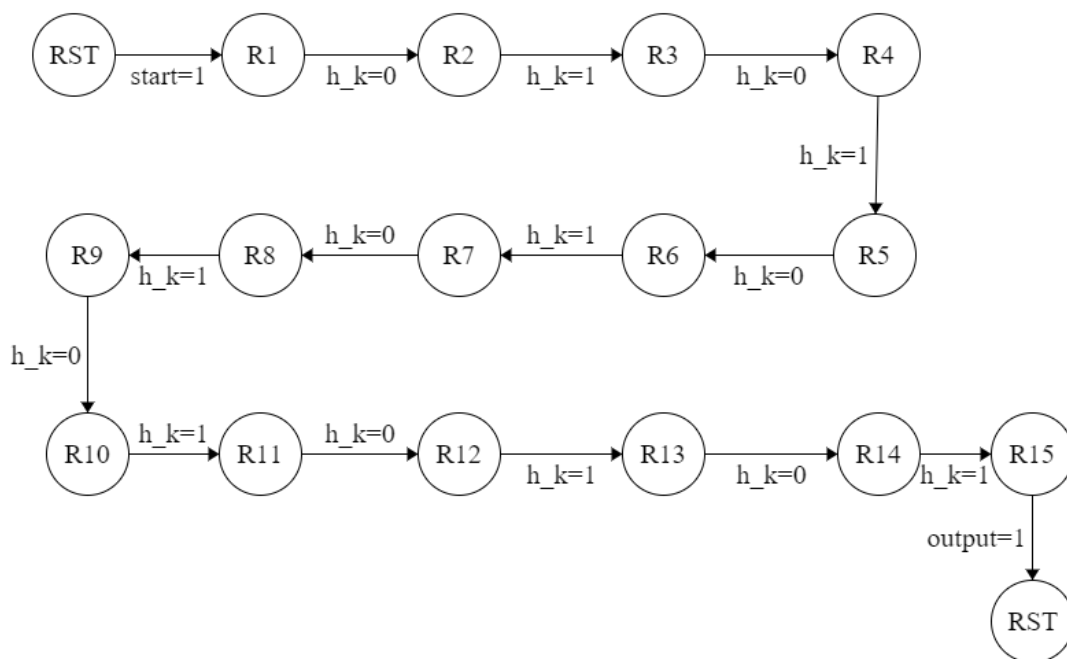


Figure 8: AES control FSM

4.2 GCM Module

The GCM module takes as input a plain text (P) that can be $2^{39} - 256$ bits long, an encryption key (K), additional authentication data (AAD) and an initialization vector (IV). The result is the ciphered text and a TAG which is used for authentication.

The plain text is separated in blocks of 128 bits. Each block is encrypted by the AES component while the output cipher block is used to produce the TAG output. The crucial component of the GCM is the GHASH function which constructs the TAG. It uses the AAD along with the cipher blocks produced by AES to create the TAG which is used from the receiver to authenticate the message. All the additional authenticated data may be used to authenticate information that must not be encrypted. For example, within a network protocol, the AAD might include addresses, ports, sequence numbers, protocol version numbers, and other fields that indicate how the plaintext should be treated.

The primary purpose of the IV is to be a nonce, that is, to be distinct for each invocation of the encryption operation for a fixed key. IV can have a fixed value or it can be generated randomly as long as distinctness of the IV values is highly likely.

Let n and u denote the unique pair of positive integers such that the total number of bits in the plaintext is $(n - 1) * 128 + u$, where $1 \leq u \leq 128$. The Plain text P is a sequence of P_i blocks where the last block is P_n and has u bits meaning that $P_n = P_n || 0^{128-u}$. The same applies for cipher text C_i .

The authenticated encryption operation is defined by the following equations:

$$H = E(K, 0^{128})$$

$$Y_0 = \begin{cases} IV || 0^{31} || 1 & \text{if } \text{len}(IV) = 96 \\ GHASH(H, \{\}, IV) & \text{otherwise} \end{cases}$$

$$Y_i = \text{incr}(Y_{i-1}) \text{ for } i = 1, \dots, n$$

$$C_i = P_i \oplus E(K, Y_i) \text{ for } i = 1, \dots, n - 1$$

$$C_n^* = P_n^* \oplus MSB_u(E(K, Y_n))$$

$$T = MSB_t(GHASH(H, A, C) \oplus E(K, Y_0))$$

In figure 9 we can see a graphical illustration of the algorithm

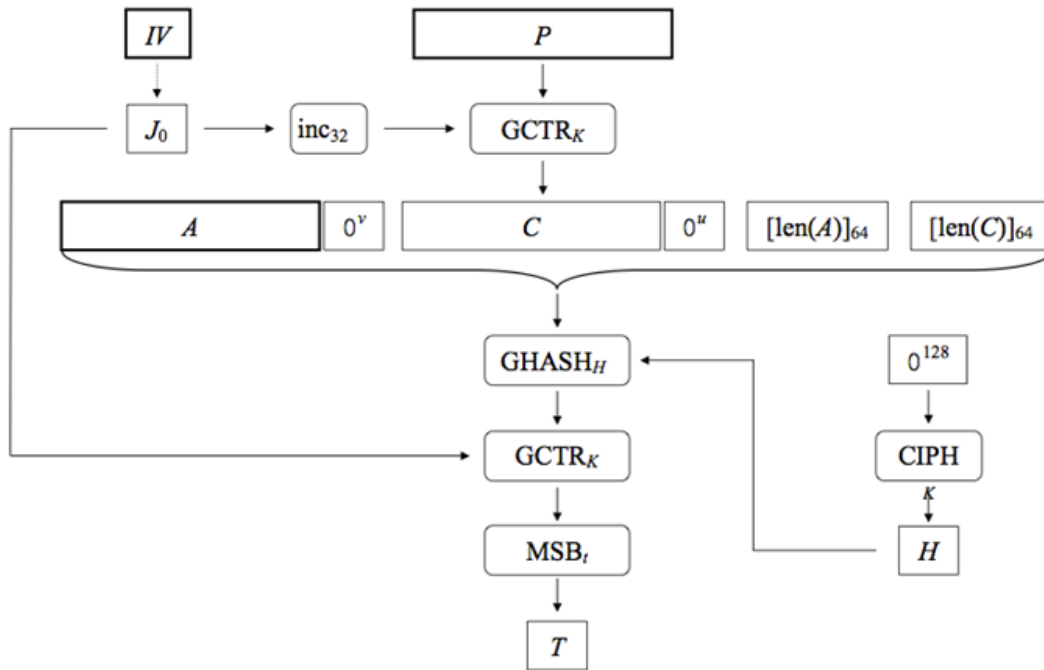


Figure 9: AES-GCM algorithm

In figure 10 we see a graphical illustration of the algorithm with two blocks of Plain text and one single block of additional authenticated data as input. $mult_H$ stands for multiplication in $GF(2^{128})$ by the hash key H an operation applied in $GHASH$ function.

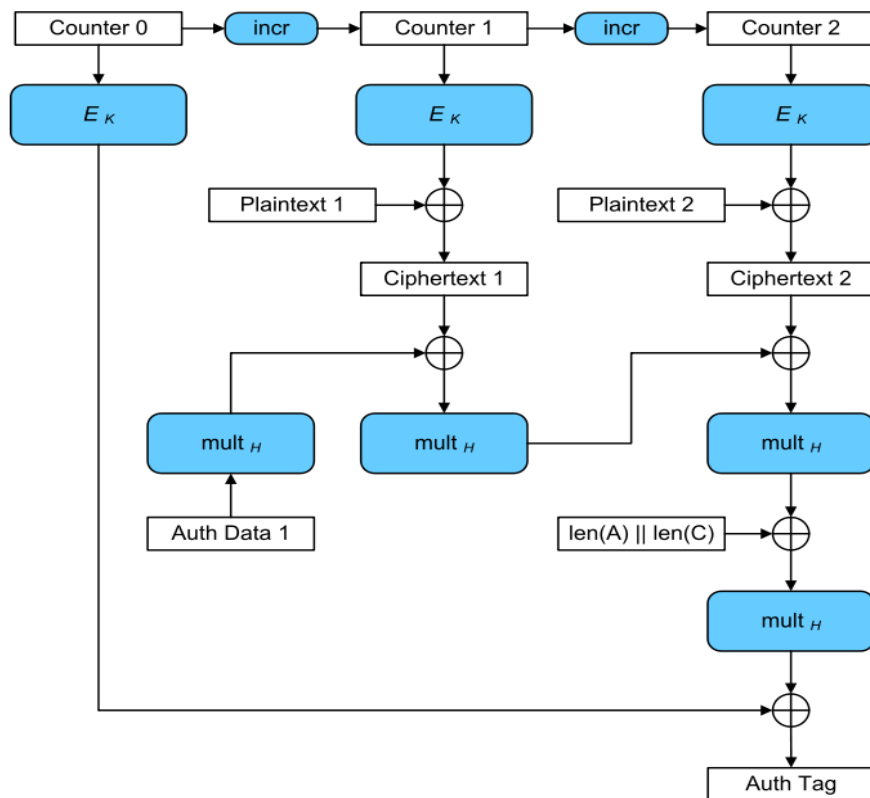


Figure 10: AES-GCM algorithm for 2 cipher blocks and 1 for ADD

4.2.1 GF multiplier

Following the algorithm NIST provided we can see that we need 128 repetitions or 128 clock cycles to find the result of $X \cdot Y$. This is highly inefficient knowing that AES can produce a result of a single block in 14 cycles of operation with 2 additional rounds for initialization and completion. One major advantage of GCM is that the multiplication operation can be parallelized so that the final output can be produced in a radius of operational cycles from 128 to 1. Each level of parallelization is ratio of area chip to cycle operation with those to be inversely proportional.

Mastrovito multiplier is a class of parallel multipliers over Galois fields based on polynomial basis representations. In the $GF(2^{128})$ considering 2 polynomials $a(x), b(x)$ the multiplication can be described as $c(x) = a(x) \cdot b(x) \text{ mod } (x^{128} + x^7 + x^2 + x + 1)$. Mastrovito proposed the use of a matrix $k \times k$ which is called the multiplication array and can be created from the combination of $a(x)$ and $x^{128} + x^7 + x^2 + x + 1$. Each element of the array Z is created from the reductive array R and $a(x)$ as follows:

$$Z_{i,j} = \begin{cases} a_i & \text{for } i = 0, 1 \dots k-1, j = 0 \\ u(i-j) \cdot a_{i-j} + \sum_{t=0}^{j-1} r_{j-1-t,i} \cdot a_{k-1-t} & \text{for } i = 0, 1 \dots k-2, j = 1, 2 \dots k-1 \end{cases}$$

$$\text{where } u(s) = \begin{cases} 1 & \text{if } s \geq 0 \\ 0 & \text{if } s \leq -1 \end{cases}$$

The result can be calculated as

$$C = Z \cdot B \rightarrow \begin{bmatrix} c_0 \\ \vdots \\ c_{k-1} \end{bmatrix} = \begin{bmatrix} Z_{0,0} & \cdots & Z_{0,k-1} \\ \vdots & \ddots & \vdots \\ Z_{k-1,0} & \cdots & Z_{k-1,k-1} \end{bmatrix} \cdot \begin{bmatrix} b_0 \\ \vdots \\ b_{k-1} \end{bmatrix}$$

It's hardware implementation can calculate each c_i with the use of AND gates and a tree structure of XOR gates. The following algorithm describes this parallel implementation.

Create an array of 128x128.

This array is Z_i for $i = 0, \dots, 127$ with $Z_0 = Y$ and

$$\cdot Z_{i+1} = \begin{cases} Z_i \gg 1 & \text{if } LSB_1(Z_i) = 0 \\ (Z_i \gg 1) \oplus R & \text{if } LSB_1(Z_i) = 1 \end{cases}$$

Each Z_i is input for Z_{i+1} . To create the result for C each bit of C will be calculated by using number of XOR and AND gates as follows.

Let $C(i)$ be the bit position i of C variable

for $i = 0, 1, 2, 3, \dots, 127$

$$C(i) = (Z_0(i) \wedge X(127)) \oplus (Z_1(i) \wedge X(126)) \oplus \dots \oplus (Z_{127}(i) \wedge X(0))$$

Figure 11 show the hardware implementation for a single bit

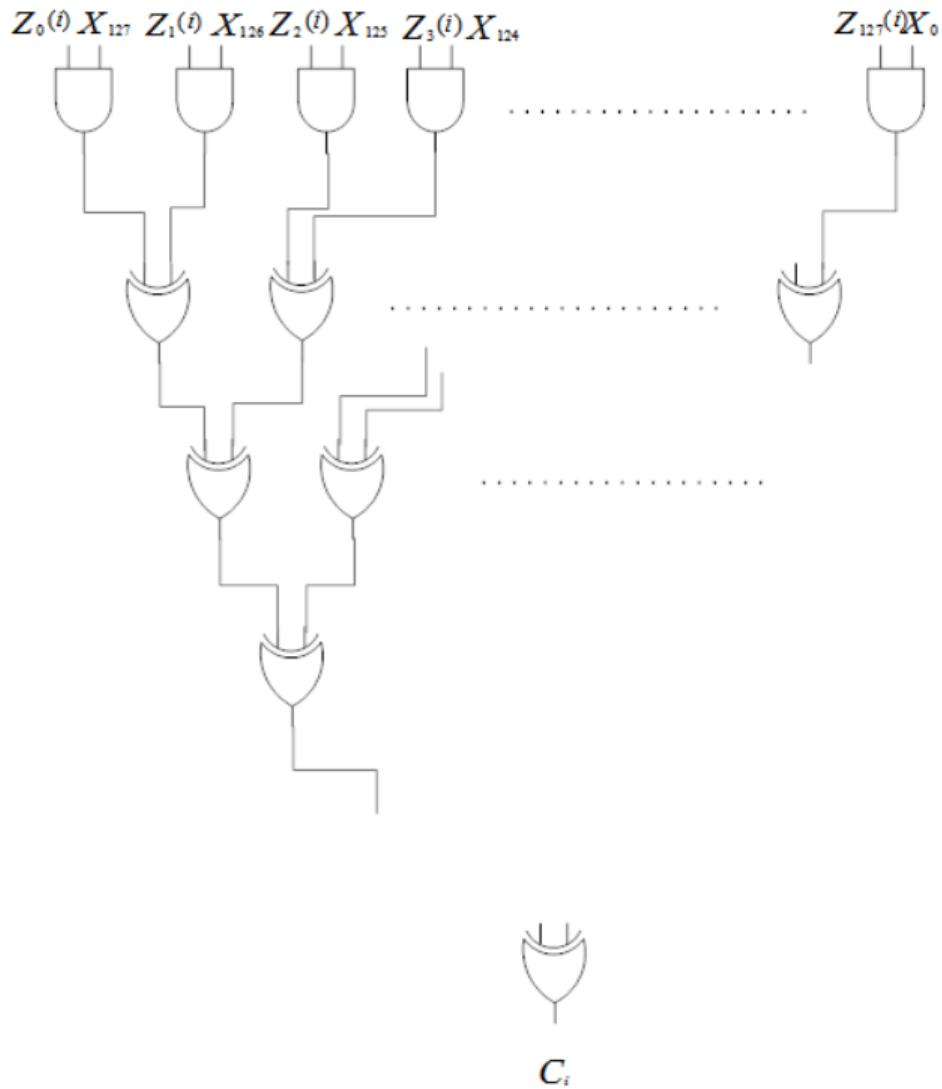


Figure 11: Matrovito multiplier logic gate representation

This can produce a result from the multiplication process in only 1 clock cycle since every input is output for the array but Z is calculating all its bits at the same time. The drawback of this implementation is that we need a large area and lot of combinational logic gates to make this multiplier component.

In figure 12 we describe the model of the GF multiplier in hardware perspective. The element R is defined in our implementation with the value $R = 7080000000000000$ in hexametrical system.

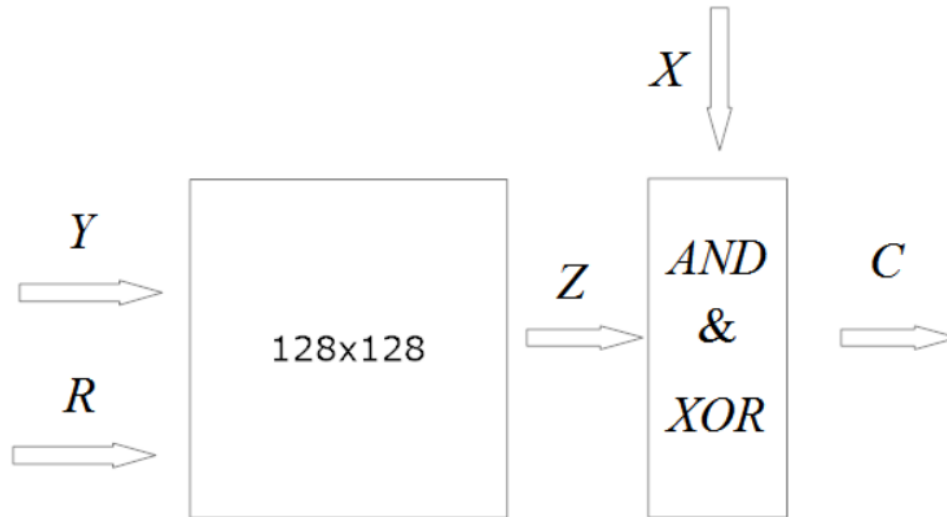


Figure 12: Matrovito model

4.2.2 GHASH

The main use of $GF(2^{128})$ multiplier is in the *GHASH* function to compress the cipher text and the additional authenticated data into one single block. The *GHASH* has a static parameter H which is the hash key and is calculated by inserting the input 0^{128} in AES and the key K . This value is calculated only at the beginning of a new message or when we have a new key.

The following algorithm describes the operations of *GHASH*

1. Let $X_1, X_2, X_3, X_4, \dots, X_m$ the unique sequence of blocks so that

$$X = X_1 || X_2 || X_3 || X_4, \dots, || X_{m-1} || X_m$$

2. Let Y_0 be the zero block 0^{128}
3. For $i = 1, \dots, m$ let $Y_i = (Y_{i-1} X_i) \cdot H$
4. Return Y_m

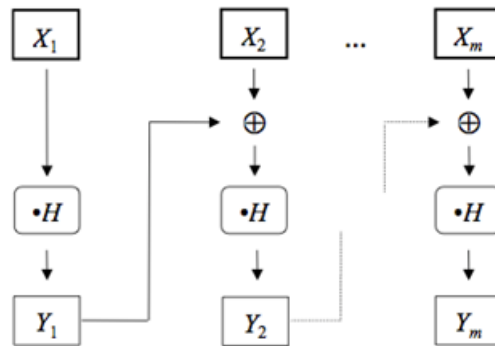


Figure 13: GHASH illustration

So we can see that *GHASH* calculates the following formula: $X_1 \cdot H^m X_2 \cdot H^{m-1} \dots \dots X_{m-1} \cdot H^2 X_m \cdot H^1$

GHASH is calculating a sequence of blocks of data and the input is depended by the output. So the operation of *GHASH* cannot be parallelized since we use the outcome for our next calculation. Considering this it is obvious that the main part of *GHASH* the $GF(2^{128})$ multiplier must be as fast as possible, making the parallel version of $GF(2^{128})$ a one way option.

4.2.3 GCTR

The mechanism of confidentiality of GCM is an alternative of CTR mode, which is called GCTR by using an incrementing function to take the necessary sequence of blocks. The first counter block is produced by incrementing one product block of the initialization vector IV.

The following algorithm describes GCTR function

Input:

1. Bit string X , of arbitrary length
2. Initial counter block icb , i. e. $IV \vee$ some values henerated IV
3. Approved block cipher $CIPH$ (such as AES) with a 128 – bit block
4. Key K

Output:

Bit string Y of bit length $len(X)$.

Steps:

0. If X is the empty string, then return the empty string as Y .
1. Let $n = \lceil \frac{\text{len}(X)}{128} \rceil$.
2. Let $X_1, X_2, X_3, \dots, X_{n-1}, X_n$ the unique sequence of bits such that: $X = X_1 || X_2 || \dots || X_{n-1} || X_n$.
3. Let $CB_1 = ICB$.
4. For $i = 2n$, let $CB_i = \text{inc}(CB_{i-1})$
5. For $i = 1n - 1$, let $Y_i = X_i \text{CIPH}_K(CB_i)$
6. Let $Y_n = X_n \text{MSB}_{\text{len}(X_n)}(\text{CIPH}_K(CB_i))$
7. Let $Y = Y_1 || Y_2 || \dots || Y_{n-1} || Y_n$
8. Return Y .

In step 1 we separate the input in a number of blocks where the last can be a complete block or nonempty partial block.

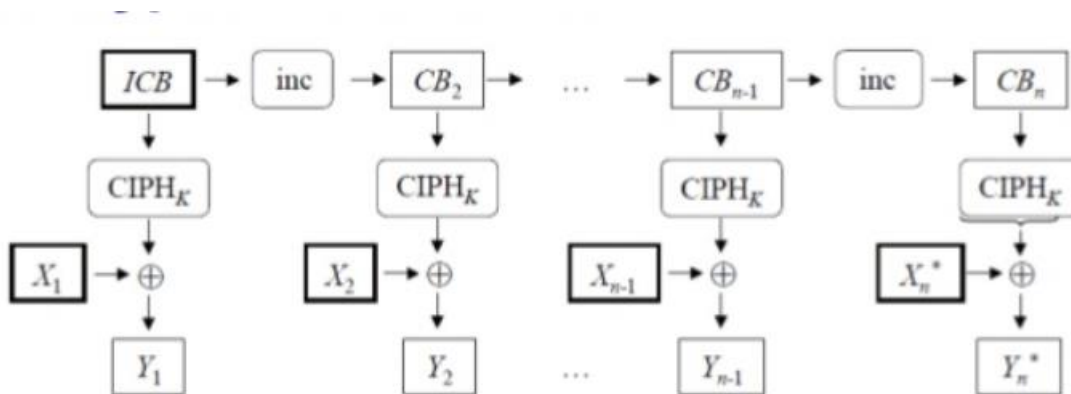


Figure 14: GCTR illustration

5. IMPLEMENTATION AND SIMULATION

The simulation process is the most important process in the design procedure and the most time consuming. It ensures that our system is functional and efficient, according to our design goals. Since we use a multi-level minimization approach on our design we must ensure that our bottom level components are simulated and optimized before we move to the next level. In this design we simulated the 2 key components AES to its upgraded version of 256-bit key size and GF multiplier. Finally, we simulated the complete design. The simulations of AES-256 and AES-GCM were completed using test vectors given by various online sources. At first, we analyze the upgraded aes-256 component with a test bench running on Isim. Then we analyze the GF multiplier and we apply a multiplication in a single clock cycle to achieve maximum efficiency using a parallel version of it. Finally, we simulate the complete design that implements the *GHASH* function and produces the TAG and uses the aes to make the cipher text.

5.1 AES-256

The main difference from version 128-bit to 256-bit is the number of rounds the algorithm needs to make the result. In the 128-bit version we need 10 rounds of data shuffling while in the 256-bit version we need 14 rounds. For this we need to change the design of key scheduler as was described in section 4.1.1. The key scheduler now takes the 256-bit key as input and it splits it into two 128 bit blocks one with the MSB and one with the LSB making the round key to be used. Following this step, the process on data is the same as the 128-bit version. We just add 4 more rounds to use all of our key products. The calculation of the new key round takes place every 2 rounds. We use the 128 LSB bits for the first round then the 128 MSB bits for the second round and then the process goes on with a new calculation for the next 2 rounds. The process ends at the 14 round where we have calculated a total of 7 different 256 bit keys, plus 2 more rounds for initialization and competition.

Continuing with the implementation of the control unit as described in section 4.1.2 and the small function components from section 3.2 we now have the complete AES module. In figure 15 we can see the schematic of the component. The GCM mode is an expansion module that will use this component for the encryption process.

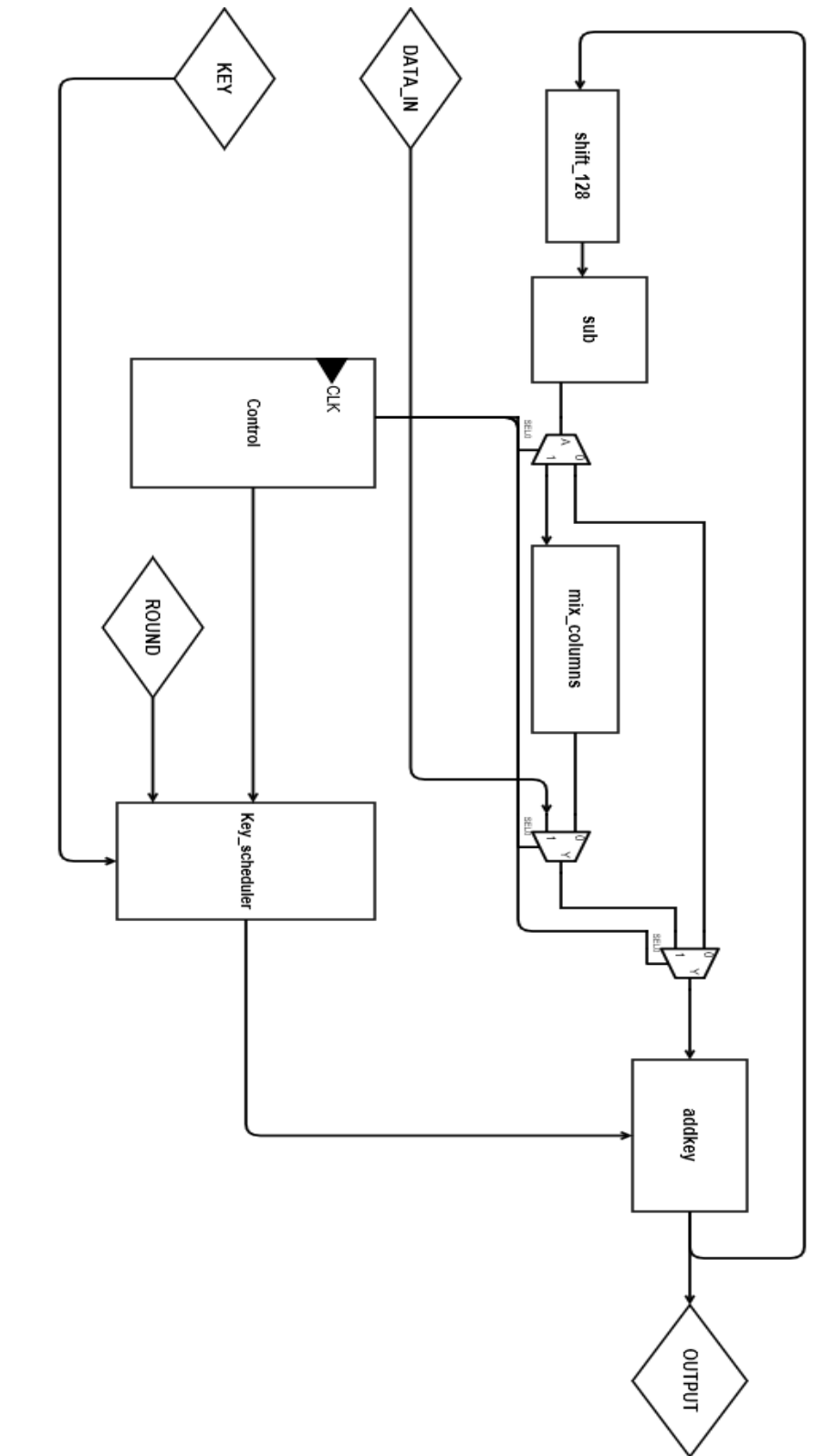


Figure 15: AES schematic

In figure 16 we can see the encryption process in a test bench.

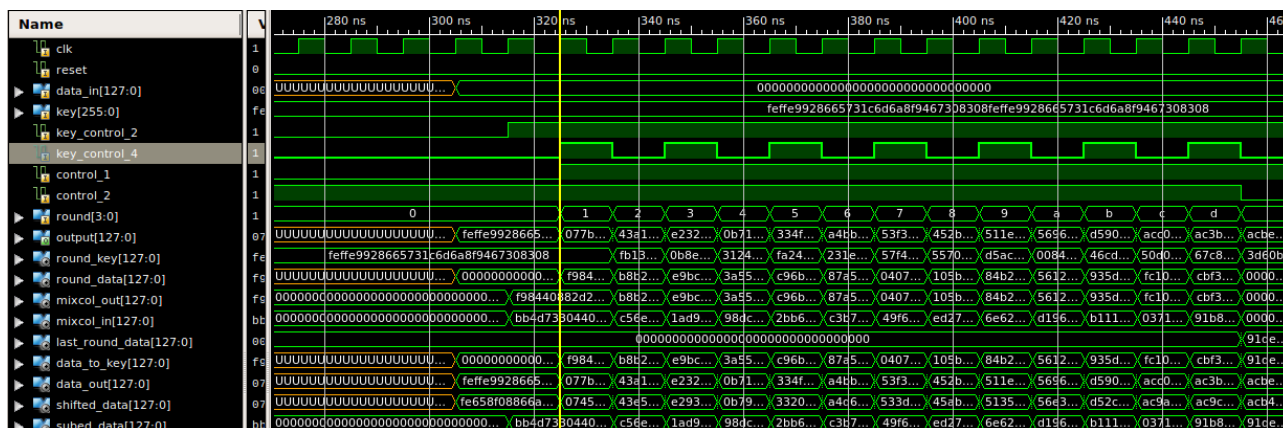


Figure 16: AES test bench

We can see that seven 256 bit keys are produced and we use the 128 MSB and LSB results to use in 14 rounds with the 128-bit block data input to make the final result. At this point we understand that this is the minimum clock cycles we need in our design per data block. This sets our bottom boundary for our design to at least 14 rounds.

5.2 GF Multiplier

The next core component is the GF multiplier. Here we wanted the parallel version from the options described above to achieve 1 single cycle per multiplication. As described above the Mastrovito edition was a parallelized version suitable for this cause. We implemented a series of AND and XOR gates following the algorithm described in 4.2.1 creating a large combinational path where each bit of the output is calculated at the same time. While this is the largest combinational path in our design, the total delay is a small fraction of the delay we would have if we were using the multi cycle version.

Following the algorithm, we initialize an array of 128 vectors V , with every vector 128 bits long. $V(0)$ equals input Y . Each $V(i)$ vector is equal to $V(i-1)$ right sifted by 1 bit when the rightmost of $V(i)$ is equal to 0, or else is equal to $V(i-1)$ right sifted by 1 bit and then a XOR operation is applied with the R vector. The R vector has a static value of $0x7080000000000000$. Each bit of the output Z is described by the following procedure:

$$Z_i = (V_i(0) \text{ AND } X_{127}) \oplus (V_i(1) \text{ AND } X_{126}) \oplus (V_i(2) \text{ AND } X_{125}) \dots \oplus (V_i(127) \text{ AND } X_0)$$

In table 1 we can see the summary report of the GF multiplier module.

Logic Utilization	Used	Available	Utilization
Number of Slice LUTs	7693	28800	25%
Number of fully used LUT-FF pairs	0	7639	0%
Number of bonded IOBs	384	480	80%

Table 1 Mastrovito multiplier utilization

In the test bench we use the following equation (All values are in hexametrical). The validation of the operation can be seen in figure 17:

$$X = \text{acbef20579b4b8ebce889bac8732dad7}$$

$$Y = \text{fac80890c2692c0a6375e2622cf925d2}$$

$$Z = X \cdot Y = \text{8efa30ce83298b85fe71abefc0cdd01d}$$

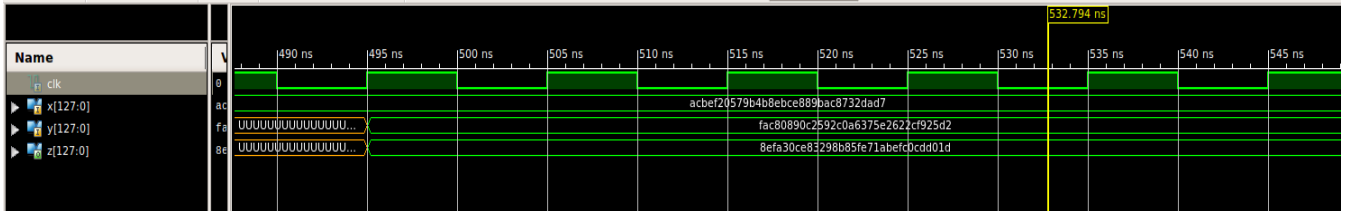


Figure 17: Mastrovito multiplier test bench

We can see the result calculated into 1 single cycle. Adding the 14 cycles we need for the AES algorithm and 1 cycle to input data we set now a new lower boundary of 16 cycles. From the summary report we can see that the total LUT slice utilization is 25% of the available slices. This component is the largest in our design with maximum combinational path delay 9.260 ns.

5.3 GCM

Next we proceeded to the implementation of the GCM algorithm. For the purposes of this Thesis we made some assumptions of the I/O mechanism since it is a streaming data system and differences from various setups might change the buffering model.

Our first assumption is that we have one single 128 bit input and one single 128-bit output. All the data needed for encryption and authentication are stored into registers at the initialization process. The data stored are: The initialization vector (IV – 96 bits) which needs 1 cycle, the key used (K – 256 bits) which needs 2 cycles, the Least significant bits of the final plain text (LSB_Last_Plain – 128 bits) which needs 1 cycle and the size of both ADD and Plain text which is 64 bit for each and we stored it into the same register (AAD_size 64 bit, Plain_size 64 bit) which need 1 final cycle. While we need IV and K at the beginning we can calculate the rest on the fly we extra hardware components. In our implementation we consider them as input. This makes a total of 5 clock cycles for initialization.

After initialization we need to calculate the hash key (H). So there is a pending time lapse were we wait the AES core to produce the hash key. When the key is ready we start fetching data from the input. Here we implement the GHASH function were at each cycle we fetch AAD until the buffer inform us that there are done and then we fetch the plain text. For each plain text we wait the AES core to encrypt them before we export the result and insert it to the GHASH function.

At the final steps we use the size of both ADD and Plain text to calculate the final output which is the TAG. The process is illustrated in figure 18.

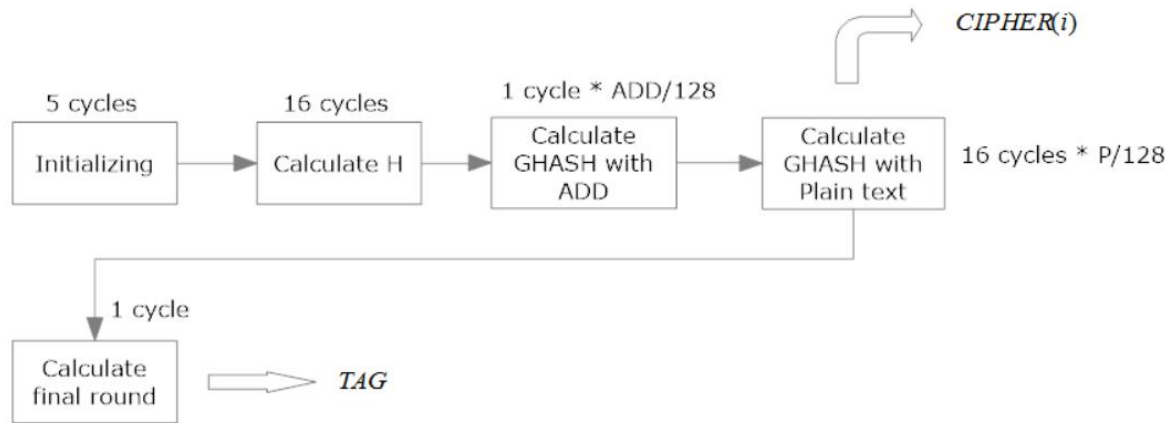


Figure 18: Life cycle of data

5.3.1 GCM control unit

The above description guides us to the creation of the control unit (FSM). We design a control unit with 12 different states managing the datapath. The RST sets the parameters to 0 for register initialization. After the final round we return to RST. The next 5 states (R_IN1, R_IN2a, R_IN2b, R_IN3, R_IN4) allow the import of the initial data as described above. In R1 state we calculate the hash key. This is a self-repeating state and will move to next stage if the signal `aes_rdy = '1'`. Since AES is responsible for the calculation, we need 14 cycles for R1. In R2 state we import the AAD to the GHASH function. Since we use a parallel multiplier we expect this state to last 1 cycle for each 128-bit block of AAD. When the flag that the AAD is finished we move to R3. In R3 state we use Plain text as input to the GHASH. Since the Plain text needs to be encrypted and then the result be multiplied we need 15 clock cycles and 1 cycle to reset AES module for the next input.

This makes a total of 16 clock cycles. This is our efficiency measurement for this algorithm implementation. Because this is a streaming algorithm and the Plain text can be up to 68 Gbits, its crucial to keep the number of clock cycles at state R3 at a minimum.

The R4 and R5 states set as input the AAD/Plain size to the GHASH to calculate the TAG value and in R6 the output is produced and placed in output with the flag output = '1' using for one last time the AES core.

Figure 19 illustrates the FSM diagram.

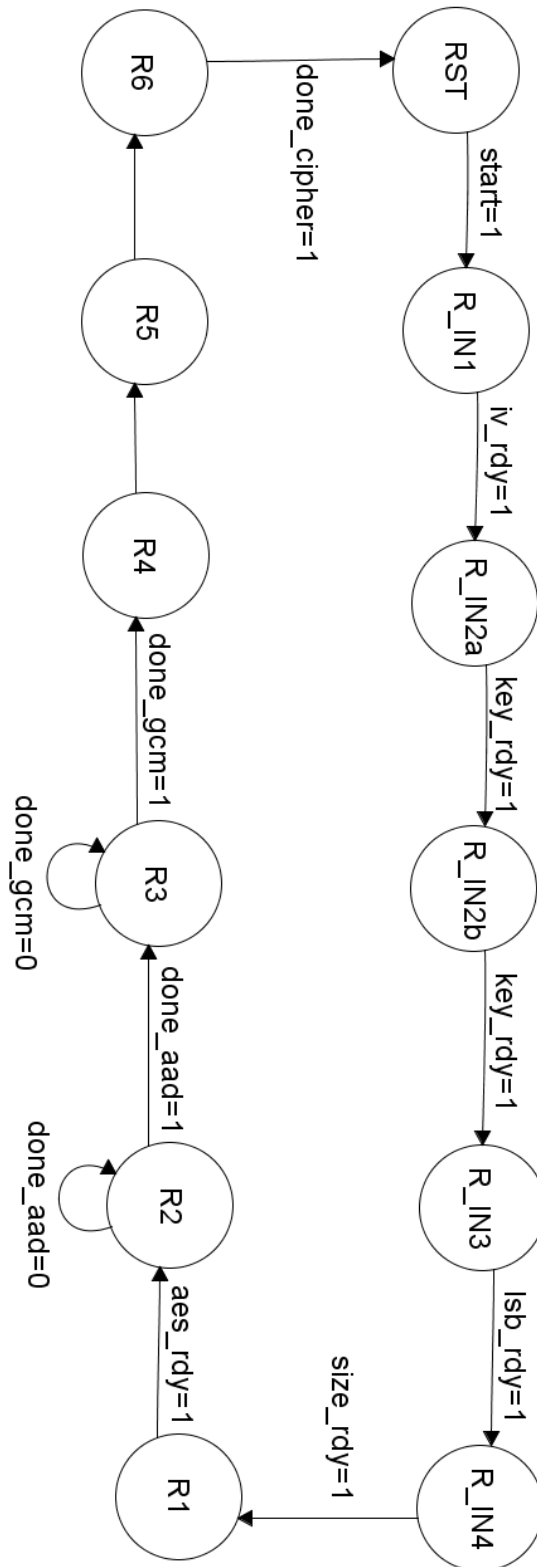


Figure 19: GCM control FSM

The test bench in figure 20 demonstrates the functionality of the FSM.

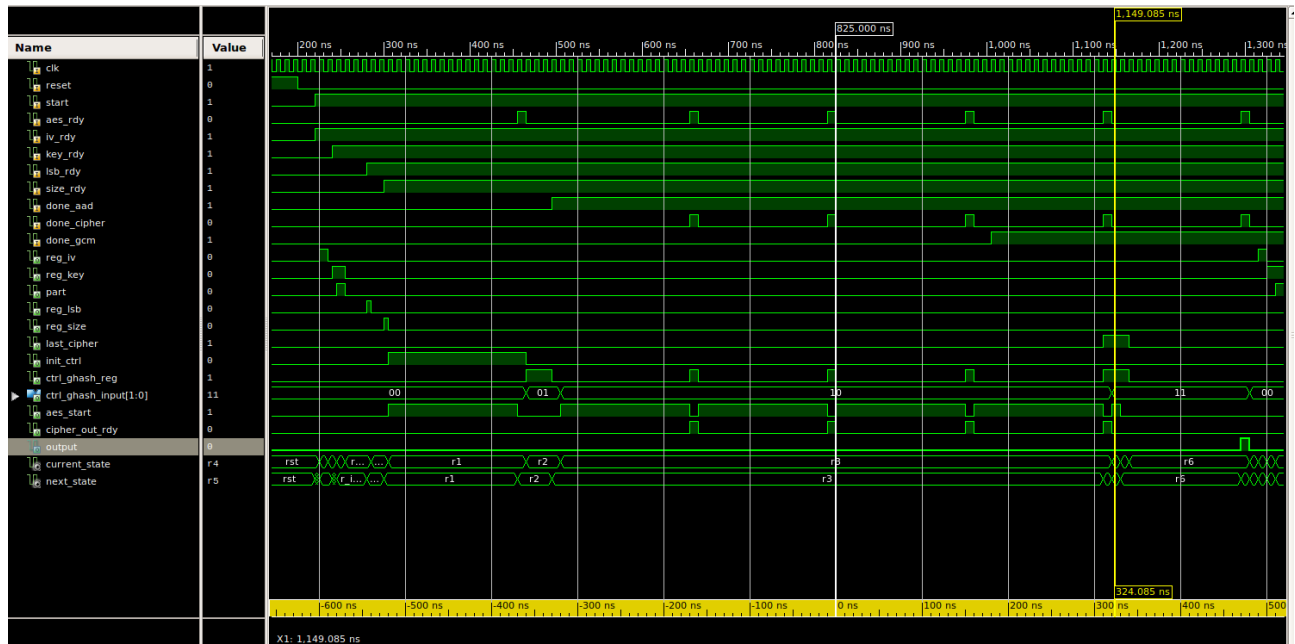


Figure 20: Test bench of the GCM control unit

5.3.2 AES-GCM module

The final step is the validation of the final component. In figure 21 we can see the top module of the implementation. The u6 multiplexer is responsible for the result of the module being either cipher or the TAG. Registers u2, u3, u4, u5 are for the initialization process.

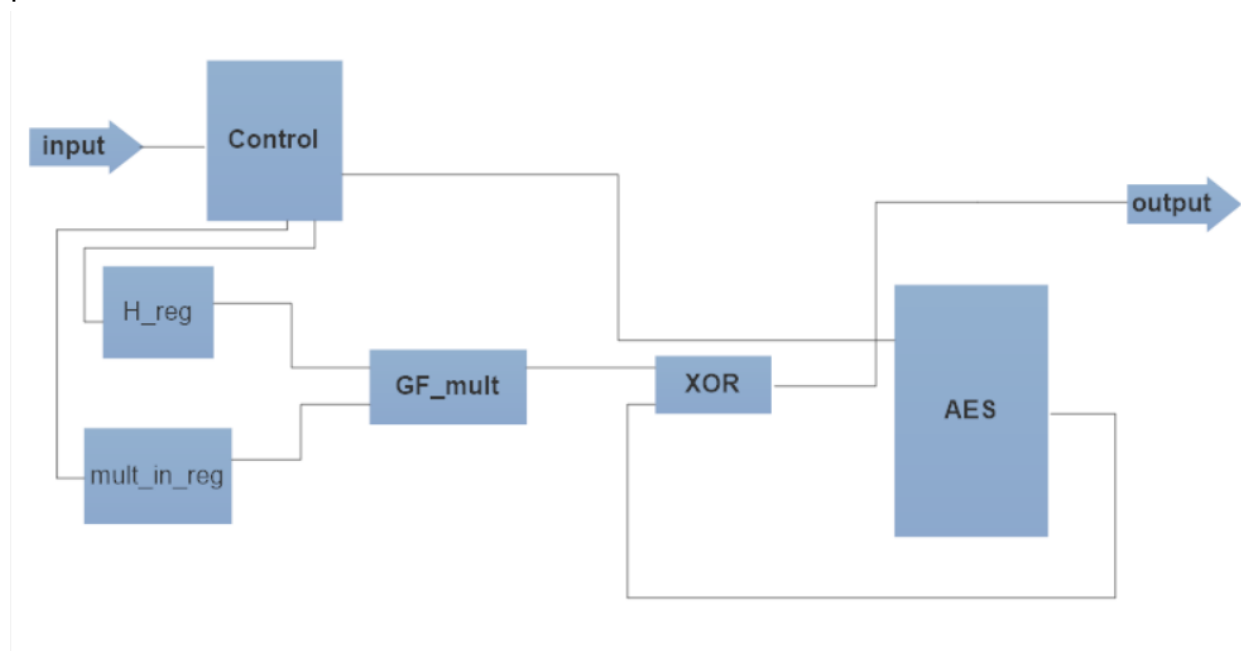


Figure 21: GCM schematic

In figure 22 we can see the simulation of a vector with 2 AAD blocks and 4 plain text blocks. The output signal C_out_rdy becomes 1 when we have a block cipher ready. When the process is over the signal done becomes 1 and the mux change the output to that of the GHASH which is the TAG.

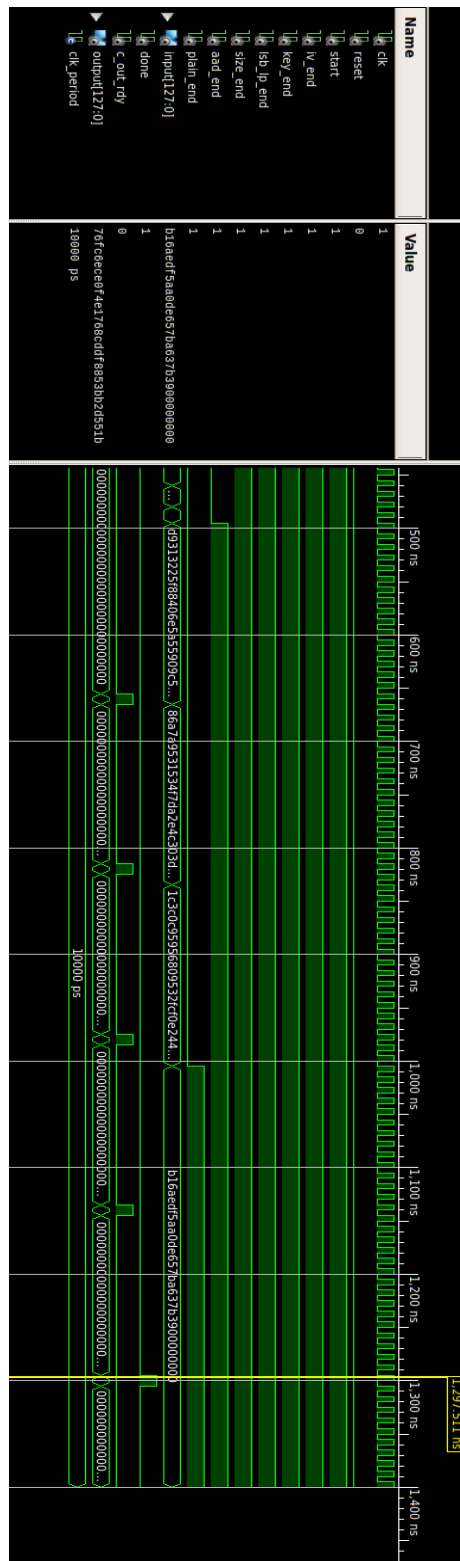


Figure 22: GCM test bench

The ending of each input is designed by a signal given as input from a buffer.

Here is the TAG we create from the GHASH function

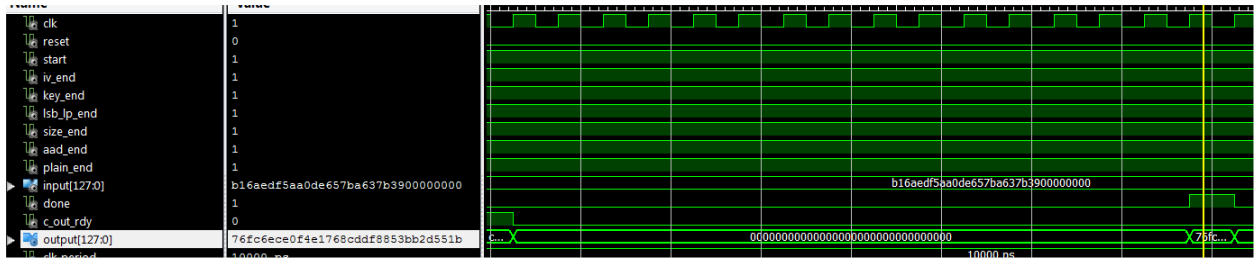


Figure 23: TAG test bench result

We are now going to present the hardware specs we used for this implementation. In table 2 we see the device type and the package.

Property name	Value
Top-Level source type	VHDL
Family	Virtex5
Device	XC5VLX50T
Package	FF1136
Speed	-2
Synthesis tool	XST (VHDL/Verilog)
Simulator	Isim (VHDL/Verilog)
VHDL Source analysis standard	VHDL - 93

Table 2: Hardware specs

From the synthesis tools we have produced the timing and memory report presented in table 3.

Property name	Value
Speed Grade	-2
Minimum period	4.392 ns
Maximum Frequency	227.690 Mhz
Minimum input arrival time before clock	3.643 ns
Maximum output required time after clock	6.662 ns
Maximum combinational path delay	6.605 ns
Total memory usage	538016 KB

Table 3: Timing and memory report

In table 4 we can see the total utilization of the device.

Logic Utilization	Used	Available	Utilization
Number of Slice Registers	1660	28800	5%
Number of Slice LUTs	10126	28800	35%
Number of fully used LUT-FF pairs	967	10819	8%
Number of bonded IOBs	267	480	55%
Number of block of RAM/FIFO	1	60	1%
Number of BUFG/BUFGCTRLs	1	32	3%

Table 4: Total utilization

We achieved a Minimum period of 4.392 ns with 16 clock cycles for processing a single plain text block. With a pipelined version we can achieve even greater results up to 1 clock cycle if we use 16 AES cores. This would require a large number of slice LUTs, were in our device we can use up to 3. But those improvements, which would allow processing 68Gbps in less than 10 seconds, are of small importance since the buffering system cannot support speeds not even close to that though limiting the potential of the FPGA.

5.4 Validation

In this chapter we are presenting the test vectors we used to validate our design, using the ISim simulator. For each test vector we validated all the intermediate results from the hash key, the encryption process, the GHASH function and the final TAG.

5.4.1 Test case 1

Test vector 1 is presented in table 5 where we don't have any AAD and plain text and key has zero values.

Variable	Value
K	00000000000000000000000000000000 00000000000000000000000000000000
P	00000000000000000000000000000000
IV	000000000000000000000000
H	dc95c078a2408989ad48a21492842087
Y0	00000000000000000000000000000001
E(K, Y0)	530f8afbc74536b9a963b4f1c4cb738b
Y1	00000000000000000000000000000002
E(K, Y1)	cea7403d4d606b6e074ec5d3baf39d18
X1	fd6ab7586e556dba06d69cfe6223b262
len(A) len(C)	00000000000000000000000000000080
GHASH(H, A,C)	83de425c5edc5d498f382c441041ca92
C	cea7403d4d606b6e074ec5d3baf39d18
T	d0d1c8a799996bf0265b98b5d48ab919

Table 5: Test vector 1

By implementing and testing our code, we have received the following results:

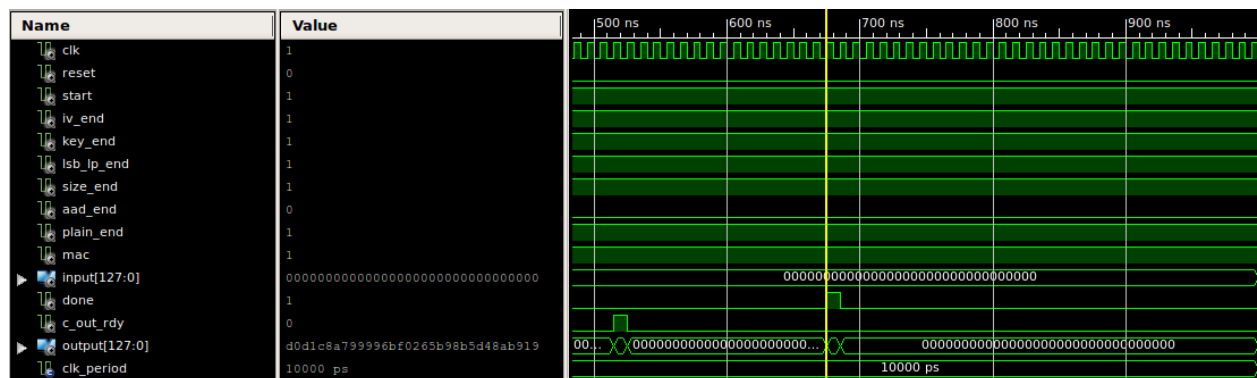


Figure 24: Test case 1 results

5.4.2 Test case 2

Test vector 2 is presented in table 6 where we don't have AAD, but we have used no-zero values for plain text and key.

Variable	Value
K	feffe9928665731c6d6a8f9467308308 feffe9928665731c6d6a8f9467308308
P	d9313225f88406e5a55909c5aff5269a 86a7a9531534f7da2e4c303d8a318a72 1c3c0c95956809532fcf0e2449a6b525 b16aedf5aa0de657ba637b391aafd255
IV	cafebabefacedbaddecaf888
H	acbef20579b4b8ebce889bac8732dad7
Y0	cafebabefacedbaddecaf88800000001
E(K, Y0)	fd2caa16a5832e76aa132c1453eeda7e
Y1	cafebabefacedbaddecaf88800000002
E(K, Y1)	8b1cf3d561d27be251263e66857164e7
Y2	cafebabefacedbaddecaf88800000003
E(K, Y2)	e29d258faad137135bd49280af645bd8
Y3	cafebabefacedbaddecaf88800000004
E(K, Y3)	908c82ddcc65b26e887f85341f243d1d
Y4	cafebabefacedbaddecaf88800000005
E(K, Y4)	749cf39639b79c5d06aa8d5b932fc7f8
X1	fcbebf78635d598eddaf982310670f35
X2	29de812309d3116a6eff7ec844484f3e
X3	45fad9deeda9ea561b8f199c3613845b
X4	ed95f8e164bf3213febc740f0bd9c6af
len(A) len(C)	0000000000000000000000000000200
GHASH(H, A,C)	4db870d37cb75fcb46097c36230d1612
C	522dc1f099567d07f47f37a32a84427d 643a8cdcbfe5c0c97598a2bd2555d1aa 8cb08e48590dbb3da7b08b1056828838 c5f61e6393ba7a0abcc9f662898015ad
T	b094dac5d93471bdec1a502270e3cc6c

Table 6: Test vector 2

By implementing and testing our code, we have received the following results:

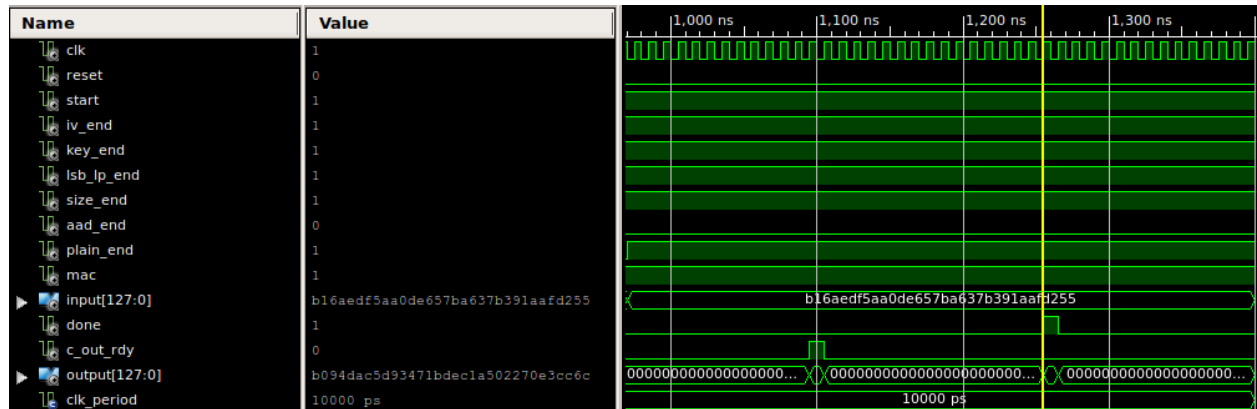


Figure 25: Test case 2 results

5.4.3 Test case 3

Test vector 3 is presented in table 7 where we have used both AAD and non-zero values.

Variable	Value
K	feffe9928665731c6d6a8f9467308308 feffe9928665731c6d6a8f9467308308
P	d9313225f88406e5a55909c5aff5269a 86a7a9531534f7da2e4c303d8a318a72 1c3c0c95956809532fcf0e2449a6b525 b16aedf5aa0de657ba637b39
AAD	feedfacedeadbeeffeedfacedeadbeef abaddad2
IV	cafebabefacedbaddecaf888
H	acbef20579b4b8ebce889bac8732dad7
Y0	cafebabefacedbaddecaf88800000001
E(K, Y0)	fd2caa16a5832e76aa132c1453eeda7e
X1	5165d242c2592c0a6375e2622cf925d2
X2	8efa30ce83298b85fe71abefc0cdd01d
Y1	cafebabefacedbaddecaf88800000002
E(K, Y1)	8b1cf3d561d27be251263e66857164e7
Y2	cafebabefacedbaddecaf88800000003
E(K, Y2)	e29d258faad137135bd49280af645bd8
Y3	cafebabefacedbaddecaf88800000004
E(K, Y3)	908c82ddcc65b26e887f85341f243d1d
Y4	cafebabefacedbaddecaf88800000005

E(K, Y4)	abe07e0bb62354177480b550f9f6cdcc
X3	fcbebf78635d598eddaf982310670f35
X4	3978e4f141b95f3b4699756b1c3c2082
X5	8abf3c48901debe76837d8a05c7d6e87
X6	9249beaf520c48b912fa120bbf391dc8
len(A) len(C)	00000000000000a000000000000001e0
GHASH(H, A,C)	8bd0c4d8aacd391e67cca447e8c38f65
C	522dc1f099567d07f47f37a32a84427d 643a8cdcbfe5c0c97598a2bd2555d1aa 8cb08e48590dbb3da7b08b1056828838 c5f61e6393ba7a0abcc9f662
T	76fc6ece0f4e1768cddf8853bb2d551b

Table 7: Test vector 3

By implementing and testing our code, we have received the following results:

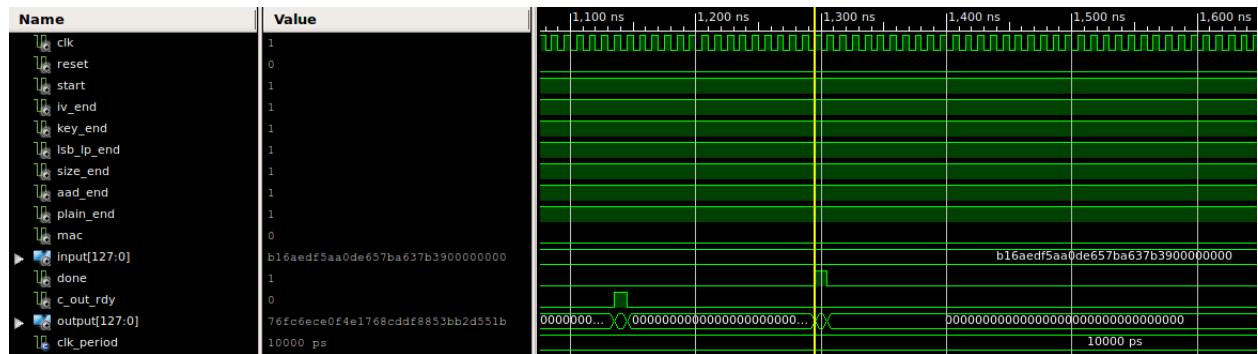


Figure 26: Test case 3 results

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