AES128IP Reference Design

1 Introduction

This document describes the detail of AES128IP reference design. In this reference design, AES128IP are used to encrypt and decrypt data between two memories in FPGA. User can fill memory with plain or cipher data patterns, set encryption/decryption key and control test operation via serial console on test PC. More details of the hardware design and CPU firmware are described as follows.
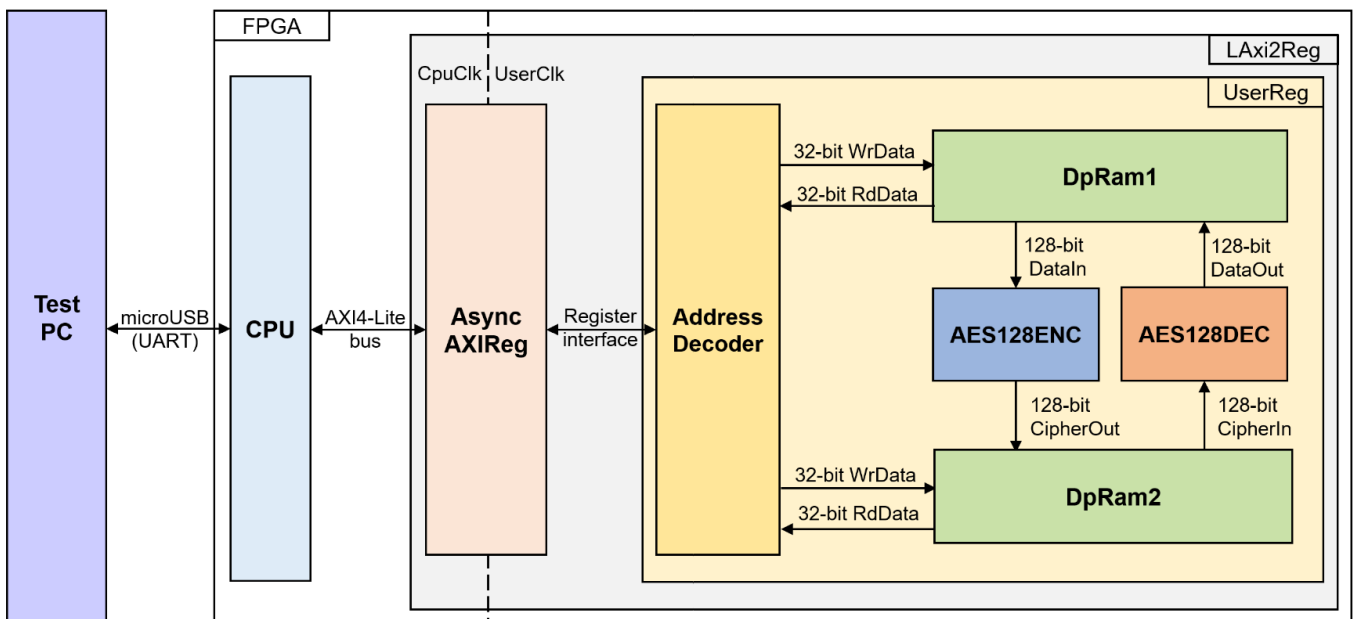
2 Hardware Overview

Figure 2-1 AES128IP reference design block diagram

In this test environment, AES128ENC and AES128DEC interface with two dual-port RAMs with asymmetric ports, which are DpRam1 and DpRam2, as shown in Figure 2-1. AES128IP and two RAMs are sub-modules in UserReg module within LAxi2Reg. CPU system is designed to interface with FPGA logic through AXI4 Lite bus and interface with user through serial console in test PC.

For user control interface, there are registers in UserReg to store parameters from user such as encryption/decryption key, number of data to encrypt or decrypt. Input parameters are received from user via serial console.

For user data interface, UserReg is designed to be able to write pattern data or read data in RAMs following user's command. DpRam1 is used to store the plain data from user which will be input data for AES128ENC in encryption mode or the decrypted data which is output data from AES128DEC in decryption mode. DpRam2 is used to store the cipher data from user which will be input data for AES128DEC in decryption mode or encrypted data which is output data from AES128ENC in encryption mode.

Because CPU system and AES128ENC/AES128DEC run in different clock domain, AsyncAXIReg module inside LAxi2Reg is designed as asynchronous circuit to support clock-crossing operation. Also, AsyncAxiReg converts AXI4-Lite bus signal which is standard bus in CPU system to be register interface. The details of LAxi2Reg module are described below.

2.1 LAxi2Reg

LAxi2Reg module is connected to CPU through AXI4-Lite bus. The hardware registers are mapped to CPU memory address, as shown in Table 2-1. The control and status registers for CPU access are designed in LAxi2Reg.

LAxi2Reg consists of AsyncAxiReg and UserReg. AsyncAxiReg is designed to convert the AXI4-Lite signals to be the simple register interface which has 32-bit data bus size (similar to AXI4-Lite data bus size). Additionally, as shown in Figure 2-1, there are two clock domains applied in this block, i.e., CpuClk which is used to interface with CPU through AXI4-Lite bus and UserClk which is user clock domain for AES128ENC/AES128DEC. AsyncAxiReg includes asynchronous circuit between CpuClk and UserClk.

UserReg includes the register file of the parameters and the status signals of test logics, including dual-port rams and AES128IP. Both data interface and control interface of AES128IP are connected to UserReg. More details of AsyncAxiReg and UserReg are described as follows.

2.2 AsyncAxiReg

This module is designed to convert the signal interface of AXI4-Lite to be register interface. Also, it enables two clock domains, CpuClk and UserClk domain, to communicate.

To write register, RegWrEn is asserted to '1' with the valid signal of RegAddr (Register address in 32-bit unit), RegWrData (write data of the register), and RegWrByteEn (the byte enable of this access: bit[0] is write enable for RegWrData[7:0], bit[1] is used for RegWrData[15:8], …, and bit[3] is used for RegWrData[31:24]).

To read register, AsyncAxiReg asserts RegRdReq='1' with the valid value of RegAddr (the register address in 32-bit unit). After that, the module waits until RegRdValid is asserted to '1' to get the read data through RegRdData signal at the same clock.

2.3 UserReg

This module is designed to write/read data in RAMs, control and check status of AES128ENC/AES128DEC corresponding with write register access or read register request from AsyncAxiReg module. Memory map of data, control and status signals inside UserReg module is shown in Table 2-1. Timing diagram of register interface is shown in Figure 2-2.

Table 2-1 Register map Definition

Address offset (From base address)	Register Name (Label in AESIPTest.c)	Rd/Wr	Description
0x0000	ADDR_A1_REG	Rd/Wr	[6:0] – address A of DpRam1 (rAddrA1[6:0]).
0x0004	ADDR_A2_REG	Rd/Wr	[6:0] – address A of DpRam2 (rAddrA2[6:0]).
0x0008	ENC_CNT_REG	Rd	[8] – AES128ENC KeyIn busy flag (rEncKeyInBusy). [7] – AES128ENC DataIn busy flag (rEncDataInBusy). [6:0] – Current remaining data to encrypt (rEncCnt[6:0]).
		Wr	[6:0] – Number of data to encrypt (rEncCnt[6:0]). rEncKeyInValid is asserted to '1' and encryption process is started.
0x000C	DEC_CNT_REG	Rd	[8] – AES128ENC KeyIn busy flag (rDecKeyInBusy). [7] – AES128DEC CipherIn busy flag (rDecCipherInBusy). [6:0] – Current remaining data to decrypt (rDecCnt[6:0]).
		Wr	[6:0] – Number of data to decrypt(rDecCnt[6:0]). rDecCipherInValid signal is asserted to '1' and decryption process is started.
0x0018	ENC_VER_REG	Rd	[31:0] – AES128ENC IP version (wEncVersion).
0x001C	DEC_VER_REG	Rd	[31:0] – AES128DEC IP version (wDecVersion).
0x0020	ENC_KEYIN_0_REG	Rd/Wr	[31:0] – Encryption key (rEncKeyIn[31:0]). When rEncKeyIn[31:0] is set, rEncKeyInValid is asserted to '1' and key setting is started.

| 0x0024	ENC_KEYIN_1_REG	Rd/Wr	[31:0] – Encryption key (rEncKeyIn[63:32]).
0x0028	ENC_KEYIN_2_REG	Rd/Wr	[31:0] – Encryption key (rEncKeyIn[95:64]).
0x002C	ENC_KEYIN_3_REG	Rd/Wr	[31:0] – Encryption key (rEncKeyIn[127:96]).
0x0040	DEC_KEYIN_0_REG	Rd/Wr	[31:0] – Decryption key (rDecKeyIn[31:0]) When rDecKeyIn[31:0] is set, rDecKeyInValid is asserted to '1' and key setting is started.
0x0044	DEC_KEYIN_1_REG	Rd/Wr	[31:0] – Decryption key (rDecKeyIn[63:32]).
0x0048	DEC_KEYIN_2_REG	Rd/Wr	[31:0] – Decryption key (rDecKeyIn[95:64]).
0x004C	DEC_KEYIN_3_REG	Rd/Wr	[31:0] – Decryption key (rDecKeyIn[127:96]).
0x0800~0x0FFF	PLAIN_BASE_ADDR	Rd/Wr	[31:0] – Plain data in DpRam1 (wRdDataB1).
0x1000~0x17FF	CIPHER_BASE_ADDR	Rd/Wr	[31:0] – Cipher data in DpRam2 (wRdDataB2).
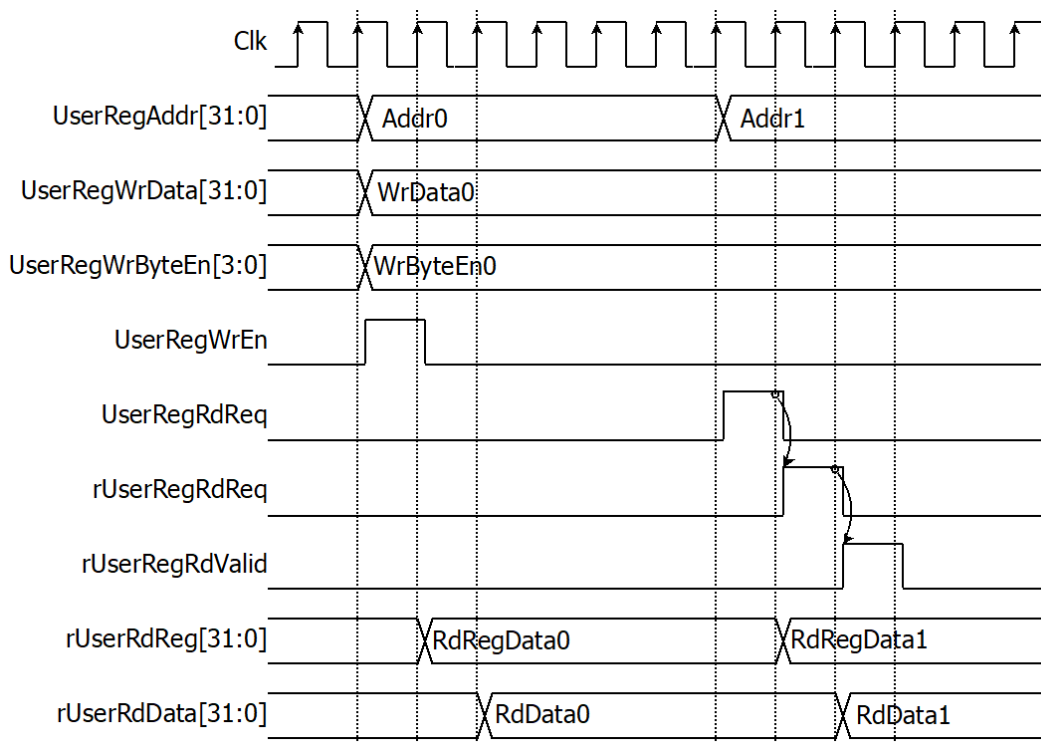
Figure 2-2 Register interface timing diagram

To write register, UserRegWrEn is asserted to '1' with the valid of UserRegAddr. UserRegAddr[15:11] are used to decode that CPU accesses dual-port ram (DpRam) or internal register area. If CPU accesses or internal register area (UserRegAddr[15:11]="00000"), UserRegWrData is loaded to internal register which has matched UserRegAddr[10:2]. For example, rAddrA1 is loaded by UserRegWrData when UserRegAddr=0x0000.

To read register, one multiplexer is designed to select the read data within each address area. UserRegAddr[10:2] is applied in each register area to select the data. Next, the address decoder uses UserRegAddr[15:11] to select the read data from each area for returning to CPU. As shown in Figure 2-2, read data is valid in next two clock cycles. When UserRegRdReq is active, rUserRegRdReq is asserted to '1'. Then rUserRdValid is active with the valid read value of UserRegAddr.

In this reference design, there are three main operations which are key setting, encryption and decryption. Each operation is described as follows.

2.3.1 Key setting

For encryption key setting, rEncKeyIn is set by writing register UserRegAddr=0x0020-0x002F as shown in Table 2-1. When ENC_KEYIN_0_REG is written (UserRegAddr=0x0020), rEncKeyIn[31:0] is set. Then rEncKeyInValid is asserted to '1' as shown in Figure 2-3. The encryption key setting takes 10 clocks cycles to finish.
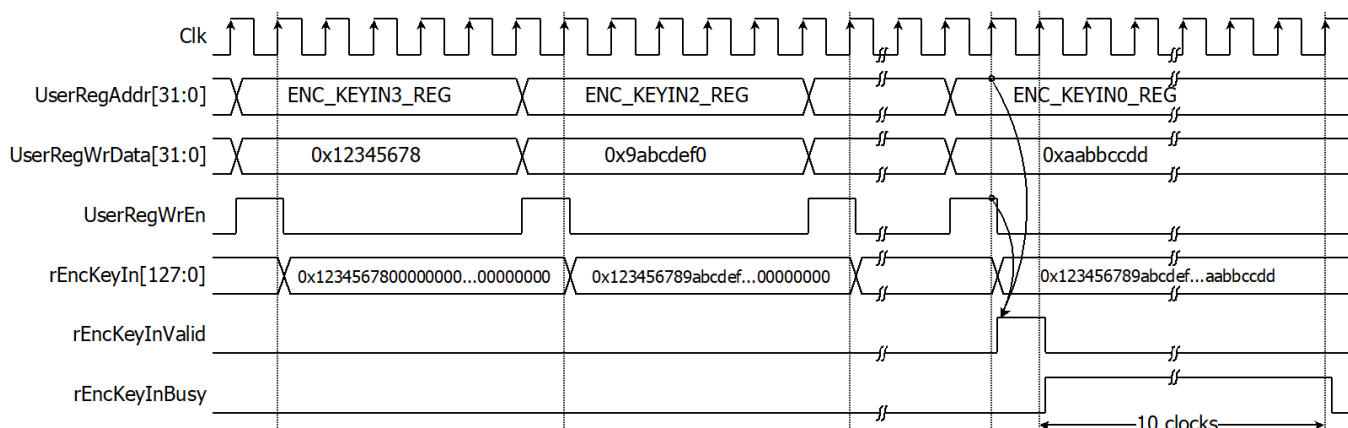

Figure 2-3 Timing diagram of encryption key setting process

For decryption key setting, rDecKeyIn is set by writing register UserRegAddr=0x0040-0x004F as shown in Table 2-1. When DEC_KEYIN_0_REG is written (UserRegAddr=0x0040), rDecKeyIn[31:0] is set. Then rDecKeyInValid is asserted to '1' and decryption key setting process is started as shown in Figure 2-4. The decryption key setting takes 10 clocks cycles to finish.
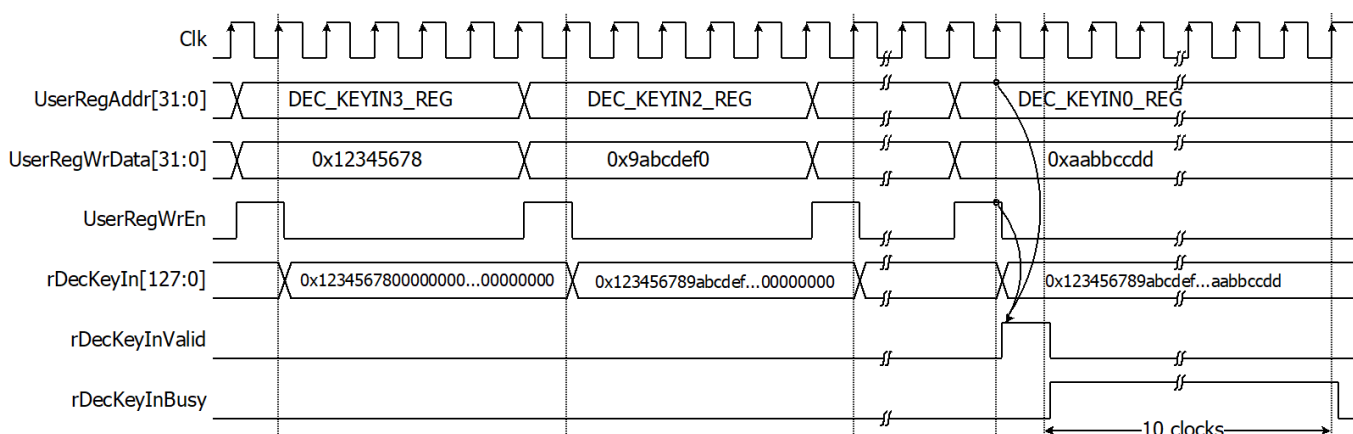

Figure 2-4 Timing diagram of decryption key setting process

2.3.2 Encryption

For encryption process, 128-bit plain data, which will be input data for AES128ENC, are stored in DpRam1. Before starting encryption process, address A of DpRam1 (rAddrA1) is set to 0x00 to access the first plain data. As shown in Figure 2-5, when UserRegAddr=0x0008 (ENC_CNT_REG) is written, UserRegWrData is loaded to rEncCnt as the number of data to encrypt and rEncDataInValid is asserted to '1' to active AES128ENC. Then rAddrA1 is increased by 1 to access next plain data in DpRam1 and rEncCnt is decreased by 1 as the remaining data to encrypt. When rEncDataInFinish='1', rEncDataInValid is asserted to '1' to encrypt next 128-bit plain data. If rEncCnt=0, no remaining data to encrypt, rEncDataInValid is not active when rEncDataInFinish='1'.

Cipher data from AES128ENC is stored in DpRam2. Before starting encryption process, address A of DpRam2 (rAddrA2) is set to 0x00 for writing the first output cipher data. When rEncCipherOut is active, rEncCipherOut is loaded to DpRam2. Then rAddrA2 is increased by 1 prepared for next cipher output.
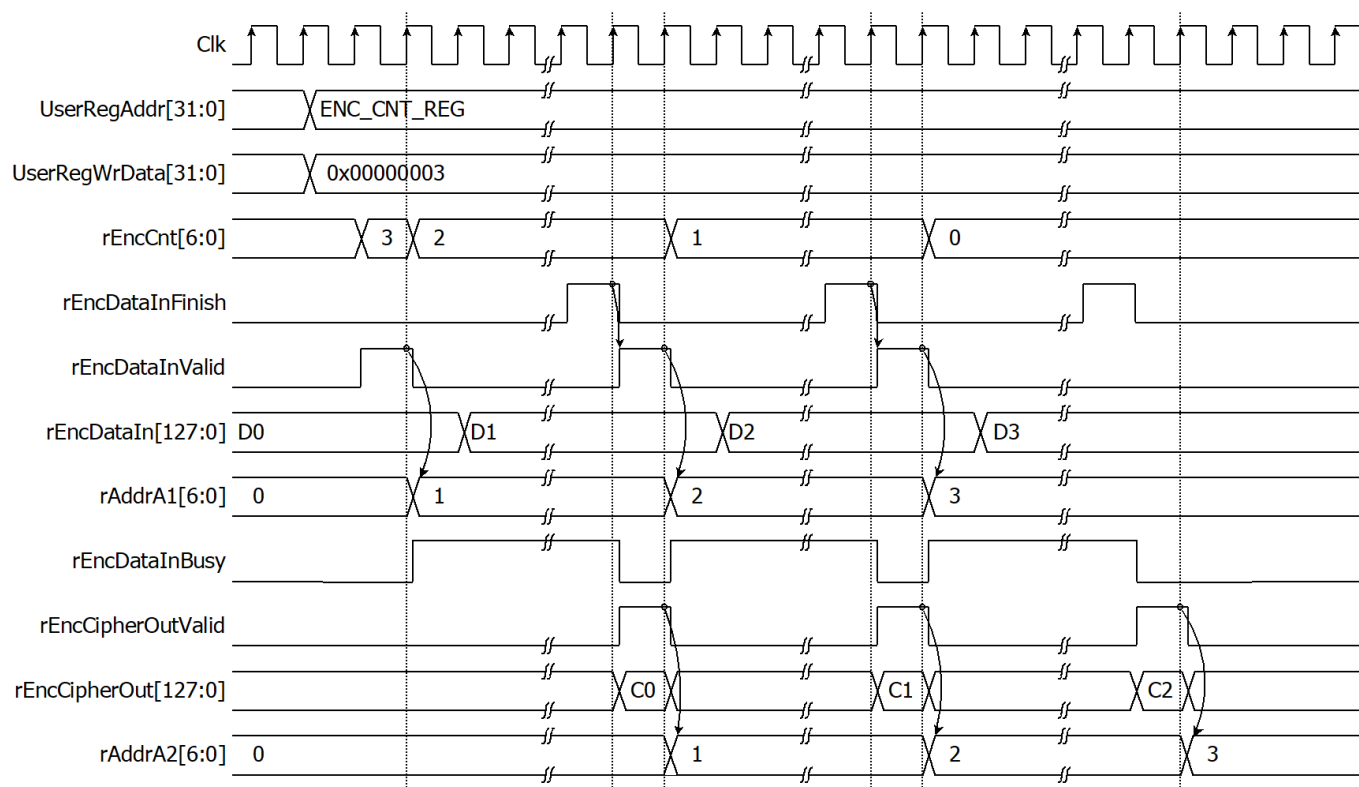

Figure 2-5 Timing diagram of encryption process

2.3.3 Decryption

For decryption process, 128-bit cipher data, which will be input data for AES128DEC, are stored in DpRam2. Before starting decryption process, address A of DpRam2 (rAddrA2) is set to 0x00 to access the first cipher data. As shown in Figure 2-6, when UserRegAddr=0x000C (DEC_CNT_REG) is written, UserRegWrData is loaded to rDecCnt as the number of data to decrypt and rDecCipherInValid is asserted to '1' to active AES128DEC. Then rAddrA2 is increased by 1 to access next cipher data in DpRam2 and rDecCnt is decreased by 1 as the remaining data to decrypt. When rDecCipherInFinish='1', rDecCipherInValid is asserted to '1' to decrypt next 128-bit cipher data. If rDecCnt=0, no remaining data to decrypt, rDecCipherInValid is not active when rDecCipherInFinish='1'.

Decrypted data from AES128DEC is stored in DpRam1. Before starting decryption process, address A of DpRam1 (rAddrA1) is set to 0x00 for writing the first output plain data. When rDecDataOut is active, rDecDataOut is loaded to DpRam1. Then rAddrA1 is increased by 1 prepared for next plain output.
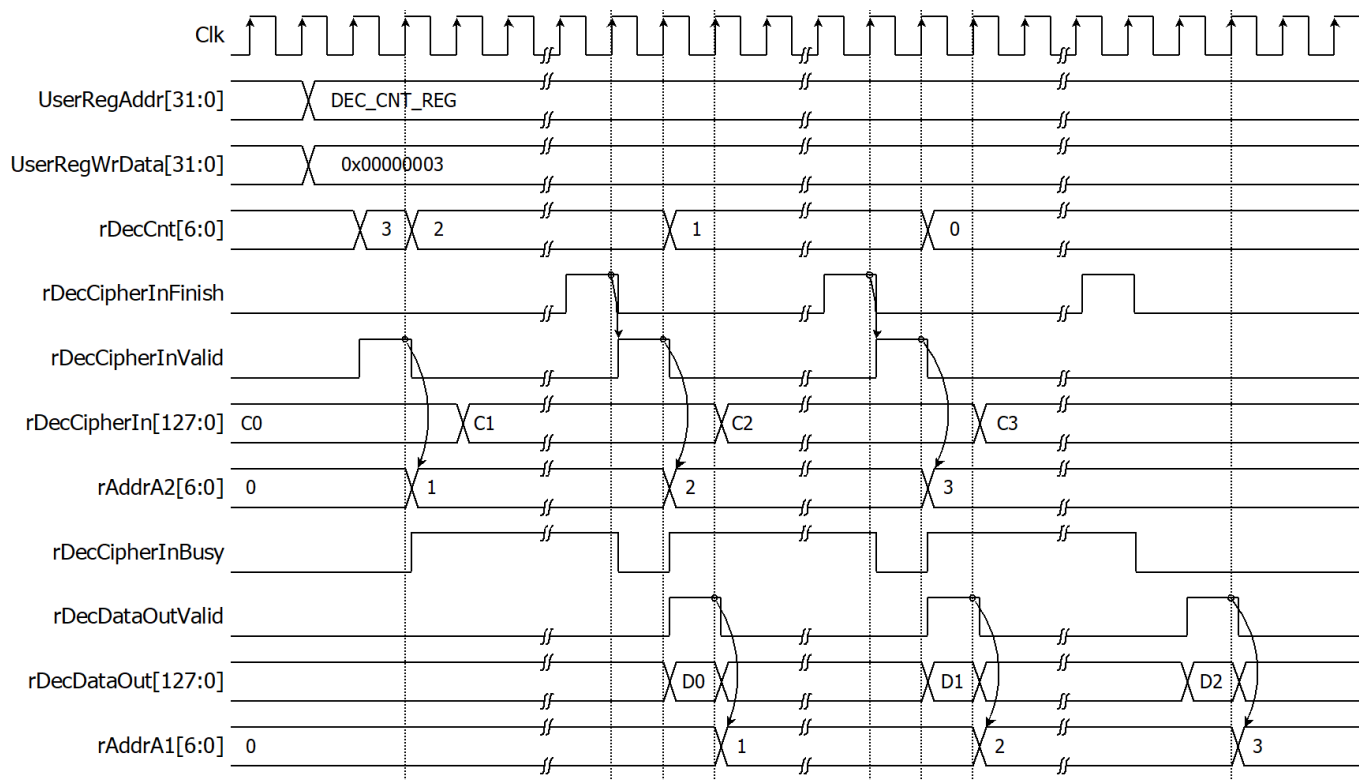

Figure 2-6 Timing diagram of decryption process

3 CPU Firmware

After system boot-up, CPU initializes its peripherals such as UART and Timer and shows IP version of AES128ENC and AES128DEC. Then main menu is displayed. Main function runs in an infinite loop to show the main menu and get keyboard input from user. User can select each menu via serial console that will call the related functions. After functions finished running, the main menu is displayed again. More details of the sequence in each menu are described as follows.

3.1 Set encryption/decryption key

This menu is used to set encryption/decryption key. The sequence of the firmware is as follows.

1) Call change_key_set function to change encryption/decryption key set. User can input "enter" key to skip input encryption key and not change current enc_key_set or to skip input decryption key and change dec_key_set similar to enc_key_set.

2) Call set_enc_key function and set_dec_key function inside change_key_set function to set enc_key_set and dec_key_set to mapped registers.

change_key_set function, set_enc_key function and set_dec_key function is described in Table 3-1, Table 3-2 and Table 3-3, respectively.

Table 3-1 change_key_set function

void change_key_set(unsigned int *enc_key_set, unsigned int *dec_key_set)	
Parameter	enc_key_set: pointer of array storing 128-bit encryption key dec_key_set: pointer of array storing 128-bit decryption key
Return value	None
Description	This function displays current encryption key on the console. Receive input new encryption key in hexadecimal format or "enter" key to skip. User's input will be ignored if it is not hexadecimal format. The encryption/decryption key is stored in enc_key_set/dec_key_set. Then set_enc_key function and set_dec_key function is called, respectively.

Table 3-2 set_enc_key set function

void set_enc_key(unsigned int *enc_key_set)	
Parameter	enc_key_set: pointer of array storing 128-bit encryption key
Return value	None
Description	This function sets 128-bit encryption key to mapped registers which are ENC_KEYIN_3_REG, ENC_KEYIN_2_REG, ENC_KEYIN_1_REG and ENC_KEYIN_0_REG.When ENC_KEYIN_0_REG is set, rEncKeyInValid is asserted to '1'. Monitor AES128ENC status until the key setting is completed. (*ENC_CNT_REG=0)

Table 3-3 set_dec_key set function

void set_dec_key(unsigned int *dec_key_set)	
Parameter	dec_key_set: pointer of array storing 128-bit decryption key
Return value	None
Description	This function sets 128-bit decryption key to mapped registers which are DEC_KEYIN_3_REG, DEC_KEYIN_2_REG, DEC_KEYIN_1_REG and DEC_KEYIN_0_REG. When DEC_KEYIN_0_REG is set, rDecKeyInValid is asserted to '1'. Monitor AES128DEC status until the key setting is completed. (*DEC_CNT_REG=0)

3.2 Show Data Memory

This menu is used to show data in memory. User can set the number of 128-bit data to show on console. The sequence of the firmware is as follows.

1) Receive the number of 128-bit data in decimal format or "enter" key to use default value. If user input '0', the number of 128-bit data to show will be default value. The number of 128-bit data to show is stored in length128.

2) Call show_data function to show data in memory with length128 as its parameter. show_data function is described in Table 3-4.

Table 3-4 show_data function

void show_data(unsigned int length128)	
Parameter	length128: number of 128-bit data to show
Return value	None
Description	This function shows data in both DpRam1 and DpRam2 corresponding to length. CPU firmware reads data in DpRam1, starting at PLAIN_BASE_ADDR, and shows on console. Also, CPU firmware reads data in DpRam2, starting at CIPHER_BASE_ADDR, and shows on console. If length is too large, length will be set to the size of memory.

3.3 Fill Plain Data Memory

This menu is used to fill DpRam1 with plain data pattern. The sequence of the firmware is as follows.

1) Call fill_data function to choose data pattern and fill DpRam1 with selected pattern. The input parameter of fill_data is PLAIN_BASE_ADDR which is base address for DpRam1. fill_data function is described in Table 3-5.

2) Call show_data function to show data in both DpRam1 and DpRam2 corresponding to default number of showing data (DEFAULT_SHOW_AFTER_FILL).

Table 3-5 fill_data function

void fill_data(unsigned int base_addr)	
Parameter	base_addr: base address to access memory
Return value	None
Description	This function fills the selected pattern in memory corresponding to base_addr. Before filling memory, the function shows data pattern choices on serial console and waits for user's input. For invalid choice, the console will display the error message and wait until user input new valid choice. Then selected data pattern is filled into memory by writing register from address base_addr+0x0000 to base_addr+0x07FF.

According to Table 3-5, there are four data pattern choices to fill memory that are zero pattern, 8-bit counter pattern, 16-bit pattern and 32-bit pattern. For zero pattern, user can select this choice to clear data memory. It makes user see the output of encryption/decryption more clearly.

3.4 Fill Cipher Data Memory

This menu is used to fill DpRam2 with cipher data pattern. The sequence of the firmware is as follows.

1) Call fill_data function to choose data pattern and fill DpRam2 with selected pattern. The input parameter of fill_data is CIPHER_BASE_ADDR which is base address for DpRam2.

2) Call show_data function to show data in both DpRam1 and DpRam2 corresponding to default number of showing data (DEFAULT_SHOW_AFTER_FILL).

3.5 Encrypt

This menu is used to set the number of 128-bit plain data to encrypt and start encryption process. The sequence of the firmware is as follows.

1) Receive the number of 128-bit plain data in decimal format or "enter" key to use default value. If user input '0', the number of 128-bit data to encrypt will be default value. The number of 128-bit data to encrypt is stored in length128.

2) Call aes_command function to set the starting address, number of data to encrypt and check status. ENC_CNT_REG and length128 are input parameters. aes_command function is described in Table 3-6.

3) Call show_data function to show data memory.

Table 3-6 aes_command function

void aes_command(unsigned int *CMD_REG, unsigned int length128)	
Parameter	CMD_REG: register for setting the number of 128-bit data to operate and checking status length128: the number of 128-bit data to operate
Return value	None
Description	This function resets the starting address of DpRam1 and DpRam2 by writing register ADDR_A1_REG and ADDR_A2_REG, respectively. Then CMD_REG is written with length128 to set the number of 128-bit data to operate. Also, CMD_REG is monitored to check whether operation finish. When operation finished, *CMD_REG=0 which means no remaining data to operate (*CMD_REG[6:0]=0) and AES128IP is not busy. (*CMD_REG[7]= '0')

3.6 Decrypt

This menu is used to set the number of 128-bit cipher data to decrypt and start decryption process. The sequence of the firmware is as follows.

1) Receive the number of 128-bit cipher data in decimal format or "enter" key to use default value. If user input '0', the number of 128-bit data to decrypt will be default value. The number of 128-bit data to decrypt is stored in length128.

2) Call aes_command function to set the starting address, number of data to decrypt and check status. DEC_CNT_REG and length128 are input parameters.

3) Call show_data function to show data memory.

4   Revision History

Revision	Date	Description
1.00	7-Apr-2022	Initial version release
1.02	29-Aug-2022	Update description for new design
1,03	3-May-2023	Revised description information