

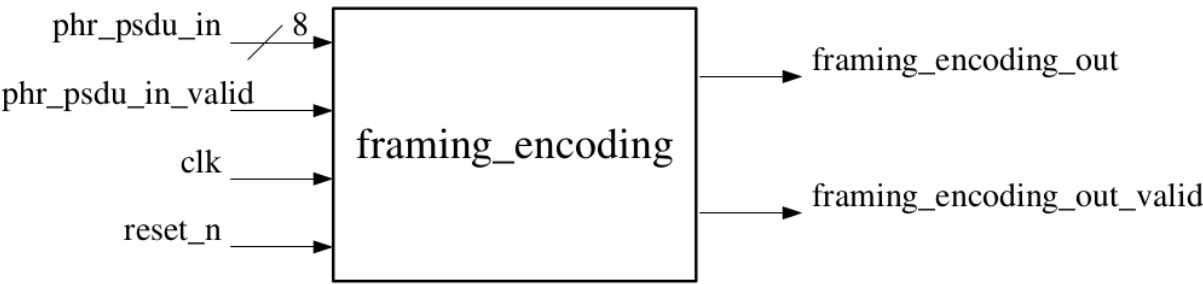
物理层组帧编码 *framing_encoding*

编码结构

SHR		PHR	PSDU	FCS
前导码	帧分隔符	物理层帧头	物理层载荷	帧校验序列
8 Byte	2 Byte	4 Byte	变长	2 Byte

顶层设计

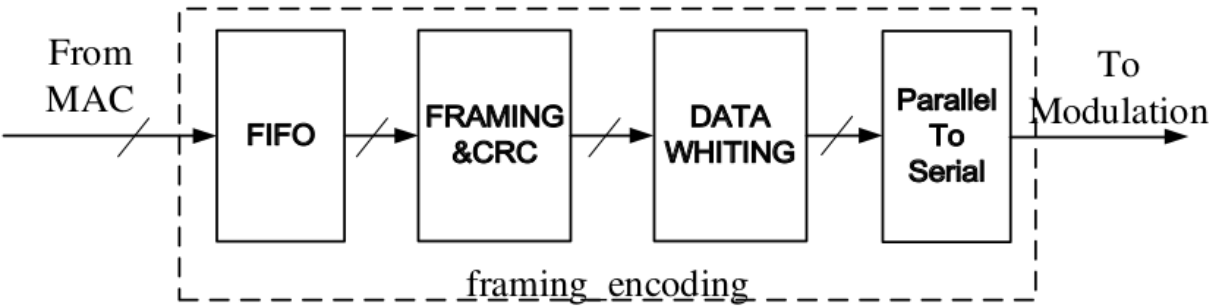
模块接口



```
input clk;
input reset_n;
input [7:0] phr_psdu_in;
input phr_psdu_in_valid;

output framing_encoding_out;
output framing_encoding_out_valid;
```

内部结构



原理分析

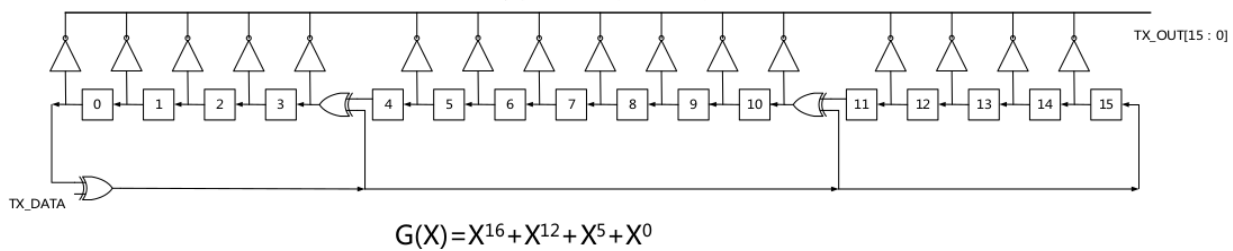
FIFO (First In First Out)

- 输入端口直接与外部相连，输入数据为 1 Byte @(posedge clk) ;

- 输出端口与下级模块 CRC 相连，具体输出形式依赖于 CRC 模块采用串行输入or并行输入；
- 输入输出均有 valid 使能信号；
- 若采用串行输出 1 Bit @(posedge clk)，由于输入输出速率不匹配，故 FIFO 内部需要一定大小的存储器，防止数据阻塞丢失；
- 若 CRC 模块采用 8 Bits 并行输入，那么 FIFO 模块可以省略；

CRC (Cyclic Redundancy Check)

串入并出



- 输入数据从低位到高位依次从 TX_DATA 输入，当数据全部输入后，此时对应的 TX_OUT[15:0] 即 CRC 产生的16位 FCS 码；
- 记图中16个D触发器当前状态为 fcs_n[15:0]，则 fcs_n 状态转移过程如下

```
always @(posedge clk) begin
    fcs_n <= {fcs_n[0]^TX_DATA, fcs_n[15:12],
              fcs_n[11]^fcs_n[0]^TX_DATA, fcs_n[10:5],
              fcs_n[4]^fcs_n[0]^TX_DATA, fcs_n[3:1]};
end

assign TX_OUT = ~fcs_n;
```

并入并出

- 根据串入并出可推导出，输入 8 Bits 数据后，fcs_n 的变化：

```
always @(posedge clk) begin
    fcs_n1 <= {fcs_n[0]^TX_DATA[0], fcs_n[15:12],
              fcs_n[11]^fcs_n[0]^TX_DATA[0], fcs_n[10:5],
              fcs_n[4]^fcs_n[0]^TX_DATA[0], fcs_n[3:1]};
    fcs_n2 <= {fcs_n1[0]^TX_DATA[1], fcs_n1[15:12],
              fcs_n1[11]^fcs_n1[0]^TX_DATA[1], fcs_n1[10:5],
              fcs_n1[4]^fcs_n1[0]^TX_DATA[1], fcs_n1[3:1]};
    fcs_n3 <= {fcs_n2[0]^TX_DATA[2], fcs_n2[15:12],
              fcs_n2[11]^fcs_n2[0]^TX_DATA[2], fcs_n2[10:5],
              fcs_n2[4]^fcs_n2[0]^TX_DATA[2], fcs_n2[3:1]};
    fcs_n4 <= {fcs_n3[0]^TX_DATA[3], fcs_n3[15:12],
              fcs_n3[11]^fcs_n3[0]^TX_DATA[3], fcs_n3[10:5],
              fcs_n3[4]^fcs_n3[0]^TX_DATA[3], fcs_n3[3:1]};
    fcs_n5 <= {fcs_n4[0]^TX_DATA[4], fcs_n4[15:12],
              fcs_n4[11]^fcs_n4[0]^TX_DATA[4], fcs_n4[10:5],
              fcs_n4[4]^fcs_n4[0]^TX_DATA[4], fcs_n4[3:1]};
    fcs_n6 <= {fcs_n5[0]^TX_DATA[5], fcs_n5[15:12],
              fcs_n5[11]^fcs_n5[0]^TX_DATA[5], fcs_n5[10:5],
              fcs_n5[4]^fcs_n5[0]^TX_DATA[5], fcs_n5[3:1]};
    fcs_n7 <= {fcs_n6[0]^TX_DATA[6], fcs_n6[15:12],
              fcs_n6[11]^fcs_n6[0]^TX_DATA[6], fcs_n6[10:5],
              fcs_n6[4]^fcs_n6[0]^TX_DATA[6], fcs_n6[3:1]};
    fcs_n <= {fcs_n7[0]^TX_DATA[7], fcs_n7[15:12],
              fcs_n7[11]^fcs_n7[0]^TX_DATA[7], fcs_n7[10:5],
              fcs_n7[4]^fcs_n7[0]^TX_DATA[7], fcs_n7[3:1]};
end
```

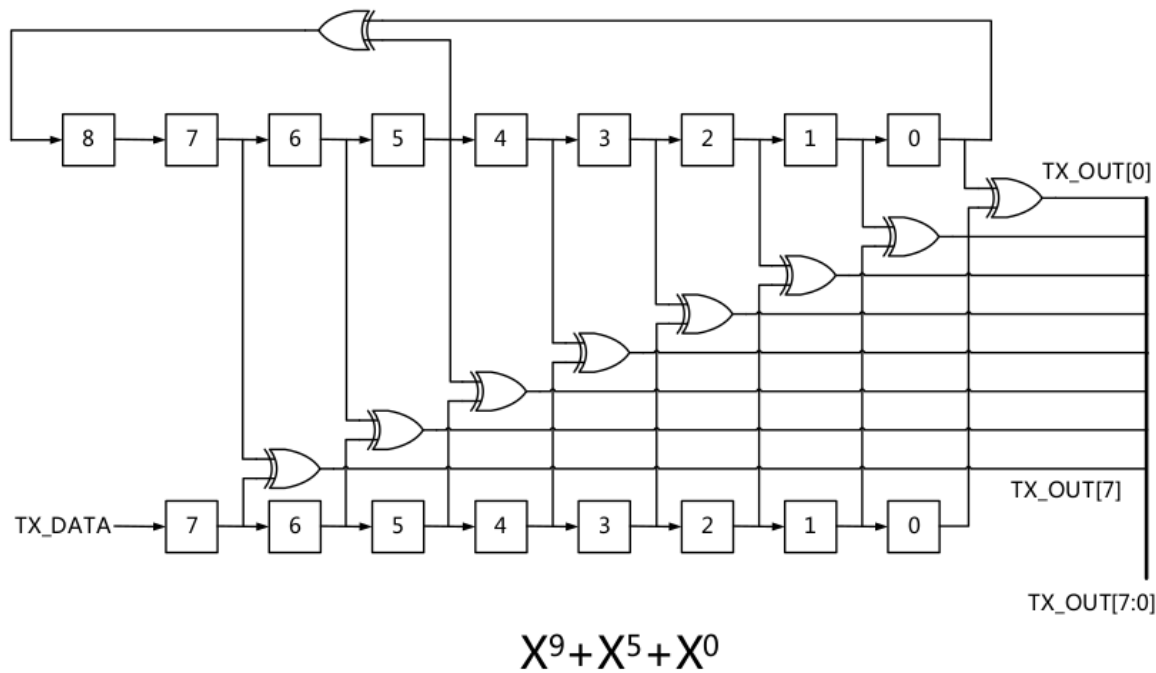
```
assign TX_OUT = ~fcs_n;
```

串行输出

- 只需在产生并行结果 TX_OUT[15:0] 后，进行移位输出即可；

Data Whiting

串入并出



串入串出

- 输入数据直接与当前伪随机序列的最低位异或，得到的结果即输出数据；

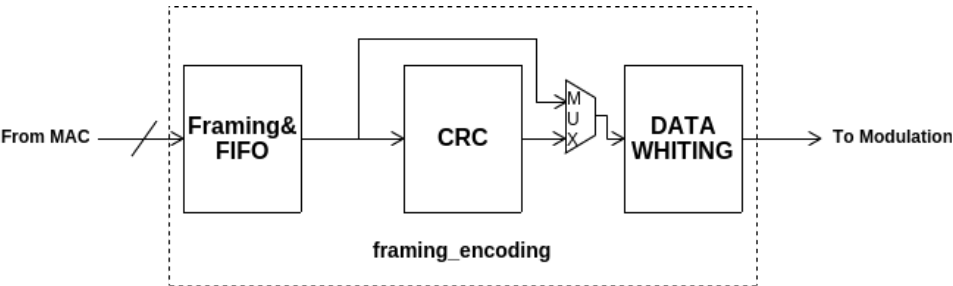
```
assign TX_OUT = pseudo_rand[0] ^ TX_DATA;
```

- 伪随机序列 pseudo_rand[8:0] 演化过程如下

```
always @(posedge clk) begin
    pseudo_rand <= {pseudo_rand[5]^pseudo_rand[0], pseudo_rand[8:1]};
end
```

综合考虑

- 由于输入 8 Bits @(posedge clk) 与输出 1 Bit @(posedge clk) 的不匹配，各模块之间用并行方式进行连接只能为 CRC 和 WHITING 提速，从整体上看，最终并转串总会使输出速率降低；
- 因此尝试在各模块之间用串行信号通信（串入串出白化编码模块较易实现）



- 编码过程:

- i. FIFO 接收输入数据，存于存储器，一旦检测到有数据输入则开始串行输出编码的 80 Bits SHR 部分，SHR 输出完毕后紧接着串行输出 PHR 和 PSDU，此过程中 fifo_output_valid 有效;
- ii. WHITING 在 fifo_output_valid 有效时接收 FIFO 输出的 {SHR, PHR, PSDU}，接收 SHR 时 WHITING 相当于 buffer，接收 {PHR, PSDU} 时从低位开始逐位白化;
- iii. CRC 在 fifo_output_valid 有效时接收 FIFO 输出的 {SHR, PHR, PSDU}，接收 SHR 时无操作，接收 {PHR, PSDU} 开始计算 FCS，当 fifo_output_valid 无效时 FCS 计算完成，开始串行输出，crc_output_valid 有效;
- iv. WHITING 在 crc_output_valid 有效时接收 CRC 输出串行 FCS 编码，此时 {PHR, PSDU} 正好白化完成并已输出，紧接着对 FCS 逐位白化，白化完成即整个编码过程结束;

模块实现

fifo

端口

```
input clk;           // 10kHz
input reset_n;       // low active
input [7:0] fifo_input; // 1 Byte data in @(posedge clk)
input fifo_input_valid; // high active

output fifo_output;   // 1 bit data out @(posedge clk)
output fifo_output_valid; // high active
```

实现机制

- 存储器解决进出速率不匹配问题

```
reg [7:0] memory [7:0]; // 8 Bytes memory
reg [2:0] count;        // count Bytes already stored in memory
reg [2:0] col, read_row; // point to bit memory ready to output
reg [2:0] write_row;    // point to next empty row in memory
// for storing input data
```

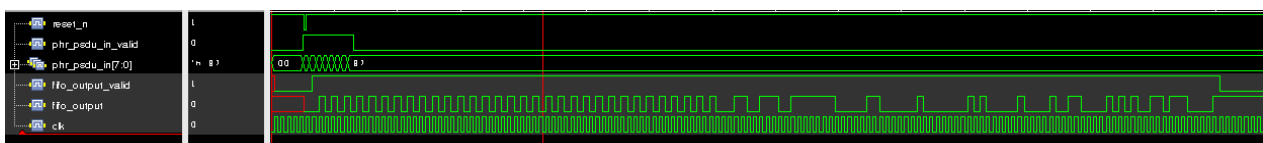
- 从第一字节数据中获取码长信息

```
reg read_data_size; // high active when a new datastream starts
reg [7:0] data_size; // data size got from first Byte
reg [7:0] send_count; // count Bytes already sent out,
// when send_count == data_size,
// read_data_size turns into high active
```

- 组合 SHR 编码，先输出 SHR，再输出 PHR 和 PSDU

```
reg [79:0] shr; // 10 Bytes SHR code
reg [6:0] shr_count; // count whether SHR ends
```

功能仿真



crc

端口

```
input clk;
input reset_n;
input tx_data;          // 1 bit data in @(posedge clk)
input tx_data_valid;

output tx_out;          // 1 bit data out @(posedge clk)
output tx_out_valid;
```

实现机制

- 串行输入含 SHR 的数据

```
reg [6:0] shr_count;      // count from 0 to 79, to count SHR
```

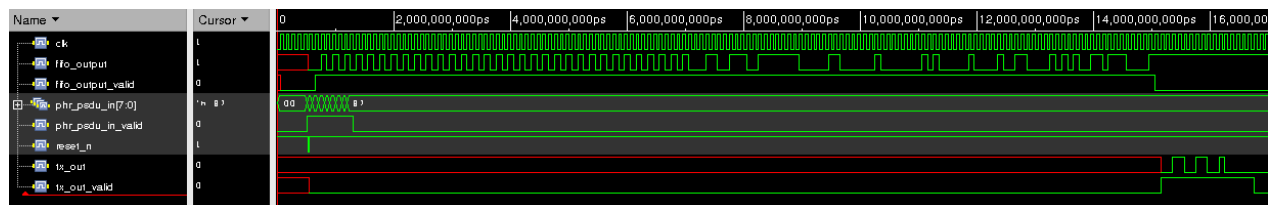
- 16个D触发器实现 fcs 码计算

```
reg [15:0] fcs_n;        // keep refreshing until tx_data_valid -> low
```

- 串行输出

```
reg [3:0] fcs_count;      // count from 0 to 15, to output fcs serially
reg tx_out_valid;         // high active when outputing fcs
```

功能仿真



whiting

端口

```
input clk;
input reset_n;
input tx_data;          // 1 bit data in @(posedge clk)
input tx_data_valid;

output tx_out;          // 1 bit data out @(posedge clk)
output tx_out_valid;
```

实现机制

- 伪随机序列生成

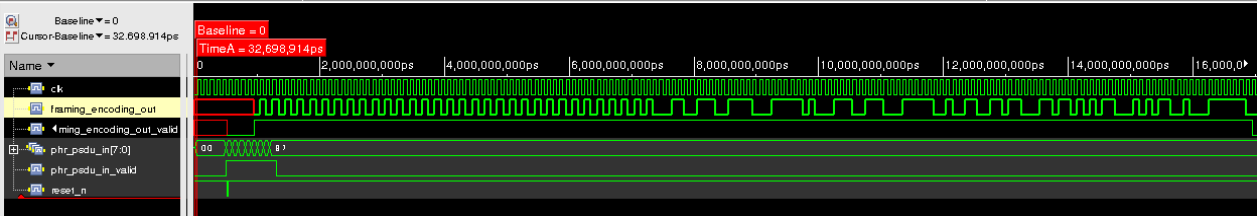
```
reg [8:0] pseudo_rand;    // 9 bits pseudo random sequence
```

- 接收 SHR 码不白化直接输出

```
reg [6:0] shr_count;      // count from 0 to 79
```

NC仿真

功能仿真



输出结果正确

DC综合

```
*****

Library(s) Used:

    typical (File: /soft1/course_lib_umc18/tt_1v8_25c.db)

Number of ports:          13
Number of nets:           19
Number of cells:          4
Number of references:      4

Combinational area:       10857.369742
Noncombinational area:    16306.012917
Net Interconnect area:    104627.203186

Total cell area:          27163.382659
Total area:               131790.585845

*****

Report : area
Design : framing_encoding
Version: D-2010.03
Date   : Sat Jun 13 22:54:19 2015
*****

*****

Operating Conditions: typical   Library: typical
Wire Load Model Mode: top

Startpoint: FIFO/count_reg[1]
             (rising edge-triggered flip-flop clocked by clk)
Endpoint:   FIFO/send_count_reg[0]
             (rising edge-triggered flip-flop clocked by clk)
Path Group: clk
Path Type:  max

Des/Clust/Port    Wire Load Model    Library
-----
framing_encoding  umc18_wl10         typical

Point              Incr              Path
-----
clock clk (rise edge)          0.00          0.00
clock network delay (ideal)     0.00          0.00
FIFO/count_reg[1]/CK (DFFRHQX1) 0.00          0.00 r
FIFO/count_reg[1]/Q (DFFRHQX1)  0.64          0.64 r
```

FIFO/U288/Y (OR4X2)	0.19	0.82 r
FIFO/U51/Y (INVX2)	0.09	0.92 f
FIFO/U42/Y (INVX2)	0.11	1.03 r
FIFO/U11/Y (INVX2)	0.10	1.13 f
FIFO/U49/Y (NOR2X1)	0.79	1.92 r
FIFO/U145/Y (AND2X1)	0.22	2.14 r
FIFO/U152/Y (NAND2X1)	0.16	2.30 f
FIFO/U50/Y (NOR2X1)	0.63	2.92 r
FIFO/U41/Y (INVX2)	0.46	3.38 f
FIFO/U47/Y (NOR2X1)	0.84	4.22 r
FIFO/U285/Y (NAND2X1)	0.07	4.29 f
FIFO/U284/Y (OAI2BB1X1)	0.15	4.44 r
FIFO/send_count_reg[0]/D (DFFRHQX1)	0.00	4.44 r
data arrival time		4.44
clock clk (rise edge)	100000.00	100000.00
clock network delay (ideal)	0.00	100000.00
FIFO/send_count_reg[0]/CK (DFFRHQX1)	0.00	100000.00 r
library setup time	-0.14	99999.86
data required time		99999.86

data required time		99999.86
data arrival time		-4.44

slack (MET)		99995.42

Report : timing

- path full
- delay max
- max_paths 1
- sort_by group

Design : framing_encoding

Version: D-2010.03

Date : Sat Jun 13 22:54:30 2015

Operating Conditions: typical Library: typical

Wire Load Model Mode: top

Startpoint: FIFO/count_reg[1]
 (rising edge-triggered flip-flop clocked by clk)

Endpoint: FIFO/send_count_reg[0]
 (rising edge-triggered flip-flop clocked by clk)

Path Group: clk

Path Type: max

Des/Clust/Port	Wire Load Model	Library	

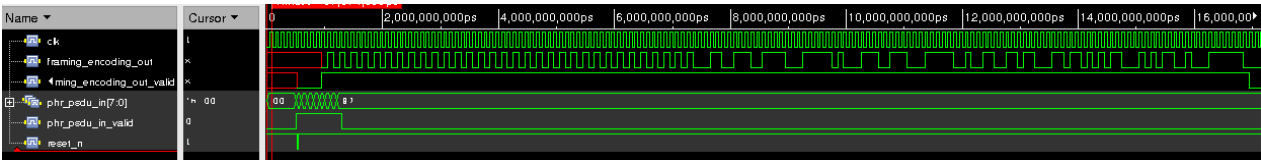
framing_encoding	umc18_wl10	typical	

Point	Incr	Path	

clock clk (rise edge)	0.00	0.00	
clock network delay (ideal)	0.00	0.00	
FIFO/count_reg[1]/CK (DFFRHQX1)	0.00	0.00 r	
FIFO/count_reg[1]/Q (DFFRHQX1)	0.64	0.64 r	
FIFO/U288/Y (OR4X2)	0.19	0.82 r	
FIFO/U51/Y (INVX2)	0.09	0.92 f	
FIFO/U42/Y (INVX2)	0.11	1.03 r	
FIFO/U11/Y (INVX2)	0.10	1.13 f	
FIFO/U49/Y (NOR2X1)	0.79	1.92 r	
FIFO/U145/Y (AND2X1)	0.22	2.14 r	
FIFO/U152/Y (NAND2X1)	0.16	2.30 f	
FIFO/U50/Y (NOR2X1)	0.63	2.92 r	
FIFO/U41/Y (INVX2)	0.46	3.38 f	
FIFO/U47/Y (NOR2X1)	0.84	4.22 r	
FIFO/U285/Y (NAND2X1)	0.07	4.29 f	
FIFO/U284/Y (OAI2BB1X1)	0.15	4.44 r	

FIFO/send_count_reg[0]/D (DFFRHQX1)	0.00	4.44 r
data arrival time		4.44
<hr/>		
clock clk (rise edge)	100000.00	100000.00
clock network delay (ideal)	0.00	100000.00
FIFO/send_count_reg[0]/CK (DFFRHQX1)	0.00	100000.00 r
library setup time	-0.14	99999.86
data required time		99999.86
<hr/>		
data required time		99999.86
data arrival time		-4.44
<hr/>		
slack (MET)		99995.42

门级仿真



波形与综合前波形几乎没有任何区别

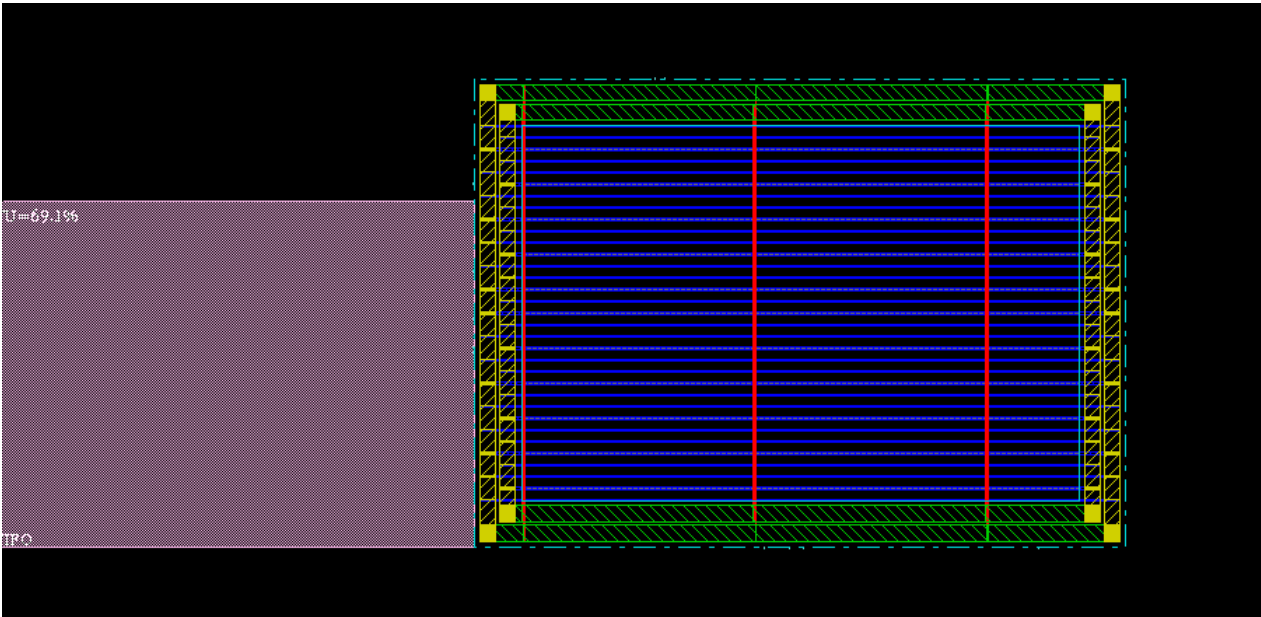
SDF反标

再次仿真波形没有区别

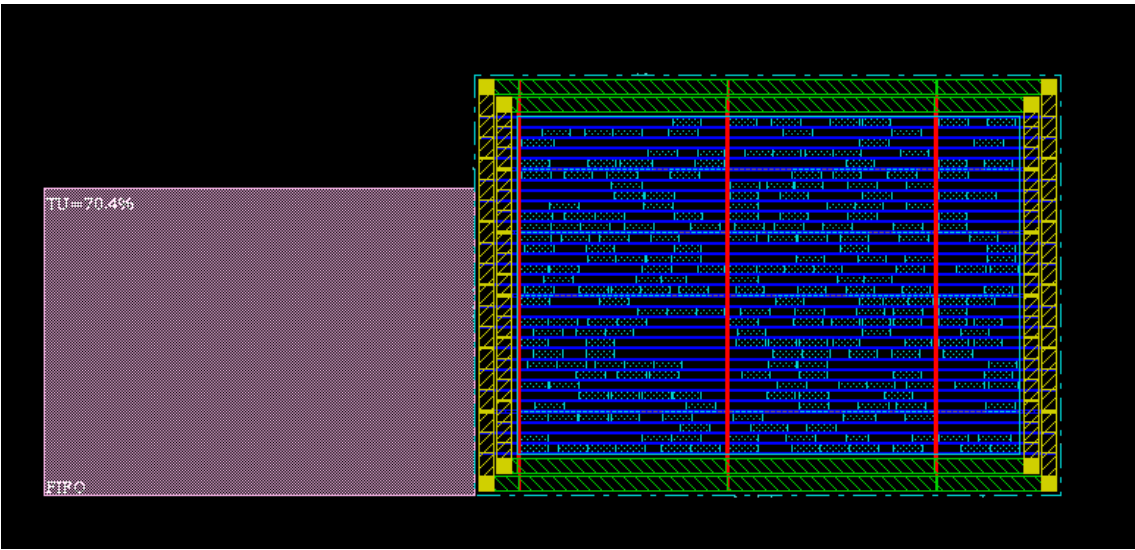
由于时钟频率**10kHz**较低, 延时造成的时序影响微乎其微, 故波形没有显著区别

布局布线

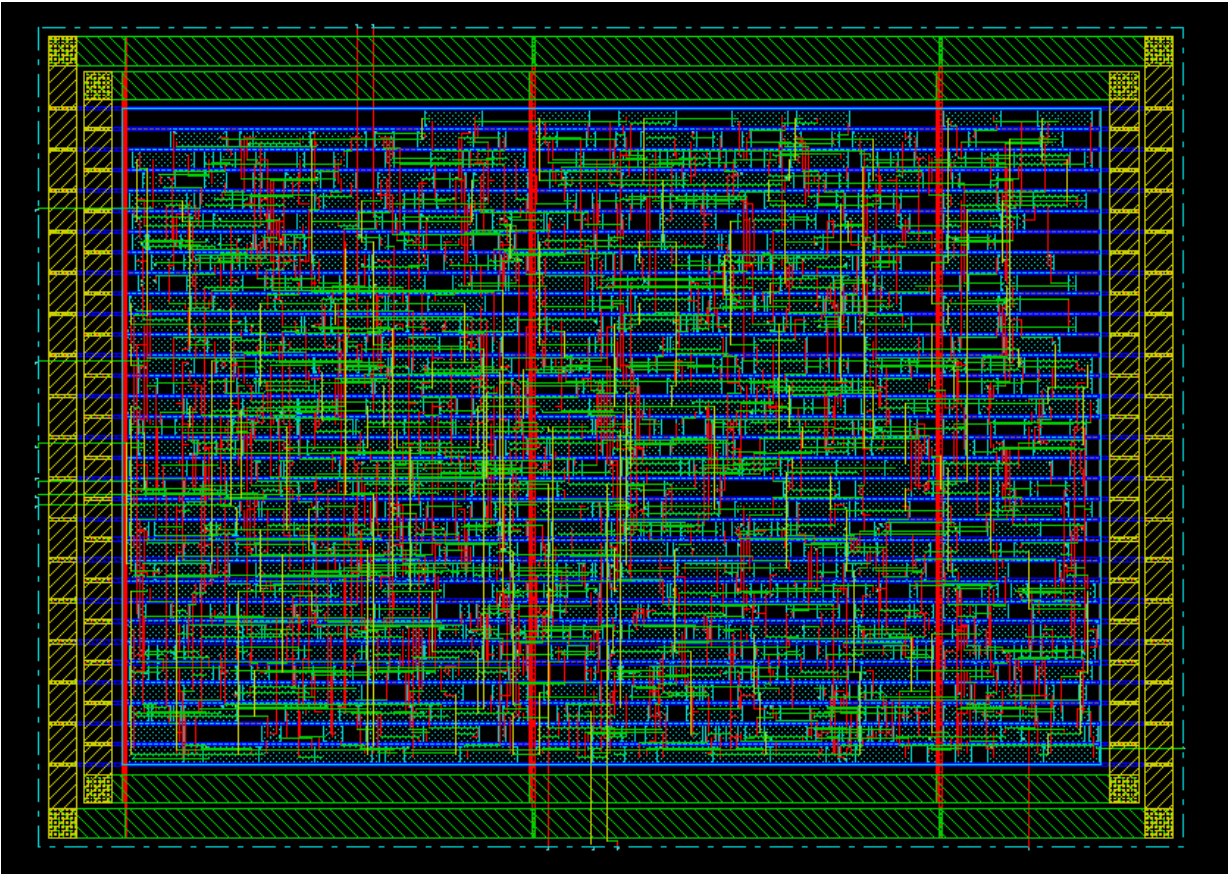
pre CTS



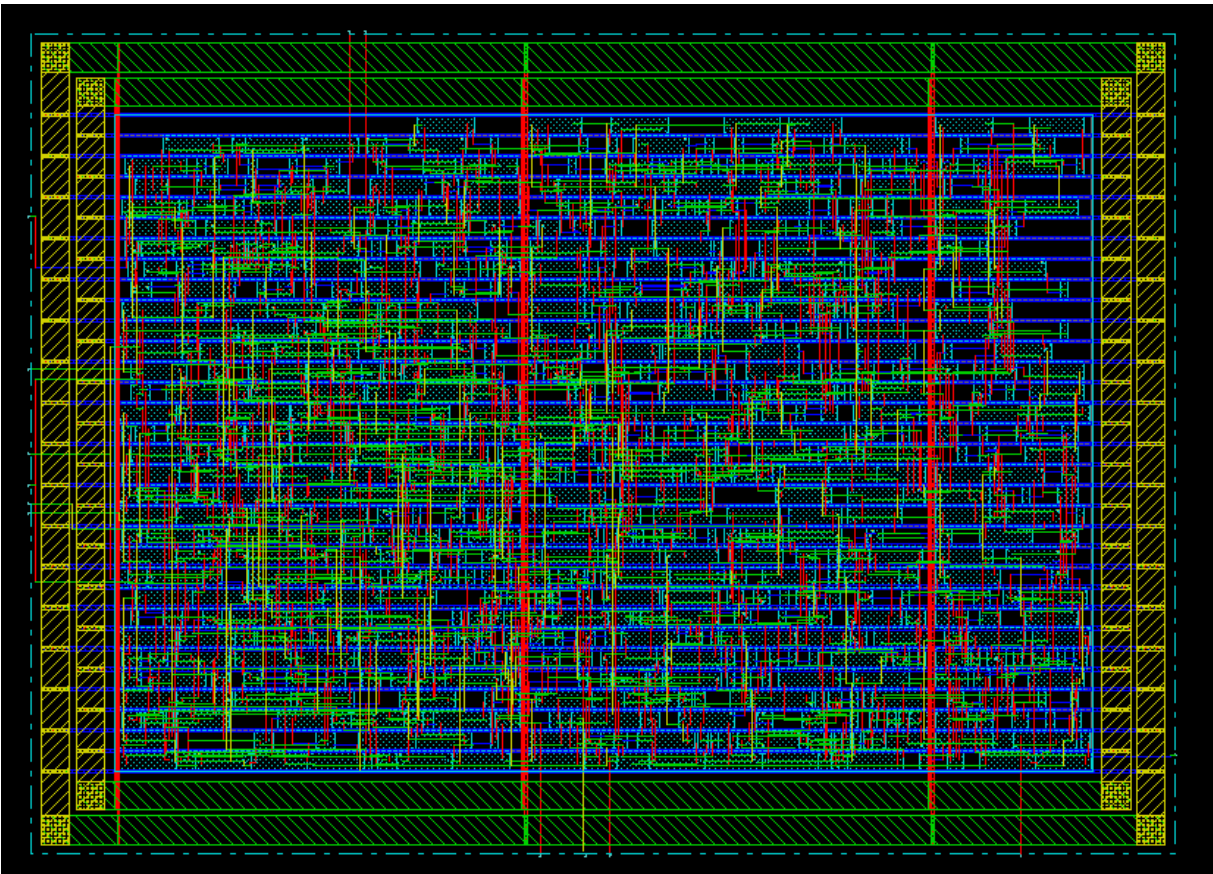
post CTS



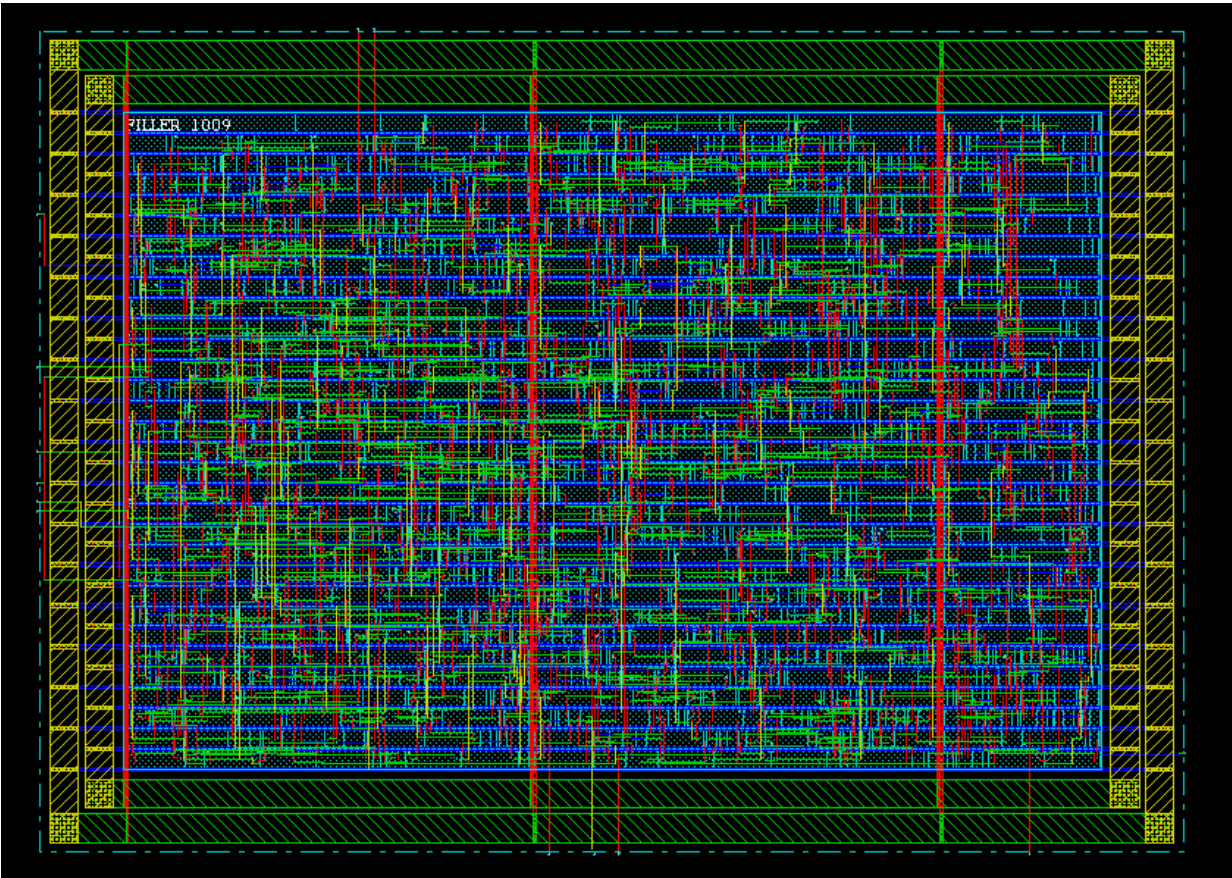
trail routing



nano routing



add filler



final



附 源码

framing_encoding.v

```
// framing_encoding.v

module framing_encoding (
    input clk, // 10kHz
    input reset_n, // asynchronous reset active low
    input [7:0] phr_psdu_in,
    input phr_psdu_in_valid,
    output framing_encoding_out,
    output framing_encoding_out_valid
);

    fifo FIFO(
        .clk(clk),
        .reset_n(reset_n),
        .fifo_input(phr_psdu_in),
        .fifo_input_valid(phr_psdu_in_valid),

        .fifo_output(fifo_output),
        .fifo_output_valid(fifo_output_valid)
    );

    crc CRC(
        .clk(clk),
        .reset_n(reset_n),
        .tx_data(fifo_output),
        .tx_data_valid(fifo_output_valid),

        .tx_out(crc_output),
        .tx_out_valid(crc_output_valid)
    );

    select_whiting_input SELECT(
        .clk(clk),
```

```

.reset_n(reset_n),
.fifo_output(fifo_output),
.fifo_output_valid(fifo_output_valid),
.crc_output(crc_output),
.crc_output_valid(crc_output_valid),

.whiting_input(whiting_input),
.whiting_input_valid(whiting_input_valid)
);

whiting WHITING(
.clk(clk),
.reset_n(reset_n),
.tx_data(whiting_input),
.tx_data_valid(whiting_input_valid),

.tx_out(framing_encoding_out),
.tx_out_valid(framing_encoding_out_valid)
);

endmodule

module select_whiting_input (
input clk,
input reset_n,
input fifo_output,
input fifo_output_valid,
input crc_output,
input crc_output_valid,
output reg whiting_input,
output reg whiting_input_valid
);

reg pre_input;
reg [1:0] state;
// state == 0: waiting for input data
// state == 1: stored one bit data in pre_input
// state == 2: pre_input is empty, turns into a buffer

always @(posedge clk or negedge reset_n) begin
if (~reset_n) begin
whiting_input_valid <= 0;
state <= 0;
end else begin
if (state == 0) begin
if (fifo_output_valid) begin
pre_input <= fifo_output;
whiting_input_valid <= 0;
state <= 1;
end else state <= 0;
end else if (state == 1) begin
whiting_input <= pre_input;
whiting_input_valid <= 1;
if (fifo_output_valid) begin
pre_input <= fifo_output;
state <= 1;
end else if (crc_output_valid) begin
pre_input <= crc_output;
state <= 1;
end else begin
state <= 2;
end
end else begin
if (fifo_output_valid) begin
whiting_input <= fifo_output;
whiting_input_valid <= 1;
state <= 2;
end else if (crc_output_valid) begin
whiting_input <= crc_output;
whiting_input_valid <= 1;
state <= 2;
end
end
end
end

```

```

        end else begin
            whiting_input_valid <= 0;
            state <= 0;
        end
    end
end
end

endmodule

```

fifo.v

```

// fifo.v

module fifo (
    input clk,
    input reset_n,
    input [7:0] fifo_input,    // 8 bit in
    input fifo_input_valid,
    output reg fifo_output,    // 1 bit out
    output reg fifo_output_valid
    // output fifo_full
);

parameter MEMORY_SIZE = 8;
integer i;

reg [7:0] memory [MEMORY_SIZE - 1:0];
reg [2:0] col; // mark which bit to output
reg [2:0] read_row; // mark which row to output
reg [2:0] write_row; // mark which row to write data
reg [3:0] count; // count the number of 1-Byte-data still in memory
reg [7:0] send_count; // count the number of data sent out
reg [7:0] data_size; // Bytes of phr + psdu is data_size
reg read_data_size; // tag: high active to catch data_size
reg [6:0] shr_count; // count: output SHR code
reg [79:0] shr; // SHR code: {16'hF3_98, 64'hAA_AA_AA_AA_AA_AA_AA_AA}

always @(posedge clk or negedge reset_n) begin
    if (~reset_n) begin
        // initialize memory
        for (i = 0; i < MEMORY_SIZE; i = i + 1) begin
            memory[i] <= 8'h00;
        end
        // initialize row, col
        // ready to output memory[0][0], but memory is empty
        col <= 3'b000;
        read_row <= 3'b000;
        write_row <= 3'b000;
        fifo_output <= 0;
        fifo_output_valid <= 0;
        count <= 0;
        send_count <= 0;
        read_data_size <= 1;
        shr_count <= 0;
        shr <= {16'hF3_98, 64'hAA_AA_AA_AA_AA_AA_AA_AA};
    end else begin
        if (fifo_input_valid && count < MEMORY_SIZE) begin // store input data
            if (read_data_size) begin
                data_size <= fifo_input; // first Byte
                read_data_size <= 0; // flag off
            end
            if (count == 0) begin
                memory[0] <= fifo_input; // store into empty memory
                read_row <= 0;
                write_row <= 1;
            end else begin
                memory[write_row] <= fifo_input;
                write_row <= write_row + 1;
            end
        end
    end
end

```

```

        end
        count <= count + 1;
    end
    if (count != 0) begin        // output data
        if (shr_count == 80) begin        // SHR end
            shr <= {16'hF3_98, 64'hAA_AA_AA_AA_AA_AA_AA_AA};
            fifo_output <= memory[read_row][col];
            fifo_output_valid <= 1;
            if (col == 7) begin        // one Byte data is sent out
                read_row <= read_row + 1;
                count <= count - 1;
                if (send_count == data_size) begin // data end
                    send_count <= 0;
                    read_data_size <= 1;        // catch next data_size
                    shr_count <= 0;
                end else send_count <= send_count + 1;
            end
            col <= col + 1;
        end else begin        // outputting SHR code
            fifo_output <= shr[0];
            fifo_output_valid <= 1;
            shr <= shr >> 1;
            shr_count <= shr_count + 1;
        end
    end else fifo_output_valid <= 0;
end
end

endmodule

```

crc.v

```

// crc.v

module crc (
    input clk, // 10kHz
    input reset_n, // asynchronous reset active low
    input tx_data,
    input tx_data_valid,
    output reg tx_out, // serial output
    output reg tx_out_valid // high active when outputting FCS code serially
);

reg [15:0] fcs_n;
reg [6:0] shr_count;
reg [3:0] fcs_count;

always @(posedge clk or negedge reset_n) begin
    if (~reset_n) begin
        fcs_n <= 16'hffff;
        shr_count <= 0;
        fcs_count <= 0;
    end else begin
        if (tx_data_valid) begin
            if (shr_count == 80) begin
                fcs_n <= {fcs_n[0]^tx_data, fcs_n[15:12],
                    fcs_n[11]^fcs_n[0]^tx_data, fcs_n[10:5],
                    fcs_n[4]^fcs_n[0]^tx_data, fcs_n[3:1]};
            end else shr_count <= shr_count + 1;
        end else if (shr_count == 80) begin
            tx_out_valid <= 1;
            tx_out <= ~fcs_n[0];
            fcs_n <= fcs_n >> 1;
            if (fcs_count == 15) shr_count <= 0; // ready to receive next data;
            fcs_count <= fcs_count + 1;
        end else begin
            tx_out_valid <= 0;
            shr_count <= 0;
        end
    end
end

```

```

    end
end

endmodule

```

whiting.v

```

// whiting.v

module whiting (
    input clk,
    input reset_n,
    input tx_data, // serial input
    input tx_data_valid,
    output reg tx_out, // serial output
    output reg tx_out_valid
);

reg [8:0] pseudo_rand;
reg [6:0] shr_count;
reg data_received;

always @(posedge clk or negedge reset_n) begin
    if (~reset_n) begin
        pseudo_rand <= 9'b111_111_111;
        tx_out_valid <= 0;
        shr_count <= 0;
        data_received <= 0;
    end else begin
        if (tx_data_valid) begin
            if (shr_count == 80) begin
                tx_out <= tx_data ^ pseudo_rand[0];
                tx_out_valid <= 1;
                pseudo_rand <= {pseudo_rand[5]^pseudo_rand[0], pseudo_rand[8:1]};
                data_received <= 1;
            end else begin
                shr_count <= shr_count + 1;
                tx_out <= tx_data;
                tx_out_valid <= 1;
                data_received <= 0;
            end
        end else if (data_received) begin // ready to receive SHR of next data
            tx_out_valid <= 0;
            shr_count <= 0;
            data_received <= 1;
        end else begin
            tx_out_valid <= 0; // waiting for PHR PSDU FCS
        end
    end
end

endmodule

```

framing_encoding_test.v

```

`timescale 1us/100ns

module framing_encoding_test;

    wire          framing_encoding_out;
    wire          framing_encoding_out_valid;
    reg [7:0]      phr_psd_u_in;
    reg           phr_psd_u_in_valid;
    reg           clk;
    reg           reset_n;

```

```

framing_encoding u0framing_encoding(
    .framing_encoding_out      (framing_encoding_out),
    .framing_encoding_out_valid (framing_encoding_out_valid),
    .phr_psdu_in              (phr_psdu_in),
    .phr_psdu_in_valid        (phr_psdu_in_valid),
    .clk                       (clk),
    .reset_n                   (reset_n)
);

// stop simulation after 20000us
initial
begin
    #20000 $stop;
end

// generate data input signal
initial
begin
    phr_psdu_in=8'h00;
    #500 phr_psdu_in=8'h07;
    #100 phr_psdu_in=8'h03;
    #100 phr_psdu_in=8'h01;
    #100 phr_psdu_in=8'h05;
    #100 phr_psdu_in=8'h21;
    #100 phr_psdu_in=8'h43;
    #100 phr_psdu_in=8'h65;
    #100 phr_psdu_in=8'h87;
end

// generate phr_psdu_in_valid signal
initial
begin
    phr_psdu_in_valid =1'b0;
    #500 phr_psdu_in_valid =1'b1;
    #800 phr_psdu_in_valid =1'b0;
end

// generate clk signal
initial
begin
    clk=1'b0;
end
always #50 clk=~clk;

// generate resrt_n signal
initial
begin
    reset_n=1'b1;
    # 520 reset_n=1'b0;
    # 20  reset_n=1'b1;
end

endmodule

```

fifo_test.v

```

// fifo_test.v
`timescale 1us/100ns

module fifo_test;

    wire          fifo_output;
    wire          fifo_output_valid;
    reg   [7:0]    phr_psdu_in;

```



```

    reg                phr_psdu_in_valid;
    reg                clk;
    reg                reset_n;

fifo fifo0 (
    .clk(clk),
    .reset_n(reset_n),
    .fifo_input(phr_psdu_in),
    .fifo_input_valid(phr_psdu_in_valid),
    .fifo_output(fifo_output),
    .fifo_output_valid(fifo_output_valid)
);

// stop simulation after 20000us
initial
begin
    #20000 $stop;
end

// generate data input signal
initial
begin
    phr_psdu_in=8'h00;
    #500 phr_psdu_in=8'h07;
    #100 phr_psdu_in=8'h03;
    #100 phr_psdu_in=8'h01;
    #100 phr_psdu_in=8'h05;
    #100 phr_psdu_in=8'h21;
    #100 phr_psdu_in=8'h43;
    #100 phr_psdu_in=8'h65;
    #100 phr_psdu_in=8'h87;
end

// generate phr_psdu_in_valid signal
initial
begin
    phr_psdu_in_valid =1'b0;
    #500 phr_psdu_in_valid =1'b1;
    #800 phr_psdu_in_valid =1'b0;
end

// generate clk signal
initial
begin
    clk=1'b0;
end
always #50 clk=~clk;

// generate resrt_n signal
initial
begin
    reset_n=1'b1;
    # 520 reset_n=1'b0;
    # 20  reset_n=1'b1;
end

endmodule

```

crc_test.v

```

// crc_test.v
`timescale 1us/100ns

module crc_test;

```

```

    wire          tx_out;
    reg    [7:0]   phr_psdu_in;
    reg           phr_psdu_in_valid;
    reg           clk;
    reg           reset_n;

fifo fifo0 (
    .clk(clk),
    .reset_n(reset_n),
    .fifo_input(phr_psdu_in),
    .fifo_input_valid(phr_psdu_in_valid),
    .fifo_output(fifo_output),
    .fifo_output_valid(fifo_output_valid)
);

crc crc0 (
    .clk(clk),
    .reset_n(reset_n),
    .tx_data(fifo_output),
    .tx_data_valid(fifo_output_valid),
    .tx_out(tx_out),
    .tx_out_valid(tx_out_valid)
);

// stop simulation after 20000us
initial
begin
    #20000 $stop;
end

// generate data input signal
initial
begin
    phr_psdu_in=8'h00;
    #500 phr_psdu_in=8'h07;
    #100 phr_psdu_in=8'h03;
    #100 phr_psdu_in=8'h01;
    #100 phr_psdu_in=8'h05;
    #100 phr_psdu_in=8'h21;
    #100 phr_psdu_in=8'h43;
    #100 phr_psdu_in=8'h65;
    #100 phr_psdu_in=8'h87;
end

// generate phr_psdu_in_valid signal
initial
begin
    phr_psdu_in_valid =1'b0;
    #500 phr_psdu_in_valid =1'b1;
    #800 phr_psdu_in_valid =1'b0;
end

// generate clk signal
initial
begin
    clk=1'b0;
end
always #50 clk=~clk;

// generate reset_n signal
initial
begin
    reset_n=1'b1;
    # 520 reset_n=1'b0;
    # 20  reset_n=1'b1;
end

```

```
end
```

```
endmodule
```