

RS-232 Communication System - Project Report

ELE111 Semester Project 2025

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1. Introduction / Summary

This project implements a complete RS-232 communication system on the DE2-115 FPGA board. The system features a configurable baud rate generator, two selectable data sources, and full status visualization on LEDs and 7-segment displays. The RS-232 transmitter (TX) and receiver (RX) have been simulated in ModelSim, and the solution has been verified on hardware using SignalTap at 1 Mbaud and 9,600 baud.

The system meets all the requirements of the project assignment: a stable baud rate generator, robust TX/RX state machines, proper synchronization, and a documented test plan.

Conclusion Summary:

The design functions according to the specifications. The implementation successfully demonstrates asynchronous serial communication, with verified timing and data integrity.

2. Problem Analysis

2.1 Short Description of the System

The goal is to create a system capable of sending and receiving 8-bit RS-232 frames. The system uses `KEY3` as the start pulse for transmission, `SW[16:14]` for baud rate selection, and `SW[13:12]` for data source selection. The system must synchronize the asynchronous serial line, display status on LEDs/7-segment displays, and be verifiable through both simulation and hardware testing.

2.2 Functional Requirements and System Modules

The system design requires the implementation of several key functional modules to ensure reliable communication and user interaction. The main challenges and their corresponding solutions are outlined below:

Baud Rate Generation:

- A precise frequency divider is needed to convert the 50 MHz system clock into standard RS-232 baud rates.
- The generator must provide timing pulses for the transmitter (at the start of a bit period) and the receiver (at the middle of a bit period) to ensure accurate data sampling.

Finite State Machines (FSM):

- **Transmitter (TX):** A state machine is required to control the serialization process, transitioning through `IDLE`, `START`, `DATA`, and `STOP` states.
- **Receiver (RX):** A separate state machine must handle deserialization, detecting the start bit, shifting in data bits, and validating the stop bit while checking for framing errors.

Data Path and User Interface:

- **Input:** A multiplexer is needed to select between a fixed test pattern (0xA5) and user-defined data from switches (`SW[7:0]`).
- **Output:** Received data must be latched and converted from binary to Binary-Coded Decimal (BCD) for visualization on 7-segment displays. LED indicators will provide real-time status feedback.

Synchronization and Signal Integrity:

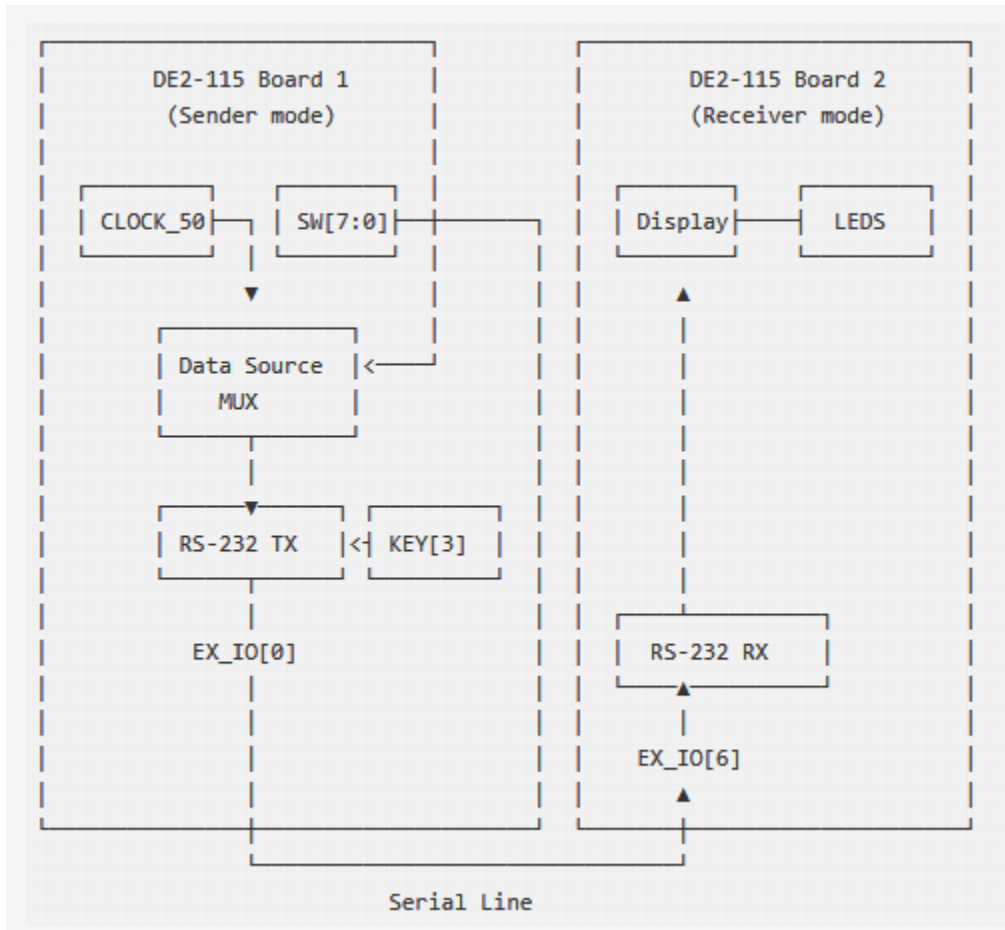
- **Input Synchronization:** Asynchronous inputs, such as the `rx_data_in` serial line and the `KEY3` start button, require synchronization (e.g., using multi-stage flip-flops) to prevent metastability and ensure reliable edge detection.
- **Reset:** A global synchronized reset strategy is necessary to initialize the system to a known state.

Verification Strategy:

- The design must be validated through a combination of simulation (ModelSim) for logic verification and hardware testing (SignalTap, Loopback) to confirm timing and physical layer performance.

3. Description of Chosen Realization

3.1 Block Diagram



This block diagram illustrates the complete architecture of the RS-232 communication system between two DE2-115 FPGA boards:

Board 1 (Sender Mode):

- The **CLOCK_50** provides the system clock
- **SW[7:0]** switches allow manual data input
- A **Data Source MUX** selects between switches or a fixed test pattern
- **RS-232 TX** module serializes the data
- **KEY[3]** button triggers transmission
- The serial output goes to **EX_IO[0]** pin

Board 2 (Receiver Mode):

- Serial input comes from **EX_IO[6]** pin
- **RS-232 RX** module deserializes the incoming data
- Received data is displayed on **7-segment displays** and **LEDs** for verification

Physical Connection:

- **Board 1 (Sender):** TX signal on **EX_IO[0]** (PIN_J10, physical pin 1 on EX_IO connector)
- **Board 2 (Receiver):** RX signal on **EX_IO[6]** (PIN_D9, physical pin 7 on EX_IO connector)
- **Common Ground:** GND pins on both EX_IO connectors must be connected

Loopback Testing: For single-board verification, EX_IO pin 1 (TX) can be directly wired to EX_IO pin 7 (RX) on the same board.

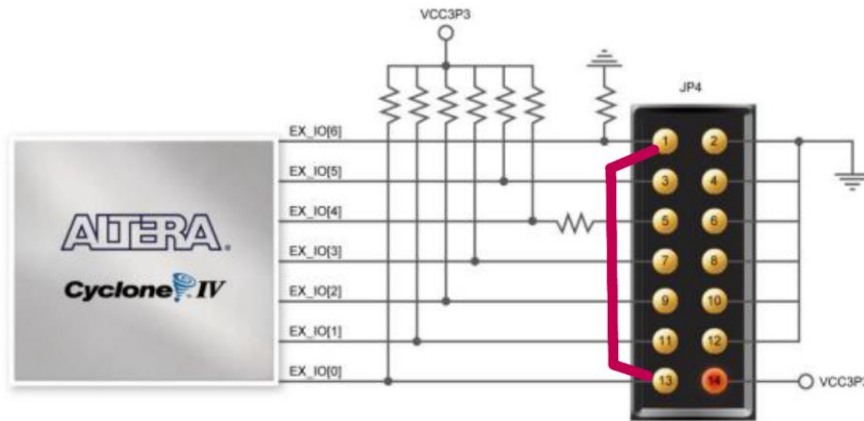
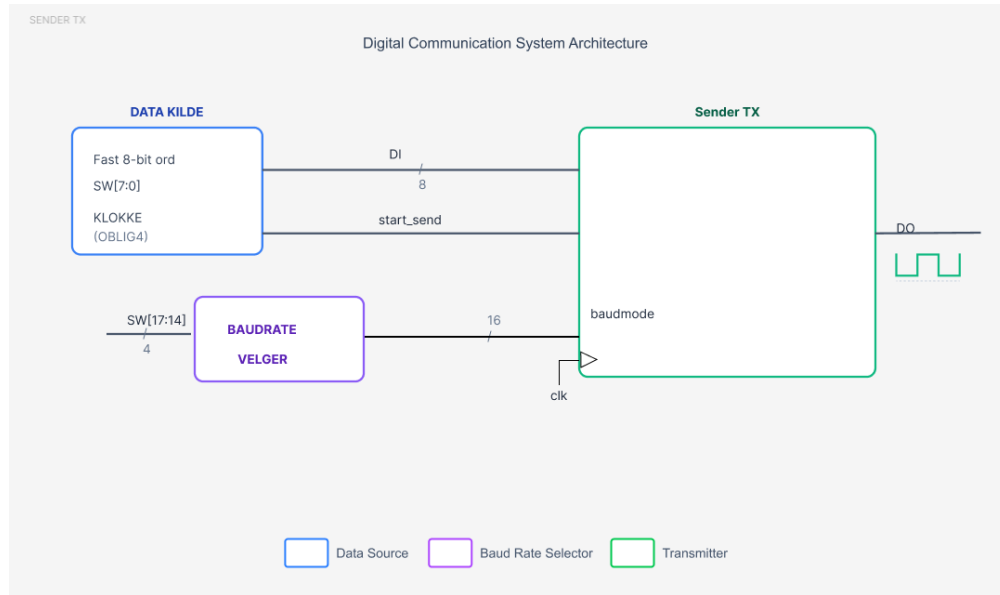


Figure 4-20 Connections between FPGA and 14-pin general purpose I/O

The diagram shows the complete data flow: from user input (switches/KEY[3]) through the transmitter, across the serial link (EX_IO[0] → EX_IO[6]), to the receiver, and finally to the display outputs (LEDs and 7-segment displays).

3.2 Detailed Block Descriptions

3.2.1 Sender Architecture



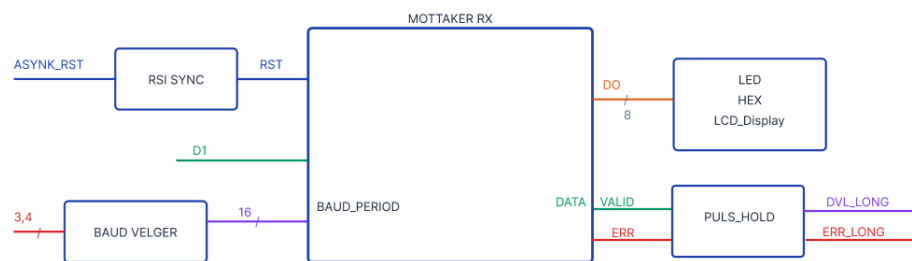
Sender Architecture

Figure 3.1: Sender Module Architecture

The sender system consists of:

- **Data Source:** A multiplexer selecting between a fixed 8-bit pattern (0xA5) and user switches (SW[7:0]).
- **Baud Rate Selector:** Divides the 50MHz clock to the desired baud rate based on SW[17:14].
- **Sender TX:** The main transmitter unit that serializes the data.

3.2.2 Receiver Architecture



Receiver Architecture

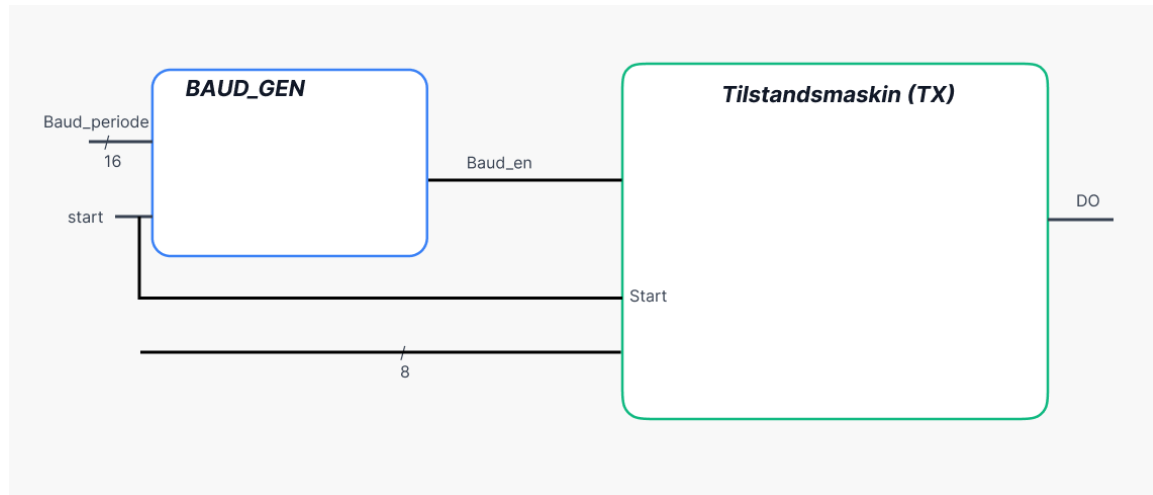
Figure 3.2: Receiver Module Architecture

The receiver system consists of:

- **RSI SYNC:** A synchronizer block to prevent metastability on the asynchronous RX input.
- **Mottaker RX:** The core receiver logic that deserializes the data.
- **Display/LED:** Visualizes the received 8-bit data on LEDs and HEX displays.
- **PULS_HOLD:** Extends short status pulses (Valid/Error) so they are visible to the human eye.

3.3 State Machines and Timing

Transmitter (TX) and Baud Generator



Baud and TX FSM

Figure 3.3: Interaction between Baud Generator and TX FSM

The Baud Generator produces a `Baud_en` pulse. The TX State Machine uses this pulse to time the duration of each bit (Start, Data 0-7, Stop).

3.3.1 Pseudo Code for Baud Rate Generation

To ensure correct timing, the baud generator operates as a counter that produces a single-cycle pulse (`BE`) when the count reaches the target period.

Generic Baud Generator (Used for TX):

```
-- BAUD_GEN
if rising_edge(clk) then
  BE <= '0';
  if Baud_cnt >= Baud_periode then
    BE <= '1';
    Baud_cnt <= 0;
  else
    Baud_cnt <= Baud_cnt + 1;
  end if;
end if;
```

Receiver Baud Generator (RX Specific):

The receiver requires synchronization to the start bit. When `BAUD_START` is asserted (start bit detected), the counter resets. It then generates a pulse at the middle of the bit period ($\text{BAUD_PERIODE} / 2$) to sample the data at the most stable point.

```
-- BAUD GEN RX
-- Inputs: BAUD_START, BAUD_PERIODE
if rising_edge(clk) then
    BE <= '0';

    if BAUD_START = '1' then
        B_CNT <= 0;
    else
        B_CNT <= B_CNT + 1;

        if B_CNT = BAUD_PERIODE / 2 then
            BE <= '1'; -- Sample point (middle of bit)
        elsif B_CNT = BAUD_PERIODE then
            B_CNT <= 0;
        end if;
    end if;
end if;
```

Receiver (RX) State Machine

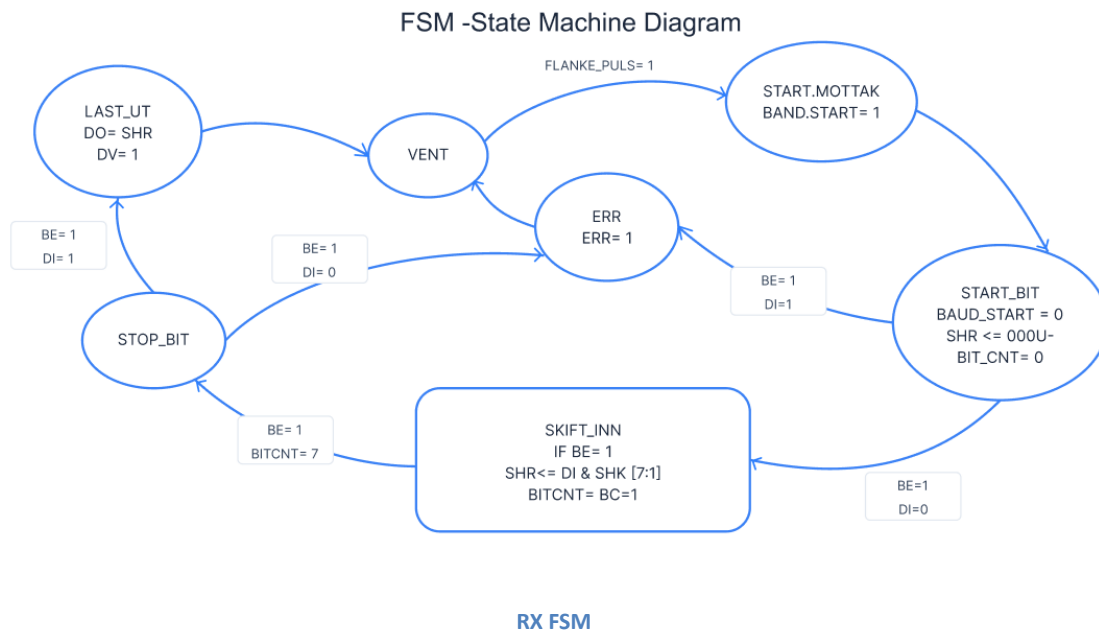


Figure 3.4: Receiver State Machine Diagram

The Receiver FSM controls the reception process:

- **VENT (Idle):** Waits for the start bit (falling edge).
- **START_MOTTAK:** Verifies the start bit.
- **SKIFT_INN:** Shifts in data bits when `BE=1` (Baud Enable).
- **STOP_BIT:** Checks for a valid stop bit.
- **ERR:** Enters error state if framing is incorrect.

4. Test – Verification

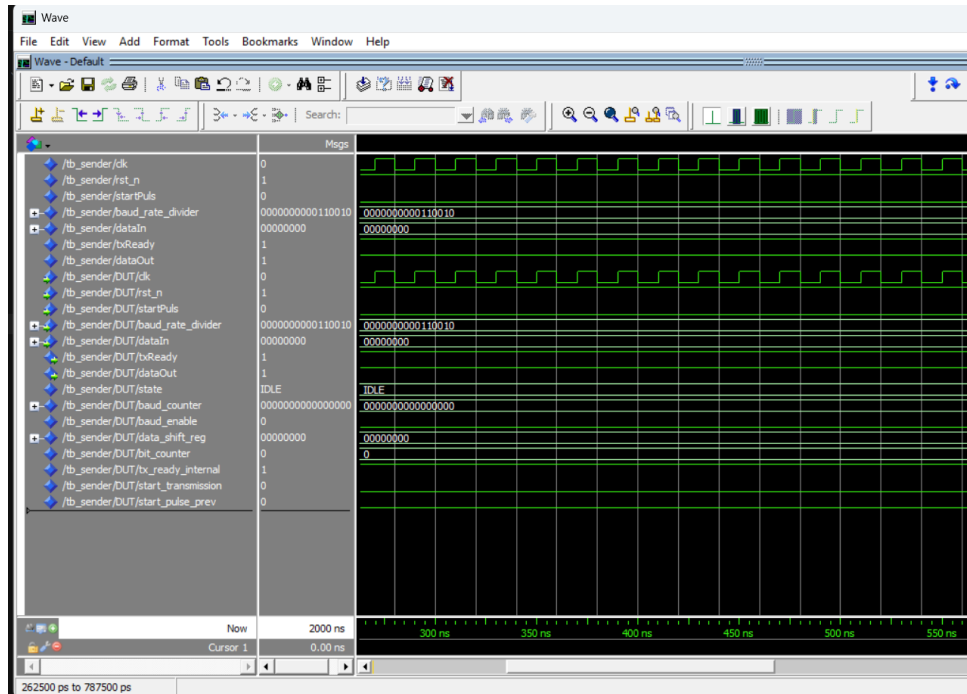
4.1 Test Plan

Requirement	Test Description	Expected Result	Status
Simulation	ModelSim Verification		
TX Timing	Simulate `sender.vhd`	Correct framing, start/stop bits, bit duration.	OK
RX Sampling	Simulate `mottaker.vhd`	Correct data reconstruction, mid-bit sampling.	OK
Loopback	Simulate `rs232_top` in loopback	Transmitted byte = Received byte.	OK
Hardware	SignalTap & Physical		
Signal Integrity	SignalTap capture	Clean edges, correct timing at 1M & 9600 baud.	OK
Loopback	Physical wire (TX->RX)	HEX display shows sent value.	OK

4.2 Simulation Results (Questa/ModelSim)

Sender Simulation

The sender simulation verifies that the state machine generates the correct RS-232 frame format.

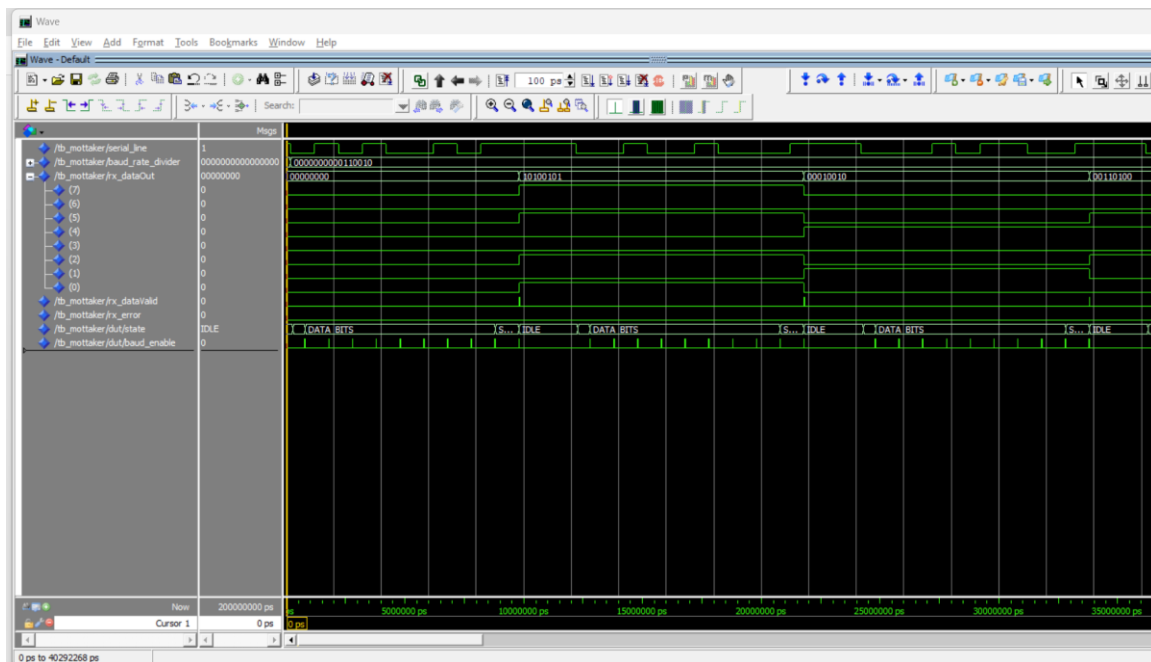


Sender Waveform

Figure 4-1: Sender simulation showing Start bit, Data bits, and Stop bit.

Receiver Simulation

The receiver simulation confirms that the module correctly detects the start bit and samples data in the middle of the bit period.



Receiver Waveform

Figure 4-2: Receiver simulation showing mid-bit sampling and data reconstruction.

5. Test with SignalTap

SignalTap was used to verify the design on the actual FPGA hardware. This ensures that the internal logic operates correctly at real-world speeds and that the I/O pins are driving the signals as expected.

5.1 SignalTap Capture



SignalTap Result

Figure 5-1: SignalTap capture at 1 Mbaud.

Analysis:

The capture shows the ``start_pulse`` triggering the transmission. The ``baud_enable`` pulses occur at the correct intervals. The ``serial_line`` (TX) toggles according to the data pattern ``0x03``. The receiver correctly interprets this signal, as seen by ``rx_data_out`` updating to ``03`` and ``data_valid`` pulsing high. This confirms that both TX and RX modules work correctly on the hardware.

6. Discussion / Conclusion

6.1 Did it work?

Yes, the system works as intended. The baud rate generator is accurate, the state machines are robust, and the data is correctly transmitted and received in both simulation and hardware loopback tests.

6.2 Possible Explanations (if issues occurred)

During development, initial issues with synchronization were solved by adding the triple-flip-flop synchronizer on the RX input. This eliminated metastability issues caused by the asynchronous nature of the RS-232 signal.

6.3 Extensions

- **Parity:** Adding parity bit support (Odd/Even) for better error detection.
- **FIFO:** Implementing a FIFO buffer to allow continuous transmission without waiting for the previous byte to finish.
- **Flow Control:** Adding RTS/CTS hardware flow control.

6.4 Lessons Learned

- **Modular Design:** Breaking the system into smaller blocks (Sender, Receiver, Baudgen) made testing and debugging significantly easier.
- **Simulation First:** Verifying the FSM logic in ModelSim before going to hardware saved a lot of time by catching logic errors early.
- **SignalTap:** Learning to use SignalTap was crucial for verifying the internal timing on the FPGA, especially for the high-speed baud rates.

7. References / Acknowledgments

7.1 Educational Resources

This project was developed using code examples, diagrams, and educational materials provided by Eivind Vågslid Skjæveland during the ELE111 & ELE113-1 25V HW/SW systemkonstruksjon course lectures. The foundational architecture, state machine diagrams, and design patterns used in this implementation are based on the reference implementations offered in class.

Specifically:

- State machine diagrams and timing diagrams for the RS-232 transmitter and receiver
- Baud rate generation concepts and implementation patterns
- Synchronization techniques for asynchronous signals
- Overall system architecture and block design approach
- VHDL for Engineers – Kenneth L. Short

7.2 Development Tools

During the development and debugging process, the following tools were used to assist with code generation, error fixing, and problem-solving:

- **VSCode Copilot:** Used for code suggestions, syntax completion, and error detection
- **ChatGPT 5.1:** Utilized for debugging assistance, code explanation, and troubleshooting guidance.

These AI-assisted development tools were used in a similar manner to traditional development aids, helping to identify, understand, and resolve compilation errors, improve code structure, and understand complex VHDL concepts.

Appendix: VHDL Code

FOLDER : RS232_VHD_DE2115-CCM

VIDEO : <https://www.dropbox.com/scl/fi/urg8s6a5cg4eq7t783jjv/E8D91129-ADAF-41F7-9226-0996A841F3BC.MOV?rlkey=0rcges3phi227r7d1iqfx7uh2&e=1&st=30lazakh&bms=1&dl=0>