



THE IMAGINATION UNIVERSITY PROGRAMME

RVfpga Lab 10

Serial Buses

1. INTRODUCTION

In this lab, we first describe how serial buses work and the main features of one of the most typical serial buses currently used, the SPI bus (Section 2). We then focus on the SPI accelerometer available on the Nexys A7 board: we analyse the high-level specification for this peripheral and propose fundamental exercises (Sections 3 and 4), and then we analyse its low-level implementation and propose some advanced exercises (Sections 5 and 6).

2. SERIAL BUSES – THE SPI BUS

Parallel buses send several bits at once, whereas serial buses send one bit at a time. We first compare these two communication schemes and then describe the SPI (serial peripheral interface) protocol, which is one of the most common serial buses currently used. You can find lots of information on the internet for extending your knowledge about this important communication protocol.

As already demonstrated in previous labs, the main purpose of embedded electronics is to connect processors and circuits to create desired functions. In order for processors and circuits to share information, they must share a common communication protocol. Hundreds of communication protocols have been defined to achieve this data exchange, and, in general, they can be separated into two main categories: parallel or serial interfaces.

Parallel interfaces transfer multiple bits in parallel, i.e., at the same time. They require buses (multiple wires) of data. For example, the protocol may transmit eight, sixteen, or more bits at the same time (see Figure 1). They also require a clock to time when new groups of N data bits are ready to transfer.

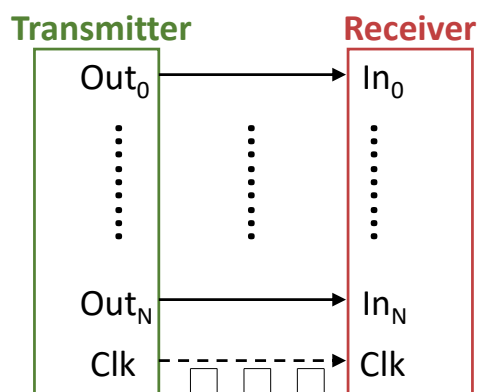


Figure 1. Example of a parallel 8-bit data bus.

In contrast to parallel communication, serial interfaces stream their data one bit at a time. These interfaces can operate using as few as one wire and usually never more than four. Figure 2 shows an example serial interface with one wire for data and one for a clock. At each new clock edge, a new data bit is transferred.



Figure 2. Example of a serial 1-bit data bus.

Parallel communication has the benefits of being fast, straightforward, and relatively easy to implement. However, it requires many more input/output (I/O) lines. So, because pins are limited, embedded systems often opt for serial communication, sacrificing potential speed for pin real estate.

SPI Bus:

The Serial Peripheral Interface (SPI) protocol is one of the most widely used interfaces between microcontroller and peripheral ICs such as sensors, ADCs, DACs, shift registers, SRAM, and others. SPI is a synchronous, full duplex interface based on controller-peripheral (formerly called master-slave) communication.

The SPI bus usually communicates via 4 ports (see Figure 3):

- **SDO** – Serial Data Out: Controller's output to peripheral device
- **SDI** – Serial Data Input: Controller's input from peripheral device
- **SCK** – Serial Clock: Sent from controller to peripheral device
- **CS** – Chip Select: Active low signal; Controller sends signal (0 when peripheral is selected) to peripheral

Note: historically, SDO has also been called MOSI (master data out, slave data in) and SDI has been called MISO (master data in, slave data out). Those terms are outdated and offensive, but they still exist in the literature and in documentation.

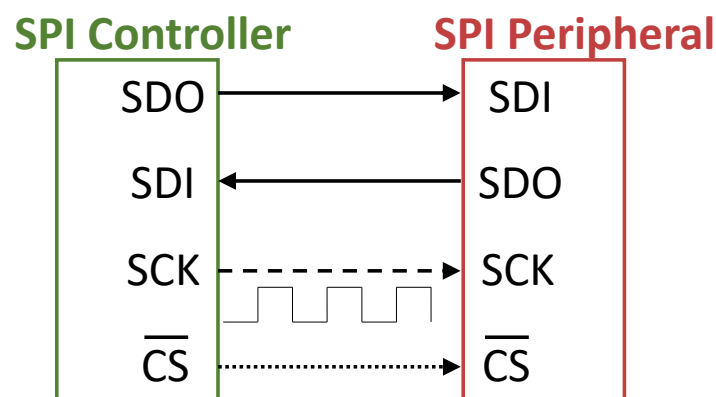


Figure 3. Example of a system with one SPI controller and one SPI peripheral.

The serial data is synchronized to the rising or falling clock edge. SPI is a full-duplex interface; the controller and the peripheral can send data at the same time via the SDO and SDI lines, respectively. SPI interfaces only have one controller, but they may have multiple peripherals. When more than one peripheral is connected, multiple low-asserted chip select signals (CS \bar) from the controller are used to select which peripheral is being accessed. SDO and SDI are the serial data lines: SDO (serial data out) is the output data from the controller to the peripheral and SDI (serial data in) is the input data from the peripheral to the controller.

To initiate SPI communication, the controller must select the peripheral device (by asserting the CS \bar signal, i.e., CS \bar = 0) and then sending the clock signal to the peripheral. During SPI communication, the data is simultaneously transmitted from and to the controller through the SDO and SDI signals, respectively. The serial clock (SCK) edge synchronizes the sampling of the data.

The SPI interface also provides additional signals, CPOL and CPHA, for selecting the idle state of the clock and the phase for sampling the signal. The clock polarity (CPOL) signal is 0 when the clock (SCK) idles at 0 and 1 when it idles at 1. The clock phase (CPHA) signal selects the phase of the clock to send and sample data. When CPHA = 0, data (on SDI or SDO) is sampled on the leading edge (i.e., the first edge after SCK stops idling - and on every cycle thereafter); so data (SDI and SDO) must change on the trailing edge, as shown in the top two timing diagrams of Figure 4. CPHA = 1 does the opposite: data is sampled on the trailing edge and data changes on the leading edge, as shown in the bottom two figures of Figure 4. The edge on which new data is transmitted is also called the *shifting edge*, because this serial communication is typically implemented using a shift register.

The SPI interface we use in this lab is CPHA = 0 and CPOL = 0, so SCK idles low and the controller and peripheral sample data on the rising edge and shift new data onto the line (SDO or SDI) just after each falling edge, as shown in the top timing diagram of Figure 4. Note that when SCK is idle, and just before it rises, SDO and SDI must carry the most significant bit of the next data byte.

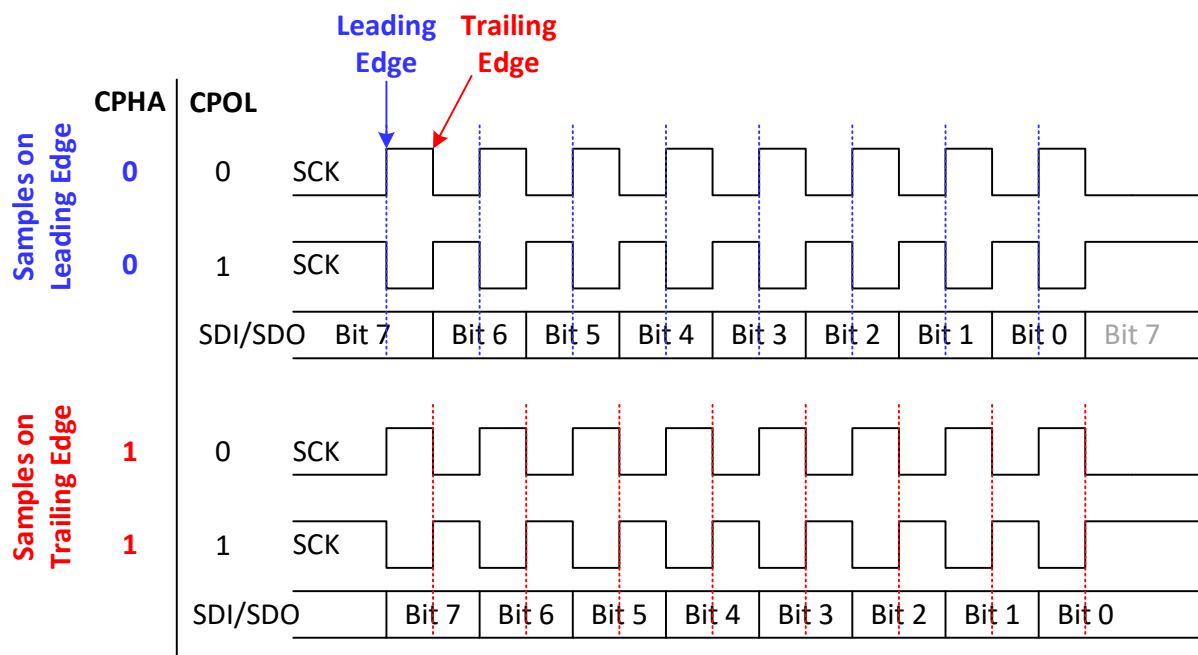


Figure 4. Relationship of CPHA/CPOL with sampling/sending data

3. SPI ACCELEROMETER: HIGH-LEVEL SPECIFICATION

Many peripherals include an SPI interface. For example, the accelerometer on the Nexys A7 board has an SPI interface. In this section we describe the high-level specification of the RVfpga System's SPI controller and introduce the ADXL362 accelerometer included on the Nexys A7 board. We also introduce an exercise that uses the accelerometer.

A. SPI controller specification

The RVfpga System's SPI module is from OpenCores (https://opencores.org/projects/simple_spi). If you download the package, a document is provided that describes the high-level specification of the module. This document is also provided here:

[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/Peripherals/spi/docs/simple_spi.pdf

We summarize the main operation and features of the SPI module; however, refer to the above document for additional information.

This module has the following main features:

- It is compatible with Motorola's SPI specifications
- It uses the 8-bit WISHBONE RevB.3 classic interface
- It contains a 4-entry read FIFO buffer and a 4-entry write FIFO buffer
- It allows interrupt generation after 1, 2, 3, or 4 transferred bytes
- It can operate with a wide range of input clock frequencies
- It is fully synthesizable

Section 3 of the SPI core specification describes the control and status registers available inside the SPI module, each of which is assigned to a different address (see Table 1). The base address of the SPI controller is **0x80001100**. These registers are described in detail below.

Table 1. SPI Registers

Name	Address	Width	Access	Description
SPCR	0x80001100	8	R/W	Control register
SPSR	0x80001108	8	R/W	Status register
SPDR	0x80001110	8	R/W	Data register
SPER	0x80001118	8	R/W	Extensions register
SPCS	0x80001120	8	R/W	CS register

The SPI Control Register (SPCR) controls the SPI module; Table 2 shows the function of each of its bits.

Table 2. SPCR bits

Bit	Access	Name & Description
0:1	R/W	SPR SPI clock Rate: These bits select the SPI clock rate.
2	R/W	CPHA Clock Phase: Determines the phase of sampling and sending data. When CPHA = 1, new data is shifted onto the wire at the leading edge and data is sampled on the trailing edge. When CPHA = 0, new data is shifted onto the wire at the trailing edge and sampled on the leading edge.
3	R/W	CPOL Clock Polarity: Determines idle state of SPI clock (SCK). When CPOL = 0, SCK idles at 0, when CPOL = 1, SCK idles at 1.
4	R/W	MSTR Mode Select: When MSTR = 1, the SPI core is a controller device. This is the only supported mode for this controller.
6	R/W	SPE SPI Enable: When SPE = 1, the SPI core is enabled. When it is cleared (SPE = 0), the SPI core is disabled.
7	R/W	SPIE SPI Interrupt Enable: When SPIE = 1, when the SPI Interrupt Flag in the status register is set, the host is interrupted.

The SPI Status Register (SPSR) provides the status of the SPI module; Table 3 shows the function of each of its bits.

Table 3. SPSR bits

Bit	Access	Description
0	R/W	RFEMPTY Read FIFO Empty: If RFEMPTY = 1, the read FIFO is empty.
1	R/W	RFFULL Read FIFO Full: If RFFULL = 1, the read FIFO is full.
2	R/W	WFEMPTY Write FIFO Empty: IF WFEMPTY = 1, the write FIFO is empty.
3	R/W	WFFULL Write FIFO Full: IF WFFULL = 1, the write FIFO is full.
6	R/W	WCOL Write Collision flag: When WCOL = 1, the SPDATA register was written to while the Write FIFO was full. Writing a 1 to WCOL clears this bit.
7	R/W	SPIF SPI Interrupt Flag: SPIF = 1 upon completion of a transfer block. If SPIF is asserted ('1') and SPIE is set, an interrupt is generated. Writing a 1 to SPIF clears it.

The SPI Data Register (SPDR) provides the data to read or write. The SPI controller includes 4 x 8-bit Write Buffer and a 4x 8-bit Read Buffer.

The SPI Extended Register (SPER) provides some additional functionality; Table 4 describes the different fields that it contains.

Table 4. SPER bits

Bit	Access	Description
0:1	R/W	ESPR Extended SPI Clock Rate Select: Add two bits to the SPR (SPI Clock Rate Select).
6:7	R/W	ICNT Interrupt Count: Determine the transfer block size. The SPIF bit is set after ICNT transfers. Thus, it is possible to reduce kernel overhead due to reduced interrupt service calls.

Finally, the SPI Chip Select (SPCS) register selects which peripheral to use. The width of this signal is configurable through parameter `SS_WIDTH` (SPI Select Width). In the RVfpga System, only one peripheral exists for each SPI interface, so `SS_WIDTH = 1`.

TASK: Locate the declaration of registers SPCR, SPSR, SPDR, SPER and SPCS in the SPI module, as well as the definition of their addresses. The SPI module is available inside folder `[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/Peripherals/spi`.

B. ADXL362 accelerometer specification

The Nexys A7 board includes an Analog Devices ADXL362 accelerometer. You can find the complete information for the device in its data sheet, located here:

<https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL362.pdf>

The ADXL362 is a 3-axis MEMS accelerometer that consumes less than 2µA at a 100Hz output data rate and 270 nA when in motion triggered wake-up mode. It provides 12-bit output resolution, although 8-bit formatted data is also provided for more efficient single-byte

transfers when a lower resolution is sufficient. Measurement ranges of ± 2 g, ± 4 g, and ± 8 g are available with a resolution of 1 mg/LSB on the ± 2 g range. While the ADXL362 is in Measurement Mode, it continuously measures and stores acceleration data in the X-data, Y-data, and Z-data registers.

The ADXL362 accelerometer includes several registers (Table 5) that allow the user to configure it and to read the acceleration data. The device is configured by writing to the control registers, and the accelerometer data is found by reading the device registers. All communication with the device must specify a register address and a flag that indicates whether the communication is a read or a write. Data transfer occurs after the register address and communication flag are sent to the device.

This accelerometer acts as a peripheral device using an SPI communication scheme. The interface between the FPGA and accelerometer is shown in Figure 5.

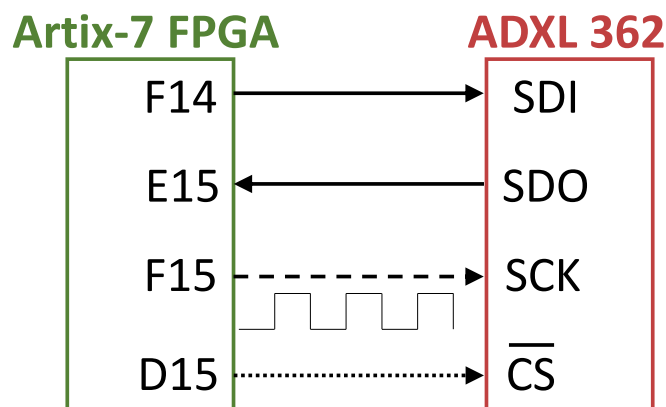


Figure 5. ADXL362 Accelerometer interface with the Nexys A7 board

The recommended SPI clock frequency ranges from 1-5 MHz. The SPI operates in SPI mode 0 (CPOL = 0 and CPHA = 0). The SPI port uses a multibyte structure wherein the first byte indicates if the communication performs a register read (0x0B) or a register write (0x0A):

<CS down>	<Write/Read (0x0A/0x0B)>	<address byte>	<data byte>	<CS up>
-----------	--------------------------	----------------	-------------	---------

Figure 6 and Figure 7 illustrate two examples of the communication between the SPI controller (controller) and the accelerometer (peripheral): Figure 6 shows the reading of a register and Figure 7 shows the writing of a register.

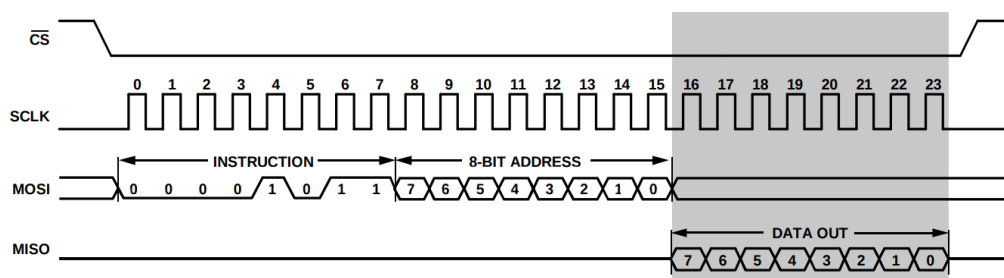


Figure 6. Register read

(Figure from <https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL362.pdf>)

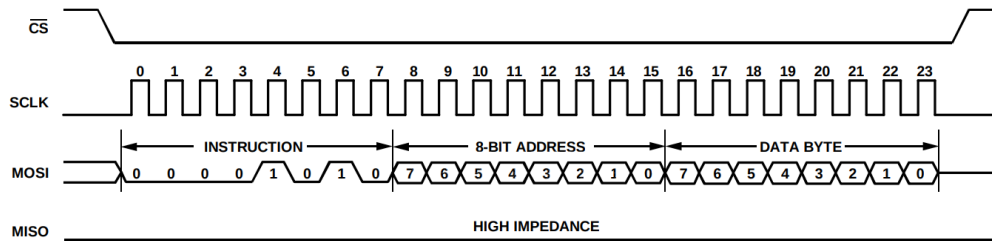


Figure 7. Register write

(Figure from <https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL362.pdf>)

Table 5 shows the registers available in the ADXL362 accelerometer. For the complete registers description, refer to the ADXL362 data sheet:
<https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL362.pdf>.

Table 5. ADXL362 accelerometer registers

(Table from <https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL362.pdf>)

Reg	Name	Bits	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Reset	RW				
0x00	DEVID_AD	[7:0]	DEVID_AD[7:0]									0xAD	R			
0x01	DEVID_MST	[7:0]	DEVID_MST[7:0]									0x1D	R			
0x02	PARTID	[7:0]	PARTID[7:0]									0xF2	R			
0x03	REVID	[7:0]	REVID[7:0]									0x01	R			
0x08	XDATA	[7:0]	XDATA[7:0]									0x00	R			
0x09	YDATA	[7:0]	YDATA[7:0]									0x00	R			
0x0A	ZDATA	[7:0]	ZDATA[7:0]									0x00	R			
0x0B	STATUS	[7:0]	ERR_USER_REGS	AWAKE	INACT	ACT	FIFO_OVER-RUN	FIFO_WATER-MARK	FIFO_READY	DATA_READY	0x40	R				
0x0C	FIFO_ENTRIES_L	[7:0]	FIFO_ENTRIES_L[7:0]									0x00	R			
0x0D	FIFO_ENTRIES_H	[7:0]	UNUSED									FIFO_ENTRIES_H[1:0]	0x00	R		
0x0E	XDATA_L	[7:0]	XDATA_L[7:0]									0x00	R			
0x0F	XDATA_H	[7:0]	SX									XDATA_H[3:0]	0x00	R		
0x10	YDATA_L	[7:0]	YDATA_L[7:0]									0x00	R			
0x11	YDATA_H	[7:0]	SX									YDATA_H[3:0]	0x00	R		
0x12	ZDATA_L	[7:0]	ZDATA_L[7:0]									0x00	R			
0x13	ZDATA_H	[7:0]	SX									ZDATA_H[3:0]	0x00	R		
0x14	TEMP_L	[7:0]	TEMP_L[7:0]									0x00	R			
0x15	TEMP_H	[7:0]	SX									TEMP_H[3:0]	0x00	R		
0x16	Reserved	[7:0]	Reserved[7:0]									0x00	R			
0x17	Reserved	[7:0]	Reserved[7:0]									0x00	R			
0x1F	SOFT_RESET	[7:0]	SOFT_RESET[7:0]									0x00	W			
0x20	THRESH_ACT_L	[7:0]	THRESH_ACT_L[7:0]									0x00	RW			
0x21	THRESH_ACT_H	[7:0]	UNUSED									THRESH_ACT_H[2:0]	0x00	RW		
0x22	TIME_ACT	[7:0]	TIME_ACT[7:0]									0x00	RW			
0x23	THRESH_INACT_L	[7:0]	THRESH_INACT_L[7:0]									0x00	RW			
0x24	THRESH_INACT_H	[7:0]	UNUSED									THRESH_INACT_H[2:0]	0x00	RW		
0x25	TIME_INACT_L	[7:0]	TIME_INACT_L[7:0]									0x00	RW			
0x26	TIME_INACT_H	[7:0]	TIME_INACT_H[7:0]									0x00	RW			
0x27	ACT_INACT_CTL	[7:0]	RES	LINKLOOP			INACT_REF	INACT_EN	ACT_REF	ACT_EN	0x00	RW				
0x28	FIFO_CONTROL	[7:0]	UNUSED									AH	FIFO_TEMP	FIFO_MODE	0x00	RW
0x29	FIFO_SAMPLES	[7:0]	FIFO_SAMPLES[7:0]									0x80	RW			
0x2A	INTMAP1	[7:0]	INT_LOW	AWAKE	INACT	ACT	FIFO_OVER-RUN	FIFO_WATER-MARK	FIFO_READY	DATA_READY	0x00	RW				
0x2B	INTMAP2	[7:0]	INT_LOW	AWAKE	INACT	ACT	FIFO_OVER-RUN	FIFO_WATER-MARK	FIFO_READY	DATA_READY	0x00	RW				
0x2C	FILTER_CTL	[7:0]	RANGE		RES	HALF_BW	EXT_SAMPLE	ODR			0x13	RW				
0x2D	POWER_CTL	[7:0]	RES	EXT_CLK	LOW_NOISE		WAKEUP	AUTOSLEEP	MEASURE		0x00	RW				
0x2E	SELF_TEST	[7:0]	UNUSED									ST	0x00	RW		

4. LOW-LEVEL IMPLEMENTATION

A. SPI Accelerometer low-level implementation

In the first part of this lab, we showed how to use the RVfpga System's SPI modules, and in this last part of the lab we describe how the SPI module is implemented in RVfpga. Similar to the format from previous labs, we divide the analysis of the SPI controller into three phases:

1. Physical connection between the SoC and the accelerometer (left shadowed region in Figure 8)
2. Integration of the SPI controller, which is included inside the VeeRwolfX System Controller (middle shadowed region in Figure 8)
3. Connection between the SPI controller and the VeeR EL2 Core (right shadowed region in Figure 8)

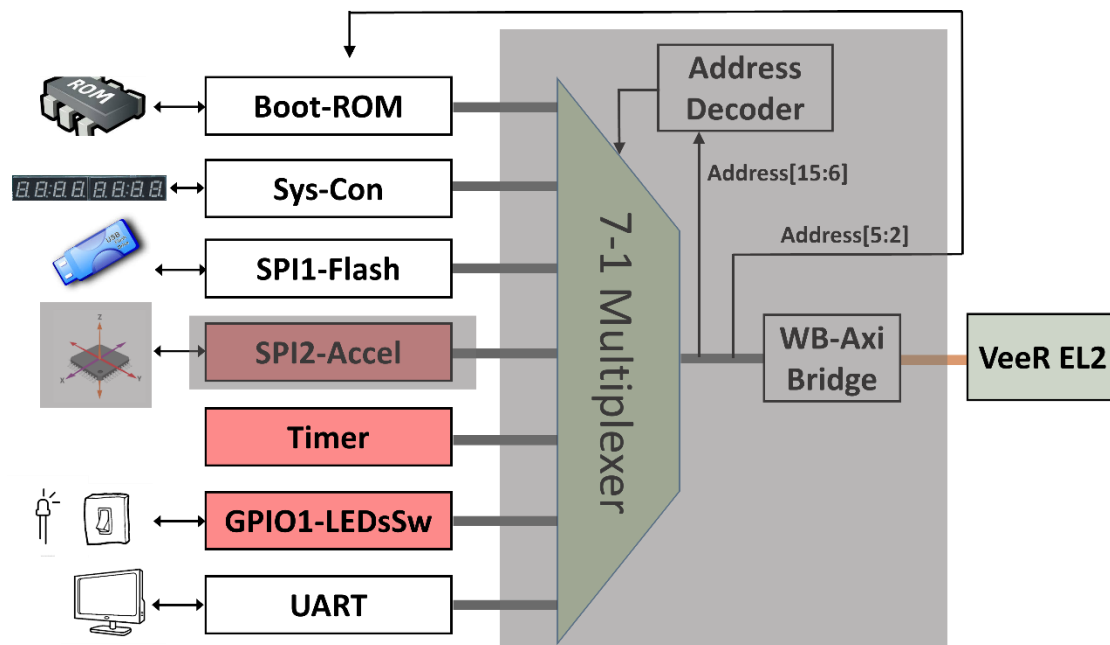


Figure 8. SPI controller integrated into the RVfpga System

1. Physical connection of the accelerometer and the SoC

As with other peripherals, the RVfpgaEL2-Nexys constraints file must include the physical connections to the accelerometer. The constraints file of the project ([RVfpgaEL2NexysA7DDRPath]/src/rvfpganexys.xdc) defines the connection between the input/output SoC signals and the board devices. The signals that connect the four pins of the accelerometer with the SoC are called: `o_accel_cs_n`, `o_accel_mosi` (equivalent to signal SDO), `i_accel_miso` (equivalent to signal SDI) and `accel_sclk`. Note that these signals refer to outdated names, but we maintain them in order to be coherent with the names used by the OpenCores's SPI module that we use in the RVfpga System (you can see the instantiation of this module at Figure 11). Figure 9 shows the piece of Verilog code where these 4 connections are defined.

```
##Accelerometer
set_property -dict { PACKAGE_PIN E15    IOSTANDARD LVCMOS33 } [get_ports { i_accel_miso }];
#IO_L11P_T1_SRCC_15 Sch=acl_miso
set_property -dict { PACKAGE_PIN F14    IOSTANDARD LVCMOS33 } [get_ports { o_accel_mosi }];
#IO_L5N_T0_AD9N_15 Sch=acl_mosi
set_property -dict { PACKAGE_PIN F15    IOSTANDARD LVCMOS33 } [get_ports { accel_sclk }];
#IO_L14P_T2_SRCC_15 Sch=acl_sclk
set_property -dict { PACKAGE_PIN D15    IOSTANDARD LVCMOS33 } [get_ports { o_accel_cs_n }];
```

Figure 9. Connection of the SoC and the accelerometer (file *rvfpganexys.xdc*).

In lines 52-55 of the top-module of RVfpgaEL2-Nexys (i.e., the *rvfpganexys* module) you can see these four signals connected to the SoC (left part of Figure 10), and the end of that module are their connection with the *veerwolf_core* module (right part of Figure 10).

<pre>25 module rvfpganexys 26 #(parameter bootrom_file = "boot_main.mem") 27 (input wire clk, 28 input wire rstn, 29 output wire [12:0] ddram_a, 30 output wire [2:0] ddram_ba, 31 output wire ddram_ras_n, 32 output wire ddram_cas_n, 33 output wire ddram_we_n, 34 output wire ddram_cs_n, 35 output wire [1:0] ddram_dm, 36 inout wire [15:0] ddram_dq, 37 inout wire [1:0] ddram_dqs_p, 38 inout wire [1:0] ddram_dqs_n, 39 output wire ddram_clk_p, 40 output wire ddram_clk_n, 41 output wire ddram_cke, 42 output wire ddram_odt, 43 output wire o_flash_cs_n, 44 output wire o_flash_mosi, 45 input wire i_flash_miso, 46 input wire i_uart_rx, 47 output wire o_uart_tx, 48 inout wire [15:0] i_sw, 49 output reg [15:0] o_led, 50 output reg [7:0] AN, 51 output reg CA, CB, CC, CD, CE, CF, CG, 52 output wire o_accel_cs_n, 53 output wire o_accel_mosi, 54 input wire i_accel_miso, 55 output wire accel_sclk); 56</pre>	<pre>... .i_ram_wready (cpu.w_ready), .i_ram_bid (cpu.b_id), .i_ram_bresp (cpu.b_resp), .i_ram_bvalid (cpu.b_valid), .o_ram_bready (cpu.b_ready), .i_ram_rid (cpu.r_id), .i_ram_rdata (cpu.r_data), .i_ram_rresp (cpu.r_resp), .i_ram_rlast (cpu.r_last), .i_ram_rvalid (cpu.r_valid), .o_ram_rready (cpu.r_ready), .i_ram_init_done (litedram_init_done), .i_ram_init_error (litedram_init_error), .io_data ((i_sw[15:0],gpio_out[15:0])), .AN (AN), .Digits Bits ({CA,CB,CC,CD,CE,CF,CG}), .o_accel_sclk (accel_sclk), .o_accel_cs_n (o_accel_cs_n), .o_accel_mosi (o_accel_mosi), .i_accel_miso (i_accel_miso)); always @(posedge clk_core) begin o_led[15:0] <= gpio_out[15:0]; end assign o_uart_tx = 1'b0 ? litedram_tx : cpu_tx;</pre>
--	--

Figure 10. Connection of the accelerometer with the top-module (file *rvfpganexys.sv*).

TASKS: Follow these four signals (`o_accel_cs_n`, `o_accel_mosi`, `i_accel_miso` and `accel_sclk`) from the constraints file to the VeeRwolfX SoC module. You will need to inspect the following files:

[RVfpgaEL2NexysA7DDRPath]/src/rvfpganexys.xdc
 [RVfpgaEL2NexysA7DDRPath]/src/rvfpganexys.sv
 [RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/veerwolf_core.v

2. Integration of the SPI2-Accelerometer module in the SoC

At lines 387-403 of module **veerwolf_core** (*[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/veerwolf_core.v*) the SPI module for the accelerometer is instantiated (see Figure 11).

```
// SPI for the Accelerometer
wire [7:0] spi2_rdt;
assign wb_s2m_spi_accel_dat = {24'd0, spi2_rdt};
wire spi2_irq;

simple_spi spi2
(
    // Wishbone slave interface
    .clk_i (clk),
    .rst_i (wb_rst),
    .adr_i (wb_m2s_spi_accel_adr[2] ? 3'd0 : wb_m2s_spi_accel_adr[5:3]),
    .dat_i (wb_m2s_spi_accel_dat[7:0]),
    .we_i (wb_m2s_spi_accel_we),
    .cyc_i (wb_m2s_spi_accel_cyc),
    .stb_i (wb_m2s_spi_accel_stb),
    .dat_o (spi2_rdt),
    .ack_o (wb_s2m_spi_accel_ack),
    .inta_o (spi2_irq),
    // SPI interface
    .sck_o (o_accel_sclk),
    .ss_o (o_accel_cs_n),
    .mosi_o (o_accel_mosi),
    .miso_i (i_accel_miso));
```

Figure 11. Integration of the SPI2-Accelerometer module (file *veerwolf_core.v*).

As usual with peripherals, the interface of the module can be divided into two blocks: Wishbone signals (Table 6) and external I/O signals (Table 7). The Wishbone signals enable the VeeR EL2 Core to communicate with the ADC using the SPI protocol.

Table 6. Wishbone Signals

Port	Width	Direction	Description
cyc_i	1	Inputs	Indicates valid bus cycle (core select)
adr_i	15	Inputs	Address inputs
dat_i	32	Inputs	Data inputs
dat_o	32	Outputs	Data outputs
sel_i	4	Inputs	Indicates valid bytes on data bus (during valid cycle it must be 0xf)
ack_o	1	Output	Acknowledgment output (indicates normal transaction termination)
err_o	1	Output	Error acknowledgment output (indicates an abnormal transaction termination)
rty_o	1	Output	Not used
we_i	1	Input	Write transaction when asserted high
stb_i	1	Input	Indicates valid data transfer cycle
inta_o	1	Output	Interrupt output

Table 7. External I/O Signals

Port	Width	Direction	Description
miso_i	1	Input	Controller data Input - Peripheral data Output
mosi_o	1	Output	Controller data Output - Peripheral data Input
ss_o	1	Output	Chip Select
sck_o	1	Output	System clock

As shown in Figure 11, bits [5:2] of the address provided by the core in the Wishbone bus signal (*wb_m2s_spi_accel_adr[5:2]*) are used for selecting one among the 5 available SPI registers (Table 1).

3. Connection between the SPI Controller and the VeeR EL2 Core

As explained in previous labs, the device controllers are connected to the VeeR EL2 Core through a multiplexer and a bridge (Figure 8). Remember that the 7:1 multiplexer is instantiated in file

[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/Interconnect/WishboneInterconnect/wb_intercon.v. Then, the *wb_intercon* module is instantiated in file

[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/Interconnect/WishboneInterconnect/wb_intercon.vh. This latter file is included in the *veerwolf_core* module located here:

[RVfpgaEL2NexysA7DDRPath]/src/VeeRwolf/veerwolf_core.v.

The multiplexer selects which peripheral to read or write, connecting the CPU (*wb_io_** signals) with the Wishbone Bus of one peripheral, depending on the address. For example, if the address generated by the CPU is in the range 0x80001100-0x8000113F, the accelerometer module is selected, and thus signals *wb_io_** are connected to signals *wb_spi_accel_**.

```

wb_mux
#(.num_slaves (7),
 .MATCH_ADDR ({32'h00000000, 32'h00001000, 32'h00001040, 32'h00001100, 32'h00001200, 32'h00001400, 32'h00002000}),
 .MATCH_MASK ({32'hffffff00, 32'hffffffc0, 32'hffffffc0, 32'hffffffc0, 32'hffffffc0, 32'hffffffc0, 32'hffffff00}))
wb_mux_io
(.wb_clk_i (wb_clk_i),
 .wb_rst_i (wb_rst_i),
 .wbm_adr_i (wb_io_adr_i),
 .wbm_dat_i (wb_io_dat_i),
 .wbm_sel_i (wb_io_sel_i),
 .wbm_we_i (wb_io_we_i),
 .wbm_cyc_i (wb_io_cyc_i),
 .wbm_stb_i (wb_io_stb_i),
 .wbm_cti_i (wb_io_cti_i),
 .wbm_bte_i (wb_io_bte_i),
 .wbm_dat_o (wb_io_dat_o),
 .wbm_ack_o (wb_io_ack_o),
 .wbm_err_o (wb_io_err_o),
 .wbm_rty_o (wb_io_rty_o),
 .wbs_adr_o ({wb_rom_adr_o, wb_sys_adr_o, wb_spi_flash_adr_o, wb_spi_accel_adr_o, wb_ptc_adr_o, wb_gpio_adr_o, wb_uart_adr_o}),
 .wbs_dat_o ({wb_rom_dat_o, wb_sys_dat_o, wb_spi_flash_dat_o, wb_spi_accel_dat_o, wb_ptc_dat_o, wb_gpio_dat_o, wb_uart_dat_o}),
 .wbs_sel_o ({wb_rom_sel_o, wb_sys_sel_o, wb_spi_flash_sel_o, wb_spi_accel_sel_o, wb_ptc_sel_o, wb_gpio_sel_o, wb_uart_sel_o}),
 .wbs_we_o ({wb_rom_we_o, wb_sys_we_o, wb_spi_flash_we_o, wb_spi_accel_we_o, wb_ptc_we_o, wb_gpio_we_o, wb_uart_we_o}),
 .wbs_cyc_o ({wb_rom_cyc_o, wb_sys_cyc_o, wb_spi_flash_cyc_o, wb_spi_accel_cyc_o, wb_ptc_cyc_o, wb_gpio_cyc_o, wb_uart_cyc_o}),
 .wbs_stb_o ({wb_rom_stb_o, wb_sys_stb_o, wb_spi_flash_stb_o, wb_spi_accel_stb_o, wb_ptc_stb_o, wb_gpio_stb_o, wb_uart_stb_o}),
 .wbs_cti_o ({wb_rom_cti_o, wb_sys_cti_o, wb_spi_flash_cti_o, wb_spi_accel_cti_o, wb_ptc_cti_o, wb_gpio_cti_o, wb_uart_cti_o}),
 .wbs_bte_o ({wb_rom_bte_o, wb_sys_bte_o, wb_spi_flash_bte_o, wb_spi_accel_bte_o, wb_ptc_bte_o, wb_gpio_bte_o, wb_uart_bte_o}),
 .wbs_dat_i ({wb_rom_dat_i, wb_sys_dat_i, wb_spi_flash_dat_i, wb_spi_accel_dat_i, wb_ptc_dat_i, wb_gpio_dat_i, wb_uart_dat_i}),
 .wbs_ack_i ({wb_rom_ack_i, wb_sys_ack_i, wb_spi_flash_ack_i, wb_spi_accel_ack_i, wb_ptc_ack_i, wb_gpio_ack_i, wb_uart_ack_i}),
 .wbs_err_i ({wb_rom_err_i, wb_sys_err_i, wb_spi_flash_err_i, wb_spi_accel_err_i, wb_ptc_err_i, wb_gpio_err_i, wb_uart_err_i}),
 .wbs_rty_i ({wb_rom_rty_i, wb_sys_rty_i, wb_spi_flash_rty_i, wb_spi_accel_rty_i, wb_ptc_rty_i, wb_gpio_rty_i, wb_uart_rty_i});

```

Figure 12. 7-1 multiplexer selects the peripheral to connect to the CPU (*wb_intercon.v*).

5. EXERCISES

Exercise 1. Create a RISC-V assembly program that reads the eight most significant bits of the X-axis, Y-axis, and Z-axis acceleration data and then displays those values on the 8-digit 7-Segment Displays.

Exercise 2. Another common serial communication protocol is called I2C (pronounced “eye two see” or also “eye squared see”). The temperature sensor on the Nexys A7 board uses

this protocol. Expand the RVfpga System to include an I2C controller, and connect it with the Nexys A7 board's ADT7420 temperature sensor (<https://www.analog.com/media/en/technical-documentation/data-sheets/adt7420.pdf>). Then write a program that communicates with this new peripheral and displays the temperature on the 7-segment displays.