# Saturn Project Notes

This document describes the FPGA for a new radio project using a Xilinx FPGA and an attached processing module. In the first instance this will be a Raspberry Pi 4 compute module but could be another embedded processor board. The interface to the FPGA will be PCI Express; the protocol code for data transfer to the “Thetis” PC will execute on the processor, not in the FPGA. The radio could be implemented on an oversize M.2 board, to fit onto several embedded processors.

This could be used in several ways:

|  |  |
| --- | --- |
| Diagram  Description automatically generated | The processor module is used simply to move data using protocol 1 – like the Red Pitaya’s processor. Low demand on the processor. Wired ethernet connection to PC running Thetis or other app. |
| Diagram  Description automatically generated | The processor module is used simply to move data using protocol 2. This will have higher demand because the data rate is higher. Wired ethernet connection to PC running Thetis or other app. |
| Diagram  Description automatically generated | The processor executes an SDR app such as Pihpsdr or linhpsdr. No PC required, and high quality display outputs are available. |
| Diagram  Description automatically generated | The processor execute Pihpsdr and has an attached 7” RPi touchscreen display. Possibly single ADC or 14 bit ADC version, with Apollo-like RF module. This could be a lower cost small radio, but there may be no market for it now. |

## FPGA Block Diagram

Diagram

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Figure : Overall block Diagram

# Interfaces

## FPGA

|  |  |
| --- | --- |
| ADC | 2x LTC2208. Each with 5 bit attenuator. |
| DAC | The “normal” TX DAC. With 6 bit attenuator and 8 bit analogue PWM drive level. |
| Envelope DAC | The current design allows for a PWM DAC like Hermes used. An SPI DAC would give faster update. |
| Codec | TLV320AIC23B, as used on Hermes etc  Its I2S port driven by FPGA. the I2C port interfaced through the FPGA but with data transactions initiated by the host processor. |
| Audio interfaces | Orion-like software settable connections to 3.5mm jack  Separate audio out for each of speaker and headphone, with separate gains  Balanced XLR mic input for “pro” audio people |
| RF | SPI-like signals for Alex header. Follows the ANAN7000 standard, 16 bit TX data, 32 bit RX data. An SPI ADC (78H90) is used for the analogue level measurement. |
| Clock generation | 122.88MHz VCXO, with C/R filter on control voltage feed.  10MHz reference XTAL oscillator  10MHz external reference in, with auto select |
| PTT, keyer | 3 strobe inputs for PTT and dot/dash input. Buffered, and active low. No dash/dot keying yet added; it just implements “key down” |
| Config PROM | 256Mbit QSPI. Must be programmable through the FPGA with no jumper changes. Able to hold processor in reset until FPGA has configured if needed. |
| JTAG | Standard Xilinx JTAG connector for debug |

## Processor (Raspberry Pi 4 Compute Module)

|  |  |
| --- | --- |
| PCIe | PCI express connection to FPGA. Gen2 x1. Provide additional PCI signals for X4; just not used with this module.  The design aim is for the connection to the radio to be entirely via PCIe; no other signals. This to make sure we can use other processor modules too. |
| USB | Tracked out to rear panel I/O connectors. |
| HDMI | Rear panel |
| Ethernet | Tracked to rear panel |
| Wi-Fi | Wi-Fi antenna connectors to connect to rear panel. |
| Power, reset | We need to investigate the power sequence / reset arrangements – if we can hold the processor in reset while the FPGA configures for perhaps 150ms, we can use a cheaper QSPI config prom. |

## RF Module Interfaces

### Alex header

|  |  |  |  |
| --- | --- | --- | --- |
| **Pin** | **Function** | **Orion mk2: J15** | **7000 RF board: J7** |
| 1 | ANT\_TUNE | Buffered input to FPGA | (grounded) |
| 2 | +12V ALEX | +12V | Not connected |
| 3 | ALEX\_SPI\_SDO | SPI verilog | SPI registers |
| 4 | ALEX\_SPI\_SCK | SPI verilog | SPI registers |
| 5 | ALEX\_RX\_LOAD | SPI verilog | SPI registers |
| 6 | ALEX\_TX\_LOAD | SPI verilog | SPI registers |
| 7 | FWD\_POWER | Analogue in | Directional coupler FWD |
| 8 | PTT | Buffered input to FPGA | Not connected |
| 9 | REV\_POWER | Analogue in | Directional coupler REV |
| 10 | GND | GND | GND |

ANT\_TUNE and PTT appear to have no relevance; may be historical?

Note this is the only connection to the RF board. The RF board also has J22, for possible connection to an Arduino-like modules for LCD display.

# Power Supply, PCB Issues

This section covers issues related to the board & interfaces to the FPGA. Much of this is as per Orion mk2, with noted differences.

## Main interfaces- Changes from Orion mk2

This section notes deltas from the Orion mk2 design:

**DAC:** The DAC is driven by the FPGA which has differential LVDS outputs: the driver is not needed. This will be essentially as per Orion.

**ADCs:** The ADCs data to the FPGA is differential LVDS. There are 18 pairs per ADC (16 data + overflow + o/p clock). The shutdown pin SHDN is hardwired rather than FPGA driven: wire to 0v. Mode=2/3 VCC (2’s complement data, clock adjustment enabled). The LVDS pin connects to 3.3v to select the signal level. Other than that its schematic should be largely as per Orion. I assume there should be 100R terminating resistors at the FPGA between the +and- differential inputs.

**RF attenuators:** ADC attenuators “as is”. The DAC attenuator is an IDT F1912. Orion has pins to drive it in serial or parallel modes. Saturn will use “Direct Parallel” mode only. Dac\_Atten\_Mode = 0 in FPGA; Dac\_Atten\_LE=1

**7000DLE board interface:** The SPI data interface for RX and TX is from the FPGA. The analogue inputs (eg fwd, rev power) from the RF board go to an ADC connected via an SPI port.

**Codec & audio:** The CODEC I2C configuration interface needs to be driven by the FPGA. The discrete logic signals to control the audio path (eg tip/ring/bias etc) are on GPIO[4:0] pins. There is a new signal GPIO5, to select a differential XLR mic input amplifier. 2 spare signals GPIO6&7 if needed. If the CODEC were put on an I/O expander board (to save room on the main PCB) these could be driven by an I2C parallel register.

## Floorplan

The current selected FPGA is Xilinx **XC7A200TFBG676-2**. It may be able to downsize to **XC7A100TFGG676-2** which is footprint compatible. I have allocated pins to the FPGA one the assumption that this approximate layout of main interfaces around the chip will be OK. IO pins are assigned to the FPGA banks to accommodate this. There are four sets of constraints:

1. The PCI Express data transceivers are fixed in bank 216 and can’t be changed;
2. The DAC LVDS output levels mean we can’t have CMOS 3.3V outputs in the same bank. (The DAC attenuator will be driven with lower voltage CMOS for that reason);
3. To enable moving down to the XC7A100T device, do not use banks 12 & 33;
4. Analogue inputs are in bank 35.

Chart, funnel chart

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## Power Supplies

FPGA I/O levels are set “per bank”.

|  |  |  |
| --- | --- | --- |
| **Bank** | **Purpose** | **I/O Voltage** |
| Bank 0 | Configuration | 3.3V |
| Bank 13 | CODEC | 3.3V |
| Bank 14 | Config + ADC2 connections | 3.3V |
| Bank 15 | ADC1 connections | 3.3V |
| Bank 16 | DAC connections | 2.5V |
| Bank 34 | General logic | 3.3V |
| Bank 35 | General logic; analogue | 3.3V |
| Banks 12, 33 | Not used | 3.3V (I assume it still needs power) |
| GTP Quad 216 | GTP buffers (PCIe) | See below |

The analogue inputs (XADC) connect to pins in bank 35. These are no longer being used for external functions, but power feed and die temp can still be monitored.

Xilinx 7 series devices have power supply sequencing requirements. Supplies should come up in this order, & be shut down in reverse order:

|  |  |  |
| --- | --- | --- |
| 1 | VCCINT | 1V |
| 1 | VCCBRAM | 1V |
| 2 | VMGTAVCC[[1]](#footnote-1) | 1V (separate regulator, <10mV p-p noise) |
| 3 | VMGTAVTT[[2]](#footnote-2) | 1.2V (separate regulator, <10mV p-p noise) |
| 3 | VCCAUX | 1.8V |
| 3 | VCCADC | 1.8V |
| 4 | VCCO | Set per bank; 2.5V and 3.3V both needed (see above) |

The on-chip VCCADC supply is derived from VCCAUX: same voltage, but via a ferrite bead. See Xilinx UG480 figure 1-2 (p15). VREFP, VREFN, GNDADC are all at ground potential but with a ferrite bead to ground. 100nF and 470nF decoupling capacitors across VCCADC and GNDADC.

Diagram

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## Decoupling

UG483 recommends a set of capacitors for each supply. These are package dependent. Assume that we will use XC7A200TFBG676.

|  |  |  |
| --- | --- | --- |
| **Pin** | **Voltage** | **Decoupling** |
| VCCINT | 1.0V | 1x 680uF; 1x100uF; 12x 4.7uF;17x 0.47uF |
| VCCBRAM | 1.0V |
| VCCAUX | 1.8V | 1x 47uF; 4x 4.7uF; 7x 0.47uF |
| VCCO\_0 | 3.3V | 1x 47uF |
| VCCO\_13 | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_14 | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_15 | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_16 | 2.5V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_34 | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_35 | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_12 (unused | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| VCCO\_32 (unused) | 3.3V | 1x 47uF; 2x 4.7uF; 4x 0.47uF |
| MGTAVCC | 1.0V | 4.7uF ceramic; 2x 0.1uF |
| MGTAVTT | 1.2V | 4.7uF ceramic; 2x 0.1uF |
| MGTRREF\_216 | Reference input. Connect via 100R resistor to MGTAVTT | 4.7uF ceramic. |

Xilinx UG483 table 2-5 recommends suitable capacitors:

|  |  |
| --- | --- |
| 680uF Tantalum D package | T530X687M006ATE018 |
| 100uF tantalum or ceramic X7R 1210 | GRM32ER60J107ME20L |
| 47uF ceramic X7R 1210 | GRM32ER70J476ME20L |
| 4.7uF ceramic X7R 0805 | GRM21BR71A475KA73 |
| 0.47uF ceramic X7R 0603 | GRM188R70J474KA01 |

For placement of the MGTAVCC/MGTAVTT capacitors see Xilinx UG482 p230 (placement within the BGA pads is recommended)

## Pinouts

There is a separate spreadsheet “iopins.csv” created by the Xilinx tools with FPGA pinouts. This is a cross reference to that describing what the signals are for.

|  |  |  |  |
| --- | --- | --- | --- |
| **Pin(s)** | **Group/Interface** | **Dir’n** | **Comment** |
| BCLK | CODEC | Out | Bit clock to CODEC |
| LRCLK | CODEC | Out | L/R clock to Codec |
| MCLK | CODEC | Out | 12.288MHz master clock output to codec |
| i2stxd | CODEC | Out | Audio TX data to codec |
| i2srxd | CODEC | In | Audio RX data from codec |
| iic\_rtl\_0\_sda\_io | CODEC | Bidir-ectional | I2C signal to codec |
| iic\_rtl\_0\_scl\_io | CODEC | Bidir-ectional | I2C signal to codec |
| pcie\_reset\_n | PCI Express | In | Reset in from processor |
| pcie\_diff\_clock\_rtl\_clk\_n[0]  pcie\_diff\_clock\_rtl\_clk\_p[0] | PCI Express | In | PCIe reference clock. differential |
| pcie\_7x\_mgt\_rtl\_0\_rxn[3:0]  pcie\_7x\_mgt\_rtl\_0\_rxp[3:0] | PCI Express | In | PCIe RX data pairs |
| pcie\_7x\_mgt\_rtl\_0\_txn[3:0]  pcie\_7x\_mgt\_rtl\_0\_txp[3:0] | PCI Express | Out | PCIe TX data pairs |
| PCI\_LINK\_LED | PCI Express | Out | 0 (LED lit) when PCI link established. See 8.1 |
| PCIe\_CLK\_REQn | PCI Express | Out | Clock request output. Driven to 0V by configured FPGA. Needs pullup resistor. |
| MGTRREF\_216 | PCI Express | in | PCIe buffer reference. Needs 100R to MGTAVTT supply (see also section 3.4 & 3.8) |
| ADC1Ovr\_in\_N  ADC1Ovr\_in\_P | ADC | In | RF ADC1 overscale. Differential LVDS |
| ADC1\_In\_N[15:0]  ADC1\_In\_P[15:0] | ADC | In | RF ADC1 16 bit input data. Differential LVDS |
| ADC1\_CLKin\_N  ADC1\_CLKin\_P | ADC | In | RF ADC1 clock from ADC to FPGA  (not used but tracked; differential) |
| ADC2Ovr\_in\_N  ADC2Ovr\_in\_P | ADC | In | RF ADC2 overscale. Differential LVDS |
| ADC2\_In\_N[15:0]  ADC2\_In\_P[15:0] | ADC | In | RF ADC2 16 bit input data. Differential LVDS |
| ADC2\_CLKin\_N  ADC2\_CLKin\_P | ADC | In | RF ADC2 clock from ADC to FPGA  (not used but tracked; differential) |
| DAC\_Out\_N[15:0]  DAC\_Out\_P[15:0] | DAC | Out | RF DAC 16 bit output data. Differential LVDS |
| clock\_122\_in\_n  clock\_122\_in\_p | Sample Clock | In | 122.88MHz VCXO clock in; PECL with level shift |
| pll\_cr | Sample Clock | Out | PLL output to C-R circuit for VCXO control input |
| ref\_in\_10 | Sample Clock | In | 10MHz reference input from ext/oscillator select |
| TX\_DAC\_PWM | TX DAC related | Out | PWM o/p for DAC bias voltage (like DAC\_ALC) |
| Dac\_Atten[5:0]  Dac\_Atten\_LE  Dac\_Atten\_MODE  Dac\_Atten\_CLK  Dac\_Atten\_DATA | DAC attenuator | Out | TX DAC attenuator parallel data (see 3.1)  (1.8V logic signals)  (the serial wires are not used)  LE: drive to 1  MODE, CLK, DATA: drive to 0 |
| ADC1\_ATTEN\_CLK | ADC attenuator | Out | ADC1 atten control |
| ADC1\_ATTEN\_DAT | ADC attenuator | Out | ADC1 atten control |
| ADC1\_ATTEN\_LE | ADC attenuator | Out | ADC1 atten control |
| ADC2\_ATTEN\_CLK | ADC attenuator | Out | ADC2 atten control |
| ADC2\_ATTEN\_DAT | ADC attenuator | Out | ADC2 atten control |
| ADC2\_ATTEN\_LE | ADC attenuator | Out | ADC2 atten control |
| RF\_SPI\_CK | RF interface | Out | RF data control to Anan 7000 |
| RF\_SPI\_DATA | RF interface | Out | RF data control to Anan 7000 |
| RF\_SPI\_TX\_LOAD | RF interface | Out | RF data control to Anan 7000 |
| RF\_SPI\_RX\_LOAD | RF interface | Out | RF data control to Anan 7000 |
| Buf\_Alex\_Pin1 | RF interface | In | Unused Input |
| Buf\_Alex\_Pin8 | RF interface | In | Unused input |
| (see also configuration wiring diagram section 3.7) | FPGA Configuration |  |  |
| GPIO\_OUT[23:0] | Various | Out | Parallel data; see also section 7.4 |
| GPIO\_OUT[0] | Audio | Out | Mic bias enable. =1 to provide electret bias on 3.5mm jack |
| GPIO\_OUT[1] | Audio | Out | Input\_PTT\_Select  0=PTT on ring; 1=PTT on tip |
| GPIO\_OUT[2] | Audio | Out | Mic\_Signal\_Select  0=mic on ring, 1 = mic on tip |
| GPIO\_OUT[3] | Audio | Out | Mic\_Bias\_Select  0=bias on ring; 1= bias on tip |
| GPIO\_OUT[4] | Audio | Out | Spkr\_amp\_Mute |
| GPIO\_OUT[5] | Audio | Out | Balanced\_Mic\_Select  =1 to enable balanced mic input |
| GPIO\_OUT[7:6] | Audio | Out | Spare, uncommitted output |
| GPIO\_OUT[8] | RF ADC | Out | ADC1 RAND =1 to randomise data |
| GPIO\_OUT[9] | RF ADC | Out | ADC1 PGA =1 to enable ADC 3dB amplifier |
| GPIO\_OUT[10] | RF ADC | Out | ADC1 DITHER =1 to dither the clock |
| GPIO\_OUT[11] | RF ADC | Out | ADC2 RAND =1 to randomise data |
| GPIO\_OUT[12] | RF ADC | Out | ADC2 PGA =1 to enable ADC 3dB amplifier |
| GPIO\_OUT[13] | RF ADC | Out | ADC2 DITHER =1 to dither the clock |
| GPIO\_OUT[15:14] | RF | Out | Spare, uncommitted output |
| GPIO\_OUT[22:16] | General | Out | Open collector outputs (7 bits) |
| GPIO\_OUT[23] | General | Out | Spare, uncommitted output |
| DRIVER\_PA\_EN | TX Strobes | Out | Enables power to 0.5W amp |
| MOX\_strobe | TX Strobes | Out | 1=TX. See Orion FPGA\_PTT signal |
| TXRX\_RELAY | TX Strobes | Out | 0 if TX. Drive LED, lit for TX |
| CTRL\_TRSW | TX Strobes | Out | Drives relay by 0.5W amp |
| BUFF\_OUT | Strobe | Out | Unused. Wired to 0v |
| ATU\_TUNE | General CMOS | Out | =1 to initiate TUNE by external ATU |
| STATUS\_IN[9:0] |  | In | Parallel data; see section 7.5 |
| STATUS\_IN[0] | General CMOS | In | PTT In (3.5mm jack & rear panel combined) |
| STATUS\_IN[1] | General CMOS | In | Not used |
| STATUS\_IN[2] | General CMOS | In | Key in 1 (Dot) |
| STATUS\_IN[3] | General CMOS | In | Key in 2 (Dash) |
| STATUS\_IN[7:4] | General CMOS | In | User IO4,5,6,8 as drawn  IO5 used as a TX inhibit input  IO8 used as a CW input |
| STATUS\_IN[8] | General CMOS | In | 13.8v detect in. 1= power valid |
| STATUS\_IN[9] | General CMOS | In | ATU tune complete. 1= complete (needs pullup) |
| STATUS\_IN[10] | General CMOS | In | 1=10MHz/122.88MHz PLL locked |
| STATUS\_IN[31] | General CMOS | In | TX enable. 1 if TX allowed. Ext input J54. |
| TX\_ENABLE | General CMOS | In | External input; if 0, TX is gated off. Needs pullup. |
| LEDOutputs[15:0] | Debug | Out | Drivers for status / debug LED. Active high, See section 8.1 |
| BLINK\_LED | Debug | Out | LED blinking at about 1Hz rate. See 8.1 |
| EMC\_CLK | Config | In | 122.88MHz CMOS clock in |
| PROM\_SPI\_ss\_io[0]  PROM\_SPI\_io3\_io  PROM\_SPI\_io2\_io  PROM\_SPI\_io1\_io  PROM\_SPI\_io0\_io  VCCBATT\_0  DONE\_0  CCLK\_0  INIT\_B\_0  M0\_0, M1\_0, M2\_0  PROGRAM\_B\_0  CFGBVS\_0  PUDC\_B | Config |  | Configuration signals. See diagram in section 3.7 |
| TCK\_0  TMS\_0  TDI\_0  TDO\_0 | Config |  | JTAG signals. See diagram in section 3.7 |
| ADC\_MOSI  ADC\_MISO  ADC\_CLK  nADC\_CS | Aux ADC; connects an SPI A-D converter |  | Pins added, and custom Verilog IP core. Not fully tested! |
| FPGA\_CM4\_EN |  | Out | Not currently used. Powers on/off the compute module 4. Drive to 1 for normal operation. |
| PCIe-T-SMBCLK  PCIe-T-SMBDAT |  | bidir | Not currently used: PCIe bus config signals |

A number of signals need pullup resistors (eg 4K7 to +3.3v):

STATUS\_IN[9]; TX\_ENABLE;

(not on the FPGA) RUN\_PG output to Raspberry pi4 CM

## Clocking

The clock arrangement should be as per Figure 2. The ADCs, DAC and FPGA should all get differential LVPECL clocks with trace lengths matched as far as possible to make the trace delays equal. The FPGA also requires a 122.88MHz clock to the EMCCLK pin (V22) used during configuration.



Figure : 122.88MHz Clock Distribution

Connect the FPGA LVPECL inputs with a similar resistor network to that on the ADCs. (The FPGA is set to LVDS levels – so we need PECL to LVDS translation).

ADC, DAC data timing at the FPGA can then be worked out (Figure 3):



Figure : Clock Timing For FPGA I/O

(In rev 1 Saturn, the ADC clocks are probably 0.7ns before the FPGA, DAC clocks)

DAC timing adjusted: a 135o clock phase gives a timing diagram something like:

Th 2.6ns min

Tsu 1.5ns max

## FPGA Configuration

The FPGA loads its configuration from an external memory device at startup. By far the best arrangement will be to use a QSPI Flash device, as long as it is fast enough. If necessary we can hold off the Raspberry pi starting up until FPGA configuration is complete. This will use Master SPI X4 Flash config mode (see Xilinx UG470).

Wire the JTAG and config PROM as per the Figure 4 & notes below:

Diagram, schematic

Description automatically generated

Figure : Schematic for Configuration Prom

|  |  |  |
| --- | --- | --- |
| **Pin** | **Package Pin** | **Comment** |
| D[00] | P22 | in-system programming of QSPI Prom. Signals PROM\_SPI\_MOSI, PROM\_SPI\_MISO, PROM\_SPI\_SSn[0] in the FPGA pin list connect to these 3 pins. |
| DIN/D[01] | R22 |
| FCS\_B | T19 |
| D[02] | P21 |  |
| D[03] | R21 |  |
| CCLK | L12 | Does not appear in the FPGA pin list |
| INIT\_B | U12 |  |
| DONE | G11 | Drives Raspberry Pi RUN\_PG via an open collector buffer and jumper |
| TDO | U13 | Use a 2mm pitch 2x7 pin header for Xilinx download cable. Xilinx suggested parts (DS593 page 15):  Molex 87832-1420 (SMT) or 87831-1420 (leaded)  FCI 98424-G52-14 (SMT) or 98414-G06-16 (leaded) |
| TDI | R13 |
| TMS | T13 |
| TCK | V12 |
| PROGRAM\_B | N12 |  |
| M0 | U11 |  |
| M1 | U10 |  |
| M2 | U9 |  |
| EMCCLK | V22 | 3.3V CMOS clock for configuration only |
| PUDC\_B | U22 |  |
| CFGBVS | U8 | Selects the correct configuration voltage. |
| VCCO\_0 | F12, T12 | 3.3V power rail |

Config LEDs lit after successful config

The S25FL256 devices are ready for read 300us after power applied. This is significantly faster than the FPGA TPOR (10-35ms) so the Flash memory will be ready when the FPGA begins.

The XC7A75T & XC7A100T both require approx. 30Mbit configuration data. The XC7A200T requires 75Mbit. Xilinx only supports commodity devices. The de-facto config prom is a QSPI device costing perhaps £2 and consuming only 8 pins. These read on quad output, fast read mode; not DDR. XAPP586 describes using a QSPI serial prom in master SPI mode with 7 series devices.

UG908 lists flash PROMs specifically supported by Xilinx. Cypress S25FL256SAGMFI003is suitable & available from Farnell. (Supported by Xilinx under manufacturer “Spansion”). These can clock at 133MHz but including setup time into FPGA, 80MHz is more realistic. Using 61.44MHz clock XC7A200T would configure in approx. 300ms in quad mode.

PCI Express has a commonly quoted “must be configured in 100ms” requirement. Actually it’s nearer 70ms:

* A PC PSU requirement is 100ms from power good until the power supply releases reset (we might have some flexibility here, as we aren’t using a PC power supply);
* PCIe says be ready for configuration 20ms after that;
* But Xilinx on-chip reset may take 50ms to release after it senses power OK.

QSPI unlikely to meet that requirement on its own BUT if we can hold off the CPU reset for a further 200ms say (Can we hold RUN\_PG low until ready – needs to be an open drain signal?), a cheap QSPI device would be fine. The on-chip RC oscillators have huge variation in clock rate caused by temp & process variation. We do have a good quality 122.88MHz VCXO available, which can be divided.

UG953 & XAPP1020 describes how to access the reserved configuration pin CCLK to be able to program the PROM: need to use a STARTUPE2 primitive.

There is an app note XAPP518 that covers in-system programming the flash device through a PCI express endpoint. There’s code for a host application to read the BIT file; and code for the FPGA to provide the data path. There is a mechanism to provide an “emergency” configuration in case the write process is interrupted and the code corrupted.

There are settings to be made in Vivado to specify config details into the bitstream. This will cover selecting the x4 data width and switching to the EMCCLK pin with a correct division ratio. See XAPP586.

### Creating the PROM file

After Vivado’s ”generate bitstream” command, it is necessary to run a further step to create a file ready to be written into the prom: “Tools > Generate Memory Configuration File”. The options for this should look something like the screenshot below. The memory part should be as shown; SPIx4 is important; and the newly generated bit file (normally found in folder <projectname>.runs\impl\_1) should be selected.

Graphical user interface, text, application, email

Description automatically generated

Figure : Vivado Settings to Generate PROM File

### Programming the Config PROM

I have created a simple linux GUI app (Figure 6) to program the configuration prom from that newly generated file. Simple select the filename and click “program”. Eventually that app will support writing a second, fallback configuration when I work out how to do that!

Graphical user interface, application

Description automatically generated

Figure : GUI App to Write Configuration PROM

There is also a command line linux application that writes the config prom. Typical usage:

cd ~/software/saturn

./spi-loader/build/spi-loader -a 0 -f prom.bin -v

The -a 0 is important: it sets the destination address to the start of the config PROM. The default is some random location elsewhere!

There is an ability in the FPGA to have a “fallback” config available. Will need to establish the address it should be at, and how to specify that into the constraints file. (There is a setting for that).

## Processor PCI Express interface

Ideally we should allow a 4 lane PCI express interface to allow for future expansion. Initially we will use 1 lane Gen2 (Gen2x1); Allow eventually for up to Gen2x4. The PCI Express bus signals are:

|  |  |
| --- | --- |
| PCIe\_nRST | Reset signal, driven by processor |
| PCIECLKREQN | Clock request. Permanently low output from FPGA, once configured. |
| PCIe\_CLK\_P,  PCIe\_CLK\_N | Differential clock; 100MHz as required by PCI Express spec; HCSL levels. Clocks the IP core. AC coupled at the RPi source. |
| PCIe\_TX\_P,  PCIe\_TX\_N | Differential RPi data out; to FPGA data in. AC coupled at the RPi source.  Lane 0 only used for RPi4. |
| PCIe\_RX\_P,  PCIe\_RX\_N | Differential RPi data in; from FPGA data out. AC coupled near the FPGA; use 0.1uF X7R. Lane 0 only used for RPi4. |
| MGTRREF\_216 | Needs 100R to MGTAVTT supply (see also section 3.4) |

Note that the ordering of the high speed GTPE2 transceivers is set in the XDMA core (actually the hard PCIe block). The pinouts can’t be reassigned.

See NVidia OEM design guide for advice on tracking: it is probably still relevant. Raspberry pi recommendation is for 90Ω Traces, and with lengths within a pair matched within 0.1mm

Diagram, schematic

Description automatically generated

Figure : PCI Express Signals

PCIe\_CLK\_nREQ: PCI express “clock request” to processor. 3.3V level. Needs a pullup resistor; driven to 0 by an FPGA output.

PCIe\_nRST: active low PCI express reset from processor. Treat as a CMOS 3.3V level input. This should reset the PCI express IP core in the FPGA.

The PCIe core has “preferred” GTP transceivers:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **PCIe Lane** | **GTP transceiver** | **Pin names**  **XC7A100T-FGG484** | **Pin Names**  **XC7A100T-FGG676** | **Pin Names**  **XC7A200T-FBG676** |
| Lane 0 | X0Y7 | D7 MGTPTXP3\_216  C7 MGTPTXN3\_216  D9 MGTPRXP3\_216  C9 MGTPRXN3\_216 | D10 MGTPTXP3\_216  C10 MGTPTXN3\_216  D12 MGTPRXP3\_216  C12 MGTPRXN3\_216 | D10 MGTPTXP3\_216  C10 MGTPTXN3\_216  D12 MGTPRXP3\_216  C12 MGTPRXN3\_216 |
| Lane 1 | X0Y6 | B6 MGTPTXP2\_216  A6 MGTPTXN2\_216  B10 MGTPRXP2\_216  A10 MGTPRXN2\_216 | B9 MGTPTXP2\_216  A9 MGTPTXN2\_216  B13 MGTPRXP2\_216  A13 MGTPRXN2\_216 | B9 MGTPTXP2\_216  A9 MGTPTXN2\_216  B13 MGTPRXP2\_216  A13 MGTPRXN2\_216 |
| Lane 2 | X0Y5 | D5 MGTPTXP1\_216  C5 MGTPTXN1\_216  D11 MGTPRXP1\_216  C11 MGTPRXN1\_216 | D8 MGTPTXP1\_216  C8 MGTPTXN1\_216  D14 MGTPRXP1\_216  C14 MGTPRXN1\_216 | D8 MGTPTXP1\_216  C8 MGTPTXN1\_216  D14 MGTPRXP1\_216  C14 MGTPRXN1\_216 |
| Lane 3 | X0Y4 | B4 MGTPTXP0\_216  A4 MGTPTXN0\_216  B8 MGTPRXP0\_216  A8 MGTPRXN0\_216 | B7 MGTPTXP0\_216  A7 MGTPTXN0\_216  B11 MGTPRXP0\_216  A11 MGTPRXN0\_216 | B7 MGTPTXP0\_216  A7 MGTPTXN0\_216  B11 MGTPRXP0\_216  A11 MGTPRXN0\_216 |
| (the preferred GTP transceivers are the same for each of: XC7A100TFGG484, XC7A100TFGG676, XC7A200TFBG676; but the pins numbers change between packages) | | | | |

# FPGA DSP Design Notes - Conventional Time Domain Processing

The board will be used in one of 3 ways:

1. With an external application, data sent over ethernet using protocol 1 by Raspberry pi. A C code app will have to collect data from the FPGA and forward packets over ethernet, and vice versa. This will include interleaving multiple DDC streams on RX. This is not demanding.
2. With an external application, data sent over ethernet using protocol 2 by Raspberry pi. This is the most stressing case and the data format at the FPGA interface should try to match protocol 2 data structures to minimise processor load.
3. With the Raspberry pi running an SDR application (eg pihpsdr). The C program will need to perform the DSP and UI functions as well as data transfer.

We know that a lesser processor can handle the data transfers for protocol 1; so managing the various control etc data registers won’t be a problem. It is only the main sample flows that need to be designed carefully.

## FPGA Requirements

* Use PCI express to communicate with host computer
* TX function
  + Accept I/Q baseband TX samples
    - 48KHz, 16 bit I/Q (protocol 1)
    - 192KHz 24 bit I/Q (protocol 2)
  + Upconvert to required TX frequency
  + Present samples to DAC
  + Be able to gate off the DAC samples when TX strobe not asserted
  + Be able to TX a test source waveform
  + For CW modes – ramp amplitude up, down as key pressed/released
  + Ramp up/down time and waveform needs to be programmable in the range 1-6ms
* Downconvert RX
  + Have at least 5 separate RX DDC; Warren requests at least 10.
    - If they were all at max sample rate, data transfer is likely a problem
    - If they were all full performance, FPGA resources may be a problem
    - Could we consider “lesser” receivers for some of them?
  + Option to interleave output samples for two DDC
  + Each DDC select samples from ADC1, ADC2, TX samples, RX test source
  + Separate selection for each of RX and TX (current design does this, but it goes beyond what protocol 2 requires)
  + Downconvert to baseband I/Q
  + Present samples to PC for each DDC streams
  + Latency is a known concern, so data transfers will have to be optimised
  + Selectable sample rate 48/96/192/384/768/1536KHz
  + Accept “overscale” input from ADC & latch
  + Present latched “overscale” to processor, which clears when read
* Clock Management
  + Accept 10MHz ref signal from local xtal or external input
  + Control 122.88MHz VCXO
  + Take clock inputs from VCXO, ADC
  + Generate 122.88MHz DAC clock
  + Derive CODEC master clock (12.288MHz)
* CODEC interface
  + CODEC setup will be via I2C; connected to the FPGA but software on the host will write the registers
  + Accept 48 KHz mic scalar samples from CODEC, send via FIFO to host computer
  + Accept 48KHz L/R speaker samples, send via FIFO to CODEC
  + When in CW mode, add to the TX path a CW sidetone
  + CW sidetone from freq programmable DDS, amplitude ramps up and down to avoid keyclick.
  + Overall sidetone amplitude set according to user preference
* RF interface
  + Provide interface signals for ANAN7000 series RF
  + Drive SPI-like interface for RX (set entirely by processor)
  + Drive SPI-like interface for TX (set by processor, updated by TX strobe)
  + Send control signals to RF attenuators
* Configuration
  + Be able to read back various strobes
  + Be able to assert TX strobe, FIFO resets, control lines for TX & RX
  + Be able to rewrite FPGA configuration PROM without jumper change
  + Be able to reset all FIFOs
  + Be able to read back an FPGA code version number
* I/O Signals
  + Accept PTT, Keyer signals and send to host PC
  + Accept analogue inputs: either attached ADC or Xilinx ADC
  + Drive I2C for codec etc

## Sampling Architecture

### RX

Uses conventional 122.88MHz clock; 16 bit ADC/DAC; designed for 2 ADC. The required Output Rates are:



I planned to adopt the concept of Phil Harman’s approach with CIC filter followed by decimate-by-8 FIR. That means the CIC is used well within its passband and is almost flat (0.4dB droop predicted at +- Fs/2). However Warren recommends a compensating FIR filter.



Consequently the FIR has the same shape and the same coefficients can be used for each sample rate setting.



Figure 8: CIC Decimate by 40, 6 stages (FIR width shown in red)

The CIC is decimate by 40 for final Fs=384KHz. Passband droop at +/-192KHz is ~ 0.4dB. The FIR is needed to accelerate the cutoff at the Fs/2 point; the number of taps driven by the sharpness desired.

The FIR aliases at its input sample rate Fs. For the diagram above for final Fs=384KHz, FIR Fs = 8\*384 = 3072KHz. So the filter aliases (at 3072KHz , 6144KHz etc) map onto the nulls in the CIC spectrum. The filter width is narrow; the CIC provides ~140dB rejection at the FIR alias points.

6 stage CIC, decimating by a variable rate



Figure : Decimate by 8 Filter

From the diagram (Figure 9) the operation of the decimating filter is clear. The bandwidth is defined at the start; decimation simply reduces the sample rate to 1/8 of the original. The spectrum display will be +/- Fs/2. A signal just above Fs/2 will alias to being just inside the passband at just above -Fs/2. So we need the filter to pass the required signals inside +/-FS/2 and reject others to the stop band required. My initial thoughts were that a stopband depth 120dB may be appropriate; Warren thinks 140dB should be a better target.

For final Fs=48KHz we could consider having the filter select 40KHz of “useful” spectrum. That would make the cutoff +/-20KHz. Potentially, CFIR compensation could be built into the FIR filter.

### TX

TX has fewer choices. It will implement a 24 bit datapath feeding a 16 bit DAC; 24 bit I/24 bit Q input samples @Fs=48KHz (protocol1) or 24 bit I/24 bit Q input samples @192KHz (protocol2). If used for protocol 1, the software will need to zero-pad the samples to 24 bits.

The DDS does not seem to need to be used in “unit circle” mode. Amplitude variation negligible after filters have settled. However it may impact Puresignal linearisation if not in that mode.



## Receiver Implementation

The receiver currently contains 5 DDCs. Each channel can accept data from ADC1, ADC2, TX samples or a test source. I/Q samples from all 5 channels go to separate FIFOs, with an option for DDC0 and DDC1 to interleave. The receiver is clocked at 122.88MHz and each DDC has an individually selectable sample rate.

### DDC Architecture

The DDC is the receiver building block; it outputs downconverted and decimated / filtered I/Q samples having processed an ADC input stream. The Vivado block design flowgraph is shown in Figure 10 and Figure 11. The first is unfortunately hard to read! The DSP is implemented entirely using Xilinx IP blocks provided as part of the Vivado package. Each IP core is customised according to user entered parameters. The DSP cores are marked in red in the first figure; the rest are infrastructure.



Figure : DDC Flowgraph in Vivado

Diagram

Description automatically generated

Figure Single Channel DDC

The processing is as follows:

* Input samples are chosen from 4 sources according to the channel select bits. Sources available are:
  + ADC1
  + ADC2
  + TX samples that go to the DAC
  + A “test sources” DDS
* The downconversion frequency is generated using a quadrature DDS. Its NCO sets the frequency, and controls a phase accumulator. sin/cos lookup tables generate I/Q. The DDS free-runs at 122.88MHz. The DDC parameters are:
  + SFDR 95dB (implies 16 bit I/Q output)
  + Frequency resolution 0.05Hz (implies 32 bit phase accumulator)
* The selected sample stream connects to one port of a complex multiplier. The data sources provides the I samples; the Q samples are zeroed. The other port connects to the 16 bit I/Q DDS. The complex multiplier parameters are:
  + 16+16 bit I/Q inputs
  + 16+16 bit I/Q outputs
  + Set to truncate to set output data width (random rounding is another option)
* The output of the complex multiplier is an I/Q stream at zero centre frequency. It now needs to be filtered and decimated to the final bandwidth and matching sample rate. A dual stage filtering scheme is used with CIC decimating to 8x the final sample rate, then a further decimate-by-8 FIR to set the final output sample rate.
* The complex sample stream is split into two separate scalar streams
* The I/Q streams each have their own CIC filter, with decimation set in binary steps from 10 to 320 depending on required final sample rate. The CIC parameters of the core are:
  + 6 CIC stages
  + Differential delay = 1
  + Output data width = 18 bits
* The two scalar filtered streams are recombined into a single complex stream. An FIR filter IP processes both the I and the Q streams, re-using its multiplier and coefficient storage resources. The coefficients were generated using a web filter design site, and converted to .coe format using an excel spreadsheet. The core takes floating point coefficients, and normalises them. The FIR parameters are as follows:
  + 512 taps
  + Coefficient file: 512tap\_TX\_filter\_tfilter.coe (yes I know it says TX!)
  + Decimate by 8
  + Coefficient width 22 bits, fractional bits 24
  + Output width 28 bits
* The output data is limited to 24 bits by taking the 23 LSBs (full amplitude is never reached).
  + The bottom 23 bits are selected at output bits (23:1); output bit 0 = 0
  + (This gives near full amplitude output data from full amplitude input sinewave)
* The single stream is expanded back to an I/Q stream giving 24+24 bit I/Q data at the required final sample rate.
* DDCs are paired, for possible interleaving of their sample streams. When the DDCs are set to interleave, DDCn will fill its FIFO with alternate DDCn and DDCn+1 samples. The DDS for DDCn downconversion will be used for DDCn+1 too.

In protocol 2 each receiver can have a different sample rate, so the same FIR can’t be shared across all receivers. Each receiver slice has one FIR shared by I and Q. The max input sample rate is 12.288MHz (CIC decimating by 10, FIR decimate by 8 to give 1536KHz I/Q sample rate). The filter implements 2 channels for each of I and Q. The final AXI stream width change gives parallel I/Q data output at the required sample rate.

Each DDC FIR uses 14 DSP48 slices and 7 Block RAMs. The CIC filters have been set to not use DSP48 slices and use FPGA logic instead; it seems to make little overall impact: it seems to fit combinatorial logic well. If the filter was not shared between I and Q we would need 2 FIR filters, each 8 DSP48 slices and 4 block RAMs. There is a marginal saving by using a shared filter.

The filter has been time domain simulated to check the word sizes. (I also found at the same time that the DDS needs a reset strobe, or its output is forever XXXX because it has accumulated XXXX when starting up). We get a useful 23 bits out of the FIR. To provide 24 bit output, use a 32 to 64 bit axi stream data width converter then a subset converter with the tdata remap string set to: tdata[54:32],1'b0,tdata[22:0],1'b0

DDC registers:

The channel config data bits select the required input sample stream.

|  |  |  |
| --- | --- | --- |
| **Input Bits** | **Function** | **Meaning** |
| Chan\_Config(1:0) | Select the input when in both RX and TX modes | 00: ADC1  01: ADC2  10: Test source  11: TX samples |

As the test source, a single DDS is used with user programmable frequency.

### DDC Registers

DDCs are paired. Each has a 32 bit frequency-setting delta phase word. Each pair of DDCs has a configuration register.

|  |  |  |
| --- | --- | --- |
| **DDC Config Register** | | |
| **Input Bits** | **Function** | **Meaning** |
| DDCxConfig(1:0) | Channel input for DDCn (0,2,4,6,8) | 00: ADC1  01: ADC2  10: Test source  11: TX samples |
| DDCxConfig (4:2) | DDCn sample rate register | Sets CIC decimation  0: 48KHz; 1: 96KHz; 2: 192KHz  3: 384 KHz; 4: 768 KHz; 5,6,7: 1536 KHz |
| DDCxConfig(9:8) | Channel input for DDCn+1 (1,3,5,7,9) | 00: ADC1  01: ADC2  10: Test source  11: TX samples |
| DDCxConfig (12:10) | DDCn+1 sample rate register | Sets CIC decimation  0: 48KHz; 1: 96KHz; 2: 192KHz  3: 384 KHz; 4: 768 KHz; 5,6,7: 1536 KHz |
| DDCxConfig(16) | Interleave | =0: DDCs are independent  =1: DDC samples interleaved into DDCn output FIFO |
| DDCxConfig(17) | Enabled | =1: normal operation  =0: reset multiplexers connecting DDCs to FIFO |
| DDCxConfig[18] | DDCx data FIFO reset | =1: normal operation  =0: DDC I/Q FIFO reset |
| Initial value for DDCxConfig | 262144 | Deasserts FIFO reset |
| DDCxTune(31:0) | DDCn DDS Tune | 32 bit phase word |
| DDCx+1Tune(31:0) | DDCn+1 DDS Tune | 32 bit phase word |

Each ADC has a single overflow bit, valid in the cycle where overflow occurred. This is latched, and cleared on processor read.

ADC randomise inverts bits 15:1 if bit0 is 1. This is automatically removed in the FPGA input circuit.

## Transmitter Implementation

The transmitter is clocked at the full output sample rate (122.88MHz). It ultimately provides sample data to the TX DAC (MAX5891) with offset binary data format. That is simply converted from 2’s complement by inverting the MSB.

### DSP Architecture

The TX uses the same approach; interpolate by 8 FIR then a CIC interpolator. For CW TX, the DDS is adjusted to offset by the sidetone frequency; sidetone is generated using a DDS. CW keying simple scales its amplitude through the I/Q sample path. We don’t need a TX test source – just need to be able to turn on the DDS output at selectable amplitude.

For protocol 1 the TX sample rate is 48KHz, 16+16 bit I/Q. For Protocol 2 it is 192KHz, 24 + 24 bit I/Q.

The TX flowgraph is shown in Figure 12 and Figure 13. This includes a partly implemented path for TX envelope generation, for EER; but this is incomplete. (I know for example it needs a different I/Q feed with a delay). The TX again uses Xilinx IP cores, marked in red.



Figure : Transmitter Vivado Flow Graph



Figure : Transmitter

The TX signal path is as follows:

* I/Q modulation samples are selected from 1 of 4 sources:
  + The TX samples from the DSP application (eg Thetis)
  + A test DDS source;
  + A CW keyer;
  + A fixed amplitude, 0Hz sample.
* The I/Q samples are multiplexed into a single scalar data stream.
* An interpolating FIR filter bandwidth limits the samples and increases the same rate. Like the RX, the FIR filter has designed using a web filter designer, then the Xilinx coefficient file is generate using an excel spreadsheet. The FIR filter parameters are:
  + Input sample width 16 its
  + 512 filter taps
  + Coefficient file: 512TapLPF\_corner\_20KHz\_tfilter.coe
  + Interpolate by 8
  + Coefficient width 22 bits, fractional bits 24
  + Output width 20 bits
* Filtered samples are converted back to an I/Q stream
* The stream is split into separate I and Q samples.
* Each stream is filtered by identical interpolating CIC filters. The CIC parameters are as follows:
  + 6 stages
  + Differential delay = 1
  + Interpolate by either 80 (protocol2) or 320 (protocol1)
  + Input data width 20 bits
  + Output data width 23 bits
* The filtered samples, now at the final sample rate of 122.88MHz, are converted back into a single I/Q stream and connected to one port of a complex multiplier.
* A quadrature DDS generated samples of the local oscillator for upconversion. The DDS parameters are:
  + SFDR 95dB (implies 16 bit I/Q output)
  + Frequency resolution 0.05Hz (implies 32 bit phase accumulator)
* A complex multiplier multiples the complex modulating samples by the complex DDS samples. The multiplier parameters are:
  + Channel A (modulation) width 23 bits
  + Channel B(DDS) width 16 bits
  + Output width 20 bits
* The In-phase output is selected and scaled in amplitude by a processor-defined 18 bit word. The top 16 bits are taken and used to drive the output DAC. The samples can be gated to 0 when TX is not in progress. The DAC samples are also passed back to the receiver to be downconverted for Puresignal processing.
* Although not fully implemented, a cordic IP core extracts the TX signal magnitude. This would then be used to generate the envelop output signal using a PWM DAC. Alternatively an SPI DAC could be used, but this is not included in the current design.

### Transmitter Registers

|  |  |  |
| --- | --- | --- |
| **TX Config Register registers** | | |
| **Input Bits** | **Function** | **Meaning** |
| TXLOTune[31:0] | TX DDS frequency | 32 bit phase word |
| TXTestFreq[31:0] | Test source tune word |  |
| TXConfig[1:0] | Select the TX data source | 00: TX I/Q Data  01: Fixed amplitude 0Hz  10: Test DDS source  11: CW keyer |
| TXConfig[2] | Output sample gating | 0: TX/RX controlled  1: always on |
| TXConfig[3] | Protocol | 0: protocol 1  1: protocol 2  (selects interpolation rate) |
| TXConfig[21:4] | Output amplitude | 18 bit ampl word, applied at DAC |
| TXConfig[22] | TX data FIFO reset | =1: normal operation  =0: TX I/Q FIFO reset |
| TXConfig[29] | Mux Reset | =1: reset 64 to 48 multiplexer |
| TXConfig[30] | IQ Deinterleave | 0: single TX I/Q stream  1: dual stream; odd samples for envelope |
| TXConfig[31] | IQ Modulation enable | 0: I/Q stream from processor disabled  1: I/Q stream enabled |
| Initial value | 4194304 | Deasserts FIFO reset |

The TX LO DDS is 29 bits with a resolution~0.4Hz. The I/Q test source DDS is 29 bits with a resolution ~0.4Hz

### EER

Note that there is no code in Orion to drive this signal; we may be able to remove it completely.

The EER function uses the TX signal envelope, a few times faster than TX I/Q sample rate (Orion is 5Fs). It is viable to calculate the envelope at the full DAC output rate which will need to be decimated to a suitable DAC speed. Note that the envelope should be generated using a different I/Q stream: it has a group delay imparted by the Puresignal software to adjust out the delays between I/Q signal and envelope arriving at the HPA.

Hermes uses a PWM DAC. Orion has no EER code at all. One option was an SPI DAC with 12 bit resolution. There is available Verilog code for an axi stream to SPI IP core. Use the Verilog code to decimate the o/p sample rate to an acceptable rate (eg 384kS/s, compatible with protocol 1 and 2 rates). A suitable DAC is MCP4821.

## Codec & Audio Interface

### Architecture

This interfaces to a TLV320AIC23B codec (same as Hermes). It uses I2S Slave mode, with timing strobes derived by the FPGA. An I2C (aka 2 wire, IIC) interface connected to the processor is used for configuration.

Audio sample rate = 48KHz for both protocols. Data is shifted MSB first.



Figure : CODEC Interface

The I2S TS and RX Verilog modules present data: right data = tdata[31:16]; left data = tdata[15:0]. For speaker data, both left and right audio are transferred (2x16 bit samples per 48KHz clock). For mic data, only the left channel data is transferred (1 16 bit sample per 48KHz clock).

### Codec Clocks

The Codec has several clocks that the FPGA needs to generate. The audio sample rate is 48KHz. The Codec has a master clock of 12.288MHz; sample clock divided by 10. This is generated by a Xilinx clock generator.

There is a data clock BCLK, generated by the I2S interface logic.



Currently the entire Codec interface including sidetone DDS is clocked at 12.288MHz rate. But the DDS is “throttled” by the data rate that the I2S interface will accept (ultimately 48KHz word rate) and the TREADY signal as part of the AXI stream interface sets the effective clock rate. The Codec interface and the TX need to maintain constant latency regardless of whether CW or other modes are used. Sidetone is added to the speaker path, not replacing it (this avoids clicks through gating off an active audio signal).

### FPGA Codec Interface Registers

|  |  |  |
| --- | --- | --- |
| **Codec Config Register registers** | | |
| **Input Bits** | **Function** | **Meaning** |
| CodecConfig(31:16) | Sidetone volume | 16 bit ampl word, unsigned |
| CodecConfig(15:0) | Sidetone frequency | 16 bit phase word (note 48KHz effective Fs) |

### Codec I2C Register Settings

Taken from the Hermes “hermes\_TLV320\_SPI.v” code: these settings will need to be made by the processor at power up. Also some settings at runtime.

The Codec has its ~CS pin wired to 0. This sets 7 bit address = 0x1A

The CODEC uses two bytes for a register write: a 7 bit register address and 9 bit register data. The 16 bit word is as follows:

<A6 A5 A4 A3 A3 A1 A0> <D8 D7 D6 D5 D4 D3 D2 D1 D0>

The I2C interface requires 3 bytes to be transferred for a bus transaction:

1. 7 bit address + R/W (noting it is write only)
2. MSB of data word: A6 A5 A4 A3 A3 A1 A0 D8
3. LSB of data word: D7 D6 D5 D4 D3 D2 D1 D0

|  |  |  |  |
| --- | --- | --- | --- |
| **Register (hex)** | **Value (9 bits, hex)** | **16 bit word** | **Meaning** |
| 0F | 000 | 0x1E00 | Reset device |
| 09 | 01 | 0x1201 | Digital interface activation: set to ACTIVE |
| 04 | 10: line  14: mic no boost  15 mic, boost | 0x0810  0x0814  0x0815 | Analogue audio path control  Line: mic not muted; line input; bypass disabled; sidetone disabled  Mic: mic not muted; mic input; bypass disabled; sidetone disabled  (set bit 0 for 20dB boost) |
| 06 | 00 | 0x0C00  0x0CFF | Power down control.  All elements powered on  All elements powered down; mic bias output disabled. |
| 07 | 02 | 0x0E02 | Digital interface format.  Slave; no swap; right when LRC high; 16 bit; I2S format |
| 08 | 00 | 0x1000 | Sample rate control  No clock divide; sample rate ctrl=0; normal mode, oversample 256Fs (suitable for MCLK=12.288MHz, 48KHz ADC & DAC) |
| 05 | 00 | 0x0A00 | Digital audio path control  DAC soft mute disabled; de-emphasis disabled; ADC high pass filter enabled |
| 00 | Line in gain  0000nnnnn | 0x00nn | Left line input volume  No mute; no simultaneous update; gain=nnnnn |

The CODEC is write only. A series of 16 bit register writes will be needed with no mechanism to determine if the interface is functioning correctly.

### Codec Hardware Interface

|  |  |  |
| --- | --- | --- |
| **CODEC Pin** | **Connection** | **Function** |
| MODE | Hardwired to 0 | Selects I2C |
| CS~ | Hardwired to 0 | Selects address = 0x1A |
| SCLK | FPGA I2C\_SCK | I2C clock; 400KHz |
| SDIN | FPGA I2C\_SDA | I2C data |
| MCLK | FPGA MCLK | 12.288MHz clock |
| BCLK | FPGA BCLK | I2S bit clock |
| LRCIN  LRCOUT | FPGA LRCLK | Left/right select. Both driven by the same FPGA signal. |
| DIN | FPGA I2STXD | I2S serial speaker audio data to CODEC |
| DOUT | FPGA I2SRXD | I2S serial microphone data from CODEC |

## DSP Improvements

There are performance improvements needed for the DSP implementation:

* TX composite noise performance is now a key discriminator between radios
* For Puresignal the TX filters need to be flatter, with CFIR compensation
* For RX the required performance isn’t clear but is important
* We are likely to want more DDCs

### FIR Filter Sizing

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Channels | Taps | DSP | BRAM |
| Original filter, as specified above | 2 | 512 | 4 | 1 |
| Original filter, rounding mode set to full precision (removes symmetric rounding to zero) | 2 | 512 | 3 | 1 |
| Original filter, 1 channel | 1 | 512 | 2 | 1 |
| Warren’s 1024 tap filter, symmetric rounding to zero | 1 | 1024 | 4 | 2 |
| Warren’s 1024 tap filter, input data size = 24 bits o/p data size 47 bits 24 bit coefficients, full precision | 1 | 1024 | 7 | 2 |
| Warren’s 1024 tap filter, input data size = 24 bits o/p data size 47 bits, coefficient size 26 bit, full precision | 1 | 1024 | 7 | 4 |
| Warren’s 1024 tap filter, input data size = 24 bits o/p data size 47 bits, coefficient size 32 bit, full precision | 1 | 1024 | 15 | 4 |
| Warren’s 1024 tap filter, input data size = 24 bits o/p data size 47 bits, coefficient size 32 bit, full precision, 2 channel (this filter implements both I and Q channels) | 2 | 1024 | 23 | 4 |

# Clock Generation

The TX and RX sample path is clocked by a 122.88MHz VCXO. That is phase locked to a 10MHz reference.

## FPGA Clocks

The FPGA uses two clocks:

122.88MHz ADC/DAC sample clock, for all RX/TX paths

Derived 12.288MHZ clock for audio codec, debounce, SPI data shifting etc. Used as the CODEC MCLK source.

The 122.88MHz sample clock may have three different phases in the FPGA:

* The “main” clock input
* The ADCs have a “clock output” connected to the FPGA. Those can be used to register samples into the FPGA; those signals will be an additional “clock capable” input to the FPGA.
* The DAC may need its data driving from a different clock phase to meet the output timing.
* The timings for all of these need to be worked out!

## PLL

The phase lock is:

1. Divide 122.88MHz clock by 3072
2. Divide 10MHz clock by 250
3. Exor the two signals
4. That output goes to the loop filter on the VCXO control voltage.

The Orion board has an auto detector for external reference, and automatically selects it if detected.



Figure : PLL For 122.88MHz VCXO

The VCXO control output needs the same C/R filter that Hermes etc have.

## AXI Bus

The PCI Express interface receives a 100MHz clock. The AXI output from the PCIe core has a 125MHz clock rate.

The AXI Buses after the AXI interconnect operate at two speeds. The AXI infrastructure IP inserts FIFOs as required to manage the different clock rates.

1. Those associated with the radio hardware operate at 122.88MHz;
2. Those providing processor peripherals operate at the native 125MHz.

# CW Keyer

## Ramp Generator

The CW ramp generaor generates an “S” shaped ramp to minimise keyclicks. The ramp is used both to modulate a CW drive to the TX, and to generate the audio sidetone. The ramp generator Verilog code has been designed using code from profile.v and Pavel Demin’s code. It is clocked at 122.88MHz (together with the remainder of the TX) and generates an I/Q ramp signal to go to the TX modulation input. The effective clock rate for ramp generation is throttled by the AXI stream tready, with an effective clock rate of 48KHz or 192KHz. The keyer also generates a PTT signal.

The keyer will generate a ramp period in the range 1-5ms with software programmable ramp shape. A single keyer provides both the I/Q modulation and an amplitude signal to the codec sidetone generation code. The sample rate for sidetone amplitude is always 48KHz, and the clock is different and needs to be remapped using an axi stream clock converter.

|  |  |  |
| --- | --- | --- |
| **CW Keyer Register** | | |
| **Input Bits** | **Function** | **Meaning** |
| CW\_Keyer[7:0] | CW PTT Delay | 0-255 ms; units ms |
| CW\_Keyer[17:8] | CW Hang time | 0-1023 ms; units ms |
| CW\_Keyer[30:18] | Ramp length | Ramp length in words \* 4 (this sets the byte address it steps up to) |
| CW\_Keyer[31] | Enable | 0=off; 1=enabled |

The Ramp amplitude is set by a dual port RAM. Needs to be configured after power up by the processor; it sets a 24 bit amplitude vs time as the keyer is pressed and released. The RAM holds amplitude samples at either 192KHz or 48KHz sample rate; the memory should hold an “S” shape waveform.

Samples of a suitable waveform have been calculated using a spreadsheet for testing.

## Iambic Keyer

Not yet implemented: but the intent will be to re-use the Verilog code from Orion “as is”. The iambic keyer will take “dot” and “dash” inputs and a programmed speed, and generate a CW “key down” bit to drive the ramp generator. Inputs can be from connected hardware, or passed through from a PC application using the “CWX” data encoded into protocol 2.

|  |  |  |
| --- | --- | --- |
| **Iambic Keyer Register** | | |
| **Input Bits** | **Function** | **Meaning** |
|  | Reverse | Swap dot/dash inputs if 1 |
|  | Iambic Enable | 1=Enable iambic keyer |
|  | Sidetone enable | 1= audio sidetone being generated |
|  | ModeB | Keyer mode B if 1; mode A otherwise |
|  | Strict | =1 if strict character spacing enforced. |
|  | Break-in | =1 to enable full break in |
|  | CWX Enable | =1 to enable host key input |
|  | CWX Host Dot |  |
|  | CWX host dash |  |
|  | Keyer speed[8] |  |
|  | Keyer weight[8] |  |

Note the sidetone bit should affect audio, not carrier ramp. Suggest set volume to 0 if set to 0.

# RF System Control & GPIO Signals

This function is clocked at 12.288MHz (Fs/10). To be included into the FPGA block:

* 2x5 bit atten control output
* 6 bit atten control output
* DAC drive level PWM output
* Aux DAC output (EER)
* RX/TX SPI control

## RF SPI Interfaces

The radio uses the ANAN7000DLE RF hardware, and its SPI control interface. Two words are used – 16 bits TX, and 32 bit RX. The data is transferred to the radio whenever a new bus write is executed.

Most significant bit shifted first

U3/U5: TX Settings: 16 bit SR. Serial data = ALEX\_SPI\_SDO; Serial clock = ALEX\_SPI\_SCK; LOAD clock = ALEX\_TX\_LOAD

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TX\_SPI[15:0]** | | | | | |
| **Bit** | **Function** | **Notes** | **Bit** | **Function** | **Notes** |
| 0 | N/A |  | 8 | ANT1 |  |
| 1 | N/A |  | 9 | ANT2 |  |
| 2 | TXRX\_STATUS | unsure | 10 | ANT3 |  |
| 3 | LED D9 | Yellow LED | 11 | TXRX\_RELAY | Operates T/R relay. 1=TX |
| 4 | BPF3 | 20-30m LPF | 12 | LED-D7 | Red LED |
| 5 | BPF2 | 40-60m LPF | 13 | BYPASS | 6m LPF |
| 6 | BPF1 | 80m LPF | 14 | BPF5 | 10-10m LPF |
| 7 | BPF0 | 160m LPF | 15 | BPF4 | 15-17m LPF |

(Note bit 11 isn’t a CPU register and is provided by a hardwired TX/RX signal)

U6/U10/U7/U13: RX Settings: 32 bit SR. Serial data = ALEX\_SPI\_SDO; Serial clock = ALEX\_SPI\_SCK; LOAD clock = ALEX\_RX\_LOAD. (See Protocol 2 document for documentation on these settings)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **RX\_SPI[31:0]** | | | | | |
| **Bit** | **Function** | **Notes** | **Bit** | **Function** | **Notes** |
| 0 | YELLOWLED |  | 16 | YELLOWLED 2 |  |
| 1 | 13HPF | 10-22MHz BPF | 17 | 13HPF 2 | 10-22MHz BPF |
| 2 | 20HPF | 22-35MHz BPF | 18 | 20HPF 2 | 22-35MHz BPF |
| 3 | 6MLNA | 50MHz BPF&LNA | 19 | 6MLNA 2 | 50MHz BPF & LNA |
| 4 | 9.5HPF | 6-10MHz BPF | 20 | 9.5HPF 2 | 6-10MHz BPF |
| 5 | 6.5HPF | 2.5-6MHz BPF | 21 | 6.5HPF 2 | 2.5-6MHz BPF |
| 6 | 1.5HPF | 1-2.5MHz BPF | 22 | 1.5HPF 2 | 1-2.5MHz BPF |
| 7 | N/A |  | 23 | N/A |  |
| 8 | XVTR RELAY | Transverter in | 24 | RX2\_GROUND | When 1, RX2 i/p disconnected |
| 9 | EXT1 RELAY | Ext 1 in | 25 | N/A |  |
| 10 | N/A |  | 26 | N/A |  |
| 11 | RX BYPASS RELAY | PS sample select: Selects main or RX\_BYPASS\_OUT | 27 | N/A |  |
| 12 | HPF\_BYPASS | RX1 Filter bypass | 28 | HPF\_BYPASS 2 | RX2 filter bypass |
| 13 | N/A |  | 29 | N/A |  |
| 14 | RX MASTER IN RELAY | (selects main, or transverter/ext1) | 30 | N/A |  |
| 15 | REDLED |  | 31 | REDLED 2 |  |

## RX Attenuators

(check whether this is the best way to set them; it might be better to follow protocol 2 if that sets them separately for RX and TX, then only one register set would be needed)

|  |  |  |
| --- | --- | --- |
| **RX Data Conversion Register 1** | | |
| ADC1\_Ctrl[4:0] | ADC1 atten when RX | 5 bit atten setting for RX state; 1dB step |
| ADC1\_Ctrl[9:5] | ADC1 atten when TX | 5 bit atten setting for TX state; 1dB step |
| ADC2\_Ctrl[14:10] | ADC2 atten when RX | 5 bit atten setting for RX state; 1dB step |
| ADC2\_Ctrl[19:15] | ADC2 atten when TX | 5 bit atten setting for TX state; 1dB step |

## TX Attenuators & Drive Level

|  |  |  |
| --- | --- | --- |
| **TX Data Conversion Register** | | |
| DAC\_CTRL[7:0] | RX DAC drive level | PWM DAC drive level when RX |
| DAC\_CTRL[15:8] | TX DAC drive level | PWM DAC drive level when TX |
| DAC\_CTRL[21:16] | RX DAC Attenuation | 6 bit atten value when RX (0.5dB steps) |
| DAC\_CTRL[29:24] | TX DAC Attenuation | 6 bit atten value when TX (0.5dB steps) |

## GPIO register

|  |  |  |
| --- | --- | --- |
| **General Purpose I/O Register** | | |
| GPIO[0] | MIC Bias Enable | =1 to provide electret bias on 3.5mm jack |
| GPIO[1] | Input\_PTT\_Select | 0=PTT on ring; 1=PTT on tip |
| GPIO[2] | Mic\_Signal\_Select | 0=mic on ring, 1 = mic on tip |
| GPIO[3] | Mic\_Bias\_Select | 0=bias on ring; 1= bias on tip |
| GPIO[4] | Spkr\_amp\_Mute |  |
| GPIO[5] | Balanced\_Mic\_Select | =1 to enable balanced mic input |
| GPIO[8] | ADC1 RAND | =1 to randomise data |
| GPIO[9] | ADC1 PGA | =1 to enable ADC 3dB amplifier |
| GPIO[10] | ADC1 DITHER | =1 to dither the clock |
| GPIO[11] | ADC2 RAND | =1 to randomise data |
| GPIO[12] | ADC2 PGA | =1 to enable 3dB amplifier |
| GPIO[13] | ADC2 DITHER | =1 to dither the clock |
| GPIO[15:14] |  | Spare outputs from FPGA |
| GPIO[22:16] | User outputs | Open collector o/p (6 bits) |
| GPIO[24] | MOX (TX strobe) | 1=TX |
| GPIO[25] | TX enable | 1=TX enabled |
| GPIO[26] | (not used) |  |
| GPIO[27] | TX\_Relay\_Disable | 0=normal; 1=TXRX relay & PA disabled |
| GPIO[28] | Puresignal enable | Not used. |
| GPIO[29] | ATU TUNE output | 1=tune |
| GPIO[30] | Transverter enable | 1=transverter |

(note PGA bits set to zero in protocol 2 Orion, and not transferred in protocol 2)

Some of these signals need gating to provide the required strobes:

|  |  |  |
| --- | --- | --- |
| **Strobe** | **Purpose** | **Logic** |
| MOX | =1 for TX | ((CPU\_MOX || keyer\_MOX) && TX\_ENABLED) |
| DRIVER\_PA\_EN | Controls driver amplifier after DAC. =1 to enable. | Same as MOX |
| CTRL\_TRSW | Additional TX/RX relay | MOX && transverter\_enable |
| TXRX\_RELAY | Controls relay drive into SPI and as an LED output | MOX && ! TX\_RELAY\_DISABLE |

Diagram

Description automatically generated

## Status Readback

Various strobes and status signals can be read back into the processor.

|  |  |  |
| --- | --- | --- |
| **Status Readback Register** | | |
| **Input Bits** | **Function** | **Meaning** |
| Status[0] | PTT in | 1=TX request |
| Status[1] | - | Not used |
| Status[2] | Dot Key in | 1=key down |
| Status[3] | Dash Key in | 1=key down |
| Status [4] | User input IO4 |  |
| Status [5] | User input IO5 | IO5 used as a ~TX inhibit input |
| Status [6] | User input IO6 |  |
| Status [7] | User input IO8 | IO8 used as a CW key input |
| Status [8] | 13.8v detect in | 1= power valid |
| Status[9] | ATU tune complete | Feedback. Valid state TBD |
| Status[10] | PLL locked | 1= 10MHz/122.88MHz PLL is locked |
| Status[31] | TX\_ENABLE | External input J54; if 0, TX is gated off |
| Status[63:32] | FPGA Version ID (4 bytes) | 32 bit user value, holding f/w ID from USR\_ACCESS register  (currently holds a date code) |

Note IO4/5/6/8 present the true input logic state; not inverted through FPGA.

|  |  |  |
| --- | --- | --- |
| Device input | Diagram, schematic  Description automatically generated | FPGA transfer to processor |

# Processor Data Interface

This section describes the connections between the processor Raspberry Pi Compute module and the FPGA. It could eventually be repurposed into an API description.

## Physical Layer Interface

The physical layer interface between FPGA and Raspberry PI is through PCI Express. This is supported natively in the Pi4 CM. A Xilinx IP core offering DMA and bus access is used to provide appropriate bus interfaces internal to the FPGA.

There are primarily two different data interfaces into the FPGA:

1. A 32 bit AXI4-Lite bus provides read/write access to the many registers in the FPGA. This is a relatively slow interface (only about 4Mbyte/s) which is fine for configuration settings and no use at all for sample data transfer.
2. A 64 bit AXI4 bus interface is accessible for Direct Memory Access transfer of blocks of sample data. There are two DMA transfer engines for each or read and write. Each can achieve ~40Mbyte/s with 4Kbyte transfers, and double that for 8Kbyte transfers; they get slower because of the setup overhead for smaller transfers.

## LED Outputs

Various LED outputs are provided, mostly for debugging. 3.3V logic, LED should connect to ground / Vdd via a suitable resistor. Today these are all software driven, but some could be assigned to hardware functions.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **LED Output Register** | | |
| **Input Bits** | **LED** | **Function** | **Meaning** |
| LED\_Out [15:0] | D44, D22, D41, D40, D35, D10, D11, D14, D12, D13, D15, D16, D17, D18, D19, D74 | =1 to light LED | To be determined. Initially software driven but could be remapped to internal h/w lines. |
| BLINK\_LED | D75 | 1Hz blink | Blinks when FPGA configured, reset not active and all clocks are present |
| PCI\_LINK\_LED | D80 | PCIe | Lit when PCIe interface has been initialised by the operating system |
| Config LEDs | D64, D73 | Lit if successful FPGA config | See section 3.7 |

## Sample Data Transfer

From the FPGA hardwire side there are 8 or more AXI-4 streams of data: two providing data to the hardware (speaker data, I/Q TX data) and 6 or more providing data from the hardware (microphone samples and DDC I/Q samples).

From the processor side there are 3 options for reading and writing data via the PCI express DMA/bridge subsystem:

1. Processor reads and writes via an AXI4-lite interface. Bandwidth available ~4Mbyte/s. OK for register setting but inappropriate for I/Q data transfer. Not considered further.
2. DMA reads and writes to separate AXI-4 streams directly interfaced to the IP core. This would be easiest, but the device driver for ARM processors is VERY slow. Requires TLAST to be asserted in data streams; see <https://github.com/XavierAudier/tlast_generator>
3. DMA reads and writes via an AXI-4 bus interface. Smaller FIFOs may be OK. This can achieve measured rates of 100Mbyte/s over a 64 bit AXI-4 bus but does need IP to access the FIFOs. **This is the selected option.**

Diagram, schematic

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Figure : AXI4 Stream connection to data FIFOs

Diagram, schematic

Description automatically generated

Figure : AXI4 Bus connection to data FIFOs

For AXI-4 bus interface to the FIFOs: The choice seems to be to use an AXI streaming FIFO, or to have some simple IP that translates an AXI-4 lite bus transaction to a stream master write (asserting TVALID) or read (accepting TREADY). I have now written suitable IP.

### FIFO sizes

There are several FIFOs required – see Figure 18:

A picture containing text, calculator

Description automatically generated

Figure : CPU to DSP FIFOs

In all cases the FIFOs on the CPU side are 64 bits; the data needs to be resized (eg using AXI stream datawidth converters) to match that width.

There 3 cases to consider:

1. RX data: 5 or more parallel RX streams, variable sample rate
2. TX data: 1 I/Q sample stream, 48KHz (protocol 1) or 192 KHz (protocol 2) sample rate
3. Audio Codec data: 48KHz sample rate, fixed size.

Each block RAM can be 4Kx9, 2Kx18 or 1Kx36 size. (There are many more options!)

### Audio Codec FIFO

This is the simplest. The data set is 16 bits mic samples, 16+16 bits L/R speaker samples at fixed 48KHz rate. At that clock rate a 1K deep FIFO holds 21ms of audio data – far more than required. Separate Codec needed for Mic samples (16 bits wide), L/R speaker samples (32 bits wide)

Design decision: 256x64 FIFO for each of read, write to CODEC.

### TX FIFO

Input data:

* 16 bit I / 16 bit Q samples @ 48KHz Fs (protocol 1)
* 24 bit I / 24 bit Q samples @ 192KHz Fs (protocol 2)

Do the sums for protocol 2; protocol 1 has much lower rate. Work this out for a FIFO width of 4 bytes, and assume that can be read out to unpack the samples.



A reasonable conclusion might be that a 1Kx32 FIFO will be adequate for both protocol 1 and 2 as long as it can be serviced by a new data transfer in <4ms.

Design decision: 1kx64 FIFO for TX path.

### RX FIFO

Input 24 bit I / 24 bit Q samples @ variable Fs. several parallel receiver channels; each needs its own FIFO, but DDC0 and DDC1 can be paired (interleaved) to use DDC0 FIFO. In that mode there is an argument for the DDC0 FIFO being larger.

Assume that in protocol 1, the data will be read from the RX hardware in protocol 2 (separated) format then stitched together by software.



The RX FIFOs are the largest memory structure in the design. For processor polling data transfers, the 4K deep FIFO is likely to be needed; for DMA a 1K FIFO may be adequate.

Consider limiting the sample rate on DDC5 and above, and giving it a smaller FIFO if needed.

However, this does hinge on the protocol used!

Design decision: Saturn currently has 2kx64 FIFO for DDC0-3 and 1Kx64 FIFO for DDC4-9

## DMA Engine

The XDMA IP core contains 4 DMA engines: 2 for raspberry Pi to FPGA transfers, and two for FPGA to Raspberry Pi transfers. The DMA engines work from DMA descriptors, which describe a transfer; transfers can be chained so several are executed one after the other. The DMA engine supports Scatter-Gather DMA (SGDMA) modes; and FPGA hardware can optionally push DMA descriptors direct to the FPGA through a Verilog interface (Descriptor bypass mode).

In the simplest mode, user code calls a function to initiate a transfer. The XDMA device driver creates appropriate DMA descriptors in host (RPi) memory. It tells the DMA engine their location and the DMA engine fetches them from host memory. The DMA engine executes the transfer, and informs the driver by interrupt when the transfer is complete. The whole process is dominated by the overheads of initiating the process for small transfers.

|  |  |  |
| --- | --- | --- |
| **Bytes** | **Average time (ms)** | **Speed (Mbyte/s)** |
| 128 | 0.114 | 1.12 |
| 256 | 0.106 | 2.42 |
| 512 | 0.134 | 3.82 |
| 1024 | 0.114 | 8.98 |
| 2048 | 0.128 | 16.00 |
| 4096 | 0.137 | 29.90 |
| 8192 | 0.13 | 63.02 |
| 16384 | 0.162 | 101.14 |
| 32768 | 0.237 | 138.26 |

Table ‑: DMA Transfer timings

A 2048 byte transfer is appropriate for a protocol 2 packet (1440 payload bytes); but the speed would not be acceptable for several DDC transfers at higher sample rates (~10Mbyte/s at 1536KHz Fs). There are several approaches which may improve timings:

* Use both DMA engines;
* Use larger transfers, accepting that latency will be impacted;
* Multiplex several DDC together so larger transfers can be used but without latency impact;
* Use a hardware engine to initiate transfers by pushing descriptors when FIFOs are full, using descriptor bypass mode;
* Use the scatter-gather mode (I don’t know how this works but it is supported by the device driver)
* Modify the device driver to initiate several transfers at once, with chained DMA (may amount to the same thing as scatter gather mode).

To use a hardware engine would probably need a device driver, because the DMA engine needs the hardware address of destination memory and the user application sees it through a memory management unit. Each DDC channel would have a block of DMA descriptors, which were set up by the Raspberry pi in advance. When a FIFO reaches a certain depth it initiates a transfer and the data is DMA’d to processor memory. FIFO depths would be smaller, and there would be less processor overhead. The hardware engine would need Verilog, but probably not too complicated.

There are some tutorials on XDMA:

<https://www.hackster.io/Roy_Messinger/pci-express-with-dma-sub-system-241d15>

<https://support.xilinx.com/s/article/71435?language=en_US>

<https://www.xilinx.com/video/technology/getting-the-best-performance-with-dma-for-pci-express.html>

The Saturn design uses an AXI-MM (memory mapped) interface for DMA. It uses an AXI4-Lite master interface to access FPGA registers using 32 bit processor reads and writes for which a 128Kbyte memory window is used.

## DMA Data Transfer

This is about the organisation of the data and its organisation so that it can be efficiently transferred between FPGA and Raspberry Pi. Required data transfer rates could reach about 40Mbytes/s; each (of 2) DMA engine will struggle to get much about 60Mbyte/s so an efficient transfer is important.

### RX data Protocol 2

#### Data Formats Required

RX I/Q data requires 24 bit I/Q samples at selectable sample rate 48KHz-1536KHz. Each DDC can have independently set sample rate. The data is 24 bits wide (therefore 48 bits, 6 bytes for an I/Q pair). The data needs to arrive in FIFOs that are 64 bits wide.

Protocol 2 keeps each data structure separate, and transferring them from separate FIFOs is the most obvious (and easiest) solution. However it needs to be possible to interleave DDC0 and DDC1. This means there are two conditions that need to be possible (Figure 19). There is never any backpressure from the FIFO: if a FIFO becomes full, the transfer has failed and can’t be recovered without resetting the FIFO and DMA process.

Diagram

Description automatically generated

Figure : RX Data Management (Protocol 2)

#### Data Interface Synchronisation

For efficient transfer, the data needs to be packed into 64 bits words for transfer to the processor. 4 consecutive I/Q samples occupy 192 bits, ie 3x64 bit words. Figure 20 shows the byte ordering required in the Protocol 2 DDC packet. For now at least I’ve given up trying to explain the byte ordering in both the Raspberry Pi and the FPGA and we’ll sort it out later. A simple IP core would fix byte ordering if required.



Figure : Data Multiplexing

The DMA transfer process always needs to deliver multiples of 3 64 bit words. If there is ever an error (eg FIFO overflow) the synchronisation to multiples of 3 words needs to be reset. In other words, it must resynchronise so that the 1st word transferred is the one where a complete I/Q sample begins. If not, the processor could begin reading a new stream of incorrect data.

DDC0&DDC1 interleaving complicates this further. If the configuration is varied so that interleaving is turned on or off, the switchover needs to be made aligned to the interleaved data stream so that the processor can always determine which word is which. Having a separate FIFO for the interleaved stream may make this easier. (The AXI4-Stream TLAST bit could assist with this but I can’t see how it could be used – it wouldn’t be practical to detect it and terminate a DMA transfer early when it was reached).

Error recovery and changeover between interleaved and non interleaved data therefore needs to:

* If a FIFO overflow or DMA error occurs:
  + Disable the data stream from the DDC (data will be lost, but it already has been!)
  + Reset the FIFO, or read the FIFO until empty
  + Reset the 48-to-64 bit multiplexer
  + Re-enable data from the DDC
    - I estimate there may have been 100-200us dead time while disabled
  + Re-start DMA
* To enable the DDC0/1 interleaver:
  + Disable the data stream from the DDC when a multiple of 4 samples has been transferred
  + Read out all data in the FIFO by DMA
    - The Protocol 2 DDC packet can send less than 238 bytes/message
  + Reconfigure the DDC0/1 multiplexer to multiplexed mode
  + Re-enable data from the DDC
    - I estimate there may have been 100-200us dead time while disabled
  + Re-start DMA
* To disable the DDC0/1 interleaver:
  + Disable the data stream from the DDC when a multiple of 4 samples has been transferred
  + Read out all data in the FIFO by DMA
    - The DDC packet can send less than 238 bytes/message
  + Reconfigure the DDC0/1 multiplexer to non multiplexed mode
  + Re-enable data from the DDC
    - I estimate there may have been 100-200us dead time while disabled
  + Re-start DMA
* To reconfigure the DDC0/1 interleaver from RX to TX or vice versa:
  + Disable the data stream from the DDC when a multiple of 4 samples has been transferred
  + Read out all data in the FIFO by DMA
    - The DDC packet can send less than 238 bytes/message, but I suspect the current Orion design doesn’t do this
  + Reconfigure the DDC0/1 frequencies and possibly sample rates
  + Re-enable data from the DDC
    - I estimate there may have been 100-200us dead time while disabled
  + Re-start DMA

#### Solution

This suggests that a single IP might be appropriate with 4 functions. The first 3 are easily done with Xilinx IP blocks, but the last may be a problem.

1. Ability to gate on/off the sample stream from the RX
2. Ability to multiplex or otherwise the DDC1&0 sample streams
3. Ability to multiplex data from 48 bit words to 64 bits words
4. Ability to reset that multiplexer if an error occurs

If I create that IP, it would also be in place between every pair of DDCs. So having separate interleaved DDC for RX and TX (rather than changing the functions & frequency of DDC 0&1) may be possible: the protocol 2 spec does allow more than one interleaver.

Doing the DDC0/1 interleaving in the Raspberry Pi could also be possible; but there is less to go wrong with a hardware multiplexer!

Diagram, schematic

Description automatically generated

Figure : DDC Multiplexer IP

Be aware of one issue when implementing. Each DDC output data rate is much lower than the clock rate, and much lower than the data rate into the FIFO; but it is possible to get two consecutive samples on adjacent clocks from the receiver IP. So TREADY may need to be used in the implementation so the DDC output can be throttled to an acceptable rate for the multiplexing.

The interleaver takes two AXI streams each 48 bits wide and gives out an interleaved stream still 48 bits wide.

* When stream\_enable goes low:
  + Deassert the on/off control for DDC0 stream
* When stream\_enable goes high:
  + Reset the 48-to-64 bit multiplexers
  + Reset the FIFOs
  + 1 or more clocks later, assert the on/off control for DDC streams

This is a moderately complex bit of IP for me!

Data flows:



### RX data, Alternative approach

Note this is not what is implemented today!

An alternative approach has been conceived which would multiplex all data streams from all enabled DDCs into a single FIFO regardless of their sample rate. A custom multiplexer would be used (an AXI stream combiner would not lead to predictable results, unless use of “TLAST” made it so). It works on the basis that it transfers data per fixed duration “beat” with a starting point for discussion being one beat = 1 48KHz sample period. Within a beat, each DDC transfers N samples depending on sample rate (48KHz = 1 sample, 192KHJz = 4 samples etc) and each enabled DDC transfer samples in DDC order. It always starts at DDC0. It would have 48 bit Axi stream inputs from DDC, A 48 bit AXI stream output, an enable input and 3 bit codes for each DDC to set the sample rate. When enabled it would start from DDC0 and go through to DDC9 in turn; and read out N samples where N is the number that the DDC generates in a beat. If enable has been cleared it would then stop, otherwise repeat.

So if we have DDC0 & 2 enabled at 96KHz, DDC 1 enabled at 192KHz and DDC5 enabled at 48 KHz a single beat will result in sequential outputs:

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **DDC** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Enabled | Y | Y | Y | N | N | Y | N | N | N | N |
| Fs (KHz) | 96 | 192 | 96 |  |  | 48 |  |  |  |  |
| Data beat 0 | DDC0n DDC0n+1 | DDC1m DDC1m+1 DDC1m+2 DDC1m+3 | DDC2p DDC2p+1 |  |  | DDC5q |  |  |  |  |
| Data beat 1 | DDC0n+2 DDC0n+3 | DDC1m+4 DDC1m+5 DDC1m+6 DDC1m+7 | DDC2p+2 DDC2p+3 |  |  | DDC5q+1 |  |  |  |  |
| Data beat 2 | DDC0n+4 DDC0n+5 | DDC1m+8 DDC1m+9 DDC1m+10 DDC1m+11 | DDC2p+4 DDC2p+5 |  |  | DDC5q+2 |  |  |  |  |

This leads to an output stream as follows:

DDC0n DDC0n+1 DDC1m DDC1m+1 DDC1m+2 DDC1m+3 DDC2p DDC2p+1 DDC5q DDC0n+2 DDC0n+3 DDC1m+4 DDC1m+5 DDC1m+6 DDC1m+6 DDC2p+2 DDC2p+3 DDC5q+1 DDC0n+4 DDC0n+5 DDC1m+8 DDC1m+9 DDC1m+10 DDC1m+11 DDC2p+4 DDC2p+5 DDC5q+1 and so on

The stream is deterministic, as long as no beats are lost. So the Raspberry pi software will always be able to find the correct data.

Diagram

Description automatically generated

Figure : Alternative DDC to CPU Connection Concept

With many DDC enabled and high sample rates the output rate could get quite high. BUT the DMA transfer chunks could be larger, and only one DMA needs to be operated to service all DDC. Overall it is likely more efficient in terms of CPU & bus utilisation. Processor loading is implied for P1 and P2 transfers to Thetis, because data needs to be reordered and packed; but the processor has little to do.

As drawn the DMA will transfer 64 bit (8 byte) words for each 48 bit I/Q sample implying some memory loss. A 4-3 word converter IP between FIFO and multiplexer would pack data into 4 bytes so there is no wasted FIFO memory. But if there is any data loss, or the DDCs need to be reconfigured, the multiplexers would need to be reset potentially leading to data loss.

For this to work it must be possible to reliably start and stop operation and reconfigure the DDCs and still get deterministic data.

* To start up:
  + Setup DDCs
  + Enable multiplexer
  + Enable DDCs
  + Start DMA transfer
* To make changes:
  + Stop multiplexer
    - Multiplexer completes the current set of DDC reads up to & including DDC9
  + DMA out all data from FIFO
  + Reconfigure DDCs
  + Enable multiplexer
  + Enable DDCs
  + Re-start DMA transfer
  + (note this needs to complete before the DDC FIFOs fill up, or there’s data loss)
* If an error is detected:
  + Stop multiplexer
    - Multiplexer completes the current set of DDC reads up to & including DDC9
  + DMA out all data from FIFO (or just delete)
  + Reset DDC o/p FIFOs
  + Enable multiplexer
  + Re-start DMA transfer

For the design to work the appropriate number of samples per beat must already be available, requiring a FIFO between DDC and multiplexer. This FIFO needs to be large enough that data is not lost while the system is reconfigured to mew DDC settings. The output FIFO has the largest data rate; if it fills, then the input FIFOs will begin to fill (because it is a stream).

It is suggested that for non enabled DDC, the multiplexer consumes data so the FIFOs maintain depth alongside the others. All data transfers should be initiated or stopped by setting a single “Active” signal.

This will not support byte packing (for transfer to Thetis), as byte packing is needed per DDC. It could include programmable byte swapping, to network byte order.

### TX I/Q data

Regardless of protocol I/Q samples are sent to the TX and these are asynchronous to other transfers. The data is either 16+16 bits @Fs=48KHz (protocol 1) or 24+24 bits @Fs=192KHz (protocol 2). Suggest transfer 24 bits always, and zero pad the LSBs for protocol 1.

The data is 24 bits wide (therefore 48 bits/6 bytes for an I/Q pair). It arrives from Thetis packed into 32 bit words, and hardware unpacking will be required. An AXI-4 Stream data width converter does this simply but there is some ambiguity about the byte positions (particularly as a native processor may be big endian and a PC little endian). Suggested approach therefore is to use a 3 stage process, which uses trivial FPGA hardware:

1. Use an AXI-4 Stream data width converter to expand from 8 to 24 bytes width;
2. Use an AXI-4 Stream subset converter to remap the data bytes as required;
3. Use an AXI-4 Stream data width converter to contract from 24 bytes to 6 bytes.

The processor (or DMA) interface needs to present an AXI-4 stream master interface. For DMA this should be 64 bits wide.

For protocol 1 assume that the ARM processor will unpack the I/Q data from the speaker samples.

### Codec Data

Microphone data requires one stream of 16 bit scalar samples at a sample rate of 48KHz. These will be read by the processor (or DMA engine) directly. The processor (or DMA) interface needs to present an AXI-4 stream slave interface. For DMA this should be 64 bits wide.

Speaker data requires one stream of 16+16 bit Left and Right sample pairs at a sample rate of 48KHz. These will be written by the processor (or DMA engine) directly. The processor (or DMA) interface needs to present an AXI-4 stream master interface. For DMA this should be 64 bits wide.

### Data Transfer Process

The details will need to be worked out, but each data stream will need to be serviced by a thread in the Raspberry pi. There are two read and two write DMA engines available; for read, they will somehow need to share.

In all cases, each data path has its own 64 bit wide FIFO. The FIFO depth can be read using the FIFO monitor IP. FIFO data is read (DDC, codec mic) by reading from one address; it is written (TX, codec speaker) by writing to one address. It is intended that the DMA transfers will do those writes and reads.

The FIFOs can be reset by deasserting the FIFO reset bit in the appropriate config registers. (DDC config bit 18; TX config bit 22). The codec FIFOs aren’t resettable, but the data path consistently transfers multiples of 16 bit words so they will always end up on a “safe” boundary if the FIFO over or underflows.

The most complicated is the DDC read process, because the DDCs could be independent on interleaved depending on Thetis settings. Possibly one thread would service one pair of DDCs. The basis sequence for the thread will be:

* To initialise:
  + Deassert the channel DDC enable
  + Reset the FIFOs for the DDC pair
  + Set the interleave bit in the DDC config register
  + Assert the channel DDC enable to initiate FIFO writes in the hardware
* To read out data:
  + Read the FIFO depth from the FIFO monitor IP.
  + If below threshold, sleep for N us then repeat
  + If at or above threshold, read the number of bytes available
    - possibly sticking to multiples of 3 64 bit words so the data aligns at DMA boundaries
* If the FIFO overflows, or the DMA returns fewer bytes than requested:
  + Deassert the channel DDC enable
    - Clear the FIFO (asserting its asynchronous reset in hardware works OK, or it could be read until empty)
  + Re-assert the channel DDC enable
    - This will reset the FIFO and multiplexer.
  + Flag the error somehow.
* To change over between interleaved or non interleaved (more detail in section 8.4.1.2):
  + Deassert the channel DDC enable
  + Read out and transfer all remaining data
  + Check FIFO depth has reached zero (using the FIFO monitor IP)
  + Reset the FIFOs for the DDC pair if not empty
  + Change the “interleave” bit
  + Assert the channel DDC enable to initiate FIFO writes in the hardware

## Clock Regions For interfaces

The AXI4 and AXI4-Lite buses from the PCI Express interface all have 125MHz bus rate. This can be changed using an AXI interconnect IP. The Various bus rates are defined here.

### AXI4 DMA Transfer bus

DMA transfers are all to or from FIFO, and FIFO devices can change the clock region. All AXI4 DMA interfaces should be full speed 125MHz on the processor side. The FIFO monitor IPs should also be clocked at 125MHz.

### AXI4-Lite Register Access bus

There is a mix of clock rates use on this bus. I’m not clear whether it is more efficient to have one split between clock rates then fully synchronous AXI interconnects, or whether I can pick & choose. Interfaces feeding control data to the radio DSP should be operated at 122.88MHz.

|  |  |  |
| --- | --- | --- |
| **Interface** | **Interface IP** | **Clock Rate** |
| FIFO monitor IPs | FIFO monitor (at least 3 IP cores) | 125MHz |
| Debug LEDs | Config 64 | 125MHz |
| SPI interface to config PROM | Xilinx SPI | 125MHz |
| XADC (for temp, PSU monitoring) | XADC | 125MHz |
| I2C interface to CODEC | Xilinx I2C | 122.88MHz |
| TX registers | Config 64 | 122.88MHz |
| Codec Registers | Config 64 | 122.88MHz |
| RX registers | Config 256 | 122.88MHz |
| Keyer Registers | Config 64 | 122.88MHz |
| CPU Readback registers, user register readback | Read64 | 122.88MHz |
| ADC overrange latch | AXI overrange | 122.88MHz |
| SPI ADC (for RF level monitoring) | AXI SPI ADC | 122.88MHz |
| Alex RF interface | AXI Alex interface | 122.88MHz |

## Data Endian-ness

The ARM processor seems to be little endian, like the Intel PC world. Apparently the PCI express interface does byte lane translation so the registers directly accessed on the AXI4-Lite bus come out OK. No additional translation required.

The data sent to or received from the PC is in “network endian” format which is big endian. This means that byte swapping is needed so that data DMA’d out into the ARM processor can be sent directly to the PC. It does mean that translation would be required if a local DSP app (eg Pihpsdr) is used.

At the moment: there is fixed, non configurable, hardware byte swapping on the data paths in the FPGA. This is implemented using Xilinx IP:

* Each individual DDC byte swaps its 48 bit I/Q output data using an axis subset converter
* The TX DUC byte swaps incoming I/Q in the I/Q modulation select block
* Codec RX and TX have byte swaps in axis subset converter (RX) and broadcaster (TX)

The process in the DDC is:

1. 48 bit I/Q data is byte swapped;
2. The DDC FIFOs are interleaved if required;
3. Data packed into 64 bit words.

# Software API

## IP Registers

This section describes the register interface for project-specific IP blocks. The header files for the Verilog modules should describe these too!

### 64 bit Config Register

The 64 bit config register IP presents two 32 bit registers. Each can be read or written; the value written is available as a 32 bit bus for hardware control.

|  |  |
| --- | --- |
| **IP** | AXIL\_ConfigReg\_64 |
| **File** | axil\_config64\_reg.v |
| **Addr space used** | 8 bytes |
| **Register Address** | **Function** |
| 0x0 | 32 bit register 0 |
| 0x4 | 32 bit register 1 |

### 256 bit Config Register

The 64 bit config register IP presents two 32 bit registers. Each can be read or written; the value written is available as a 32 bit bus for hardware control.

|  |  |
| --- | --- |
| **IP** | AXIL\_ConfigReg\_256 |
| **File** | axil\_config256\_reg.v |
| **Addr space used** | 32 bytes |
| **Register Address** | **Function** |
| 0x00 | 32 bit register 0 |
| 0x04 | 32 bit register 1 |
| 0x08 | 32 bit register 2 |
| 0x0c | 32 bit register 3 |
| 0x10 | 32 bit register 4 |
| 0x14 | 32 bit register 5 |
| 0x18 | 32 bit register 6 |
| 0x1C | 32 bit register 7 |

### Status Readback Register

The 64 bit config register IP presents two 32 bit registers. Each can be read or written; writes are ignored. The value read back is that presented on a 32 bit input bus.

|  |  |
| --- | --- |
| **IP** | AXIL\_ReadReg\_64 |
| **File** | axil\_read64\_reg.v |
| **Addr space used** | 8 bytes |
| **Register Address** | **Function** |
| 0x0 | 32 bit register 0 |
| 0x4 | 32 bit register 1 |

### FIFO Monitor

This IP monitors 4 FIFOs. It provides a way to read the FIFO depth, and latches any “full” (RX) or “empty” (TX) indication.

|  |  |
| --- | --- |
| **IP** | FIFO\_Monitor |
| **File** | FIFO\_Monitor.v |
| **Addr space used** | 32 bytes |
| **Register Address** | **Function** |
| 0x00 | Status register 1 (read only, with side effect) |
| 0x04 | Status register 2 (read only, with side effect) |
| 0x08 | Status register 3 (read only, with side effect) |
| 0x0C | Status register 4 (read only, with side effect) |
| Each Status reg: | bit(15:0) Current FIFO Depth  bit 31 1 if an overflow has occurred. Cleared by read. |
| 0x10 | Control register 1 (read/write, with no read side effect) |
| 0x14 | Control register 2 (read/write, with no read side effect) |
| 0x18 | Control register 3 (read/write, with no read side effect) |
| 0x1C | Control register 4 (read/write, with no read side effect) |
| Each control reg: | bit(15:0) Threshold FIFO depth  bit 30 Write or read FIFO. 1 for Write FIFO  (if 1, we detect FIFO underflow not overflow)  bit 31 Interrupt enable |

### ADC Overflow Register

A single AXI-lite read register that passes latched overrange readings for two ADCs. Any overrange is latched and stored until the register is read; a read operation clears the latch.

|  |  |
| --- | --- |
| **IP** | AXI\_ADC\_overrange\_reader |
| **File** | AXI\_ADC\_overrange\_latch\_reader.v |
| **Addr space used** | 4 bytes |
| **Register Address** | **Function** |
| 0x0 | bit 0: =1 if ADC1 overrange has occurred  bit 1: =1 if ADC2 overrange has occurred  side effect: read clears both bits |

### SPI ADC Reader Registers

This IP reads an SPI A-D converter (78H90) periodically and stores the data is AXI readable registers. The VSWR forward/reverse power readings store the peak value; the peak reading is cleared when the register is read.

|  |  |
| --- | --- |
| **IP** | AXI\_SPI\_ADC |
| **File** | axi\_spi\_adc.v |
| **Addr space used** | 32 bytes |
| **Register Address** | **Function** |
| 0x00 | [11:0] AIN1 reading; has peak hold (Fwd\_power) |
| 0x04 | [11:0] AIN2 reading; has peak hold (Rev\_power) |
| 0x08 | [11:0] AIN3 reading (J16 pin 12) |
| 0x0C | [11:0] AIN4 reading (J16 pin 11) |
| 0x10 | [11:0] AIN5 reading (Exciter\_power) |
| 0x14 | [11:0] AIN6 reading (13.8V monitor) |
| 0x18, 1C | Reads AIN1 |

### Alex SPI Registers

This IP writes data from the AXI4-Lite bus to the Alex registers for RX and TX RF control. Data is shifted following a change in the data presented.

|  |  |
| --- | --- |
| **IP** | AXILite\_Alex\_SPI |
| **File** | AXILite\_Alex\_SPI.v |
| **Addr space used** | 8 bytes |
| **Register Address** | **Function** |
| 0x00 | 16 bit TX SPI data  After shift, data should be latched by a rising edge on Strobe\_0  For Alex RF interface: see section 7.1 for data bits |
| 0x04 | 32 bit RX SPI data  After shift, data should be latched by a rising edge on Strobe\_1  For Alex RF interface: see section 7.1 for data bits |

### Codec SPI Registers

This IP writes data from the AXI4-Lite bus to the Codec “processor access” registers. Data is shifted following a processor write operation. If there are subsequent write transactions while data is being shifted, the bus will stall until the shifter is idle and then the write will complete. Thus there is no data loss, but check how long a stall is allowed before a bus error is declared.

The SPI clock rate is a programmable parameter, expressed as a clock divide. The core is clocked at 122.88MHz; a clock divide of 6 gives a core clock rate or around 20MHz and SPI clock around 10MHz.

|  |  |
| --- | --- |
| **IP** | AXIL\_SPIWriter |
| **File** | axil\_SPIWriter.v |
| **Addr space used** | 16 bytes |
| **Register Address** | **Function** |
| 0x00 | 16 bit SPI data  After shift, data should be latched by a rising edge on Strobe\_0  For Codec: see codec datasheet |
| 0x04 | 32 bit SPI data  After shift, data should be latched by a rising edge on Strobe\_1  For Codec: do not use |
| 0x08 | Status register  Bit0: =1 if data is being shifted; =0 if idle. |

### Product & Version ID registers

A 64 bit read register provides version number design time constants and 4 bits readback of the clock monitor status.

|  |  |  |
| --- | --- | --- |
| **Address** | **Bits** | **Function** |
| 0x0C000 | 31:20 | Software ID  1=1st prototype, board test with no DSP  2=1st prototype, Saturn DSP |
| 0x0C000 | 19:4 | Software Version |
| 0x0C000 | 3 | Clock monitor =1 if 122MHz clock present (duplicates bit 0) |
| 0x0C000 | 2 | Clock monitor: =1 if 122MHz EMC clock present |
| 0x0C000 | 1 | Clock monitor: =1 if 10MHz ext reference clock present |
| 0x0C000 | 0 | Clock monitor: =1 if 122MHz clock present |
| 0x0C004 | 31:16 | Product ID  1=Saturn 1st prototype |
| 0x0C004 | 15:0 | Product Version  1 |

## AXI4 DMA Bus Address Map

Each AXI stream reader/writer supports one RX stream and one TX stream.

Suggest each interface should have a 32Kbyte address space, allowing at least 16Kbyte DMA. This is more than needed but there is little incremental resource cost. Allow a 1Mbyte PCI BAR window.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **IP Device** | **Streams supported** | **Address Start** | **Address End** | **Size** | **FIFO monitor port** |
| Reader/writer 0 | RX DDC0, TX DDC | 0x00000 | 0x0FFFF | 64K | RX: Mon 0 i/p 0  TX: Mon 3 i/p 2 |
| Reader/writer 1 | RX DDC1 | 0x10000 | 0x1FFFF | 64K | Mon 0 i/p 1 |
| Reader/writer 2 | RX DDC2 | 0x20000 | 0x2FFFF | 64K | Mon 0 i/p 2 |
| Reader/writer 3 | RX DDC3 | 0x30000 | 0x3FFFF | 64K | Mon 0 i/p 3 |
| Reader/writer 4 | RX DDC4 | 0x40000 | 0x4FFFF | 64K | Mon 1 i/p 0 |
| Reader/writer 5 | RX DDC5 | 0x50000 | 0x5FFFF | 64K | Mon 1 i/p 1 |
| Reader/writer 6 | RX DDC6 | 0x60000 | 0x6FFFF | 64K | Mon 1 i/p 2 |
| Reader/writer 7 | RX DDC7 | 0x70000 | 0x7FFFF | 64K | Mon 1 i/p 3 |
| Reader/writer 8 | RX DDC8 | 0x80000 | 0x8FFFF | 64K | Mon 2 i/p 0 |
| Reader/writer 9 | RX DDC9 | 0x90000 | 0x9FFFF | 64K | Mon 2 i/p 1 |
| Reader/writer 10 | Codec speaker, mic audio | 0xA0000 | 0xAFFFF | 64K | TX: Mon 3 i/p 0  RX: Mon 3 i/p 1 |

## AXI4-Lite Register Bus Address map

There are a lot of I/O registers! These can be read/write accessed from the Raspberry Pi easily via the device driver. I’ve create AXI4-Lite IP to provide 64 bits of config data (2x32 bit words) and another with 256 bits of config data (8x32 bit words).

Byte addresses given as an offset address within the AXI4-lite BAR. All addresses are byte addresses, but the bus only accepts 32 bit accesses with an address step of 4.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **IP** | **Byte Address** | **Addr**  **Width** | **Register** |  | **Reference** |
| Config256\_0 | 0x00000 | 4K | DDC0 Frequency |  | See 4.3.2 |
| Config256\_0 | 0x00004 | 4K | DDC1 Frequency |  | See 4.3.2 |
| Config256\_0 | 0x00008 | 4K | DDC0/1 Config |  | See 4.3.2 |
| Config256\_0 | 0x0000C | 4K | DDC2 Frequency |  | See 4.3.2 |
| Config256\_0 | 0x00010 | 4K | DDC3 Frequency |  | See 4.3.2 |
| Config256\_0 | 0x00014 | 4K | DDC2/3 Config |  | See 4.3.2 |
| Config256\_0 | 0x00018 | 4K | DDC4 Frequency |  | See 4.3.2 |
| Config256\_0 | 0x0001C | 4K | DDC5 Frequency |  | See 4.3.2 |
| Config256\_1 | 0x01000 | 4K | DDC4/5 Config |  | See 4.3.2 |
| Config256\_1 | 0x01004 | 4K | DDC6 Frequency |  | See 4.3.2 |
| Config256\_1 | 0x01008 | 4K | DDC7 Frequency |  | See 4.3.2 |
| Config256\_1 | 0x0100C | 4K | DDC6/7 Config |  | See 4.3.2 |
| Config256\_1 | 0x01010 | 4K | DDC8 Frequency |  | See 4.3.2 |
| Config256\_1 | 0x01014 | 4K | DDC9 Frequency |  | See 4.3.2 |
| Config256\_1 | 0x01018 | 4K | DDC8/9 Config |  | See 4.3.2 |
| Config256\_1 | 0x0101C | 4K | RX Test DDS Frequency |  | See section 4.3.2 |
| Config256\_2 | 0x02000 | 4K | KeyerConfig |  | See section 6 |
| Config256\_2 | 0x02004 | 4K | CodecConfig |  | See section 4.5.3 |
| Config256\_2 | 0x02008 | 4K | TXConfig |  | See section 4.4.2 |
| Config256\_2 | 0x0200C | 4K | TXFrequency |  | See section 4.4.2 |
| Config256\_2 | 0x02010 | 4K | TX Modulation test source |  | See section 4.4.2 |
| Config256\_2 | 0x02014 | 4K | RF GPIO |  | See section 7.4 |
| Config256\_2 | 0x02018 | 4K | ADC\_Ctrl |  | See section 7.2 |
| Config256\_2 | 0x0201C | 4K | DAC\_Ctrl |  | See section 7.3 |
| Config64 | 0x03000 | 4K | Processor LED |  | See section 8.2 |
| Read64\_0 | 0x04000 | 4K | Status |  | See section 7.5 |
| Read64\_0 | 0x04004 | 4K | Date code Register |  | See section 7.5 |
| ADC\_OV\_0 | 0x05000 | 4K | ADC Overflow | ADC1, 2 latched overflow bits | See 9.1.5 |
| Fifo\_Mon\_0 | 0x06000 | 4K | FIFO monitor | DDC 0-3 FIFO | See 9.1.4 |
| Fifo\_Mon\_1 | 0x07000 | 4K | FIFO monitor | DDC4-7 FIFO | See 9.1.4 |
| Fifo\_Mon\_2 | 0x08000 | 4K | FIFO monitor | DDC 8-9 FIFO | See 9.1.4 |
| Fifo\_Mon\_3 | 0x09000 | 4K | FIFO monitor | TX DUC FIFO, Codec RX FIFO, Codex TX FIFO | See 9.1.4 |
| SPI ADC\_0 | 0x0A000 | 4K | SPI ADC reader | Alex analogue inputs | See 9.1.6 |
| Alex\_SPI\_0 | 0x0B000 | 4k | AXILite\_Alex\_SPI | SPI interface to RF board | See 9.1.7 |
| Read64\_ID | 0x0C000 | 4K | ID1 | Version ID (31:16)  Revision (15:4)  Clock monitor bits(3:0) | See 9.1.8 |
| Read64\_ID | 0x0C004 | 4K | ID2 | Product ID (31:16)  S/W ID (15:0) | See 9.1.8 |
| Xil\_SPI\_0 | 0x10000 | 16K | SPI Config Prom | Xilinx SPI interface | See Xilinx PG153 |
| Xil\_I2C\_0 | 0x14000 | 16K | I2C codec bus | Xilinx I2C interface | See Xilinx PG090 |
| Xil\_XADC\_0 | 0x18000 | 16K | On-chip XADC | Xilinx XADC interface | See Xilinx PG091 |
| AxiBRAM | 0x1C000 | 16K | AXI block RAM access | CW keyer ramp waveform |  |

## XADC registers

The XADC block is set to measure 4 analogue values:

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Current reading Register | Min Reading Register | Max Reading Register |
| Temperature | 0x18200 | 0x18290 | 0x18280 |
| VCCINT | 0x18204 | 0x18294 | 0x18284 |
| VCCAUX | 0x18208 | 0x18298 | 0x18288 |
| VCCBRAM | 0x18218 | 0x1829C | 0x1828C |

All values are 12 bit in bit positions 15-4, zero padded in bits 3-0; so treat as a 16 bit read.

To scale to meaningful measurements, according to UG480 p23:

Temperature (Celsius) = (16 bit ADC reading \* 503.975)/65536 – 273.15

Voltage = 16 bit ADC reading \* 3.0)/65536

## Sample Data Formatting

As currently implemented, the data arriving from a DMA transfer is ordered appropriately for reading into a local DSP application. It is not ordered as required for bulk transfer to a PC app. This is a potential problem for protocol 2 because data would need to be transferred at a fair data rate. Less of a problem for protocol 1 because it needs to be re-ordered anyway to interleave audio samples. Current ordering:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| data | I7:0 | I15:8 | I23:16 | Q7:0 | Q15:8 | QI23:16 |
| Byte # | 0 | 1 | 2 | 3 | 4 | 5 |

Protocol 1 & 2 required ordering:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| data | I23:16 | I15:8 | I7:0 | Q23:16 | Q15:8 | QI7:0 |
| Byte # | 0 | 1 | 2 | 3 | 4 | 5 |

There will be a similar issue with byte ordering for audio data. Current ordering:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| data | L7:0 | L15:8 | R7:0 | R15:8 |
| Byte # | 0 | 1 | 2 | 3 |

Protocol 1&2 required ordering (noting that Orion always had its 3.5mm jack the wrong way round, so this order may be reverse in software):

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| data | L15:8 | L7:0 | R15:8 | R7:0 |
| Byte # | 0 | 1 | 2 | 3 |

A viable solution is to implement a permanent byte swap, and rearrange data if reading for local processing. This only affects a local (Pihpsdr type) app and the code to read in samples would be similar to the implementation in Thetis where it is read in as three bytes then converted to a 32 bit integer. It makes little difference because you can’t do a “pure” 24 bit read anyway. An AXI Stream Subset Converter IP can do this using equal input and output stream widths and a remap string. For an IQ stream the remap string has to remap a 48 bit path: tdata[31:24], tdata[39:32], tdata[47:40], tdata[7:0], tdata[15:8], tdata[23:16]

In principle a programmable byte swap could be written but adds little value. I would need a byte swap for 24 bit data (I and Q paths on TX and RX) and probably 32 bit for the audio paths.

# IP Modules used in Design

## Xilinx IP

|  |  |  |
| --- | --- | --- |
| **IP** | **Used For** | **Documentation** |
| DMA/Bridge Subsystem for PCI Express | PCI express interface, with DMA and individual read/write capability | PG195 |
| AXI IIC Bus Interface  v2.0 | I2C interface to Codec (IIC is the same thing) | PG090 |
| DDS |  |  |
| FIR |  |  |
| CIC |  |  |

## Local Verilog Modules

Verilog modules used in the design:

|  |  |  |
| --- | --- | --- |
| **Module** | **File** | **Description** |
| Usr\_Reg\_Access | usr\_reg\_access.v | Wrapper around Xilinx IP to access the user register, whose content is specified in the constraints file when the bitstream is generated. Used to provide a version number. |
| reg\_to\_axis | reg\_to\_axis.v | Takes parallel input and adds a permanently asserted valid signal. |
| double\_D\_register | double\_register.v | Two cascaded D registers, for example to synchronise asynchronous inputs |
| D\_register | register.v | A simple D register |
| axis\_mux\_2 | axis\_mux\_2.v | Simple 4:1 selector for AXI stream inputs. |
| axis\_mux\_4 | axis\_mux\_4.v | Simple 4:1 selector for AXI stream inputs. |
| regmux\_2\_1 | regmux\_2\_1.v | Simple 2:1 data selector |
| regmux\_4\_1 | regmux\_4\_1.v | Simple 4:1 data selector |
| regmux\_8\_1 | regmux\_8\_1.v | Simple 8:1 data selector |
| axis\_variable | axis\_variable.v | Takes a parallel input and asserts its Valid output for one cycle if the data changes. |
| axis\_constant | axis\_constant.v | Takes a parallel input and appends a permanently asserted valid output. |
| axis\_adder | axis\_adder.v | Simple signed or unsigned adder for two AXI streams. |
| Axis\_multiplier |  | Signed pipelined axi stream multiplier |
| i2s\_clk\_lrclk\_gen | i2s\_clk\_lrclk\_gen.v | Phil Harman/Kirk Weedman code – generate a divided clock for the Codec |
| I2S\_xmit | I2S\_xmit.v | Kirk Weedman code for codec TX data, modified Laurence Barker to present an AXI Stream data interface |
| I2S\_rcv | I2S\_rcv.v | Kirk Weedman code for codec RX data, modified Laurence Barker to present an AXI Stream data interface |
| cw\_key\_ramp | cw\_key\_ramp.v | CW keyer to generate sidetone and ramp up/down the amplitude as key pressed/released |
| debounce | debounce.v | Asynchronous input debounce. Used for PTT, key and other external inputs. |
| ClockDivider | clockdivider.v | N:1 clock divider. Still used in input debouncing. |
| PWM\_DAC | pwm\_dac.v | Generate a PWM pseudo-DAV output for an 8 bit DAC. May need to be parameterizable to a different width. |
| Serial\_Atten | attenuator.v | Phil Harman’s code – serial data shift for Minicircuits DAT-33-SP+ attenuator |
| LTC2208\_derandomise | ltc2208\_derand.v | Removes the “randomised” data option for the LTC2208 ADC input, to give 2’s complement data |
| cvt\_offsetbinary | cvt\_offsetbinary.v | Takes 2’s complement data and provides offset binary data for MAX5891 TX RF DAC |
| ADC\_overrange\_reader | ADC\_overrange\_latch\_reader.v | AXI4-Lite bus reader for ADC overrange signals. Latches and holds the overrange indication until read. |
| AXI\_Stream\_Reader\_Writer | Stream\_reader\_writer.v | AXI stream interface to full AXI-4 bus. Provides a burst-capable data transfer from the processor / DMA bus to and from an AXI4-Stream to connect FIFOs. |
| AXI\_SPI\_ADC | axi\_spi\_adc.v | 78H90 SPI ADC data reader, modified by Laurence Barker to add an AXI-Lite bus interface |
| FIFO\_Monitor |  | Overflow and depth monitor for FIFO; AXI4-Lite interface |
| AXIL\_SPIWriter | Axil\_SPIWriter.v | Axi-4 lite bus interface; dual SPI 9one 16 bit, one 32 bit) serial shifter. Designed for CODEC bus interface. |
| AXILite\_Alex\_SPI | AXILite\_Alex\_SPI.v | Axi-4 lite bus interface and SPI shifter from Orion. |
| AXIS\_Sizer\_48to64 | axi\_stream\_resizer.v | Resizes an axi stream from 48 to 64 bits; resettable. RX DDC datapath. |
| AXIS\_Sizer\_64to48 | axi\_stream\_resizer\_64to48.v | Resizes an axi stream from 64 to 48 bits; resettable. TX DUC datapath. |
| AXIS\_Interleaver | axi\_stream\_interleaver.v | Either passes separately or interleaves two AXI4 streams, 48 bits wide. To interleave pairs of DDC eg DDC0/1. |
| AXIL\_ConfigReg\_64 | axil\_config64\_reg.v | 64 bit config write register, with axi4-lite interface. |
| AXIL\_ConfigReg\_256 | axil\_config256\_reg.v | 256 bit config write register, with axi4-lite interface. |
| AXIL\_ReadReg\_64 | axil\_read64\_reg.v | 64 bit status read register, with axi4-lite interface. |

There are several testbenches to test some of the IP modules.

# Packaging the Project

This is about getting the FPGA source design into Github.

The approach I have used is:

1. Begin with a simple folder (in my case E:\xilinxdesigns\Pluto)
2. It holds just a few files:
3. Constraints folder – holds the 3 constraints files
4. Sources folder with 3 subfolders:
   1. sources\coefficientfiles – files (generated by spreadsheets) with filter coefficients and keyer waveshape
   2. sources\verilogmodules – HDL sources for the Verilog needed
   3. sources\wrapper – the HDL wrapper which is not automatically managed by Vivado.
5. create\_pluto\_project.tcl: this is a TCL file which reconstructs the project and its block diagram
6. The various git files. .gitignore includes the folder “pluto\_project”

The consequence of this is that git manages the sources files and the TCL script; it does not store all the reconstructed project files. To reconstruct follow the guidance in readme.md:

To use this repository:

1. Install vivado 2020.2

2. Copy this repository to c:\xilinxdesigns\pluto

3. Open vivado and find the TCL command line

4. type: cd c:/xilinxdesigns/pluto

5. type: source create\_pluto\_project.tcl

As the design evolves:

1. create any new Verilog sources in the “sources” folder
2. Periodically recreate the TCL script using the command **File > Project > Write TCL**…
3. Tick “recreate block designs using TCL”
4. Select the “create\_pluto\_project.tcl” file
5. Press OK
6. Publish changes to github



# Linux DMA Device Driver

The XDMA IP core has a Xilinx supplied device driver. See AR65444. Unfortunately it isn’t as simple as it could be. There is a folder missing (/etc/udev/rules.d) and you can get it here: <https://github.com/ramonaoptics/xilinx-dma-driver>

## Building & Patching The Module

The build process requires the files for building kernel modules. The simple way to get them is

**sudo apt install raspberrypi-kernel-headers**

but the documentation says the file could be out of date by several weeks; if the kernel build is recent, you may have to rebuild the kernel from scratch to get them. See <https://www.raspberrypi.org/documentation/linux/kernel/headers.md> and if necessary follow the “build section” link.

The newest code published by Xilinx (with those /etc files added) compiles OK on the raspberry pi. However the /dev/xdma0\_user access to axi4-lite bus does not work. Function bridge\_mmap() in file xdma\_cdev.c maps the memory segment: but pci\_resource\_start (around line 196) returns a 64 bit number which is stored into a 32 bit value. Resize the 4 local variables to uint64\_t and it works correctly.

sudo ./load\_driver.sh runs OK but doesn’t actually need running as the module loads automatically.

./perform\_hwcount.sh runs, and appears to report success

./dma\_memory\_mapped\_test.sh 1024 16 1 1 runs and reports success

./dma\_streaming\_test.sh 1024 16 1 1 does not run (but there are no streaming DMA channels)

In /dev I how have:

* /dev/xdma/card0
* /dev/xdma0\_c2h\_0
* /dev/xdma0\_h2c\_0
* /dev/xdma0\_control
* /dev/xdma0\_user (axi4-lite bus)
* /dev/xdma0\_xvc
* 16 more drivers: /dev/xdma0\_eventsn (/dev/xdma0\_events0 to /dev/xdma0\_events15)

See instructions in the AR65444 document:

Here is an example of how to read from the bypass channel at a specified offset (0x0000).

$Linux> ./reg\_rw /dev/xdma0\_bypass 0x0000 w

Here is an example of how to write to the bypass channel at a specified offset (0x0000) with specific data (0x1234567): $Linux> ./reg\_rw /dev/xdma0\_bypass 0x0000 w 0x1234567

Application program ‘reg\_rw’ has 32Kbytes allocated space as default. If ‘PCIe to AXI Lite Master’ or ‘PCIe to DMA Bypass’ interface selected size is less than 32Kbytes and try to use ‘reg\_rw’ application for read/write will produce an error. If selected size is less than 32Kbytes modify this define in ‘reg\_rw.c’ to corresponding value and compile (make) the file. E.g. #define MAP\_SIZE (128\*1024UL)

## Data Transfer Performance

Memory mapped reads and writes are limited by the speed of the memory window mapped to the PCIe bus. I seem to achieve approx. 40Mbytes/s write and 4Mbyte/s read with 32 bit transfers. This is OK for register writes but not for data transfer.

The memory mapped DMA performance is transfer size dependent. With the driver recompiled without debug, 4K byte transfers achieve around 50Mbyte/s and 8Kbyte transfers sometimes 80Mbyte/s. AR68049 is relevant to this: a lot of overhead time is taken up in the device driver.

Occasional transfers are much slower (1.5us compared with 70us) – possibly a scheduling issue. Data transfer width unknown; it may be possible to speed this up. This is fast enough for dual RX 1536KHz operation, as long as care is taken! The streaming DMA performance is also very slow (maybe 2-5Mbyte/s) so I do need the memory mapped version.

Data transfers will be from the AXI bus, which can be 64 bits wide. The choice to read an AXI stream from an AXI bus is:

1. Use an AXI streaming FIFO (which presents an AXI bus one one side, but you need to write a transfer length after each batch of accesses); or
2. Create IP to read or write a stream. I have implemented this solution.

If processor controlled DMA transfers aren’t fast enough, a hardware DMA engine may be possible. That would feed DMA descriptors straight into the DMA engine in response to a FIFO having achieved a certain depth; it would then transfer data to the next location in the PC in a circular buffer. The processor would need to write at startup a big list of DMA descriptors; the h/w engine would simply read the next one from a memory. That means the processor would need to find the true h/w address of the memory buffer in use.

|  |  |  |
| --- | --- | --- |
| **bytes** | **average time (ms)** | **Speed (Mbyte/s)** |
| 128 | 0.114 | 1.12 |
| 256 | 0.106 | 2.42 |
| 512 | 0.134 | 3.82 |
| 1024 | 0.114 | 8.98 |
| 2048 | 0.128 | 16.00 |
| 4096 | 0.137 | 29.90 |
| 8192 | 0.13 | 63.02 |
| 16384 | 0.162 | 101.14 |
| 32768 | 0.237 | 138.26 |

# Raspberry Pi Issues

## LCD DSI port

The “normal” Raspberry Pi boards have a 15 pin, 2 lane DSI connector for the LCD. The CM4 has a 22 pin connector; you can get an adapter or a special flexi PCB with 15 pin at one end and 22 pin at the other.

Need to provide 5V power to the display. Although there is 5V on the flexi PCB, the display does not take power from it. There is a 5 pin 0.1” pitch connector on the display itself with this pinout:

GND; SCL; SDA; (cut off, as an index pin); 5V

The CM4 has 2 display connectors, DISP0 and DISP1. DISP1 is the default, with 4 DSI lanes. There is a documented process to download an overlay (/boot/dt\_blob.bin) for the device tree for the display. As downloaded this drives DISP1. To make it drive DISP0, make these edits in the CM4 section:

DISPLAY\_I2C\_PORT set to <0> (default=0, so no change)

DISPLAY\_DSI\_PORT set to <0> (default=1)

DISPLAY\_SCL set to <1> (default=45)

DISPLAY\_SDA set to <0> (default = 44)

## IDE

Microsoft Visual Studio Code has proven to be a usable IDE on the Raspberry pi

## Simple Apps

I have created simple apps for programming a serial configuration prom and for reads and writes to/from the AXI4-Lite register bus.

Graphical user interface, application

Description automatically generated

Graphical user interface, text, application

Description automatically generated

# Useful Information

Phil Harman provided this post about PWM: [[hpsdr] EER Support in PowerSDR and Hermes (openhpsdr.org)](http://lists.openhpsdr.org/pipermail/hpsdr-openhpsdr.org/2014-June/045625.html)

# Notes

* I removed 2 strobe signals from the original Andromeda design:
  + Puresignal\_Enable (which should never have been a strobe – it is used in Orion purely to choose which frequency is used in DDC4)
  + Bias\_Ctrl(which was never an Orion strobe);
* TXRX\_Relay is retained as a strobe, to drive an LED when TX is asserted & enabled

1. Source: Xilinx AR# 51017 [↑](#footnote-ref-1)
2. There appears to be no constraint between GTP supplies and VCCAUX & VCCO: so they could be powering up while MGTAVCC and MGTAVTT power up. [↑](#footnote-ref-2)