**GFE System Description**

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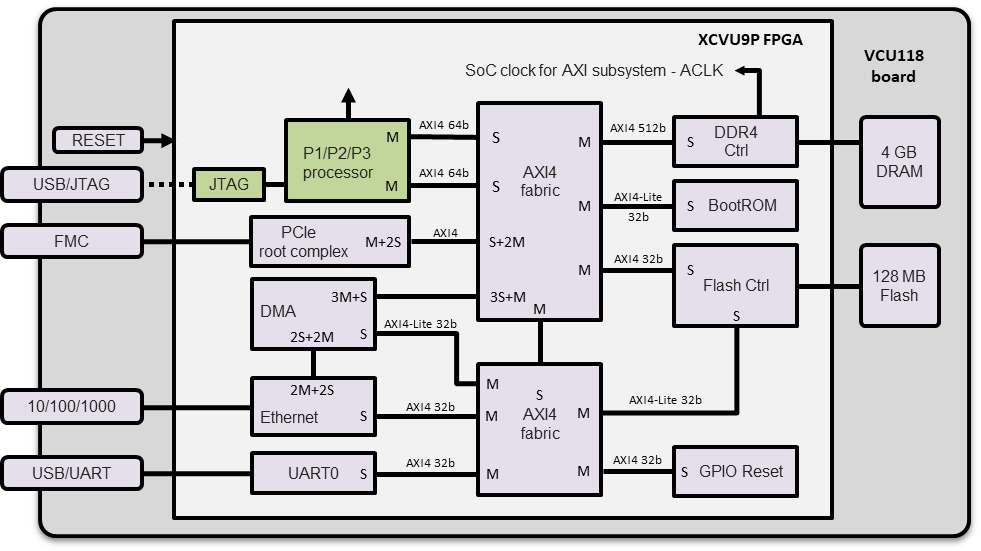
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# Capabilities, System and Components

Figure 1 is a block diagram of the Release 4 GFE hardware. The system in the XCVU9P FPGA is a physical memory system with P1 processors inserted and a virtual memory system with P2/P3 processors. Programs can run on bare metal or in an operating system (FreeRTOS for P1 and Linux kernel for P2/P3). A host-based gdb debugger connects to the system over the USB/JTAG connector, and a host-based console connects over the USB/UART connector. The Release 4 system can access 2 GB of the 4GB on-board DRAM through the Xilinx DDR controller and PHY.



**Figure 1: GFE P{1,2,3} VCU118 FPGA board and FPGA device block diagram**

The GFE system consists of a Rocket, Piccolo, Flute, BOOM or Toooba RISC-V core (see specifications below), a BootROM, GPIO Reset and JTAG, UART, Ethernet/DMA, PCIe root complex DMA, DDR4 and Flash controllers. All components but the P{1,2,3} processors and the JTAG block (green) are Xilinx IP (purple). The BootROM is a read only memory constructed from a BRAM and AXI BRAM controller. The GFE system is the same for all RISC-V cores.

The P{1,2,3} processors include Debug Modules (not shown) that connect to a custom JTAG block (<https://gitlab-ext.galois.com/ssith/gfe/tree/master/jtag>) that uses Xilinx BSCAN primitives under the hood. This enables a tap into the FPGA’s JTAG system controller to multiplex the P{1,2,3} JTAG channel onto the external USB/JTAG port (dotted line connection).

The components are connected through an AXI4 fabric. The fabric automatically translates between protocols (AXI4-Lite and AXI4) and channel widths (32, 64, 256, 512 bit).

See section “Xilinx UltraScale+ Implementation” for the Xilinx circuit implementation of this block diagram.

Table 1 lists the Xilinx IP cores used in the GFE system:

|  |  |  |
| --- | --- | --- |
| **Component** | **Product** | **Documentation** |
| AXI Interconnect | PG059 | <https://www.xilinx.com/support/documentation/ip_documentation/axi_interconnect/v2_1/pg059-axi-interconnect.pdf> |
| DDR4 Controller | PG150 | <https://www.xilinx.com/support/documentation/ip_documentation/ultrascale_memory_ip/v1_4/pg150-ultrascale-memory-ip.pdf> |
| AXI BRAM Controller | PG078 | <https://www.xilinx.com/support/documentation/ip_documentation/axi_bram_ctrl/v4_0/pg078-axi-bram-ctrl.pdf> |
| AXI UART 16550 | PG143 | <https://www.xilinx.com/support/documentation/ip_documentation/axi_uart16550/v2_0/pg143-axi-uart16550.pdf> |
| AXI 1G/2.5G Ethernet | PG138 | <https://www.xilinx.com/support/documentation/ip_documentation/axi_ethernet/v7_0/pg138-axi-ethernet.pdf> |
| AXI DMA | PG021 | https://www.xilinx.com/support/documentation/ip\_documentation/axi\_dma/v7\_1/pg021\_axi\_dma.pdf |
| AXI Quad SPI (Flash ctrl) | PG153 | https://www.xilinx.com/support/documentation/ip\_documentation/axi\_quad\_spi/v3\_2/pg153-axi-quad-spi.pdf |
| AXI GPIO Controller | PG144 | https://www.xilinx.com/support/documentation/ip\_documentation/axi\_gpio/v2\_0/pg144-axi-gpio.pdf |
| DMA/Bridge Subsystem for PCI Express v4.1 | PG194 | <https://www.xilinx.com/support/documentation/ip_documentation/axi_pcie3/v3_0/pg194-axi-bridge-pcie-gen3.pdf> |

**Table 1: Xilinx IP cores**

# Processor Specifications

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **P1 Rocket** | **P1 Piccolo** | **P2 Rocket** | **P2 Flute** |
| Instruction set | RV32IMAC | | RV64IMAFDC | |
| Privilege levels | machine, user | | machine, user, supervisor (SV39) | |
| Memory management | No | | Yes | |
| Physical memory protection | No | | No | |
| Compliance tests | <https://github.com/riscv/riscv-tests> | | | |
| rv32u{i,m,a,c}-p, rv32mi-p | | rv64u{i,m,a,f,d,c}-{p,v},  rv64{m,s}i-{p,v} | |
| Pipeline stages | 5 | 3 | 5 | 5 |
| Default GFE clock MHz | 50 | 50 | 100 | 100 |
| Max GFE clock MHz | 50 | 50 | 100 | 100 |
| Superscalar | No | | | |
| Out-of-order | No | | | |
| ICache/DCache | 4 KB | | 8 KB | |
| Multiply-Divide unit | Yes | | | |
| Single/double FPU unit | No | | Yes | |
| RISC-V debug module | RISC-V External Debug Support Version 0.13 | | | |
| program buffer | system bus | program buffer | system bus |
| Interrupts (PLIC) | Chapter 8, SiFive U54-MC-RVCoreIP v1p0 – 16 interrupts | | | |
| Timer (CLINT) | Chapter 9, SiFive U54-MC-RVCoreIP v1p0 | | | |
| System bus | 64-bit AXI4 | | | |
| Operating system | FreeRTOS | | Linux kernel | |
| Implementation language | Chisel | BSV | Chisel | BSV |

**Table 2a: P1 and P2 Processor Specifications**

|  |  |  |
| --- | --- | --- |
|  | **P3 BOOM** | **P3 Toooba** |
| Instruction set | RV64IMAFDC | |
| Privilege levels | machine, user, supervisor (SV39) | |
| Memory management | Yes | |
| Physical memory protection | No | |
| Compliance tests | https://github.com/riscv/riscv-tests | |
| rv64u{i,m,a,f,d,c}-{p,v}, rv64{m,s}i-{p,v} | |
| Pipeline stages | 10 | 8 |
| Default GFE clock MHz | 50 | 50 |
| Max GFE clock MHz | 50 | 50 |
| Superscalar | dual-issue | |
| Out-of-order | yes | |
| ICache/DCache | 32 KB | 16 KB |
| Multiply-Divide unit | yes | yes |
| Single/double FPU unit | yes | yes |
| RISC-V debug module | RISC-V External Debug Support Version 0.13 | |
| program buffer | system bus |
| Interrupts (PLIC) | Chapter 8, SiFive U54-MC-RVCoreIP v1p0  16 interrupts | |
| Timer (CLINT) | Chapter 9, SiFive U54-MC-RVCoreIP v1p0 | |
| System bus | 64-bit AXI4 | |
| Operating system | Linux kernel | |
| Implementation language | Chisel | BSV |

**Table 2b: P3 Processor Specifications**

“Default GFE clock MHz” is the current frequency setting for the ACLK signal (Figures 1,2) that clocks all AXI based GFE components except the DDR4 controller. For convenience, ACLK is generated by the clock generator inside the DDR4 controller. The ACLK frequency can be modified by adjusting the advanced clocking settings of the DDR controller.

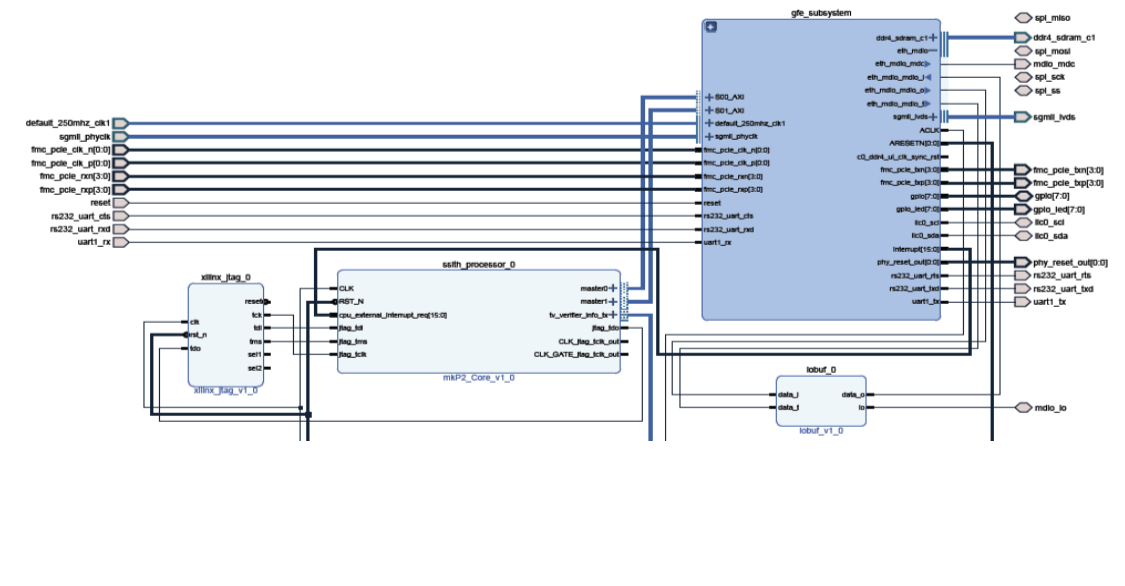
“Max GFE clock MHz” is the maximum clock frequency at which the GFE has been tested for a given RISC-V core.

# Xilinx UltraScale+ Design Implementation

The block diagram in Figure 2 is implemented using Vivado’s IP Integrator design flow: <https://www.xilinx.com/content/dam/xilinx/support/documentation/sw_manuals/xilinx2018_3/ug995-vivado-ip-subsystems-tutorial.pdf>

The IP Integrator enables quick and easy graphical connections of Xilinx IP that is instantiated and configured within an IP Integrator project session. In addition, the P{1,2,3} processors are imported into IP Integrator as 3rd party reusable IP blocks that can be connected as easily as Xilinx IP.

The top-level GFE is a Vivado block design consisting of five instances (Figure 2): (1) a Xilinx JTAG module (xilinx\_jtag\_0) (2) P{1,2,3} processor (ssith\_processor\_0); (3) a subsystem block design (gfe\_subsystem) that instantiates all the other Xilinx modules; (4) an Ethernet IO buffer (iobuf\_0).



**Figure 2: GFE top-level Vivado block design**

The *gfe\_subsystem* module instantiates all the Xilinx cores that are necessary to implement the fabric, UART, DDR4, Ethernet, Flash, BootROM, SPI and PCIe root complex. In addition, it instantiates two blocks to implement a GPIO reset mechanism.

# Address Mapping

The following table provides the memory map for the memory mapped devices. The CLINT and PLIC are included inside the P{1,2,3} processors and are therefore not mapped into the AXI fabric.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Device** | **GFE Instance Name** | **Slave Interface** | **Base Name** | **Offset Address** | **Range** | **High Address** | |
| CLINT | Addressed inside processor |  |  | 0x0000\_0000\_1000\_0000 | 64K | 0x0000\_0000\_1000\_FFFF | |
| PLIC | Addressed inside processor |  |  | 0x0000\_0000\_0C00\_0000 | 4M | 0x0000\_0000\_0C3F\_FFFF | |
| DRAM | ddr4\_0 | C0\_DDR4\_S\_AXI | C0\_DDR4\_S\_AXI\_ADDRESS\_BLOCK | 0x0000\_0000\_8000\_0000 | 2G | 0x0000\_0000\_FFFF\_FFFF | |
| Boot ROM | axi\_bram\_ctrl\_0 | S\_AXI | Mem0 | 0x0000\_0000\_7000\_0000 | 4K | 0x0000\_0000\_7000\_0FFF | |
| DMA | axi\_dma\_0 | S\_AXI\_LITE | Reg | 0x0000\_0000\_6220\_0000 | 64K | 0x0000\_0000\_6220\_FFFF | |
| ETHERNET | axi\_ethernet\_0 | s\_axi | Reg0 | 0x0000\_0000\_6210\_0000 | 256K | 0x0000\_0000\_6213\_FFFF | |
| FLASH | axi\_quad\_spi\_0 | AXI\_FULL | MEM0 | 0x0000\_0000\_4000\_0000 | 256M | 0x0000\_0000\_4FFF\_FFFF | |
| FLASH | axi\_quad\_spi\_0 | AXI\_LITE | Reg | 0x0000\_0000\_6240\_0000 | 4K | 0x0000\_0000\_6240\_0FFF | |
| GPIO Reset | axi\_gpio\_0 | S\_AXI | Reg | 0x0000\_0000\_6FFF\_0000 | 64K | 0x0000\_0000\_6FFF\_FFFF | |
| UART0 | axi\_uart16550\_0 | S\_AXI | Reg | 0x0000\_0000\_6230\_0000 | 4K | 0x0000\_0000\_6230\_0FFF | |
| XDMA | xdma\_0 | S\_AXI\_B | BAR0 | 0x0000\_0000\_3000\_0000 | 256M | 0x0000\_0000\_3FFF\_FFFF | |
| XDMA | xdma\_0 | S\_AXI\_LITE | CTL0 | 0x0000\_0000\_2000\_0000 | 256M | 0x0000\_0000\_2FFF\_FFFF | |
| **Table 3: Address Mapping** | | | | | | |

The memory map for devices connected to the AXI fabric can be viewed in the “Address Editor” tab next to the “Diagram” tab in the Vivado GFE project window.

Addresses 0x8000\_0000 to 0xBFFF\_FFFF are configured as uncached in the Bluespec and Chisel processors. This designation enables coherent memory between the DMA and RISC-V processors. The Linux device tree (bootrom/devicetree.dts) reserves this region for DMA.

Note that the UART register is at 0x6230\_0000, not 0x6230\_1000 as the UART documentation would suggest. This is a result of the small address space allocated to UART in the Xilinx interconnect. The interconnect allocates 0x6230\_0000 to 0x6230\_0fff to the UART, but the UART registers in the Xilinx documentation are defined at 0x6230\_100X. Synthesis causes the upper bits to be ignored within the UART block, so the resulting UART registers are located at 0x6230\_000X

Our reference code uses the proper addresses (0x6230\_000X). Writing to and reading from 0x6230\_100X causes undefined behavior (this is processor dependent).

# Interrupt Mapping

The following table shows the interrupt mapping for cpu\_external\_interrupt\_req[15:0]:

|  |  |
| --- | --- |
| **Pin** | **Connection** |
| 0 | uart\_0 |
| 1 | interrupt pin on axi\_ethernet |
| 2 | mm2s\_introut on axi\_dma |
| 3 | s2mm\_introut on axi\_dma |
| 4 | quad\_spi\_0 |
| 5:7 | tied to zero |
| 8 | misc interrupt, pcie |
| 9 | msi0 interrupt, pcie |
| 10 | msi1 interrupt, pcie |
| 15:11 | tied to zero |

**Table 4: Interrupt Mapping**

The PLIC used by the GFE processors indexes interrupts starting from 1. This means that the interrupt signal connected to cpu\_external\_interrupt\_req[0] corresponds to PLIC interrupt 1. This offset is reflected in the Linux device tree provided in bootrom/devicetree.dts.

# FreeRTOS

The P1 processors boot FreeRTOS 10.2.0.

The Galois FreeRTOS repository is a fork of <https://github.com/coldnew/FreeRTOS-mirror> which is just a mirror of FreeRTOS SVN, the upstream FreeRTOS. The folder FreeRTOS-mirror/FreeRTOS/Demo/RISC-V\_Galois\_P1/demo contains applications specific to the P1 and GFE.

See gfe/README.md for instructions on how to run the FreeRTOS demo applications.

# Linux Kernel

The P2/P3 processors boot the Linux 4.20 kernel.

The kernel configuration is in the repository at gfe/bootmem/linux.config. It indicates which Linux drivers are in use.

The “Linux/Busybox” test exercises the basic kernel boot and initialization of devices. See gfe/README.md for instructions on how to boot Linux.