The CEFHALIC PRNG Package

Andrew W. Rose

April 4, 2022

1 Overview

- The CEFHALIC PRNG Package is a set of high-performance Pseudo-Random Number Generators for FPGAs.
- The firmware is implemented in VHDL-2008 for maximum portability.
- The firmware has been tested in simulation using MENTOR/SIEMENS ModelSim SE-64 2019.2 and tested for implementation in Xilinx Vivado 2020.2.
- Software emulations of the firmware is provided, implemented in C++-11, and a Makefile is provided for compiling the software with GCC.
- The Makefile includes automated installation of the TestU01, PractRand and GJrand random-number test-suites.
- The software includes executables for testing the software emulations with TestU01 and PractRand.
- In simulation, the firmware includes debugging output for testing with PractRand, or with TestU01 via the included executable.

Discussion of the algorithms, their implementation, resource usage, performance, etc. may be found in the accompanying paper, which is currently still in preparation. This document is intended as a practical guide.

2 Getting the code

The Cefhalic PRNG package is hosted on GitHub. To checkout anonymously via git, use

```
git clone git@github.com:Cefhalic/PRNG.git
```

To simply download a plain copy of the code, a zip-file is also available.

3 Firmware interfaces

3.1 Xoshiro64bit

The Xoshiro64bit generator is a 64-bit integer generator. The firmware implements the functional code as VHDL procedures for maximum code reuse, and which could be used directly within the user's processes. The primary interface for most user, however, will be through the VHDL entity:

```
ENTITY Xoshiro64bit IS
  GENERIC( Seed : tArray( 0 TO 3 ) := ( ... );
           Debugging : BOOLEAN := FALSE );
  PORT( Clk   : IN STD_LOGIC ;
        Data : OUT tData ;
        Pull : IN BOOLEAN := TRUE;
        Reset : IN BOOLEAN := FALSE;
        ResetVal : IN tArray( 0 TO 3 ) := Seed
        );
END Xoshiro64bit;
```

Where the generics are

- **Seed** - The default value to which the state is reset if the 'ResetVal' port interface is not instantiated
- **Debugging** - Used in simulation to write the values to a file or pipe

It should be noted that both generics have default values and may be safely omitted if not required.

The ports are

- **Clk** - The algorithm clock
- **Data** - The pseudo-random number output
- **Pull** - Used to indicate that a new PRN should be emitted on the next clock-cycle
- **Reset** - Used to reset the state of the generator and scrambler
- **ResetVal** - The value to which the state should be reset

It should be noted that 'Pull', 'Reset' and 'ResetVal' have default values and may be safely omitted if not required.

The types 'tData' and 'tArray' are defined in the package 'PkgPRNG' and can be included using the VHDL

```
USE WORK.PkgPRNG64bit.ALL;
```

Example usages of Xoshiro64bit can be found in the file 'Testbench.vhd', an excerpt of which is shown here:

```
  Instance0 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_With_Pull_And_Reset ,
            Pull => PullInt , Reset => ResetInt );
  Instance1 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_With_Pull_No_Reset  ,
            Pull => PullInt );
  Instance2 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_No_Pull_With_Reset  ,
            Reset => ResetInt );
  Instance3 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_No_Pull_No_Reset );
  Instance4 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_With_Pull_And_ResetVal ,
            Pull => PullInt ,
            Reset => ResetInt , ResetVal => ResetVal );
  Instance5 : ENTITY WORK.Xoshiro64bit
  PORT MAP( Clk => Clk , Data => Data_No_Pull_With_ResetVal  ,
            Reset => ResetInt , ResetVal => ResetVal );
```

It should be noted that due to pipelining, the first three values emitted after a reset are 0. The behaviours of these six instances can be seen in figure 1.

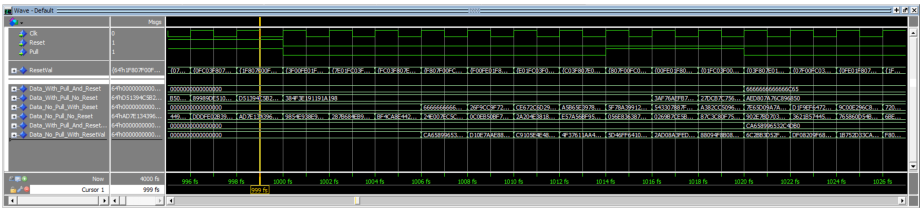

Figure 1: Waveform outputs from six example instantiations. Data_No_Pull_No_Reset produces a new output on every clock; Data_No_Pull_With_Reset produces a new output on every clock, three clock-cycles after the reset line goes low; Data_With_Pull_No_Reset produces a new output on any clock-cycle after the 'Pull' input is high; and Data_With_Pull_And_Reset produces a new output on any clock-cycle after the 'Pull' input is high, three 'Pulls' after the reset line goes low. Data_No_Pull_With_ResetVal and Data_With_Pull_And_ResetVal are equivalent to Data_No_Pull_With_Reset and Data_With_Pull_And_Reset, but with their value taken from the input port.

3.2 XoshiroDouble

The XoshiroDouble generator is a double-precision floating-point generator. As with Xoshiro64bit, the firmware implements the functional code as VHDL pro-

cedures for maximum code reuse but, again, the primary interface for most user will be through the VHDL entity:

```
ENTITY XoshiroDouble IS
  GENERIC( Seed : tArray( 0 TO 3 ) := ( ... );
           Debugging : BOOLEAN := FALSE );
  PORT( Clk   : IN STD_LOGIC ;
        Data : OUT tFpData ;
        Pull : IN BOOLEAN := TRUE;
        Reset : IN BOOLEAN := FALSE;
        ResetVal : IN tArray( 0 TO 3 ) := Seed
        );
END XoshiroDouble;
```

Where the only difference in the interface is that the output data is of type 'tFpData' instead of 'tData'. If the 'Seed' or 'ResetVal' are not required, the user need only include the floating-point package using the VHDL

```
USE WORK.PkgPRNGdouble.ALL;
```

If the 'Seed' or 'ResetVal' interfaces are required, the user should include both packages, using the VHDL

```
USE WORK.PkgPRNG64bit.ALL;
USE WORK.PkgPRNGdouble.ALL;
```

Example usages of XoshiroDouble with the equivalent set of interfaces as the Xoshiro64bit examples, can also be found in the file 'Testbench.vhd'. It should be noted that due to pipelining, the first eight values emitted after a reset are 'NAN'. The behaviours of six instances can be seen in figure 2.

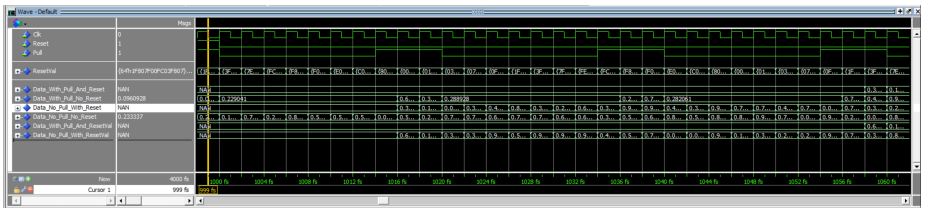

Figure 2: Waveform outputs from six example instantiations. Data_No_Pull_No_Reset produces a new output on every clock; Data_No_Pull_With_Reset produces a new output on every clock, eight clock-cycles after the reset line goes low; Data_With_Pull_No_Reset produces a new output on any clock-cycle after the 'Pull' input is high; and Data_With_Pull_And_Reset produces a new output on any clock-cycle after the 'Pull' input is high, eight 'Pulls' after the reset line goes low. Data_No_Pull_With_ResetVal and Data_With_Pull_And_ResetVal are equivalent to Data_No_Pull_With_Reset and Data_With_Pull_And_Reset, but with their value taken from the input port.

4 Testing

4.1 Testing Xoshiro64bit software emulators

To compile the software, in the software directory, from the commandline execute

```
make
```

To test the emulated Xoshiro64bit generator with TestU01, run

```
./bin/test_64bit.exe --suite 0 --bits 0
```

Where the arguments are

- **suite** - The test-suite to use: 0=SmallCrush, 1=Crush, 2=BigCrush
- **bits** - The bits to test with TestU01: 0=Low-32, 1=High-32, 2=Low-32 reversed, 3=High-32 reversed

To test the emulated xoshiro64bit generator with PractRand, run

```
./bin/test_64bit.exe --suite 3 | ./PractRand/RNG_test.exe stdin64
```

PractRand runs indefinitely until the user halts execution.

4.2 Testing XoshiroDouble software emulator

To test the emulated XoshiroDouble generator with TestU01, run

```
./bin/test_double.exe --suite 0
```

Where the 'Suite' argument is the same as for the testing Xoshiro64bit.

Please note - this program produces a seg-fault in the garbage-collection - I cannot for the life of me figure out why. There is a discussion of this in the source-code.

4.3 Testing all software emulators on a batch-system

A bash-script is included for launching all permutations of the TestU01 suite and PractRand suite on a batch-system via the Sun grid engine, that is a batch system using 'qsub'. This is experimental code and meant as illustrative only, as local queue limits and policies may affect the behaviour on your system. From the software directory, simply execute

```
./run_tests.sh
```

The output is placed into individual text-files in the 'batch_output' subdirectory

4.4 Testing firmware with Modelsim GUI

To run the Xoshiro64bit testbench in Modelsim with the GUI, use the following invocation from the Linux or Microsoft Windows commandline within the firmware directory:

```
vsim -i -nolog -do modelsim-gui.tcl
```

This invocation was used to produce the output seen in figure 1.
Similarly for XoshiroDouble, the invocation is

```
vsim -i -nolog -do modelsim-double-gui.tcl
```

This invocation was used to produce the output seen in figure 2.

4.5 Testing Xoshiro64bit firmware with Modelsim and either PractRand or TestU01

To test the Xoshiro64bit firmware implementation using either TestU01 or PractRand, the firmware includes 'debugging' output which opens and appends the binary data to an operating-system 'file' called 'NamedPipe' located in the firmware directory. On operating systems which do not support FIFO files, 'NamedPipe' is simply a binary file. On other operating systems, 'NamedPipe' should be created as a FIFO, so that Modelsim dumps data into one end of the Fifo, and the output of the FIFO be streamed into PractRand or the TestU01 test-executable.

To create a fifo, in a BASH environment, in the firmware directory:

```
mkfifo NamedPipe
```

A modelsim tcl script is provided to run the Xoshiro64bit indefinitely, dumping PRNs in binary format to 'file', without visual wave output. This can, in principle, be run in batch mode, but newer versions of Modelsim appear to suffer from a malloc issues when run without the GUI, so we run vsim interactively:

```
vsim -i -nolog -do modelsim.tcl &
```

If 'NamedPipe' exists and is a FIFO, rather than a regular file, Modelsim will pause until a consumer is bound to the FIFO.

If you want to validate that Modelsim is running and writing to the FIFO, it can be convenient to use hexdump:

```
hexdump < ./NamedPipe
```

To test the firmware with TestU01, from the sofware directory run

```
./bin/test_stdin_64bit.exe --suite 0 --bits 0 < ../firmware/NamedPipe
```

where the commandline options are the same as those for testing the C++ emulation.

To test the firmware with PractRand, from the software directory run

```
./PractRand/RNG_test.exe stdin64 < ../firmware/NamedPipe
```

PractRand runs indefinitely until the user halts execution.

4.6 Testing XoshiroDouble firmware with Modelsim and TestU01

Similarly to Xoshiro64bit, the XoshiroDouble firmware includes 'debugging' output which opens and appends the binary data to an operating-system 'file' called 'NamedPipe' located in the firmware directory. A modelsim tcl script is provided to run the XoshiroDouble indefinitely, dumping PRNs in binary format to 'file', without visual wave output. :

```
vsim -i -nolog -do modelsim-double.tcl &
```

Again, if 'NamedPipe' exists and is a FIFO, rather than a regular file, Modelsim will pause until a consumer is bound to the FIFO.

To test the firmware with TestU01, from the sofware directory run

```
./bin/test_stdin_double.exe --suite 0 < ../firmware/NamedPipe
```

where the commandline options are the same as those for testing the C++ emulation.

5 Firmware builds

A Xilinx Vivado tcl script is provided to produce an example build with Xoshiro64bit:

```
vivado -nolog -nojournal -source xilinx-vivado.tcl
```

and similarly for testing XoshiroDouble:

```
vivado -nolog -nojournal -source xilinx-vivado-double.tcl
```

These TCL scripts create a Vivado project in a 'vivado' subdirectory, import the necessary files, run builds through synthesis and implementation for an XCKU15P-FFVA1156-2-e FPGA, and produce utilization reports and timing reports for a nominal clock-speed of 750MHz. Example output is shown in figure 3.

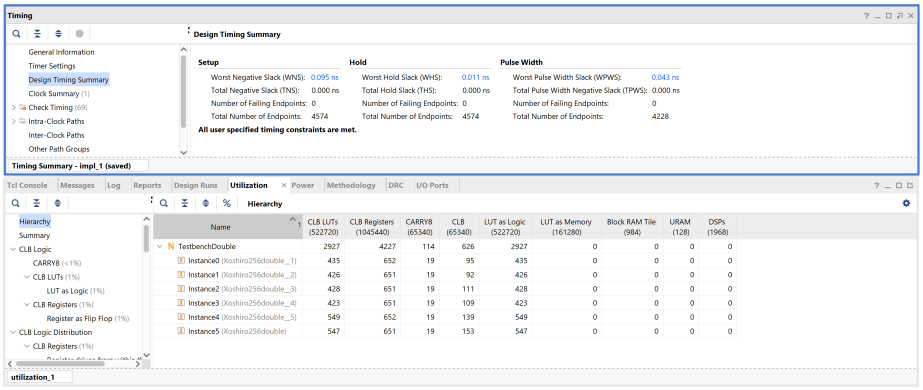

Figure 3: Example reports from Vivado implementation runs.

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Version 3, 29 June 2007

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```
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