

# **Design and Verification of AHB to APB Bridge**

## **Project Report**

*Submitted by*

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*In fulfillment of the completion of work for the course*

**Industry Defined Project**

*Under the guidance of*

**MR. Umesh Saw**



**VLSI Department**

**CDAC ACTS PUNE**

**MARCH-2024**

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VLSI Department

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## **CERTIFICATE**

**Date :**

This is to certify that the dissertation entitled “Design and verification of AHB to APB Bridge” has been completed by 1.Mukesh kumar 2.Shubham Singh 3.Aditi Nishad 4.Dasa Sai Deepika 5.Akhila Sunkireddy 6.Manne Chanakya under my guidance in fulfillment of completion of work for the course Industry Defined Project offered in by VLSI Department, CDAC ACTS, PUNE during the academic year March-2024.

**Guide :**

## ACKNOWLEDGEMENT

I would like to highly acknowledge all associates who guided and supported me throughout my project, **Design and verification of AHB to APB Bridge**. I would like to express sincere thanks to the project guide **Mr. Umesh Saw.** for their valuable guidance and advice, insightful comments and suggestions.

This project is dedicated to all those who contributed for its completion.

## **ABSTRACT**

The Advanced Microcontroller Bus Architecture (AMBA) is an open System-on-Chip bus protocol for high performance buses to communicate with low-power devices. In the AMBA High-performance Bus (AHB) a system bus is used to connect a processor, a DSP, and high-performance memory controllers where as the AMBA Advanced Peripheral Bus (APB) is used to connect (Universal Asynchronous Receiver Transmitter) UART. It also contains a Bridge, which connects the AHB and APB buses. Bridges are standard bus-to-bus interfaces that allow IPs connected to different buses to communicate with each other in a standardized way.

In this project, We have developed design and verification of AHB to APB bridge and testbench for the functional verification of the same in verilog HDL and System Verilog. We have also written shell script for testing the required feature only at a time. The software tools that We have used are Sublime Text (Text Editor), Xilinx Vivado (synthesizer tool) and Questa-sim (Simulator tool).

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# Chapter 1 : Introduction & Theoretical Background

## 1.1 ARM :

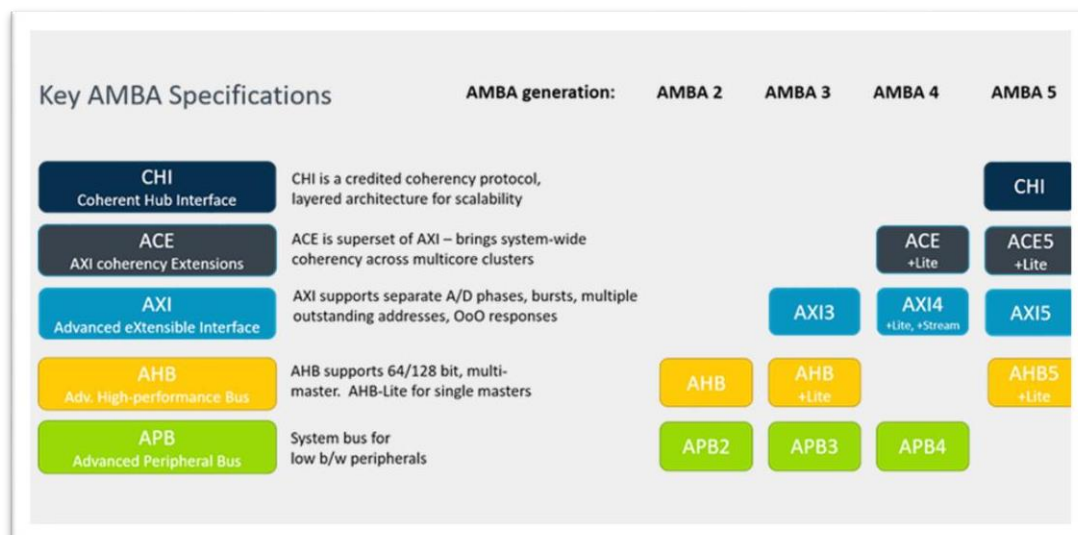
Acorn RISC Machine, is a family of reduced instruction set computing (RISC) architectures for computer processors, configured for various environments. Arm Holdings develops the architecture and licenses it to other companies, who design their own products that implement one of those architectures including systems-on-chips (SoC) and systems-on-modules (SoM) that incorporate memory, interfaces, radios, etc. It also designs cores that implement this instruction set and licenses these designs to a number of companies that incorporate those core designs into their own products.

Processors that have a RISC architecture typically require fewer transistors than those with a complex instruction set computing (CISC) architecture (such as the x86 processors found in most personal computers), which improves cost, power consumption, and heat dissipation. These characteristics are desirable for light, portable, battery-powered devices—including smart-phones, laptops and tablet computers, and other embedded systems but are also useful for servers and desktops to some degree. For supercomputers, which consume large amounts of electricity, Arm is also a power-efficient solution.

Arm Holdings periodically releases updates to the architecture. Architecture versions Armv3 to Armv7 support 32-bit address space (pre-Armv3 chips, made before Arm Holdings was formed, as used in the Acorn Archimedes, had 26-bit address space) and 32-bit arithmetic; most architectures have 32-bit fixed-length instructions. The Thumb version supports a variable-length instruction set that provides both 32- and 16-bit instructions for improved code density. Some older cores can also provide hardware execution of Java byte codes; and newer ones have one instruction for JavaScript. Released in 2011, the Armv8-A architecture added support for a 64-bit address space and 64-bit arithmetic with its new 32-bit fixed-length instruction set.

Some recent Arm CPUs have simultaneous multithreading (SMT) with e.g. Arm Neoverse E1 being able to execute two threads concurrently for improved aggregate throughput performance. Arm Cortex-A65AE for automotive applications is also a multithreaded processor, and has Dual Core Lock-Step for fault-tolerant designs (supporting Automotive Safety Integrity Level D, the highest level). The Neoverse N1 is designed for "as few as 8 cores" or "designs that scale from 64 to 128 N1 cores within a single coherent system.

## 1.2 ARM AMBA :



AMBA (Advanced Microcontroller Bus Architecture) is a freely-available, open standard for the connection and management of functional blocks in a system-on-chip (SoC). It facilitates right-first-time development of multi-processor designs, with large numbers of controllers and peripherals.

AMBA specifications are royalty-free, platform-independent and can be used with any processor architecture. Due to its widespread adoption, AMBA has a robust ecosystem of partners that ensures compatibility and scalability between IP components from different design teams and vendors.



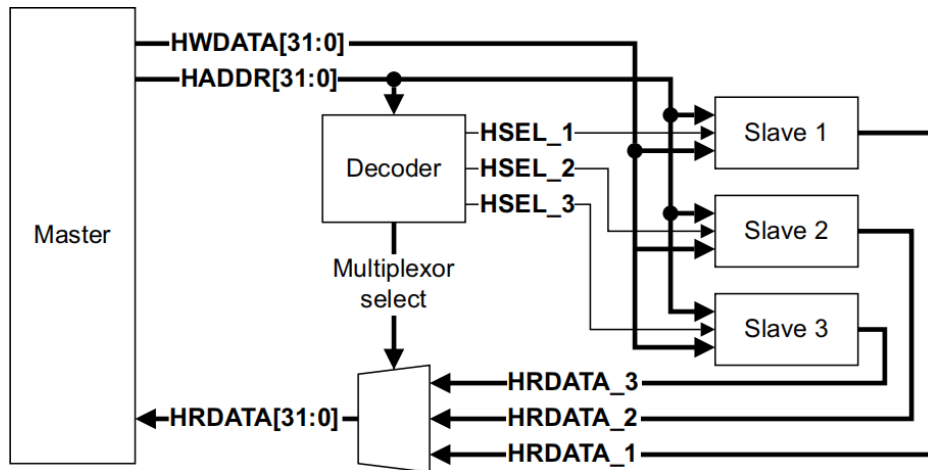
### **1.3 AHB (AMBA High-performance Bus) :**

AMBA AHB is a bus interface suitable for high-performance synthesizable designs. It defines the interface between components, such as masters, interconnects, and slaves.

AMBA AHB implements the features required for high-performance, high clock frequency systems including:

- Burst transfers.
- Single clock-edge operation.
- Non-tri state implementation.
- Wide data bus configurations, 64, 128, 256, 512, and 1024 bits.

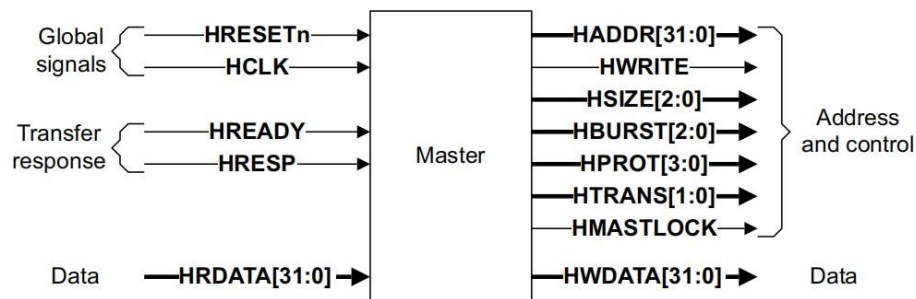
The most common AHB slaves are internal memory devices, external memory interfaces, and high-bandwidth peripherals. Although low-bandwidth peripherals can be included as AHB slaves, for system performance reasons, they typically reside on the AMBA Advanced Peripheral Bus (APB). Bridging between the higher performance AHB and APB is done using an AHB slave, known as an APB bridge.



**Figure 1-1 AHB block diagram**

Figure 1-1 shows a single master AHB system design with the AHB master and three AHB slaves. The bus interconnect logic consists of one address decoder and a slave-to-master multiplexor. The decoder monitors the address from the master so that the appropriate slave is selected and the multiplexor routes the corresponding slave output data back to the master. AHB also supports multi-master designs by the use of an interconnect component that provides arbitration and routing signals from different masters to the appropriate slaves.

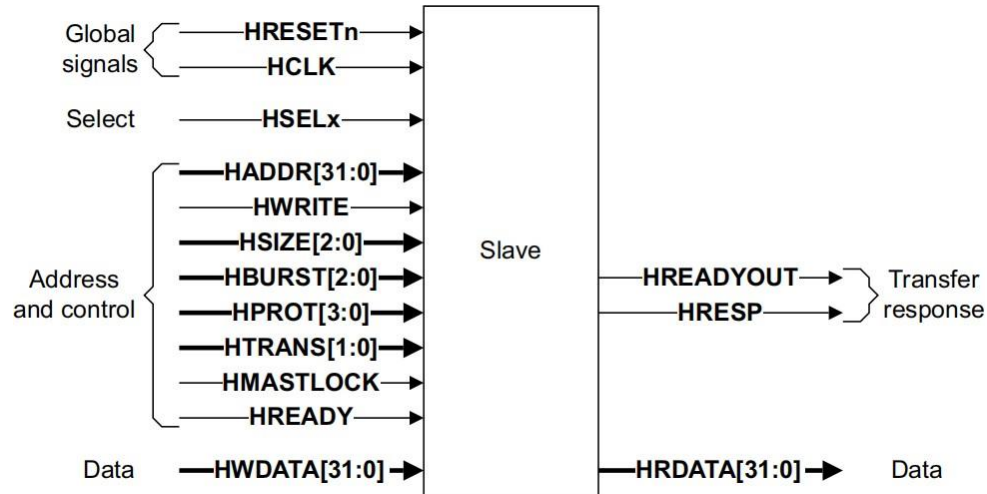
### 1.3.1 AHB Master Interface :



**Figure 1-2 AHB master interface**

A master provides address and control information to initiate read and write operations. Figure 1-2 shows a master interface.

### 1.3.2 AHB Slave Interface :



**Figure 1-3 AHB slave interface**

A slave responds to transfers initiated by masters in the system. The slave uses the HSELx select signal from the decoder to control when it responds to a bus transfer.

The slave signals back to the master:

- The completion or extension of the bus transfer.
- The success or failure of the bus transfer.

Figure 1-3 shows a slave interface.

## **1.4 APB (Advanced Peripheral Bus) :**

The Advanced Peripheral Bus (APB) is part of the Advanced Microcontroller Bus Architecture (AMBA) protocol family. It defines a low-cost interface that is optimized for minimal power consumption and reduced interface complexity.

The APB protocol is not pipelined, use it to connect to low-bandwidth peripherals that do not require the high performance of the AXI protocol.

The APB protocol relates a signal transition to the rising edge of the clock, to simplify the integration of APB peripherals into any design flow. Every transfer takes at least two cycles.

The APB can interface with:

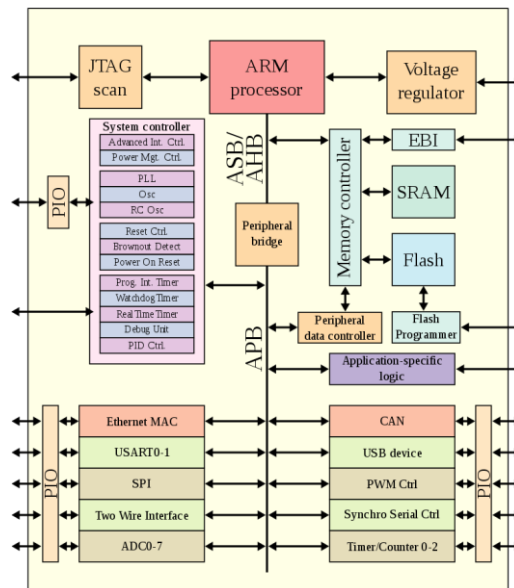
- AMBA Advanced High-performance Bus (AHB)
- AMBA Advanced High-performance Bus Lite (AHB-Lite)
- AMBA Advanced Extensible Interface (AXI)
- AMBA Advanced Extensible Interface Lite (AXI4-Lite)

You can use it to access the programmable control registers of peripheral devices.

## 1.5 AHB to APB Bridge :

The AHB to APB bridge interface is an AHB slave. When accessed (in normal operation or system test) it initiates an access to the APB. APB accesses are of different duration (three HCLK cycles in the EASY for a read, and two cycles for a write). They also have their width fixed to one word, which means it is not possible to write only an 8-bit section of a 32-bit APB register. APB peripherals do not need a PCLK input as the APB access is timed with an enable signal generated by the AHB to APB bridge interface. This makes APB peripherals low power consumption parts, because they are only strobed when accessed.

### 1.5.1 Importance :



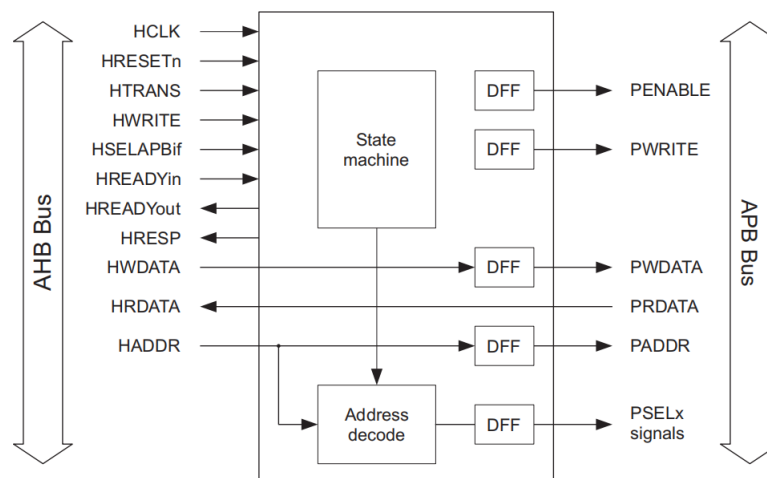
**Figure 1-4 ARM Architecture**

The AHB to APB bridge is an AHB slave, providing an interface between the high speed AHB and the low-power APB. Read and write transfers on the AHB are converted into equivalent transfers on the APB. As the APB is not pipelined, then wait states are added during transfers to and from the APB when the AHB is required to wait for the APB.

It is required to bridge the communication gap between low bandwidth peripherals on APB with the high bandwidth ARM Processors and/or other high-speed devices on AHB. This ensures that there is no data loss between AHB to APB or APB to AHB data transfers. AHB2APB interfaces AHB and APB. It buffers address, controls and data signal from the AHB, drives the APB peripherals and return data along with response signal to the AHB.

The AHB2APB interface is designed to operate when AHB and APB clocks have the any combination of frequency and phase. The AHB2APB performs transfer of data from AHB to APB for write cycle and APB to AHB for Read cycle. Interface between AMBA high performance bus (AHB) and AMBA peripheral bus (APB). It provides latching of address, controls and data signals for APB peripherals.

### 1.5.2 Architecture :



**Figure 1-5 AHB to APB Bridge block diagram**

The main sections of this module are:

- AHB slave bus interface
- APB transfer state machine, which is independent of the device memory map
- APB output signal generation.

To add new APB peripherals, or alter the system memory map, only the address decode sections need to be modified.

The base addresses of each of the peripherals (timer, interrupt controller, and remap and pause controller) are defined in the AHB to APB bridge interface, which selects the peripheral according to its base address. The whole APB address range is also defined in the bridge.

These base addresses can be implementation-specific. The peripherals standard specifies only the register offsets (from an unspecified base address), register bit meaning, and minimum supported function

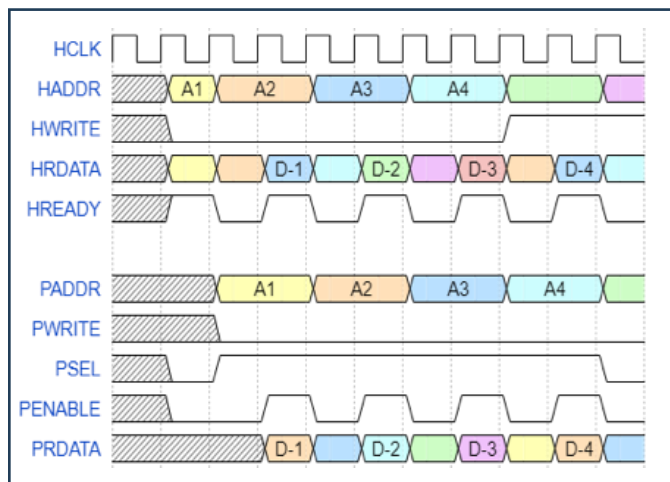
The APB data bus is split into two separate directions:

- read (PRDATA), where data travels from the peripherals to the bridge
- write (PWRITE), where data travels from the bridge to the peripherals.

This simplifies driving the buses because turnaround time between the peripherals and bridge is avoided.

In the default system, because the bridge is the only master on the bus, PWRITE is driven continuously. PRDATA is a multiplexed connection of all peripheral PRDATA outputs on the bus, and is only driven when the slaves are selected by the bridge during APB read transfers.

It is possible to combine these two buses into a single bidirectional bus, but precautions must be taken to ensure that there is no bus clash between the bridge and the peripherals.



**Interfacing AHB to APB Read transfer**

### 1.5.3 Signals Description :

Signals	Type	Direction	Description
<b>HCLK</b>	Bus clock	Input	This clock times all bus transfers.
<b>HRESETn</b>	Reset	Input	The bus reset signal is active LOW, and is used to reset the system and the bus.
<b>HADDR[31:0]</b>	Address bus	Input	The 32-bit system address bus.
<b>HTRANS[1:0]</b>	Transfer type	Input	This indicates the type of the current transfer, which can be NONSEQUENTIAL, SEQUENTIAL, IDLE or BUSY.
<b>HWRITE</b>	Transfer direction	Input	When HIGH this signal indicates a write transfer, and when LOW, a read transfer.
<b>HWDATA[31:0]</b>	Write data bus	Input	The write data bus is used to transfer data from the master to the bus slaves during write operations. A minimum data bus width of 32 bits is recommended. However, this may easily be extended to allow for higher bandwidth operation.
<b>HSELAPBif</b>	Slave select	Input	Each APB slave has its own slave select signal, and this signal indicates that the current transfer is intended for the selected slave. This signal is a combinatorial decode of the address bus.
<b>HRDATA[31:0]</b>	Read data bus	Output	The read data bus is used to transfer data from bus slaves to the bus master during read operations. A minimum data bus width of 32 bits is recommended. However, this may easily be extended to allow for higher bandwidth operation.



<b>HREADY<sub>in</sub></b> <b>HREADY<sub>out</sub></b>	Transfer done	Input/output	When HIGH the HREADY signal indicates that a transfer has finished on the bus. This signal may be driven LOW to extend a transfer.
<b>HRESP[1:0]</b>	Transfer response	Output	The transfer response provides additional information on the status of a transfer. This module will always generate the OKAY response.
<b>PRDATA[31:0]</b>	Peripheral read data bus	Input	The peripheral read data bus is driven by the selected peripheral bus slave during read cycles (when PWRITE is LOW).
<b>PWDATA[31:0]</b>	Peripheral write data bus	Output	The peripheral write data bus is continuously driven by this module, changing during write cycles (when PWRITE is HIGH).
<b>PENABLE</b>	Peripheral enable	Output	This enable signal is used to time all accesses on the peripheral bus. PENABLE goes HIGH on the second clock rising edge of the transfer, and LOW on the third (last) rising clock edge of the transfer.
<b>PSEL<sub>x</sub></b>	Peripheral slave select	Output	There is one of these signals for each APB peripheral present in the system. The signal indicates that the slave device is selected, and that a data transfer is required. It has the same timing as the peripheral address bus. It becomes HIGH at the same time as PADDR, but will be set LOW at the end of the transfer.

<b>PADDR[31:0]</b>	Peripheral address bus	Output	This is the APB address bus, which may be up to 32 bits wide and is used by individual peripherals for decoding register accesses to that peripheral. The address becomes valid after the first rising edge of the clock at the start of the transfer. If there is a following APB transfer, then the address will change to the new value, otherwise it will hold its current value until the start of the next APB transfer.
<b>PWRITE</b>	Peripheral transfer direction	Output	This signal indicates a write to a peripheral when HIGH, and a read from a peripheral when LOW. It has the same timing as the peripheral address bus.

The APB bridge responds to transaction requests from the currently granted AHB master. The AHB transactions are then converted into APB transactions.

- the AHB transactions with the HREADYout signal
- the generation of all APB output signals.

The individual PSELx signals are decoded from HADDR, using the state machine to enable the outputs while the APB transaction is being performed.

If an undefined location is accessed, operation of the system continues as normal, but no peripherals are selected.

## Chapter 2 : Design

### 2.1 Bridge Module Description :

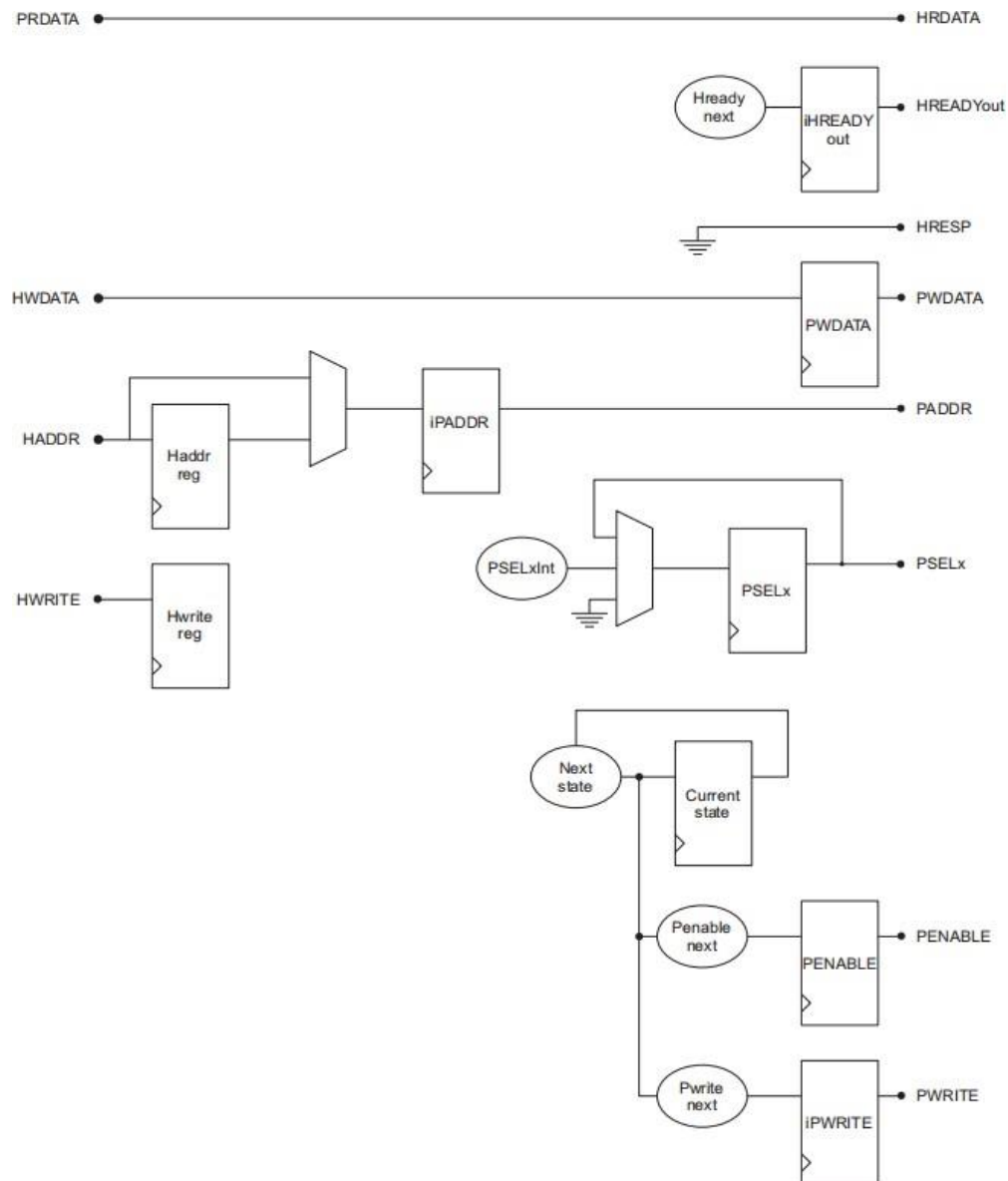


Figure 2-1 Bridge module system diagram

The AHB to APB bridge comprises a state machine, which is used to control the generation of the APB and AHB output signals, and the address decoding logic which is used to generate the APB peripheral select lines.

All registers used in the system are clocked from the rising edge of the system clock HCLK, and use the asynchronous reset HRESETn.

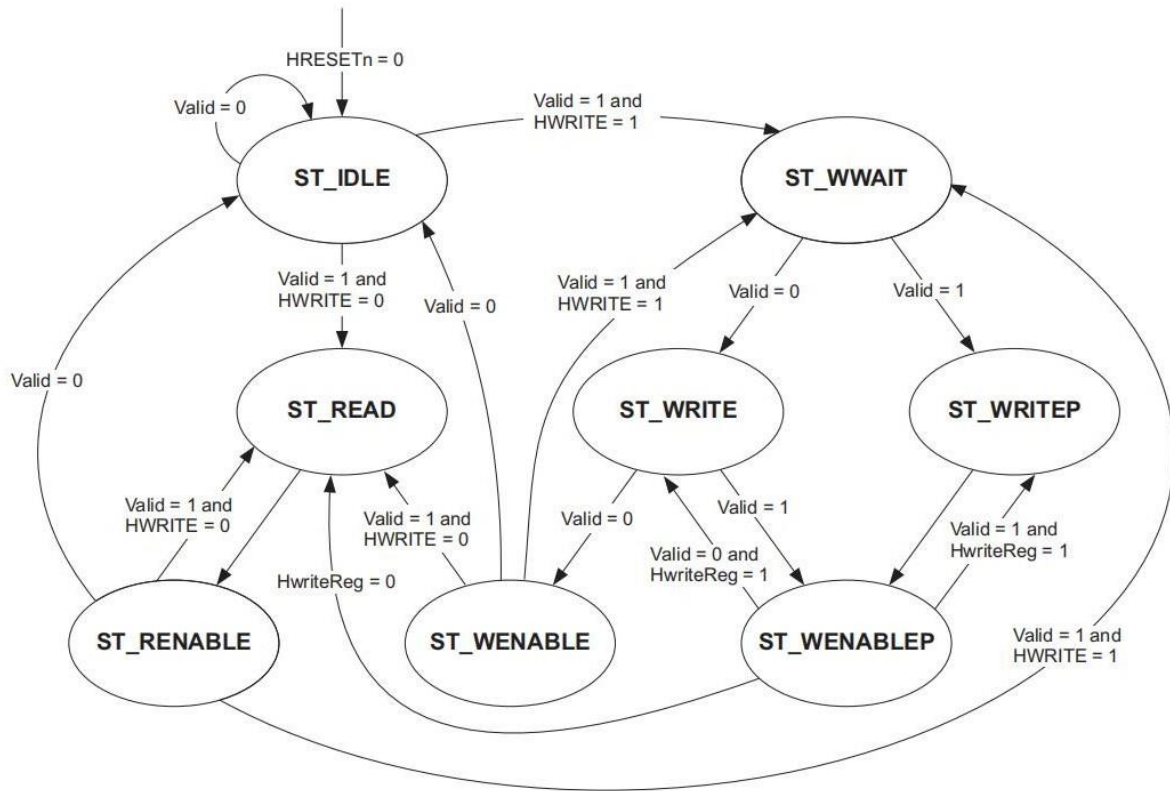
### **2.1.1 AHB slave bus interface :**

This module uses the standard AHB slave bus interface, which comprises:

- the valid transfer detection logic which is used to determine when a valid transfer is accessing the slave.
- the address and control registers, which are used to store the information from the address phase of the transfer for use in the data phase.

Due to the different AHB to APB timing of read and write transfers, either the current or the previous address input value is needed to correctly generate the APB transfer. A multiplexor is therefore used to select between the current address input or the registered address, for read and write transfers respectively.

### 2.1.2 APB transfer state machine :



**Figure 2-2 AHB to APB transfer state machine**

The transfer state machine is used to control the application of APB transfers based on the AHB inputs. The state diagram in Figure 2-2 shows the operation of the state machine, which is controlled by its current state and the AHB slave interface.

The individual states of the state machine operation are described in the following sections:

### **ST\_IDLE :-**

During this state the APB buses and PWRITE are driven with the last values they had and PSEL and PENABLE lines are driven LOW.

The ST\_IDLE state is entered from:

- reset, when the system is initialized
- ST\_RENABLE, ST\_WENABLE, or ST\_IDLE, when there are no peripheral transfers to perform.

The next state is:

- ST\_READ, for a read transfer, when the AHB contains a valid APB read transfer
- ST\_WWAIT, for a write transfer, when the AHB contains a valid APB write transfer.

### **ST\_READ :-**

During this state the address is decoded and driven onto PADDR, the relevant PSEL line is driven HIGH, and PWRITE is driven LOW. A wait state is always inserted to ensure that the data phase of the current AHB transfer does not complete until the APB read data has been driven onto HRDATA.

The ST\_READ state is entered from ST\_IDLE, ST\_RENABLE, ST\_WENABLE, or ST\_WENABLEP during a valid read transfer.

The next state will always be ST\_RENABLE.

### **ST\_WWAIT**

This state is needed due to the pipelined structure of AHB transfers, to allow the AHB side of the write transfer to complete so that the write data becomes available on HWDATA. The APB write transfer is then started in the next clock cycle.

The ST\_WWAIT state is entered from ST\_IDLE, ST\_RENABLE, or ST\_WENABLE, during a valid write transfer.

The next state will always be ST\_WRITE.

### **ST\_WRITE :-**

During this state the address is decoded and driven onto PADDR, the relevant PSEL line is driven HIGH, and PWRITE is driven HIGH.

A wait state is not inserted, as a single write transfer can complete without affecting the AHB.

The ST\_WRITE state is entered from:

- ST\_WWAIT, when there are no further peripheral transfers to perform
- ST\_WENABLEP, when the currently pending peripheral transfer is a write, and there are no further transfers to perform.

The next state is:

- ST\_WENABLE, when there are no further peripheral transfers to perform
- ST\_WENABLEP, when there is one further peripheral write transfer to perform.

### **ST\_WRITEP :-**

During this state the address is decoded and driven onto PADDR, the relevant PSEL line is driven HIGH, and PWRITE is driven HIGH. A wait state is always inserted, as there must only ever be one pending transfer between the currently performed APB transfer and the currently driven AHB transfer.

The ST\_WRITEP state is entered from:

- ST\_WWAIT, when there is a further peripheral transfer to perform.
- ST\_WENABLEP, when the currently pending peripheral transfer is a write, and there is a further transfer to perform.

The next state will always be ST\_WENABLEP.

### **ST\_RENABLE :-**

During this state the PENABLE output is driven HIGH, enabling the current APB transfer. All other APB outputs remain the same as the previous cycle.

The ST\_RENABLE state is always entered from ST\_READ.



The next state is:

- ST\_READ, when there is a further peripheral read transfer to perform.
- ST\_WWAIT, when there is a further peripheral write transfer to perform.
- ST\_IDLE, when there are no further peripheral transfers to perform.

### **ST\_WENABLE :-**

During this state the PENABLE output is driven HIGH, enabling the current APB transfer. All other APB outputs remain the same as the previous cycle.

The ST\_WENABLE state is always entered from ST\_WRITE.

The next state is:

- ST\_READ, when there is a further peripheral read transfer to perform.
- ST\_WWAIT, when there is a further peripheral write transfer to perform.
- ST\_IDLE, when there are no further peripheral transfers to perform.

### **ST\_WENABLEP :-**

A wait state is inserted if the pending transfer is a read because, when a read follows a write, an extra wait state must be inserted to allow the write transfer to complete on the APB before the read is started.

The ST\_WENABLEP state is entered from:

- ST\_WRITE, when the currently driven AHB transfer is a peripheral transfer.
- ST\_WRITEP, when there is a pending peripheral transfer following the current write.

The next state is:

- ST\_READ, when the pending transfer is a read.
- ST\_WRITE, when the pending transfer is a write, and there are no further transfers to perform.
- ST\_WRITEP, when the pending transfer is a write.

## 2.2 Bridge Functional Description :

### 2.2.1 APB output signal generation :

The generation of all APB output signals is based on the status of the transfer state machine:

- **PWDATA** is a registered version of the HWDATA input, which is only enabled during a write transfer. As the bridge is the only bus master on the APB, then it can drive PWDATA continuously.
- **PENABLE** is only set HIGH during one of three enable states, in the last cycle of an APB transfer. A register is used to generate this output from the next state of the transfer state machine.
- **PSELx** outputs are decoded from the current transfer address. They are only valid during the read, write and enable states, and are all driven LOW at all other times so that no peripherals are selected when no transfers are being performed.
- **PADDR** is a registered version of the currently selected address input (HADDR or the address register) and only changes when the read and write states are entered at the start of the APB transfer.
- **PWRITE** is set HIGH during a write transfer, and only changes when a new APB transfer is started. A register is used to generate this output from the next state of the transfer state machine.
- The APBen signal is used as an enable on the PSEL, PWRITE and PADDR output registers, ensuring that these signals only change when a new APB transfer is started, when the next state is ST\_READ, ST\_WRITE, or ST\_WRITEP.

### 2.2.2 AHB output signal generation :

**HRDATA** is directly driven with the current value of **PRDATA**. APB slaves only drive read data during the enable phase of the APB transfer, with **PRDATA** set **LOW** at all other times, so bus clash is avoided on **HRDATA** (assuming OR bus connections for both the AHB and APB read data buses).

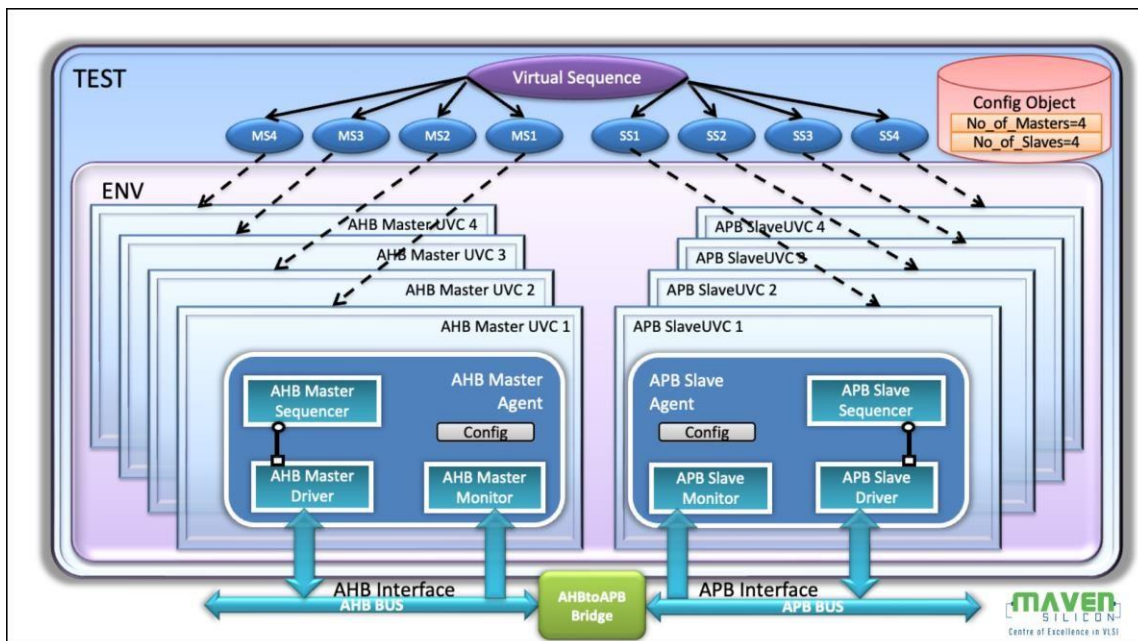
- **HREADYout** is driven with a registered signal to improve the output timing. Wait states are inserted by the APB bridge during the **ST\_READ** and **ST\_WRITEP** states, and during the **ST\_WENABLEP** state when the next transfer to be performed is a read.

- **HRESP** is continuously held **LOW**, as the APB bridge does not generate **SPLIT**, **RETRY** or **ERROR** responses.

## Chapter 3 : Verification

The verification process starts with the preparation of the Verification Plan(Vplan). The verification plan defines the verification intent of the DUV/DUT[Design Under Verification/Test]. It captures all the design features and defines how each feature can be verified and tracked closely, including TB architecture, Coverage Model, Verification Strategy, Test Scenarios, list of assertions etc. The verification team will develop the TB and write multiple testcases taking the Vplan as a reference.

A typical AMBA system supports connections of up to 16 AHB Masters. Among all the masters, the granted bus masters communicate with the AHB slave, in this case, AHB2APB Bridge. The Bridge intun communicates with one of the APB peripherals.



**AHB2APB Bridge UVM Verification Environment**

The functionality of the AHB2APB Bridge is verified by connecting the DUT with an AHB master agent and an APB slave agent and by initiating the write and read transfers from the AHB agent.

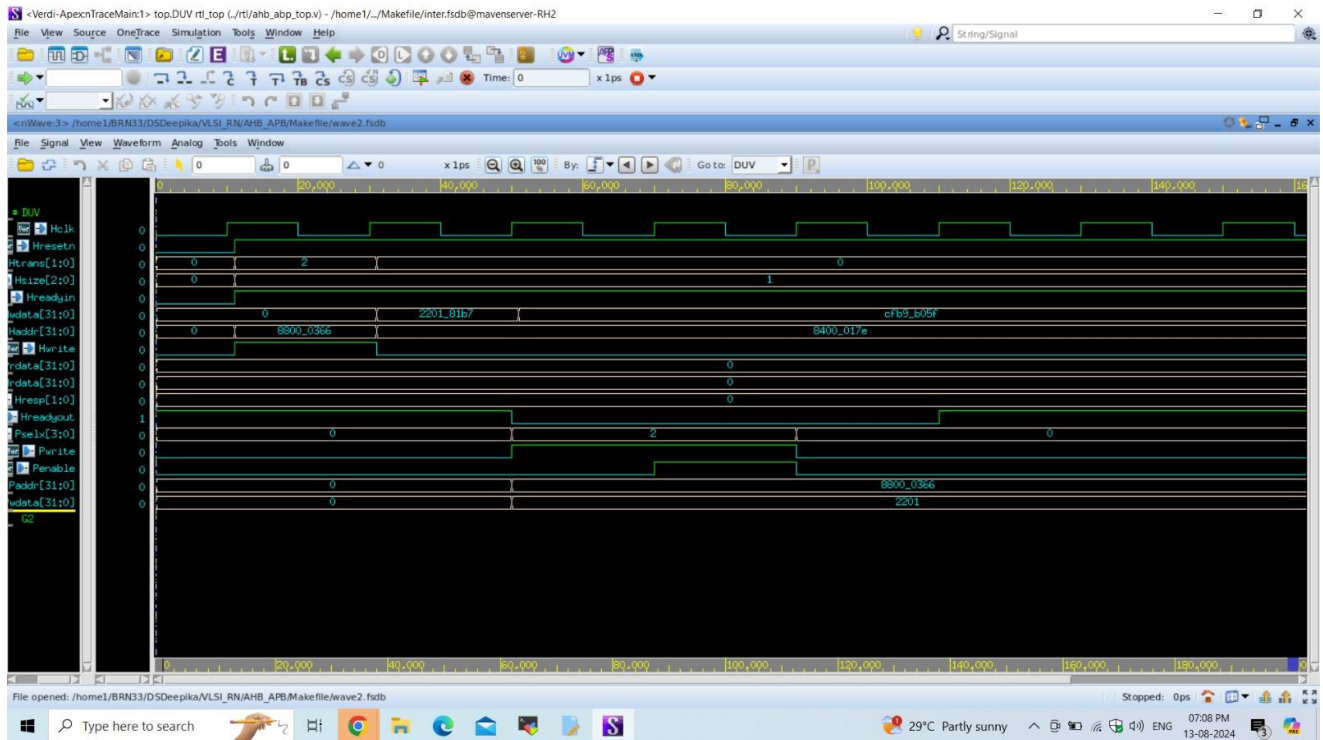
Testbench/VE is developed in such a way that from the test we can configure the number of AHB masters, and the number of APB Peripherals. With the help of a virtual sequence, in each test case, we can control the communication between different AHB bus masters and APB peripherals. Different sequences

are developed to verify scenarios like increment & wrapping type bursts of various data sizes for both read and write operations.

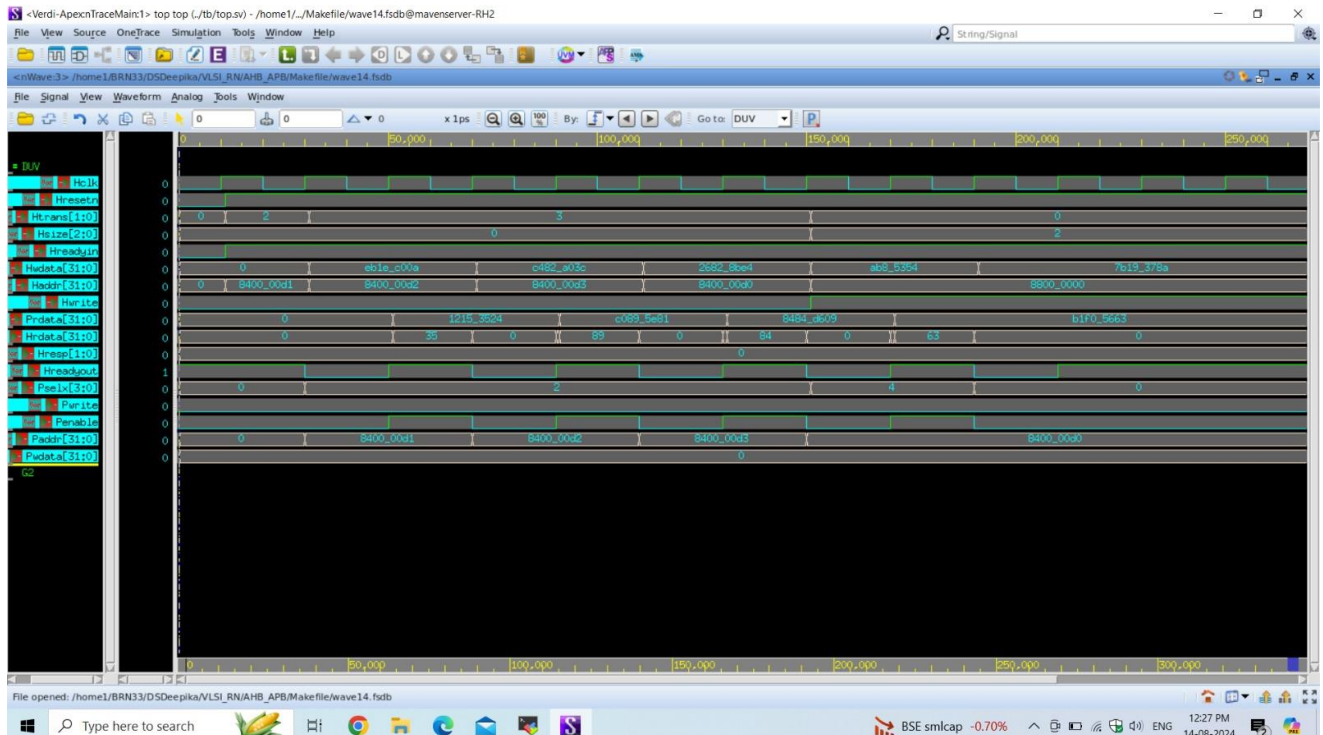
Based on the coverage analysis, we may need to add additional test cases to cover the missed features by overriding the existing constraints. This is how

## Chapter 4 : Summary

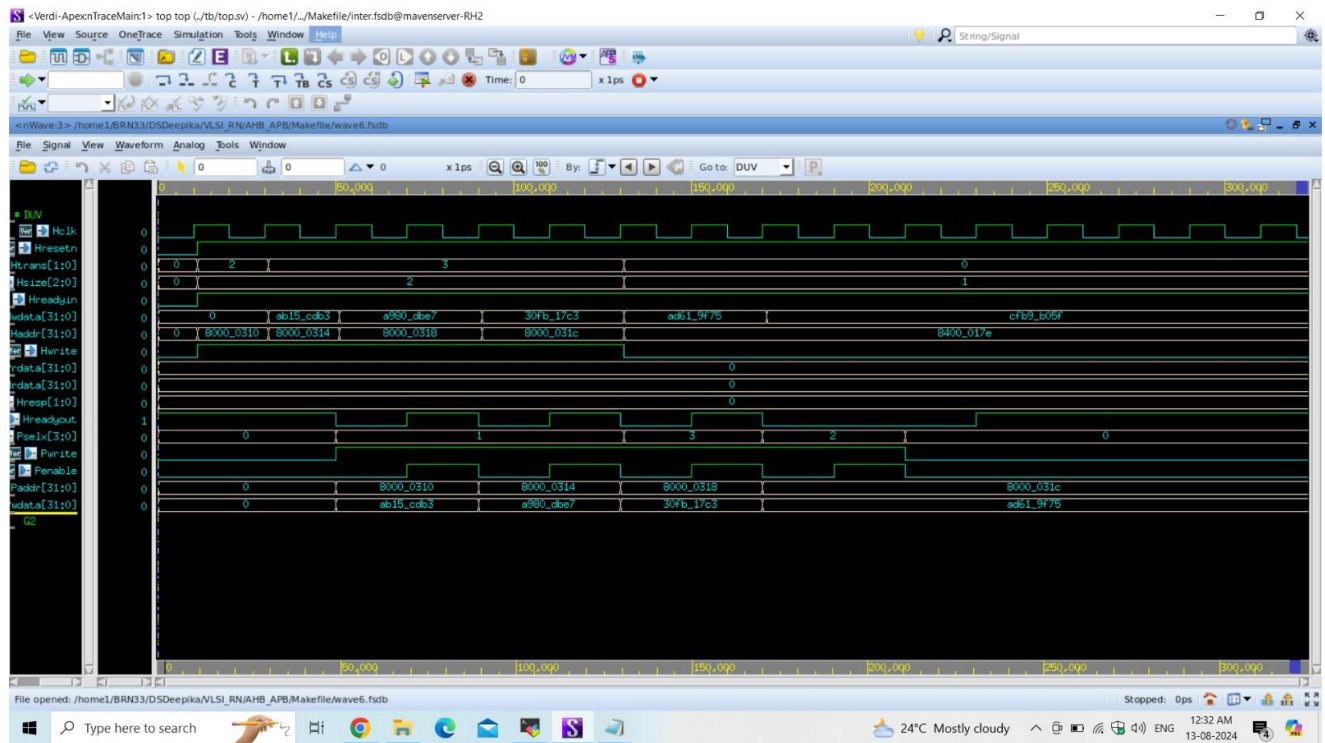
### 4.1 Simulation Results :



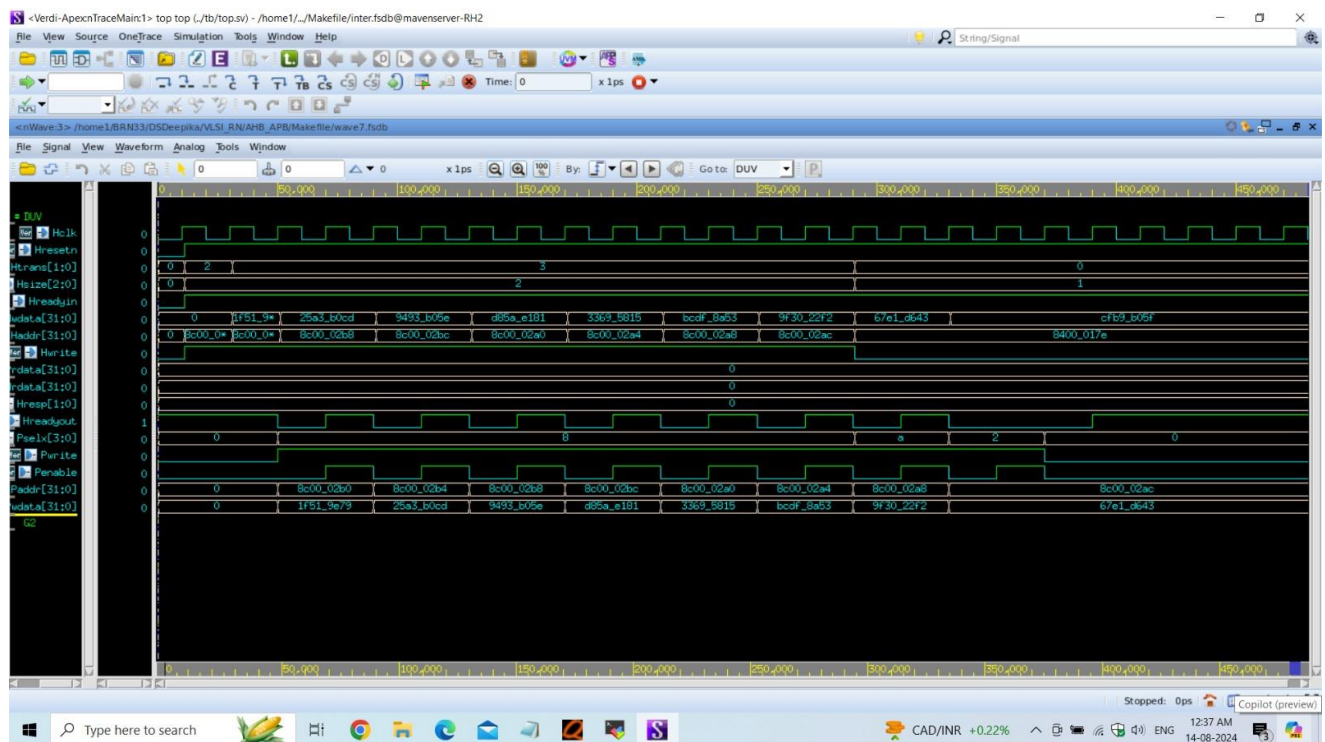
Single write Transfer



Burst Wrap-4 read Transfer

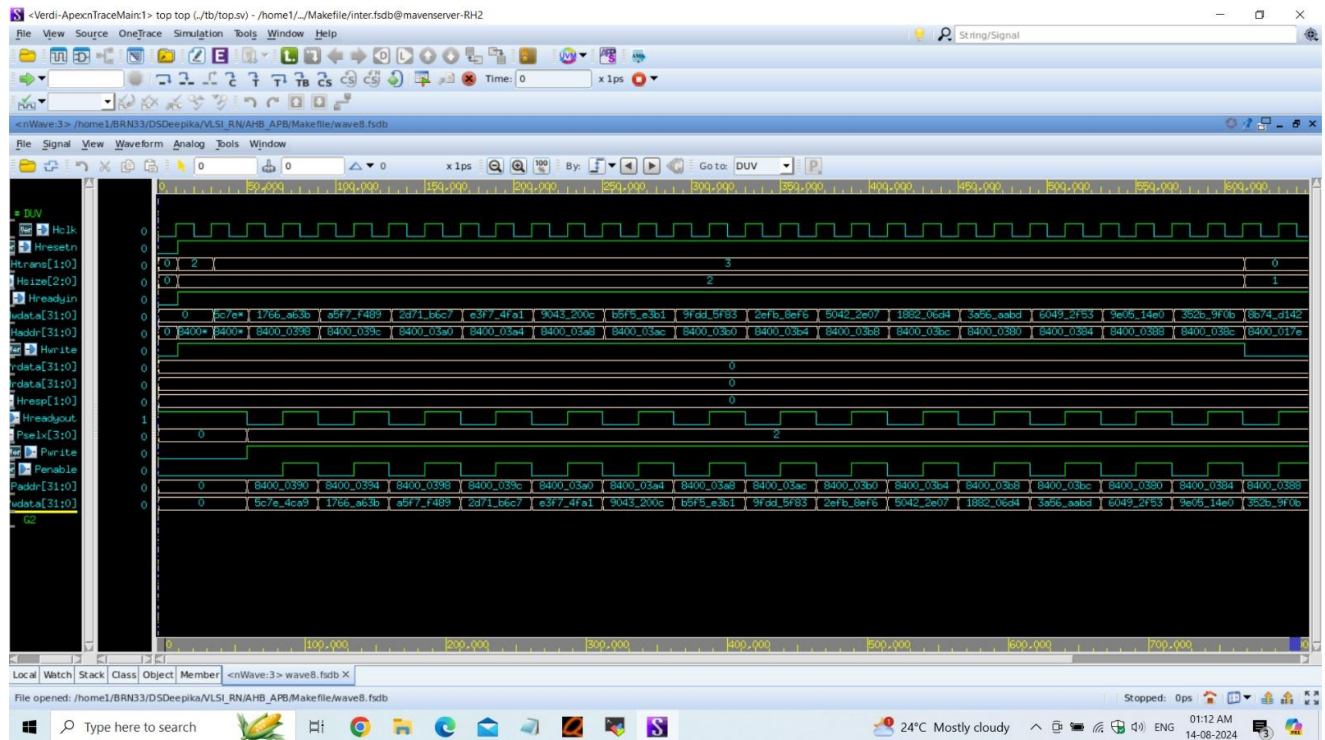


Burst Wrap-4 write transfer

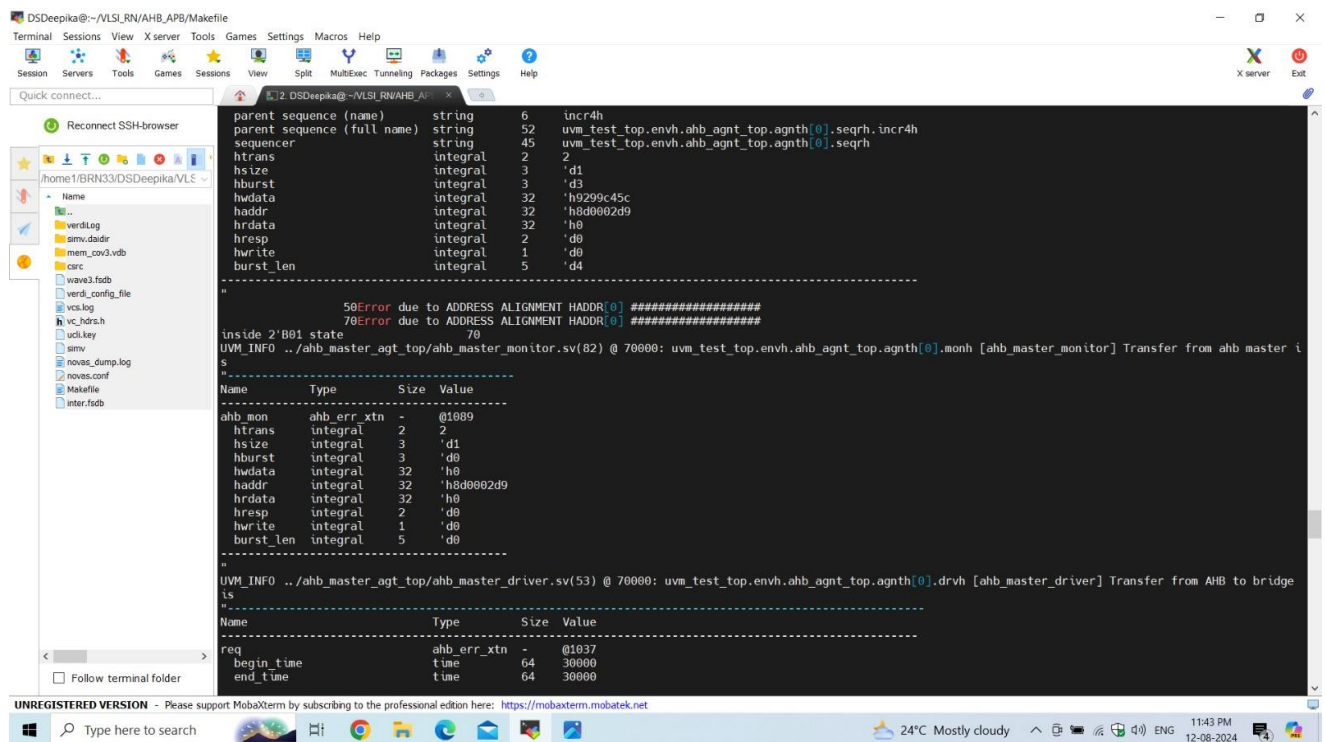


Burst Wrap-8 write Transfer



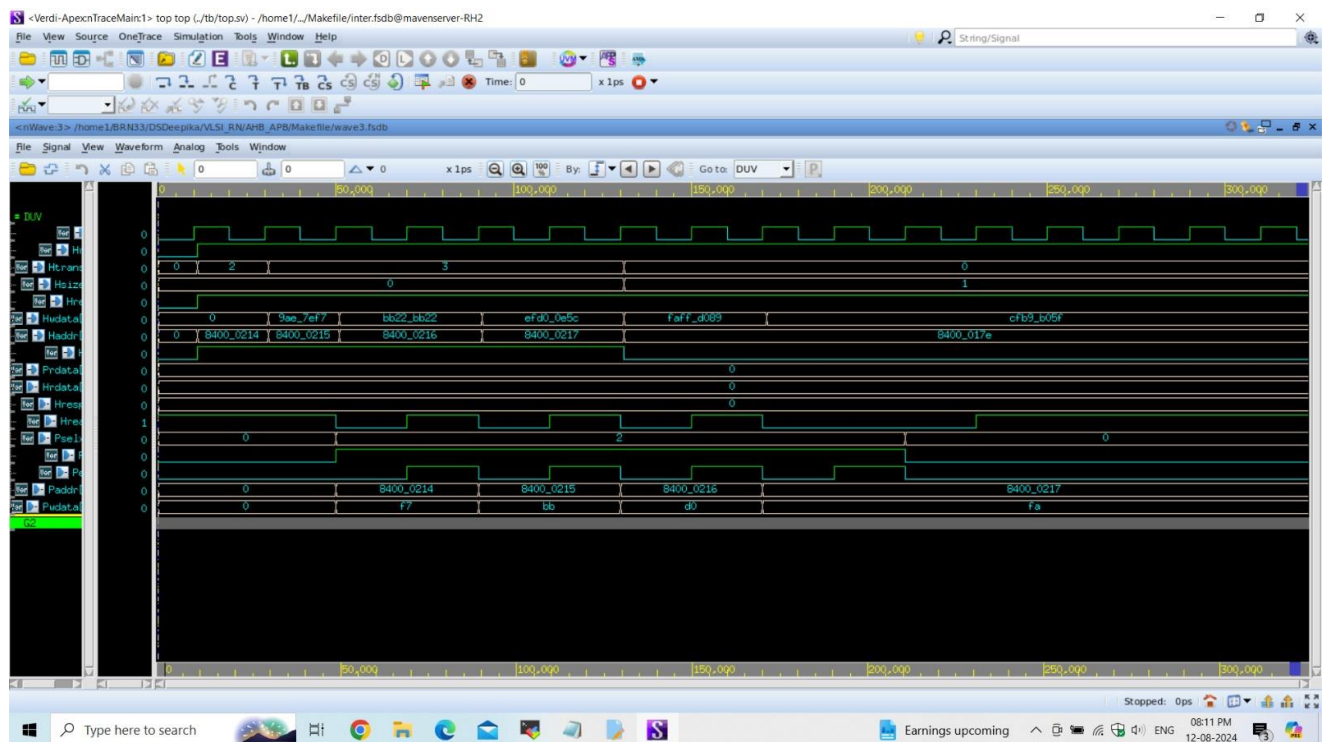
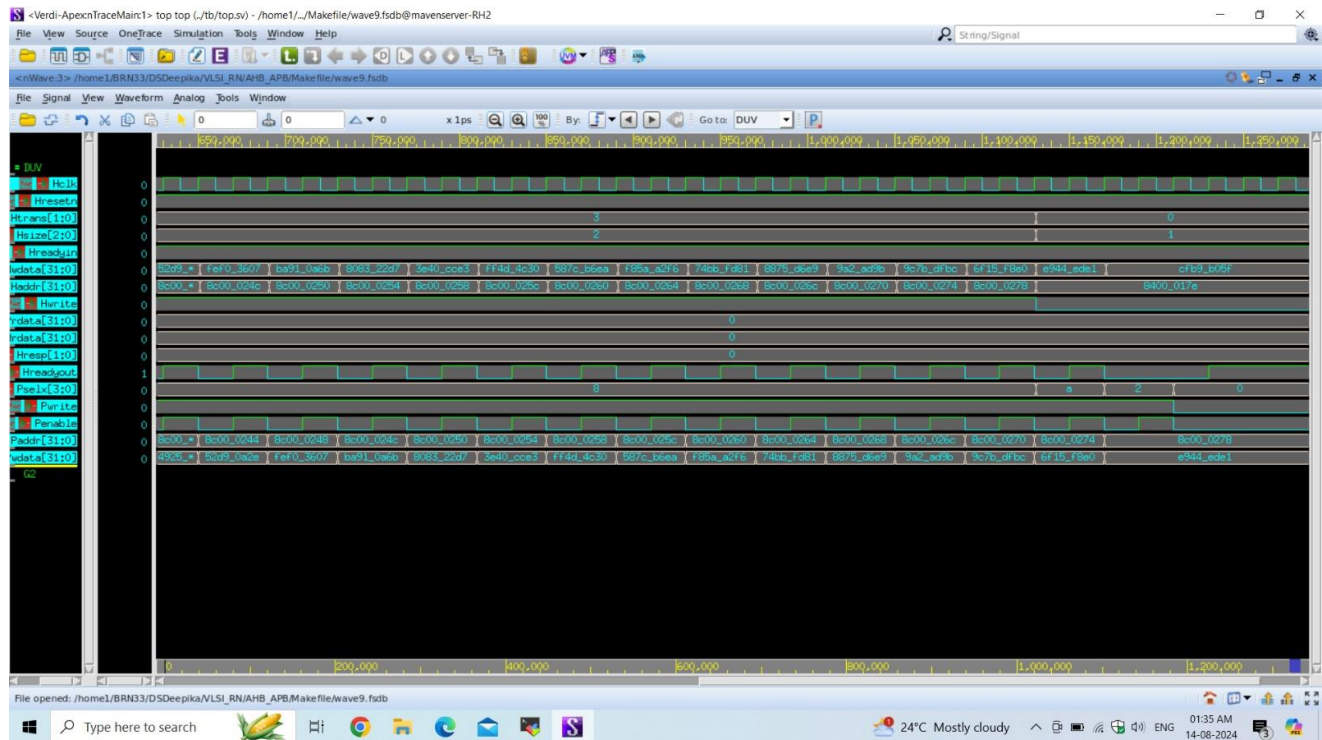


Burst Wrap-16 write Transfer



Error Test







## **4.2 Conclusion :**

The design and verification of the AHB to APB Bridge in verilog HDL and System verilog were done. The HCLK and PENABLE mechanism was implemented for making it the low-power consuming system. The functional verification of the bridge was done by driving various testcases to the design for testing the features. The one master and multi-slave AHB to APB bridge is one of the future scope.

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