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MASTER'S THESIS

**AUTOMATED FUNCTIONAL COVERAGE
DRIVEN VERIFICATION WITH UNIVERSAL
VERIFICATION METHODOLOGY**

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ABSTRACT

In this Master's thesis, the validity of Universal Verification Methodology in digital design verification is studied. A brief look into the methodology's history is taken, and its unique properties and object-oriented features are presented. Important coverage topics in project planning are discussed, and the two main types of coverage, code and functional coverage, are explained and the methods how they are captured are presented.

The practical section of this thesis shows the implementation of a monitoring environment and an Universal Verification Methodology environment. The monitoring environment includes class-based components that are used to collect functional coverage from an existing SystemVerilog test bench. The Universal Verification Methodology environment uses the same monitoring system, but a different driving setup to stress the design under test. Coverage and simulation performance values are extracted and from all test benches and the data is compared. The results indicate that the Universal Verification Methodology environment incorporating constrained random stimulus is capable of faster simulation run times and better code coverage values. The simulation time measured was up to 26 % faster compared to a module-based environment.

Key words: Universal Verification Methodology, coverage, coverage-driven verification, methodology comparison.

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TIIVISTELMÄ

Tässä diplomityössä tutkitaan universaalien varmennusmenetelmän (Universal Verification Methodology) soveltuvuutta digitaalisten laitteiden verifiointiin. Työssä tehdään lyhyt katsaus menetelmän historiaan. Lisäksi menetelmän omia ainutlaatuisia ja olio-pohjaisia ominaisuuksia käydään läpi. Kattavuuteen liittyviä käsitteitä esitetään projektihallinnan näkökulmasta. Kattavuudesta käsitellään toiminnallinen ja koodikattavuus, ja tavat, miten näitä molempia kerätään simulaatioista.

Työn käytännön osuudessa esitetään monitorointiympäristön ja universaalien varmennusmenetelmän pohjalta tehdyn ympäristön toteutus. Monitorointiympäristössä on luokkapohjaisia komponentteja, joiden avulla kerätään toiminnallista kattavuutta jo olemassa olevasta testipenkistä. Universaalien varmennusmenetelmän pohjalta tehdyssä ympäristössä on samojen monitorointikomponenttien lisäksi testattavan kohteen ohjaamiseen vaadittavia komponentteja. Eri testipenkeistä kerätään kattavuuteen ja suorituskykyyn liittyvää dataa vertaamista varten. Tulokset viittaavat siihen, että rajoitettua satunnaista herätettä hyödykseen käyttävät universaalit varmennusmenetelmäympäristöt pääsevät nopeampiin suoritusaikoihin ja parempiin koodikattavuuslukuihin. Simulaation suoritusajaksi saatiin parhaassa tapauksessa jopa 26 % parannus.

Avainsanat: universaali varmennusmenetelmä, kattavuus, kattavuuden ohjaama verifiointi, menetelmien vertailu.

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FOREWORD

This Master's thesis was conducted at Nordic Semiconductor ASA Finland. The work had its ups and downs, and especially the first two months turned out to be quite stressful. Nevertheless, resolving all problems on the way and completing the thesis has been a very rewarding and satisfying process.

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Martti Tiikkainen

LIST OF ABBREVIATIONS AND SYMBOLS

AHB	AMBA High-performance Bus
APB	Advanced Peripheral Bus
AVM	Advanced Verification Methodology
CDV	Coverage-Driven Verification
DMA	Direct Memory Access
DUT	Design Under Test
EDA	Electronic Design Automation
eRM	e Reuse Methodology
FEC	Focused Expression Coverage
IP	Intellectual Property
MAC	Media Access Control
MECE	Mutually Exclusive, Collectively Exhaustive
MDV	Metric-Driven Verification
OOA	Object-Oriented Approach
OOD	Object-Oriented Design
OOP	Object-Oriented Programming
OVM	Open Verification Methodology
RVM	Reuse Verification Methodology
SV	SystemVerilog
TLM	Transaction-Level Modeling
UCDB	Unified Coverage Database
UML	Unified Modeling Language
URM	Universal Reuse Methodology
UVC	UVM Verification Component
UVM	Universal Verification Methodology
vAdvisor	Verification Advisor
VMM	Verification Methodology Manual

1. INTRODUCTION

Verification plays a very big role in the development of digital designs. It is used to measure if a design has been implemented correctly. Since modern designs, especially system-on-chips (SoCs), are getting bigger and more complex, planning and implementing a verification environment becomes a large and demanding task. Verification can take up to 75% of the total design time and it usually becomes a bottleneck in project completion [1]. The availability of reusable off-the-shelf components creates more problems for verification since it allows engineers to implement more functionality without excessive project development time [2].

This verification problem is tackled by leaning towards more modular and abstract verification environments that use randomization when generating stimulus. Class-based environments give modularity and easy access to randomization, and Universal Verification Methodology (UVM) is the current go-to candidate because it is a well-known standard and is supported by all major electronic design automation (EDA) tool vendors [3]. In addition, functional coverage can be used during the simulation to determine whether to continue with new random values or stop the simulation, or to modify constraints used in the simulation. Combining these principles one can create very efficient automated coverage-driven verification (CDV) environments [4].

This thesis studies the advantages and disadvantages of a class-based CDV environment for verifying intellectual properties (IPs). The objective is to create a monitoring environment using UVM principles in parallel of an already existing traditional SystemVerilog (SV) test bench. This monitoring system will enable the collection of functional coverage from the design under test (DUT). In addition, a complete UVM verification environment is created based on the original test bench. The execution sequence of the new UVM environment is the same as the original test bench, but the UVM environment uses constrained random stimulus and CDV to its advantage.

The two verification environments are created in order to collect simulation data regarding code and functional coverage, simulation performance and reusability. The data from two environments is analyzed and conclusions are made about the effectiveness of an UVM environment in IP verification. Depending on the results, this type of verification environment could be used to verify future IPs or SoCs. Because the implementation of the UVM environment is done keeping modularity in mind, future reuse would not be as big of a step as creating from scratch.

Chapter 2 introduces the concept of UVM. A brief look is taken into the history of class-based verification in SV; how UVM became what it is now. The general concepts of object-oriented programming (OOP) are presented and the common structure of UVM class hierarchy is explained using these OOP concepts. In addition, this chapter shows how classes are used in SV verification.

Chapter 3 takes a look into coverage collection and usage in SV. The concepts of code and functional coverage are presented and different coverage types are presented. The chapter shows how coverage is captured in simulations and what are SV specific coverage methods. The chapter also goes through some applications that use the collected coverage data.

Chapter 4 presents the implementation of the UVM monitoring system that is injected to the original IP test bench. A short description of the DUT is given. The chosen points in the design for coverage collection are explained. Finally, the added

UVM components are gone through and the test bench used in the simulations is presented.

In Chapter 5, the finalized complete UVM verification environment is presented. Additions and changes needed for the environment are gone through. In addition, the chapter shows problems found when integrating a C-model to a class-based environment.

Chapter 6 lists the results got from the two environments shown in Chapters 4 and 5. This includes coverage numbers, number of total tests and execution times for different scenarios.

Chapter 7 presents the final discussion about the topic of this thesis. The results are analyzed and the usability of class-based CDV environments for future use is concluded.

Chapter 8 rounds up this thesis. The main chapters and the conclusions made from the results are summarized.

2. UNIVERSAL VERIFICATION METHODOLOGY

This chapter takes a look into Universal Verification Methodology (UVM) as a whole. Section 2.1 gives a brief overview to UVM verification. Section 2.2 goes through some of the predecessor methodologies that led to the creation of UVM. Section 2.3 presents the concepts behind object-oriented programming (OOP) and the OOP practices in UVM. Lastly, Section 2.4 takes a look into some of the essential UVM-specific features.

2.1. Introduction to UVM

UVM is a complete methodology that presents the best practices for efficient, reusable and thorough digital design verification. Reusability is one of UVM's key fundamentals and it is achieved by introducing the concept of UVM verification components (UVCs). These components, as well as other parts of UVM, follow the principles of OOP. UVM can be used to verify both small and large IP-based designs. On top of that, UVM is an open-source verification library, and Accelera provides reference manuals and user guides for the methodology [5][6]. [7, p. 1]

The goal of UVM is to give the designer confidence that their design has been verified thoroughly in an efficient way, and to point out possible bugs as early as possible. The best way to get to this type of verification is to use automatic environments incorporating random stimulus. Figure 1 illustrates a verification flow that incorporates verification like that [7, p. 3].

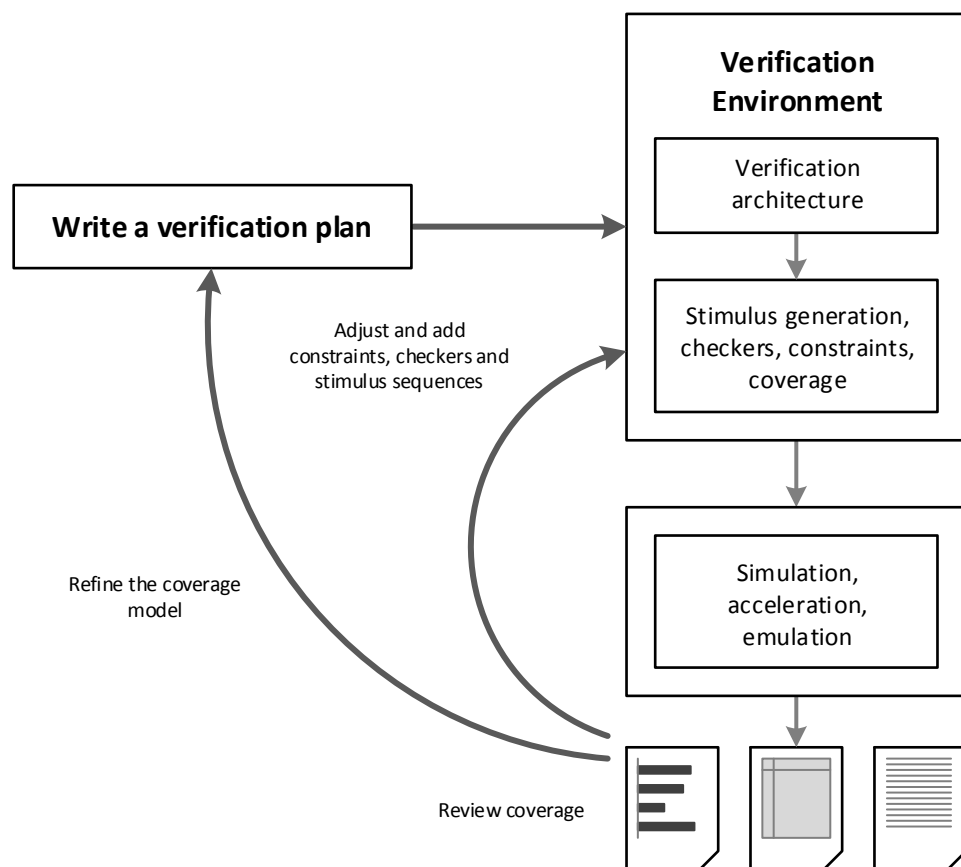


Figure 1. A verification planning and execution flow.

In addition to automation and random stimulus, few other aspects need to be taken into account as well when creating these types of environments:

1. The test bench needs to be self-checking to ensure the applied random stimulus gives correct response from the design under test (DUT).
2. The different generated stimulus needs to be tracked to know what scenarios have been checked and what not.
3. Control logic should be created between the gathered results and applied stimulus. This allows steering the generated stimulus towards uncovered scenarios during the simulation.

The preferred way to track the stimulus and responses with UVM is to use functional coverage. For example, in SystemVerilog (SV) this can be done by writing covergroups. UVM provides one of the best frameworks to achieve this type of versatile and thorough verification. [7, p. 2-3]

UVM test benches are built using already existing base building blocks and customizing them how one sees fit. These base blocks are called UVCs. Since the components are SV classes [8, pp. 8], a hierarchical environment can essentially be built in endless possible ways. Although to build an UVM environment that follows good verification principles, certain guidelines should be followed. A very common UVM test bench structure from a top view perspective is presented in Figure 2 [6].

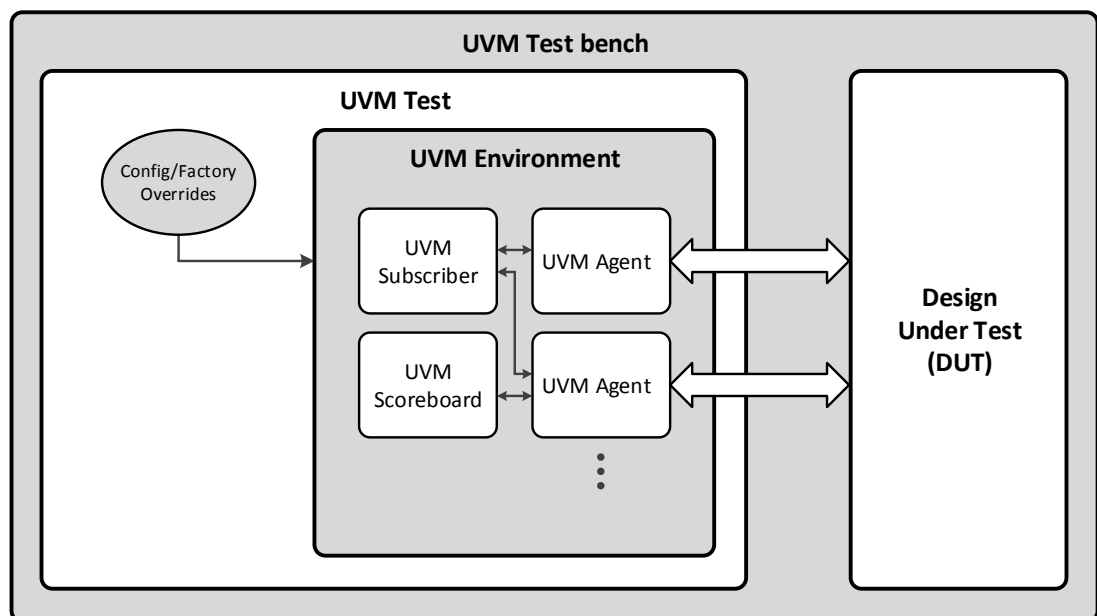


Figure 2. Typical UVM test bench architecture.

Generally speaking, if the test bench is able to drive the pins of the DUT, monitor signals and check correctness, it is good to go. From this point more properties can be added to make the test bench towards a CDV environment. A deeper look into some of the UVM features is taken in section 2.4.

2.2. History

UVM was announced on December 23rd 2009 by Accellera Systems Initiative. The first official UVM version (1.0) was accepted for release on February 18th 2011. Even though UVM brought new improvements, like run-time phasing and callbacks, most of what UVM provided was already introduced in Open Verification Methodology (OVM). Nonetheless, the benefits UVM brought were massive; it provided a single, industry- and vendor-wide standard for SV verification. Figure 3 shows the timeline that includes the development of verification methodologies that led to UVM. [7, p. xxii]

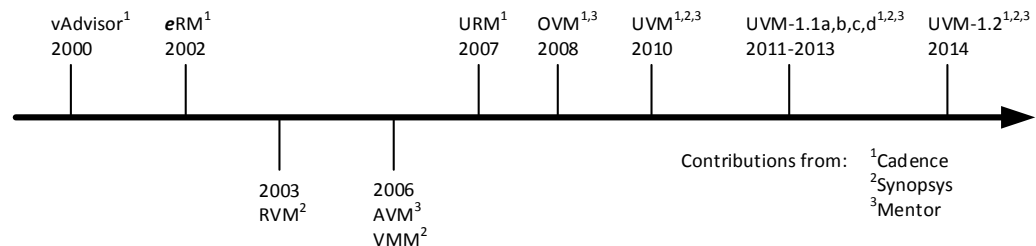


Figure 3. Verification methodology timeline.

Verisity Design, Inc. (currently part of Cadence Design Systems, Inc.) released a collection of best verification practices in 2000. This collection was called Verification Advisor (vAdvisor) and it was meant for the e verification language user community. vAdvisor explained many points of verification, including stimuli creation, self-checking test benches and coverage model creation, with the purpose of speeding up development and supporting people working with verification. The package did not have any ready-to-use verification code and this posed an area for further improvement. Thus Verisity announced the first verification library, e Reuse Methodology (eRM), in 2002. eRM contained packaging guidelines, architecture requirements, messaging facilities, an objection mechanism and much more. Even a register package was later added to the methodology. The library was very well received and its core functionality guided the following methodologies to the same direction, including UVM. [7, p. xxii]

In 2003, Synopsys took its part in the verification methodologies by announcing the Reuse Verification Methodology (RVM). RVM included parts of the properties of eRM and it was developed to the Vera verification language. Because RVM was missing some of the eRM functionality, like sequences and objection mechanism, it was considered as a subset of eRM. Nevertheless, RVM introduced the callback solution which was new in the verification community. Later, RVM was transformed into the SV Verification Methodology Manual (VMM) which supported the new and growing SV standard. [7, p. xxii]

Cadence Design Systems, Inc. started developing a SV version of eRM in 2005 after acquiring Verisity. Thus the Universal Reuse Methodology (URM) was introduced in 2007. Cadence took notes from Mentor's Advanced Verification Methodology (AVM) and made URM open-source. URM was a huge step in SV verification since it transformed the proven eRM core functionalities into SV. New solutions, including abstract factory and configuration mechanism, were also introduced to enhance SV verification even further. [7, p. xxiii]

In 2008, Mentor and Cadence worked together and introduced OVM. Many of the URM properties were used in OVM because of URM's proven high-level methodology infrastructure. OVM was once again a huge step in verification methodologies since it was the first multi-vendor solution that could be used with more than one vendor simulator. This led OVM to be the methodology of choice for people who wanted their environments to be simulator-neutral. In addition, OVM spawned larger scale community sites for questions and idea sharing. [7, p. xxiii]

In 2010, the development of UVM was started and the OVM version 2.1.1 was chosen as the base. Soon after the first release of UVM it became the go-to verification methodology. UVM removed all vendor specific gimmicks since it is supported and tested with all major EDA tool vendor simulators. UVM versions 1.1a, 1.1b, 1.1c and 1.1d have improved the quality of the methodology while maintaining the APIs of the standard. The latest version (1.2) remains a bit controversial since verification experts disagree with some of the new features [9]. Thus 1.1d is currently the most used methodology in SV verification, at least until 1.2 is more mature. [7, p. xxiii]

2.3. Object-oriented programming

This section explains few of the most important features of object-oriented programming (OOP). This includes the common idea behind OOP, classes and objects, and inheritance. SV classes and interfaces are also gone through separately. Even though the OOP principles are explained from a general object-oriented (OO) point of view, the same properties are present in UVM.

2.3.1. Definition of term object-oriented

From a programming point of view, object-oriented means that the software components are organized as a selection of discrete objects that include data and possible action over it [10, pp. 1-1]. The idea is to create more abstract, configurable and reusable building blocks for programming. The user does not need to know all the details what is going on under the hood. Only the needed attributes and commands from the top view perspective can be given to the user and the more detailed implementation remains hidden. With this kind of object-oriented approach (OOA), the tools used in programming appear much more like how humans think of objects instead of machine-like parameters and instructions. For example, in a UVM verification environment it is not necessary to know how a driver controls an APB bus; the availability of a write and read task is sufficient.

2.3.2. Classes and objects

For OOP, information hiding and abstraction are one of the key points for the foundation of a clear design [11]. Both of these are introduced with classes. A class is a derived data-type, similar to a structure. Instead of grouping together only elements of different data-types like a structure, a class can also include functions [10, pp. 10-1]. Therefore, a class can have attributes to store data and methods to implement functionality. Figure 4 illustrates a Unified Modeling Language (UML) class diagram

used in object-oriented design (OOD) [12, p. 6]. UVM hierarchies including similar class blocks can be extracted from UVM simulations.

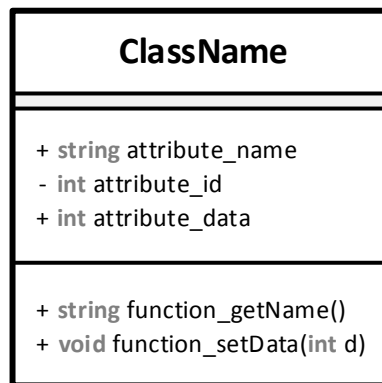


Figure 4. UML diagram presentation of a class. Diagram includes the class name, attributes, methods and their types.

Attributes and methods can be declared as public, protected or private (local in SV). This can be used to make some functionalities of the class unavailable to the outside world, adding information hiding. In Figure 4 this can be seen as plus and minus signs, plus meaning public and minus private.

Object is an instance of a defined class. It is important to remember that defining a class is not enough to use its properties. Only after an object is created from a class can the class attributes and methods be accessed through the object. Any number of objects can be created from a class and thus they can have different identity, state and behavior even though they are all derived from the same class [13, pp. 5]. When creating an object, it allocates the needed amount of memory. It is required to keep track of created objects to make sure they are destructed and the allocated memory is freed. Fortunately, in SV this is handled very well automatically and the user does not need to worry about memory leaks [8, pp. 8-29]. [14, pp 3-1]

2.3.3. *Inheritance*

Alongside with the concept of classes and objects, inheritance is one the most powerful features of OOP. In OOP, the process of creating a new derived class from an already existing class (base class) is called inheritance. This process is also known as class extension. The extended class inherits all public and protected attributes and methods from the base class. Inheritance is visualized in Figure 5 by extending the example class presented in Figure 4 [13, pp. 8].

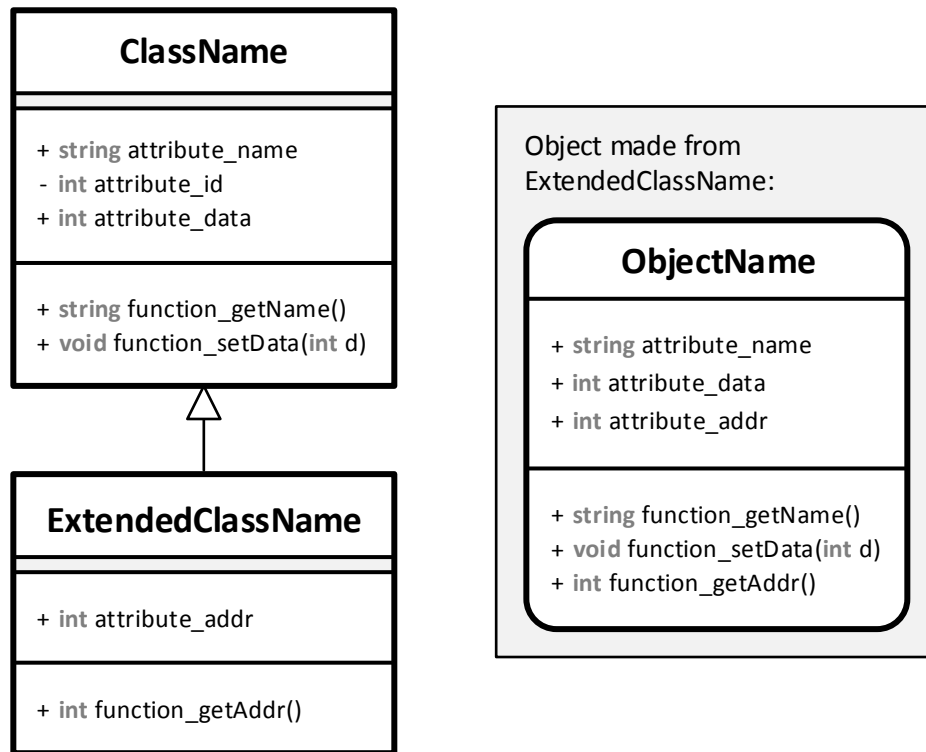


Figure 5. Inheritance presented in UML class diagram form with an object example.

As it can be seen in Figure 5, the example object *ObjectName* created from the extended class has access to all public attributes and methods from the classes *ClassName* and *ExtendedClassName*. The base class remains completely unchanged with extension. [10, pp. 12]

The advantage got from inheritance is reusability. If more functionality is needed, it can be added with extension instead of changing already working and verified code. This allows creating new code from another company's or person's existing code without modifying the source [10, pp. 12]. In UVM, the idea is to extend existing UVM components and modify them to fit to the verification environment. The UVM base classes bring many positive properties to the verification environment like automatic phasing and transaction-level communication models. In addition, if a common class-based verification environment is created for a larger project, all subtests can extend the common environment to make more targeted tests.

2.3.4. System Verilog classes

For SV classes, all OOP principles mentioned in the previous sections are present. In addition, the usage of tasks [8, pp. 13] is also possible alongside with functions in SV classes. Tasks need to be used if time-consuming statements are desired inside classes. SV classes also have properties, like *rand* type definition and constraints, that are essential with verification environments using random stimulus. The following paragraphs take a deeper look into these two features.

A very powerful feature of SV classes is that the attributes can be defined with a randomize type (*rand*) [8, pp. 8-12]. This makes randomization of parameters very efficient because all *rand* defined attributes in the same hierarchy level can be assigned

a random legal value with a single function call. The randomization can also be targeted to single attributes. An example SV class and its randomization is presented in Figure 6 below.

<p>Class definition:</p> <pre> class class_example; // attributes protected int id; rand int data; rand int addr; rand bit readwrite; // constructor, methods, etc. : endclass </pre>	<p>Test program:</p> <pre> class_example cl1; int check; initial begin cl1 = new(); check = cl1.randomize(); assert (check); else \$error("rand failed!"); end </pre>
--	---

Figure 6. Class instantiation and randomization in SV.

In Figure 6, an instance *cl1* of the class *class_example* is created with the *new()* constructor and the randomization is done with *cl1.randomize()*. The randomize method returns an integer that indicates whether the randomization was successful or not. The integer *check* and an assertion is used to report any errors regarding the randomization. In this example, the randomize call will change the values of *data*, *addr* and *readwrite* attributes to random integer and bit values. Integer *id* remains unchanged since it does not have a *rand* type defined.

The legal range of values can be changed using SV constraints [8, pp. 18-5]. Constraints can be used to ensure that the randomized values will be reasonable and will actually stress the DUT. For example, without constraints the attribute *data* in Figure 6 will be randomized to any possible value of a 32-bit signed integer. A constraint could be added to limit the result of randomization into a small set of values. Inside these values, weight factor can also be used to make some values more likely to be the result of the randomization than ones with smaller weight.

2.3.5. SystemVerilog interfaces

In SV, interfaces encapsulate the communication between blocks, allowing a smooth migration from abstract system-level design through successive refinement down to lower level register-transfer and structural views of the design. At its lowest level, an interface is a named bundle of nets and variables. In addition, SV interfaces can include functionality in the form of SV tasks and functions, and module ports (*modports*) to restrict interface access by declaring the direction of the interface signals. Using module ports is an useful way to create different types of components, like masters and slaves, that use the same interface signals, but with different signal directions. [8, pp. 25]

Interfaces are not limited to class-based SV applications, but they are essential when giving SV classes access to specific signals found in the DUT. This is done by giving the class a reference to the original interface. The reference is given as a virtual interface. The component using the virtual interface can access any signal, task or

function it is permitted to use through the virtual interface. Using virtual interfaces adds abstraction and separates the test environment from the actual signals in the design, promoting code reuse. [8, pp. 25-9]

2.4. UVM features

This section shows the most important UVM components found in a typical UVM test bench. In addition, some of the essential UVM features are gone through. These features consist of simulation phasing, data transactions, factory registration, configuration and information reporting. To get the most out of UVM verification, these properties should be capitalized in the environment.

2.4.1. Essential UVCs

Even though UVM environments can be built in multiple possible ways and allow high amount of customization, nearly all of them include the most common UVCs that are needed for test bench creation and DUT interaction. Specific components should be used for their purposes only to ensure the code remains readable and follows the general verification guidelines. The most common UVCs are described in Table 1 below [6, pp. 1-1].

Table 1. List of common UVM verification components

UVM component	Description
Test	The UVM Test is the top-level component in the UVM test bench. The UVM Test typically performs three main functions: instantiates the top-level environment, configures the environment and applies stimulus to the DUT with UVM Sequences.
Environment	The UVM Environment groups together other components that are interrelated. These components include UVM Agents, Subscribers, Scoreboards, or even other Environments.
Subscriber	The UVM Subscriber's function is to check correct behavior and collect functional coverage. A UVM Scoreboard is a similar component to the UVM Subscriber.
Agent	The UVM Agent contains components that are dealing with a specific DUT interface. A typical UVM Agent includes a UVM Sequencer, Driver and Monitor.
Monitor	The UVM Monitor samples the DUT interface and stores the information to transactions, which are sent out to the rest of the UVM test bench for further analysis.
Driver	The UVM Driver receives individual transactions and transforms them into DUT pin wiggles.
Sequencer	The UVM Sequencer serves as an arbiter for controlling transaction flow to a UVM Driver. The transaction flow is determined by UVM Sequences.
Sequence	UVM Sequences are objects that contain behavior for generating stimulus.

2.4.2. Phasing

UVM has a set of automated function and task calls during UVM simulations that all UVCs execute at the same time. These function and task calls create the phasing mechanism of UVM. All UVCs are always synchronized with respect to these phases [15]. Thus if an extended UVM class has a specific named function or task declared, it will be executed automatically when the UVM simulation enters that specific phase.

The UVM class library includes common phases and they can be found in the UVM class reference manual [5, pp. 9-6]. From these phases, the build, connect and run phase are used to set up the environment and run the simulation. Build phase is used to create all subcomponents (objects) for the class and to assign needed virtual interfaces. It is good to understand that the UVM environment does not exist until all build phase functions have been run. In connect phase, all transaction level modeling (TLM) connections are made between the required UVCs. Only after the connect phase is the environment complete and ready to be used in simulations. Lastly, all simulations are done in the run phase, or they can be divided into subsections of the run phase if desired. [5, pp. 9-6]

2.4.3. Transactions

Transactions in UVM are basic data objects that represent data movement between different UVCs [15]. They are used to represent communication at a more abstract level. Because transactions are SV classes as well, all necessary information can be stored in the attributes of the transaction class. It is up to the driver to transform transactions into pin wiggles the DUT can understand. With the help of a UVM sequencer [5, pp. 19-3], creating activity becomes a very simple task. Transactions eliminate the need to know all the details happening at pin level and the focus can go towards creating more scenarios. In addition, UVM sequences can be used to model multiple consecutive transactions. [5, pp. 5-3]

2.4.4. Factory and configuration database

The UVM factory mechanism is an implementation of the factory pattern found in OOP literature [15]. The factory can be used to create UVM objects and components if the type of the created class is registered to the factory. User-defined components and objects are usually registered to the factory with UVM macros. If a new object or component is requested to be created from the factory, the factory will create an object according to its configuration. A registered class can be overridden with another class that extends the original. This allows replacing components in the verification hierarchy with custom ones, and it can even be done during the simulation. [5, pp. 8-2]

The UVM configuration database functions as a centralized database where type specific information can be stored and retrieved [5, pp. 10]. The database also supports hierarchical configuration; information can be stored for specific components only or multiple components under one hierarchy level. The latest write to the database will always overwrite previous existing configurations for the selected level of hierarchy.

Even though the database can be used for multiple different purposes, it has one especially important application: to configure the test bench as it is constructed [16].

All references to top module-level components need to be transferred to the UVM class environment through the database. This is how the UVM agents get their accesses to the interfaces connected to the DUT. In addition, the whole behavior or structure of the UVM test bench can be changed according to the setup values fetched from the configuration database before building the UVM environment.

2.4.5. Message reporting

UVM also has a built in message reporting system. Available message types are info, warning, error and fatal. The system enables reporting messages with different severity levels and keeps track of messages with the same ID. In the end of the simulation, UVM gives a recap of all different sources and the number of reports from every source. Visibility of different severity level messages can be changed by UVM simulation parameters. Custom prints can be also added to the UVM info type messages. The common way to use the system is through the UVM report macros, which makes writing the reporting code more user friendly [5, pp. 21-1]. [5, pp. 6]

2.5. Related work

UVM has been in the spotlight in RTL verification for the past few years and verification engineers have been eager to put its praised features to use. Francesconi J. et al. successfully used UVM in the building of two RTL verification environments, and experienced increased productivity when reusing the UVM verification components from the first environment [17]. Zhaohui H. et al. studied the integration of IP-level UVM test benches and test cases to SoC-level, which also showed a high amount of possible reuse while saving resources needed for the integration [18].

The two main points used for UVM validation in this thesis are coverage results got with CDV and simulation performance statistics. The measurement and analysis of functional verification and coverage, including CDV, has been studied by Piziali A. [19]. In his work, Piziali presents methods and guidelines for functional coverage related applications. Söderlund T. and Kärenlampi L. studied test bench performances in their theses [20][21]. Kärenlampi used profiling for accurate performance results in his work, and Söderlund implemented an UVM environment based on a legacy test bench and compared these two.

3. COVERAGE

This chapter introduces the concepts of functional and code coverage in SystemVerilog (SV); how they are collected and what is done with them. Section 3.1 starts with the reasons, phases and CDV. Sections 3.2 and 3.3 list the parts that make up code and functional coverage and go through how they are captured.

3.1. Importance of coverage

In verification, it is not practical to run test cases without any indicator telling when all required functionalities have been checked. Data got from code and functional coverage can be used to address this verification problem. Coverage models can be manually written to fit the needs of the design. However, even though the tools available nowadays make the verification environment creation process less painful, it is very important to think about all verification related problems from a coverage point of view [22]. This kind of approach is essential when creating a coverage collection infrastructure.

Planning and implementing a thorough coverage environment requires more time and effort but when done correctly, it pays itself out in the end [23, pp. 1-4]. A well-written coverage environment saves many hours of working time spent on manual checking for correctness and verification status. In addition, giving a thought to functional coverage before design implementation can help to bring out key points in the design specification. This can make the actual implementation process easier and reduce verification needs later in the project.

3.1.1. Coverage planning

The process of efficiently developing functional coverage models for today's projects is still found fairly difficult amongst many engineers. The coverage models usually lack proper planning, and often contain poorly defined objectives, uncertain estimates of effort and unrealistic expectations. The implementation of the coverage environment is often prone to errors, regardless of using methodologies like UVM or SV's built-in functional coverage features. Problems like this lead to incomplete coverage closure and might leave bugs unnoticed. [24]

A coverage plan connects the requirements defined in the specification and the implemented model with the results got from simulations. Proper planning ensures that no points are missed from the specification and makes the actual implementation of the coverage model towards more routine programming. There are three important things when planning coverage: the model needs to be accurate, representative and complete [24]. Accurate coverage means that the model captures only the desired states or transitions from the design and avoids false positives and unnecessary events. For coverage to be representative, it needs to include the needed amount of the specified functionality and balance the covered core properties with the project's business goals. Lastly, complete verification is defined based on a scope and representative subset of functionality; all functionalities in that scope and subset should be identified.

Sometimes the specification can be quite demanding, and implementing a coverage model is a very difficult task. One method that can help when planning the coverage

model for hard-to-implement properties is the Mutually Exclusive, Collectively Exhaustive (MECE) approach [25]. Using the MECE approach, a coverage requirement can be divided into multiple definitions. All definitions are a subset of the full requirement and independent from each other, and together they form a coverage model for the original requirement. The MECE approach is illustrated in Figure 7 [24].

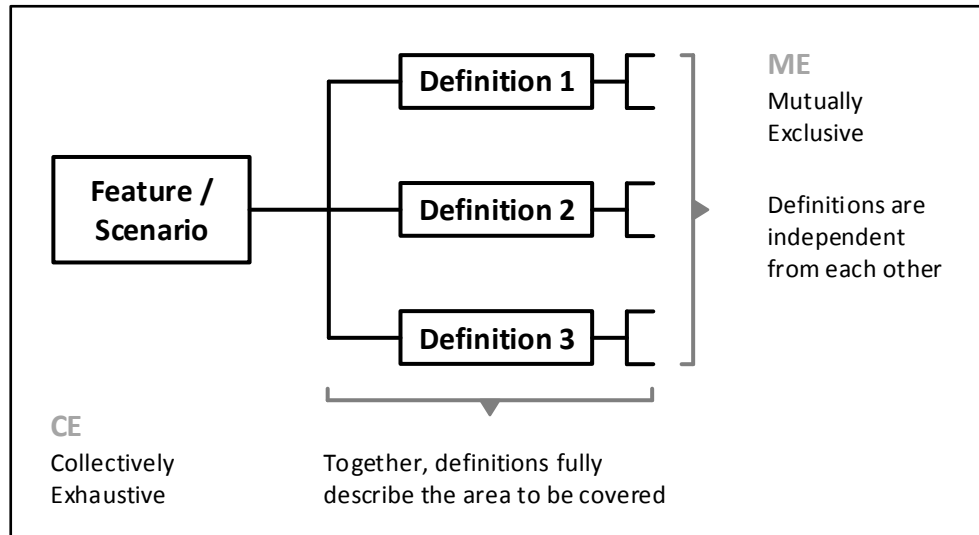


Figure 7. MECE approach for coverage collection.

3.1.2. *Reviewing coverage*

A single coverage metric is not enough to get a complete coverage closure. Also, just looking at the coverage numbers got from the simulations is not sufficient; depending on the size of the project, a significant amount of processing and reviewing can be required to determine the actual coverage status. For example, having code coverage of 100 % does not necessarily mean that the DUT has been completely verified. Some functionalities might be missing and the 100 % comes from a subset of the whole requirement [26]. On the other hand, complete functional coverage but lacking code coverage might suggest that the coverage model is faulty, or the implementation has redundant, unnecessary properties that were never specified.

This is why carefully reviewing coverage results is important, even with a flawless coverage plan. It helps to bring out the lacking aspects of the design or the coverage model and understand them better, and guide engineers towards what should be verified next. In addition, reviewing is a good time to make sure everyone related to the particular design is on the same information level. Just as with verification planning, frequent reviewing ensures on-time project completion with zero bugs unnoticed.

3.1.3. *Verification driven by coverage*

One application for coverage data is to use the data to automate or drive the verification during the simulation. The approach where coverage is used as the engine that drives the verification flow is called coverage-driven verification (CDV) [27]. With CDV,

the environment can be made automatic by using coverage as the indicator whether to continue the simulation or not. On the other hand, coverage can also be used to tweak the constraints that affect the randomized parameters during stimulus generation. With a proper algorithm, changing the constraints according to the coverage results can be very beneficial for reaching complete coverage closure [4]. Both of these scenarios require the use of manually declared functional coverage models. In SV, the recommended way to do this is to use covergroups and its built in features (see Section 3.3.1.).

3.2. Code coverage

Code coverage is one of the first methods invented for systematic software testing. It is used as a measurement that tells how many structures within the source code files have been activated during the simulations. Code coverage itself is not enough for complete coverage closure since it does not tell whether all functionalities have been implemented or not. Functional coverage is always required in addition to code coverage. Even with this limitation, code coverage is a very efficient tool and it requires close to no extra work because the process of creating the coverage model is automated by the simulator [19, pp. 5]. Information regarding code coverage capture should be searched from vendor-specific user guides. The following subsections go through the most common code coverage metrics: line, statement, branch, expression, toggle and finite-state machine (FSM) coverage. [26]

3.2.1. Line coverage

Line coverage is a simple metric used to determine which lines of the source code have been executed during the simulations, excluding commented lines. In addition to the source code lines, the line coverage report incorporates a count associated with each line of source code notifying how many times each line has been executed. This can be used to determine if a line has been executed a minimum number of times required, or to spot out unexecuted code. [26]

3.2.2. Statement coverage

Statement coverage metric indicates whether a statement within the source code has been executed or not. Statement coverage analysis is often found to be more useful than line coverage since a statement may span multiple lines of source code, or one line of source code can include multiple statements [19, pp. 5-2-2]. The reasons for statement coverage usage are similar to line coverage. [26]

3.2.3. Branch coverage

Branch coverage (also known as decision coverage) metric reports if Boolean expressions tested in control structures have been evaluated to both true and false. In SV, the control structures include *if*, *case*, *while*, *repeat*, *forever*, *for* and *loop* statements [19, pp. 5-2-3]. The expression in the statement is considered as one true-or-false evaluation regardless whether the expression contains multiple logical

operators or not. Very typical application for branch coverage is to check that reset paths or all states in a case statement have been executed. [26]

3.2.4. Expression coverage

Expression coverage (referred also as condition coverage) is a coverage metric used to identify if each condition evaluated true and false values. The conditions are Boolean operands that do not contain logical operations. Thus, expression coverage measures the Boolean conditions separately from each other. Focused expression coverage (FEC) is a variation of expression coverage, and it is stronger than condition and decision coverage. [26]

3.2.5. Toggle coverage

Toggle coverage metric measures the number of times each bit of a register or a wire has toggled its value. A 100 % toggle coverage is often very hard to reach, and usually projects settle on a requirement where all ports and registers must have experienced a zero-to-one and one-to-zero transitions. For example, toggle coverage is often used for basic connectivity checks between IP blocks. [26]

3.2.6. FSM coverage

Today's coverage collection tools can also identify FSMs from the source code and create coverage models for them. For example, it is possible to extract information regarding how many times each state was visited and each transition occurred. Even sequential arc coverage to identify state visitation transitions is available. Figure 8 presents an example FSM and its coverage status [19, pp. 5-2-7]. [26]

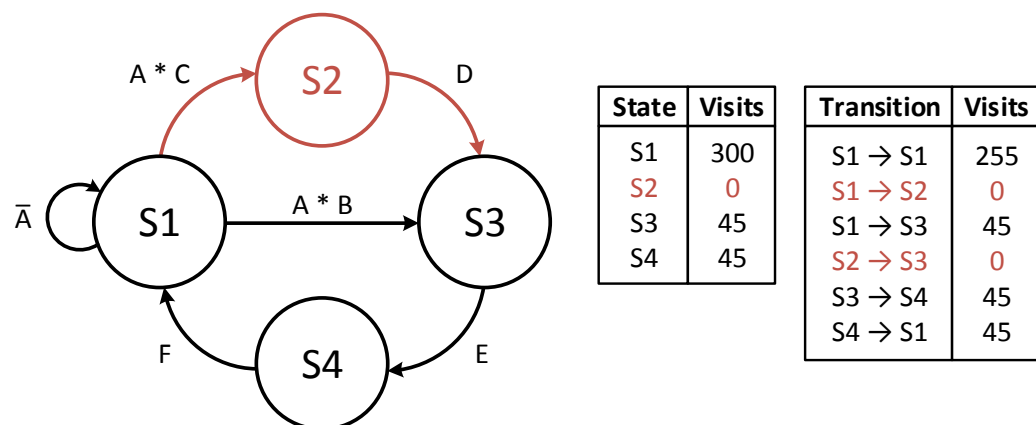


Figure 8. FSM and coverage data with a coverage hole.

3.3. Functional coverage

The goal of functional coverage is to determine if the implemented design requirements defined in the specification are working as intended. In addition,

functional coverage is a good indicator to measure verification progress, better than code coverage. From a high-level perspective, there are two main steps present when creating a functional coverage model: identifying the functionality or design to be verified, and implementing the coverage model using language features to measure the intended functionality or design [26]. The downside with functional coverage is that it cannot be extracted automatically; manual work is required. With SV, the implementation of coverage models can be done with covergroups, or with assertions while using its cover directive [28]. These SV features are explained more thoroughly in subsections 3.3.1. and 3.3.2. Figure 9 below demonstrates verification paths to reach definitive functional coverage [29, p. 9].

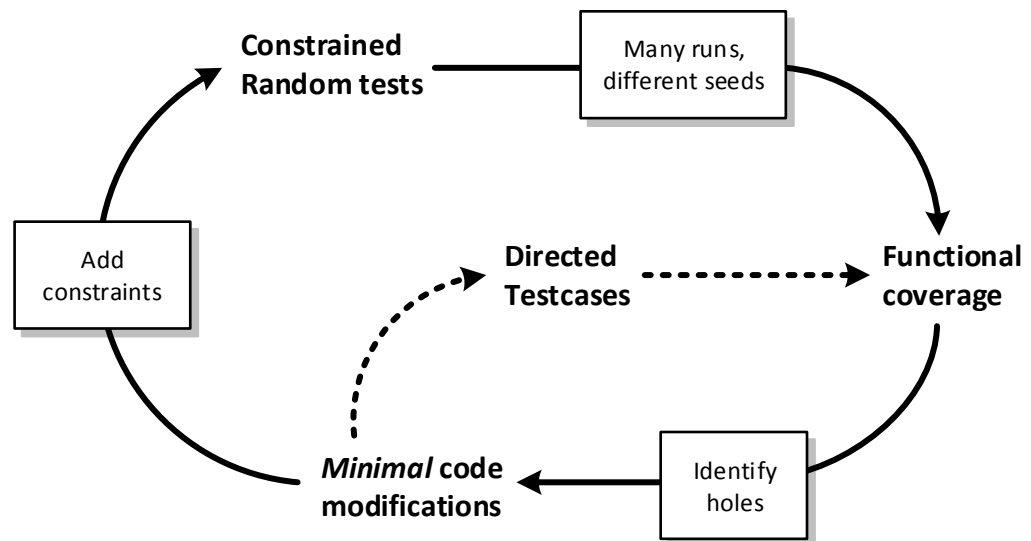


Figure 9. Verification steps to achieve complete functional coverage.

3.3.1. Covergroups

The covergroup construct encapsulates the specification of a coverage model. The construct is a user-defined type and it can include the following components:

1. A clocking event that is used to synchronize the sampling of the defined coverage points.
2. A set of coverage points.
3. Cross coverage between defined coverage points.
4. Coverage options to change the behavior of the covergroup or to modify how multiple covergroup instances are handled.
5. Optional formal arguments used when creating a covergroup instance.

Covergroups can be used to collect information from simple temporal sequences, but its main advantage comes from collecting and correlating information from multiple data points [30, pp. 18-2-3]. Once defined, multiple instances of the covergroup can be created in different contexts. Covergroups can be defined in packages, modules, programs, interfaces, checkers and classes. Covergroups are instantiated with the *new()* operator, similar to classes. When instantiating covergroups inside classes, it needs to be done inside the class constructor. Figure 10 presents the usage of the mentioned covergroup components in SV syntax. [8, pp. 19-3]


```

covergroup cg_example @(sampling_event);
    type.option.merge_instances = 1; // covergroup options
    // coverpoints
    LABEL1 : coverpoint readwrite; // automatic bin creation
    LABEL2 : coverpoint data {
        bins data_point_1 = { 8'h12 };
        bins data_point_2 = { 8'hbe };
    } // manual bin creation
    LABEL3 : cross LABEL1, LABEL2; // cross coverage
endgroup

```

Figure 10. Covergroup syntax in SystemVerilog.

A sampling event (clocking event) defines when a covergroup is sampled [31]. In Figure 10, the sampling of the covergroup is defined on the first line as `@(sampling_event)`. If a sampling event is not specified, the user must manually trigger the covergroup sampling by calling its built-in `sample()` method [8, pp. 19-3]. This is often the preferred way in UVM environments since hierarchical references are not allowed inside classes, and the sampling event is easy to synchronize with a transaction sent by a monitor.

A coverpoint covers a variable or an expression, and it includes a set of bins associated with its sampled values or its value transitions. The bins can be automatically generated by the tool or manually declared. Automatic generation is useful when creating separate bins for a range of values. A bin will be marked as covered if the value associated to the bin is present in the coverpoint variable at the covergroup sampling event. Coverpoints can also include a label, and in Figure 10 the coverpoints and their labels can be found as `LABEL1-3`. Cross coverage can also be created between all the bins for the chosen coverpoints (`LABEL3`). A covergroup can contain one or more coverpoints. [8, pp. 19-5]

The cumulative covergroup coverage considers the contribution of all instances of a particular covergroup, and it can be obtained by calling the covergroup's built-in `get_coveage()` method. In contrast, the coverage of a specific covergroup instance can be acquired by calling the `get_inst_coverage()` method. The coverage value of a single covergroup is the weighted average of the coverage of all items (coverpoints and cross coverages) defined in the covergroup. For coverpoints and cross coverage, the coverage is simply calculated by dividing the number of covered bins with the total number of bins. Cross coverage calculation excludes ignored and illegal bins, and possible duplicates created with the cross coverage. With automatically declared coverpoints, the maximum number of automatically declared bins is taken into account in the coverage calculation. [8, pp. 19-11]

3.3.2. Assertions

An assertion specifies expected behavior in a design and it is mainly used to validate that the behavior is correct. In addition, the cover directive found in assertions can be used to provide functional coverage [8, pp. 16-2]. Assertions are not as practical as covergroups at checking data values, delays and multiple data points, but they are

useful at detecting the occurrence of some specific series of Boolean values [30, pp. 18-2-3].

There are two types of assertions: immediate and concurrent assertions. Immediate assertions are simple, non-temporal domain assertions that are executed like statements in a procedural block [32, pp. 3]. Immediate assertions can only be specified with a procedural statement and the evaluation happens immediately with the values updated at that moment. On the other hand, concurrent assertions describe behavior that spans over time and are great at verifying specific sequences. The evaluation model is based on a clock and the assertions is evaluated only at the occurrence of a clock tick [8, pp. 16-5]. In this work, assertions are only used in the design and the functional coverage is captured only with covergroups in the test bench.

4. UVM MONITORING ENVIRONMENT

This chapter goes through the implementation of the UVM monitoring environment, which runs in parallel with the existing SV test bench. First, a brief description of the DUT is given. Then, the chosen coverage points and the implementation of environment components, like UVM monitors and subscribers, are gone through. Lastly, the whole test bench is presented.

4.1. Design under test

The DUT chosen for this experiment is a decoder. In normal operation, the decoder is configured and run, and the results can be checked during and at the end of each run. The decoder's interface includes Advanced Peripheral Bus (APB) and AMBA High-performance Bus (AHB) buses, and a general interface for interrupt, status and control signals. Figure 11 shows a top view of the DUT including the interfaces, which are the main points for collecting the functional coverage.

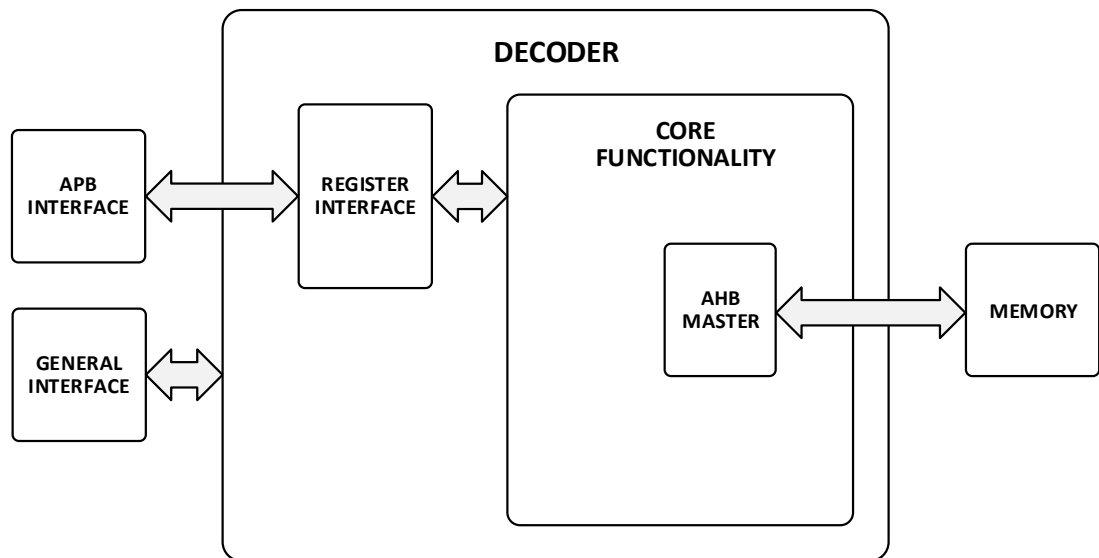


Figure 11. DUT top view.

The APB bus is used to access the registers of the decoder. The registers include configuration, control and status registers. The APB bus is the key point with the functional coverage model since it provides register access and decoder configuration data values. The decoder has an AHB master that fetches data from memory through an AHB bus. The memory is modeled with a SV class-based AHB slave.

4.2. UVM verification components

Since no extra DUT driving is required at this point, the first UVM environment created was quite straightforward. A separate UVM test environment was still required because if the classes had been instantiated in the SV module environment, the automatic UVM properties would not have been present. The created UVM hierarchy includes test, environment, monitor and subscriber classes. The test and environment

classes only create the needed subclasses, in this case monitors and subscribers, pass the virtual interface references and make necessary connections between the subcomponents. The following subsections take a more detailed look into the implementation of the UVM monitors and subscribers, which create the actual functional coverage collection model.

4.2.1. UVM monitors

UVM monitors were created for the APB bus and the general interface. AHB bus monitoring was left out since the traffic consists only of decoder memory data transfers. This did not bring any addition to the functional coverage model. The monitors connect the class-based UVM environment to the module-based DUT. They watch the interfaces during the whole simulation, and automatically send transactions to the higher hierarchy levels when there is valid data on the interface. With the APB monitor, all read and write commands are captured. Similarly, the general interface monitor captures all interrupt and status signal changes. The transactions are sent forward through an UVM analysis port [5, pp. 16]. Figure 12 illustrates the behavior of the APB monitor. With a different interface and transaction forwarding condition, a similar model could be used with the general monitor.

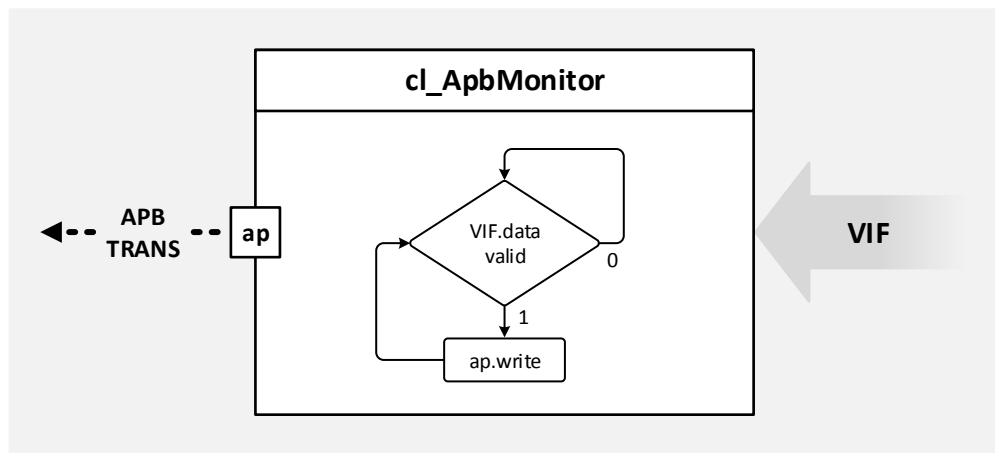


Figure 12. APB monitor operation flow.

The analysis port (*ap*) presented in Figure 12 is of type *uvm_analysis_port#()*, which is parameterized with the APB transaction. The port is a class that has a built-in function *write* that takes a transaction as an argument. Whenever the virtual interface *VIF* has valid data, the data is fetched to a local APB transaction parameter and the analysis port's *write* function is called with this transaction. The port's *write* function forwards the function call automatically to every component that is connected to the analysis port and has the same *write* function implemented. The monitor also has a message printing system for sent transactions that can be enabled or disabled with the UVM severity levels. The behavior and naming of the APB monitor was made to be as general as possible to ensure reusability in other APB buses. The same was done with the general monitor by parameterizing the amount of interrupts and status signals.

4.2.2. UVM subscribers

The UVM subscribers implement the covergroup models for the decoder and use the transactions sent by the monitors to sample the covergroups. Two subscribers were created in total: one for APB and one for the general interface related covergroups. The APB subscriber collects data regarding register access (read and write) and decoder configuration values set through the APB bus, and the general interface subscriber keeps track that all interrupt, status and control signals have been set and cleared. Both of these subscribers include covergroups and their constructors, and the write function with additional logic to determine what covergroups to sample with each transaction. Figure 13 demonstrates how the transactions sent by the monitor are handled inside the APB subscriber.

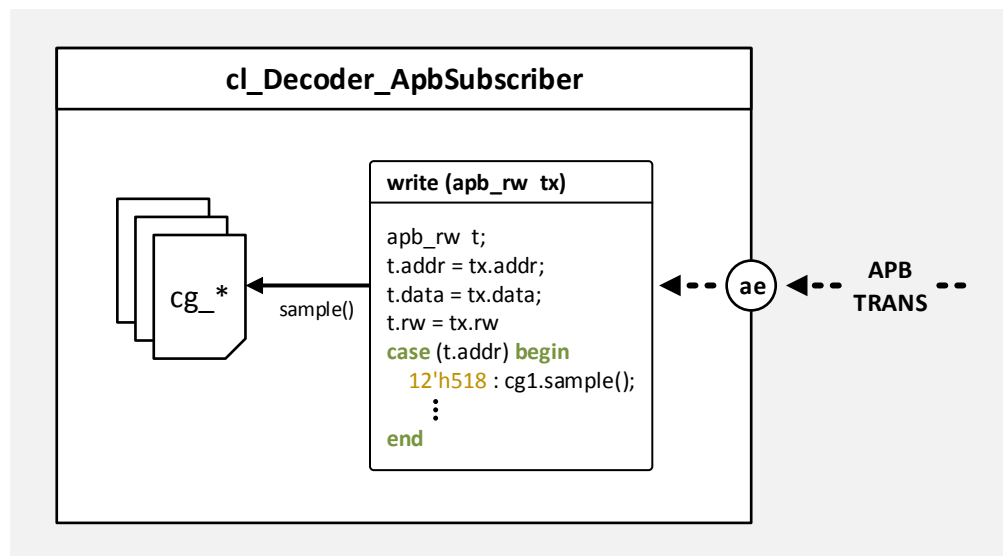


Figure 13. APB subscriber transaction processing.

The subscribers extend UVM subscribers and thus have a built-in analysis export (*ae*) used for receiving transactions. As mentioned in the previous section, the write function is executed automatically whenever the export receives a transaction. The write function captures the transaction information to a local transaction parameter to ensure the data used remains the same, and samples the correct covergroups. The covergroups were implemented using the covergroup properties presented in Chapter 3.1.1.

4.3. Parallel test bench

The finished test bench uses the IP's existing test bench to execute the original test program flow: stimulate the DUT and check design correctness. The original test bench is done in a SV module based manner. In addition, the test bench has the UVM monitoring environment described in the previous sections running in parallel to the module environment. The whole test bench structure is presented in Figure 14, highlighting the separation of the UVM and module hierarchies.

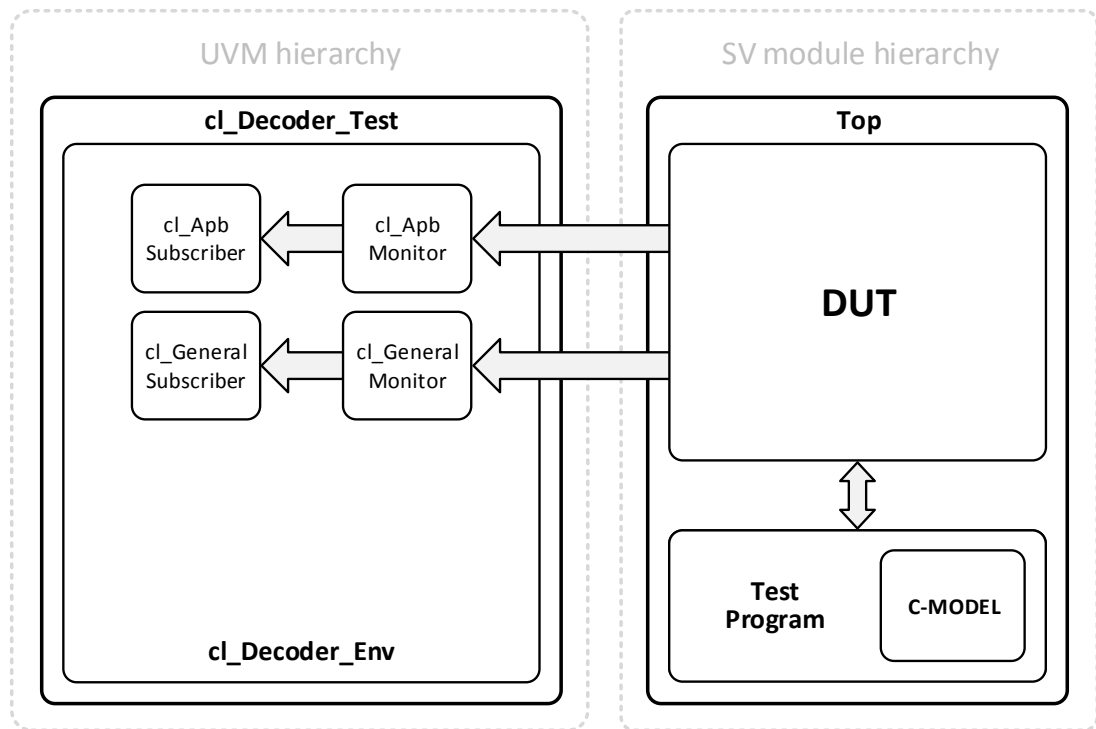


Figure 14. Full test bench for the monitoring environment.

The top SV module instantiates the DUT module, and the decoder test program as automatic SV program. The test program uses the built-in direct programming interface (DPI) [33] to integrate a C-model for the decoder, which is used to calculate the configuration parameters and expected results, and to do correction checks between the C-model and DUT results. In one run, the test program starts the C-model with a set of parameters and the C-model calculates required decoder parameters and starts the DUT with the chosen settings. Finally, the DUT and reference results are compared. The DUT is configured and started via the APB interface.

In addition, the top module also starts the construction of the UVM environment and sets the references of the DUT interfaces to the UVM configuration database. The top selects which UVM test class is the top class in the UVM hierarchy, and that test will construct the rest according to its build and connect phase functions. Here, the *cl_Decoder_Test* test class creates the *cl_Decoder_Env* environment class and the environment creates the monitors and subscribers, connects them and sets the correct interface references to the monitors.

The simulations are done with Mentor's Questa simulator. Coverage is captured by storing the code and functional coverage into a UCDB file in the end of simulations. The coverage data is transformed into HTML format using Questa's coverage features for better readability. The simulator also keeps log of messages that appear during compile, optimization and simulation phases, and the logs are stored to separate files. Questa's *simstats* formal argument is used to get accurate data regarding different simulation execution times. This information is used in performance comparison of the different test benches. The results are gone through in Chapter 6.

5. COMPLETE UVM ENVIRONMENT

This chapter presents the second part of the experiment, where the whole test bench is converted into the UVM environment. The chapter starts with the modifications made to the UVM environment shown in previous chapter to make it able to drive the interfaces and model the AHB memory. In addition, the test program conversion to UVM test format is gone through and the final test bench is presented.

5.1. Addition of UVM agents

With the final test bench, the UVM environment needed to be able to do the same DUT driving as the original module based test program. Thus UVM agents were created for the APB, AHB and general interface. The APB and general interface agents include a driver and a sequencer as new components, and the existing monitor presented in the previous chapter. The AHB agent has only a slave component since its only function is to act as memory that is connected to a AHB bus. The general structure of a driving and monitoring UVM agent is illustrated in Figure 15.

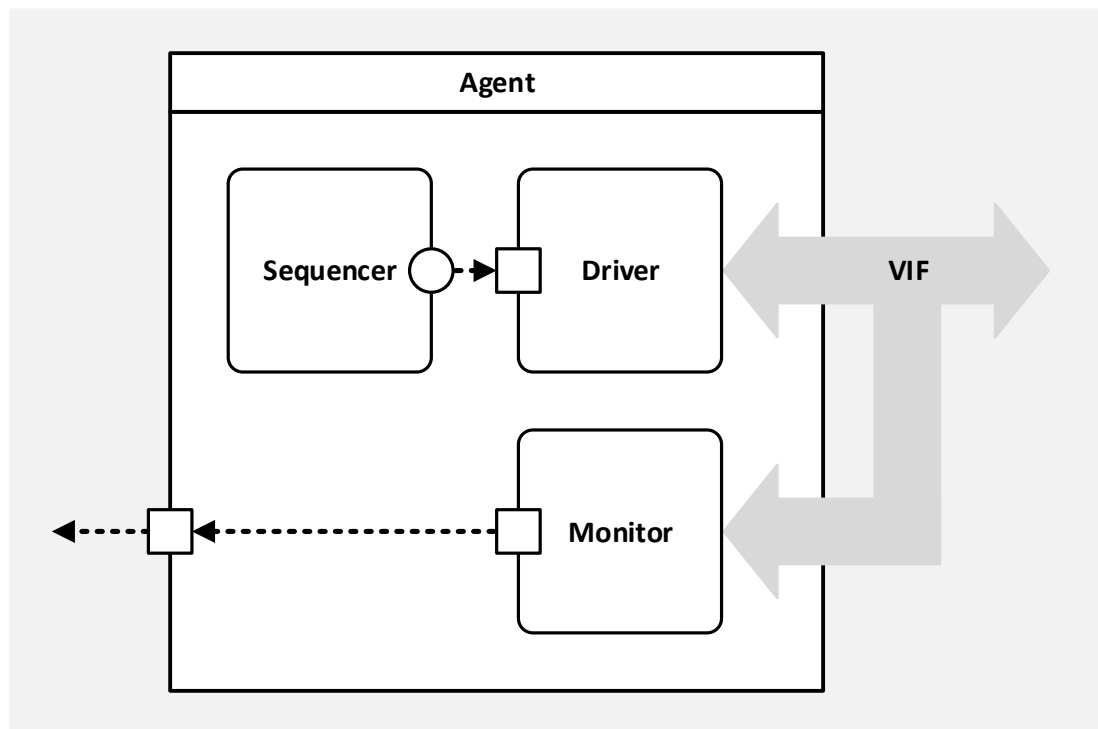


Figure 15. UVM agent and its subcomponents.

5.1.1. Drivers and sequencers

The drivers extend the UVM driver class and their main function is to wait for new transactions to be ready in the sequence item port found inside the drivers, and to transform the transactions into DUT pin wiggles by using the virtual interface reference to the DUT interface. The drivers were built to capitalize the UVM phasing, making them start and operate automatically. They also support passive-active

configuration, where passive agent only instantiates a monitor and active adds the driving components as well. The APB driver checks whether the incoming transaction is a read or write operation and executes them according to the APB protocol, and the general interface driver simply sets the selected control signals active and releases them after few clock cycles.

The sequencers were implemented to make the transaction passing to different drivers more straightforward. The sequencers in this test bench did not need any extra features, thus the base UVM sequencers were used with minor naming changes to fit the IP's test bench. In this test bench, the top UVM test class adds sequences to the sequencers, and the sequencers parse the sequences into transactions for the drivers to fetch.

5.1.2. AHB slave

The implemented AHB slave follows the same functionality as the original slave to ensure timing regarding AHB memory accesses remains the same. Thus the slave's functionality was ported unchanged to be UVM environment compatible, and only minor additions were made to the slave automation using the UVM phases. The slave uses a SV queue as the memory container, and an automatically running function that either stores data to the container (write) or puts data from the container to the AHB bus (read). Because the DUT uses two memories with different AHB bus data widths, the AHB slave class and its functions were parameterized.

5.2. Test program

In the new UVM environment, the test program was implemented inside the top UVM test class `cl_Decoder_Test`. Linking the C-model to the UVM test class was problematic since the C code required access to SV tasks through the DPI, and class tasks cannot be exported unless they are declared as static. On the other hand, static tasks would have nullified the hierarchical benefits got from the UVM environment. This problem was bypassed by importing the C-model inside an SV interface wrapper and giving the UVM test class a reference to this interface. This structure is presented in Figure 16 below.

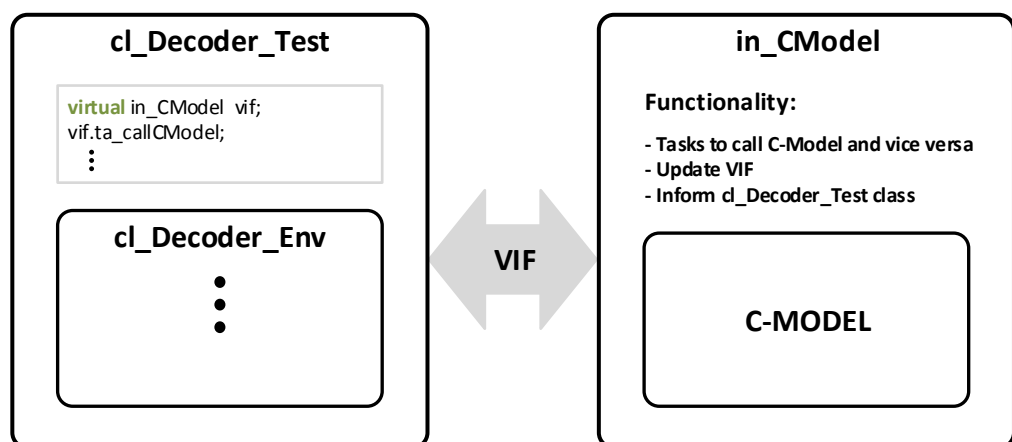


Figure 16. UVM Test class and C-model communication.

The structure presented in Figure 16 allows the test class to call any tasks found inside the *in_CModel* interface through the virtual interface reference. All data between the test class and C-model is transferred through the reference. This requires some additional synchronization compared to a straight task call, but nevertheless was found to be the best solution without modifying the C source code.

Apart from the C-model integration, there were no compatibility issues with the test program implementation inside the UVM test class. The program was divided into subtasks inside the class, and parameters regarding configuration and simulation conditions were declared with the *rand* type with additional constraints. Tasks to fetch and check the covergroup coverage values from the subscribers were also implemented. The main program loop was changed to be coverage-driven, where the covergroup coverage values are used as a condition whether to continue or not. The top includes a set of coverage goal parameters that can be tweaked to modify the importance of some coverage segments in the evaluation of the end condition. In addition, reporting tasks were implemented to inform the user about test progress, and configuration and coverage values.

5.3. Final test bench

The final UVM test bench consists of the new components presented in this chapter and the previous test bench shown in Chapter 4.3. All DUT driving is now done by different UVM agents and the data is processed inside the top UVM test class *cl_Decoder_Test*, disregarding the data calculated by the C-model running inside the *in_CModel* interface. The complete test bench is presented in Figure 17.

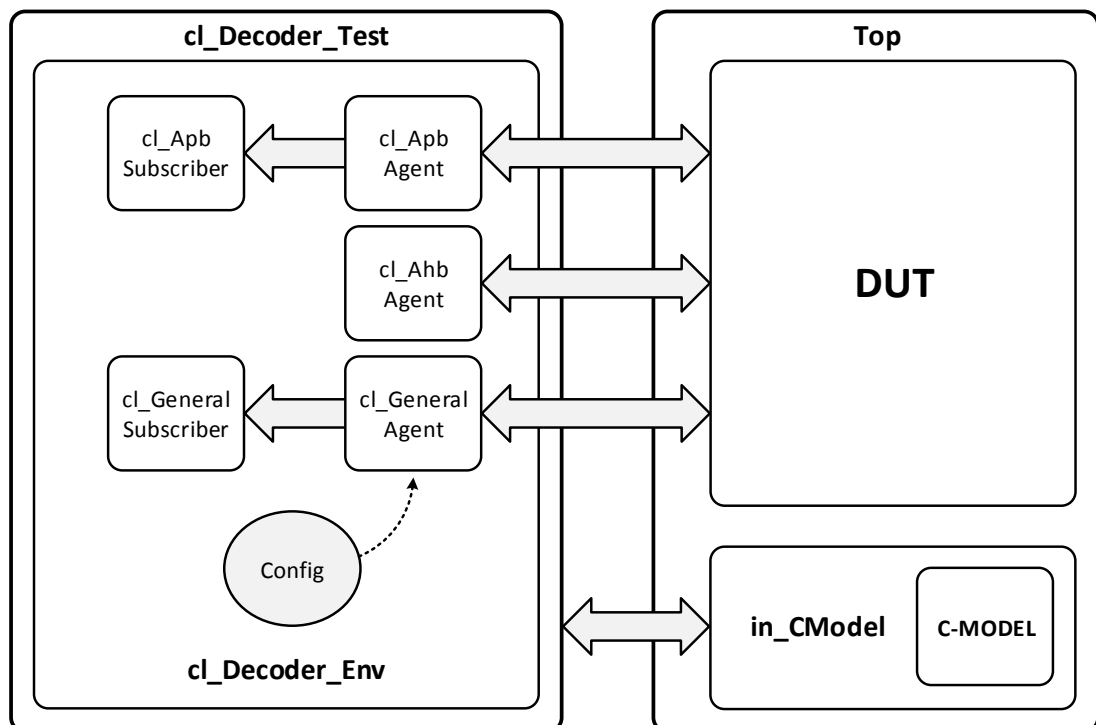


Figure 17. Final UVM test bench.

Here, the *cl_Decoder_Env* environment instantiates the agents instead of only monitors. The environment also includes additional configuration parameters used when creating the agents. The *Top* module only instantiates the DUT and necessary interfaces for the UVM test bench, leaving out the test program found in the parallel test bench. Other than these changes, the test bench structure and instantiation remains the same as in the previous test bench shown in Chapter 4.3. No changes were made to the coverage data collection or simulation logs.

6. RESULTS

This chapter presents the coverage and simulation performance results got from the original, original with monitoring and full UVM test benches shown in Sections 4.3. and 5.3. First, Section 6.1 shows code and functional coverage statistics got from Questa's coverage reports. Then, Section 6.2 presents data regarding test bench performance for all test benches used in this experiments.

6.1. Coverage

Both code and functional coverage results were extracted from the HTML reports generated by Questa. Practically, 100 % coverage should be reached in all coverage fields, and if not, exclusions with explanations should be used. The results presented in this chapter use no exclusions. And since the UVM environment uses the original test program flow, some functional coverage misses present in the original test bench will be present in the UVM the bench as well. The changes mainly come from changing the decoder configuration parameters to randomized parameters. Code and functional coverage results are shown in the following subsections.

6.1.1. Code

The code coverage statistics for the original and UVM test bench are presented in Figures 18 and 19, and the coverage number differences of these two are highlighted in Figure 20 (UVM compared to original). The code coverage was limited to the decoder unit, leaving out all test bench items. With the UVM test bench, 85 % coverage goal was used for the *cg_Decoder_Config_Iterations* covergroup (see Section 6.1.2.), and 100 % for other configuration and interrupt covergroups. These simulation goals resulted in a total of 7112 decoder test runs. The original test bench was run for the whole test program duration, which resulted in a total of 9144 test runs.

Scope	TOTAL	Statement	Branch	FEC Expr.	FEC Cond.	Toggle
TOTAL	65.12	88.99	66.98	64.64	31.75	73.24
la_Include	87.50	100.00	--	75.00	--	--
u_PowerControl	31.64	84.46	37.02	20.00	0.00	16.74
u_Decoder_Control	85.61	100.00	--	78.57	--	78.26
u_Decoder_ApbAdapter	78.14	100.00	--	66.66	--	67.76
u_Decoder_PeripAccess	51.90	51.88	60.06	53.84	33.78	59.96
u_Decoder_Tcm	85.21	95.76	92.13	100.00	82.14	56.02
u_Decoder_Ram	71.38	82.53	77.41	100.00	50.00	46.94
u_Decoder_MemoryIntf	92.96	100.00	100.00	--	--	78.89
u_Decoder_Core	91.02	99.47	97.64	75.00	90.00	93.00

Figure 18. Code coverage statistics (percentage) of the decoder unit got from the original test bench.

Scope	TOTAL	Statement	Branch	FEC Expr.	FEC Cond.	Toggle
TOTAL	65.65	89.03	67.07	66.66	31.75	73.74
la_Include	100.00	100.00	--	100.00	--	--
u_PowerControl	31.67	84.46	37.02	20.00	0.00	16.89
u_Decoder_Control	87.99	100.00	--	85.71	--	78.26
u_Decoder_ApbAdapter	78.48	100.00	--	66.66	--	68.78
u_Decoder_PeripAccess	52.31	52.09	60.36	53.84	33.78	61.47
u_Decoder_Tcm	85.21	95.76	92.13	100.00	82.14	56.02
u_Decoder_Ram	71.38	82.53	77.41	100.00	50.00	46.94
u_Decoder_MemoryIntf	92.96	100.00	100.00	--	--	78.89
u_Decoder_Core	91.11	99.47	97.64	75.00	90.00	93.48

Figure 19. Code coverage statistics (percentage) of the decoder got from the UVM test bench.

Scope	TOTAL	Statement	Branch	FEC Expr.	FEC Cond.	Toggle
TOTAL	+ 0.53	+ 0.04	+ 0.09	+ 2.02	--	+ 0.50
la_Include	+ 12.50	--	--	+ 25.00	--	--
u_PowerControl	+ 0.03	--	--	--	--	+ 0.15
u_Decoder_Control	+ 2.38	--	--	+ 7.14	--	--
u_Decoder_ApbAdapter	+ 0.34	--	--	--	--	+ 1.02
u_Decoder_PeripAccess	+ 0.41	+ 0.21	+ 0.30	--	--	+ 1.51
u_Decoder_Tcm	--	--	--	--	--	--
u_Decoder_Ram	--	--	--	--	--	--
u_Decoder_MemoryIntf	--	--	--	--	--	--
u_Decoder_Core	+ 0.09	--	--	--	--	+ 0.48

Figure 20. Differences of the UVM test bench code coverage compared to the original one (in percent).

It was known that the original test bench did stress the DUT quite thoroughly in the functional aspect. The behavior of the test program and the DUT operation also caused the code coverage to reach reasonably high values rather quickly, only getting small improvements with a very high number of tests. However, even with this baseline the randomization present in the UVM environment brought some increase to the code coverage with a lesser amount of tests, as it can be seen from Figure 20. The main reason for this is the different toggle values got from randomization, which also caused few extra statements, branches and expression to be executed.

6.1.2. Functional

Figures 21 and 22 show the functional coverage got from the covergroups for the original and UVM test bench, in respective order. The simulation coverage goals for the UVM environment, and the total number of decoder test runs for the UVM and the original test bench were the same as shown in Section 6.1.1. If 100 % coverage goal was also used for the iterations covergroup, the total number of test runs was 10033.

Covergroup	Total Bins	Hits	Hits %	Goal %	Coverage %
cg_Decoder_Registers	179	84	46.92%	100.00%	68.07%
cg_Decoder_Config_Length	127	127	46.01%	100.00%	100.00%
cg_Decoder_Config_Iterations	31	5	16.12%	100.00%	16.12%
cg_Decoder_Config_Prediction	4	4	100.00%	100.00%	100.00%
cg_Decoder_Config_CRC	2	2	100.00%	100.00%	100.00%
cg_Decoder_Config_ABS	2	2	100.00%	100.00%	100.00%
cg_Decoder_Interrupts	12	12	100.00%	100.00%	100.00%
cg_Decoder_Status	12	12	100.00%	100.00%	100.00%
cg_Decoder_Control	8	0	0.00%	100.00%	0.00%

Figure 21. Covergroup functional coverage of the original test bench.

Covergroup	Total Bins	Hits	Hits %	Goal %	Coverage %
cg_Decoder_Registers	179	84	46.92%	100.00%	68.07%
cg_Decoder_Config_Length	127	127	46.01%	100.00%	100.00%
cg_Decoder_Config_Iterations	31	27	87.09%	100.00%	87.09%
cg_Decoder_Config_Prediction	4	4	100.00%	100.00%	100.00%
cg_Decoder_Config_CRC	2	2	100.00%	100.00%	100.00%
cg_Decoder_Config_ABS	2	2	100.00%	100.00%	100.00%
cg_Decoder_Interrupts	12	12	100.00%	100.00%	100.00%
cg_Decoder_Status	12	12	100.00%	100.00%	100.00%
cg_Decoder_Control	8	2	25.00%	100.00%	25.00%

Figure 22. Covergroup functional coverage of the UVM test bench with iterations coverage goal of 85 %.

As it can be seen from Figures 21 and 22, the main neglects of the original test bench are the iterations configuration, and control covergroups. The parameter that determines the maximum iterations of the decoder was added to the pool of randomized parameters in the UVM test bench, making the coverage results much better for the *cg_Decoder_Config_Iterations* covergroup. The usage of control inputs was missing, and a small feature was added to make the usage possible, resulting in the 25 % coverage increase in the *cg_Decoder_Control* covergroup. The UVM environment goes through a wider range of configuration values than the original test bench with lesser tests. However, if all combinations of the configuration values would be gone through, the total number of test runs would be much higher than the 9144 test runs with the original test bench due to duplicate random values.

As it was stated in the previous section, the functional aspect of the DUT was already thoroughly tested with the original test bench. The results show that randomization itself did not bring much addition to the overall functional coverage. The main reason

for this was that the DUT operates in one specific way, not allowing much free space other than the decoder configuration. The iterations configuration in the original test bench was low due to using the most fitting value with majority of the runs, and stressing only both maximum and minimum values. Nevertheless, if a range of possible values have been implemented, all of them should be tested. The iterations covergroup being higher with the UVM test bench is reasoned with the original test bench being partly lacking, rather than with the benefits of the randomization. The same can be said about the *cg_Decoder_Control* covergroup.

6.2. Test bench performance

Test bench performance is measured in the terms of total CPU run time for each simulation using the different test benches presented so far. The total CPU run time consists of CPU time spent on optimization (Vopt), elaboration, simulation and Tcl command phases. The run time logging was enabled by using Questa's *simstats* formal argument. The CPU times were taken straight from Questa's log, and no extra profiling properties were used.

Simulation run times were measured with a shorter, single decoder test runs with multiple recursions, and a full decoder test runs with fewer recursions due to long simulation times. The UVM environment was run in manual mode to make sure the test flow was identical to the original test program. The total CPU run time results for these both cases can be found in Figures 23 and 24 below.

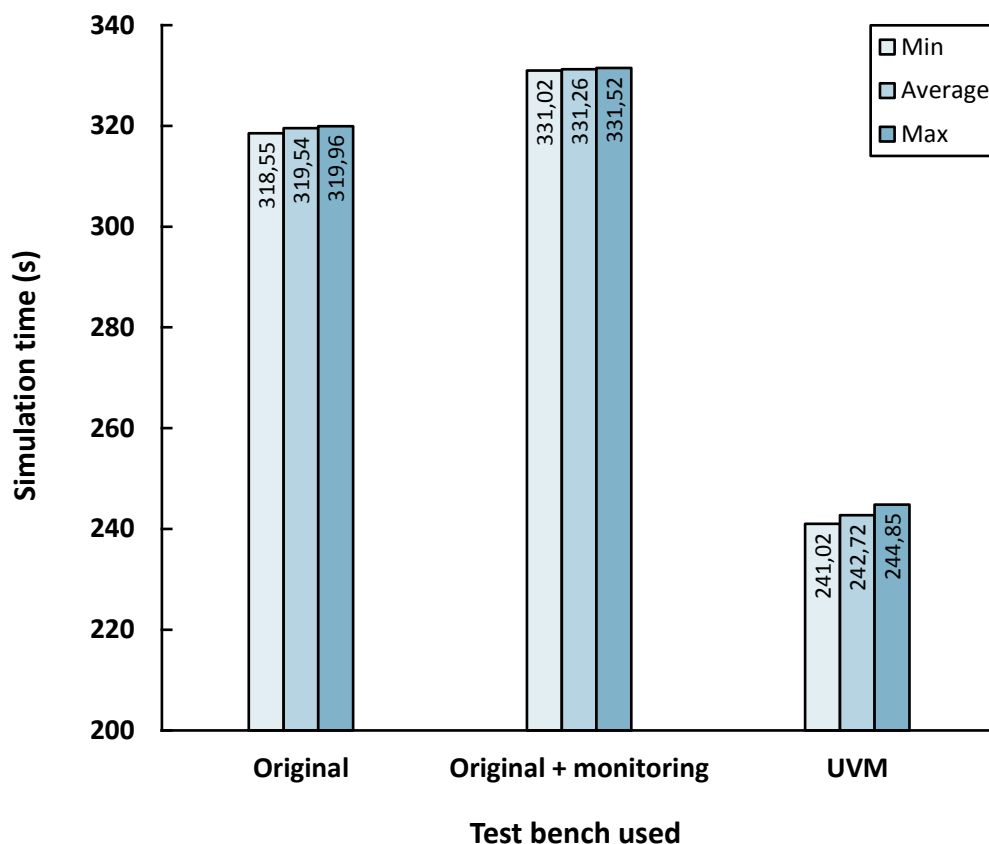


Figure 23. Total simulation CPU run time comparison using one decoder test run.

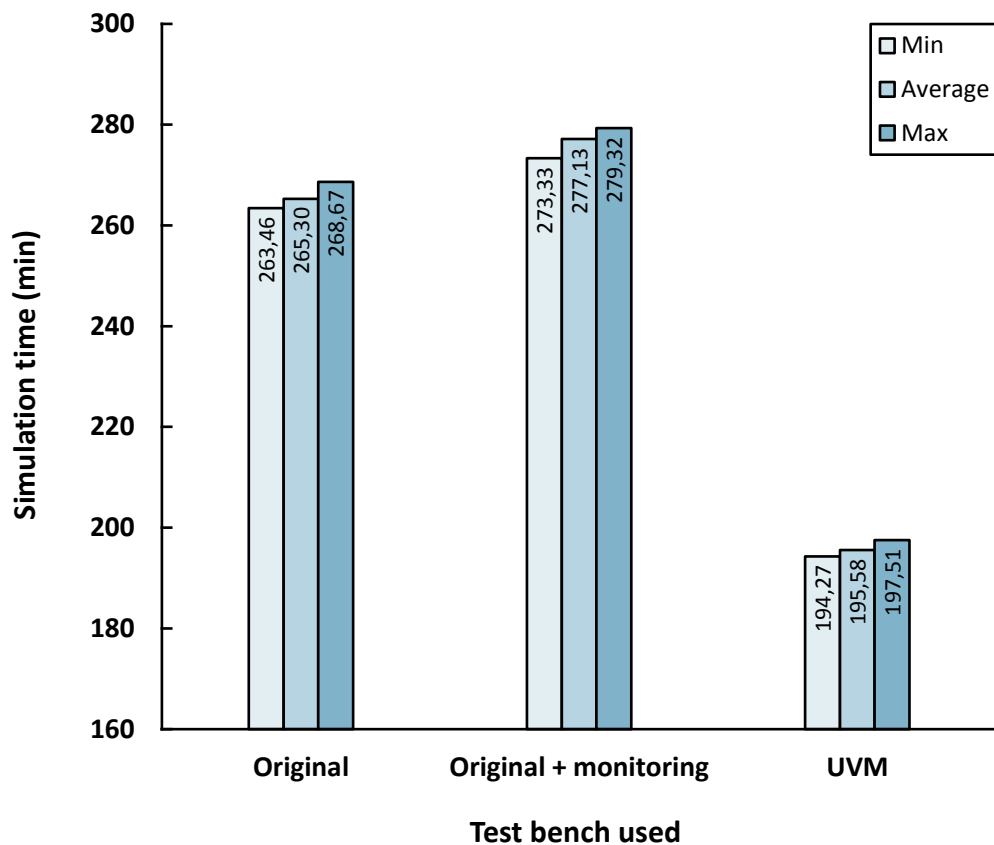


Figure 24. Total simulation CPU run time comparison using the full set of test runs.

Figures 23 and 24 show an expected result that the original test bench with monitoring enabled has longer run time compared to the original test bench only. With monitoring enabled, the increase in total CPU run time is around 4 % in both cases, which is not a groundbreaking time delay considering there are two test programs running in parallel.

The run times got from the UVM environment runs are surprising, since the UVM test program has extra synchronization compared to the original test bench because of the inconvenience of the C-model implementation. Due to this, the expectations were even worse than with the original test bench with monitoring enabled. Nevertheless, with this test program flow the UVM test bench provided significantly faster total CPU run times than the other two test benches. In the single test run, the UVM test bench total run time was around 24 % faster compared to the original test bench, and with the full test run, around 26 % faster. With longer simulations, improvements like this have a notable impact.

7. DISCUSSION

The objective of this thesis was to develop a UVM simulation environment based on an existing SV test bench. The environment was created to test the applicability of a UVM environment in IP verification compared to a more traditional module-based SV environment. The results got from this thesis show both positive and negative aspects of the adequacy of the UVM test bench with this particular IP.

The compatibility of a module-based SV test program and a class-based UVM test is good. The implementation done in this thesis showed only difficulties with the C-model integration. This problem seems to occur only when the C-model also uses tasks or functions from the SV side. The problem can be bypassed with some gimmicks, but it can be impractical for people working with test benches that often incorporate bidirectional C-models. This proposes that an update to the SV DPI and UVM interface could be done, making the C-model integration less problematic. In addition, it is important to remember that hierarchical references to the DUT do not go well together with class-based environments. With the test bench used in this thesis, this did not prove to be a problem, but with module-based environments incorporating a lot of hierarchical references, or with users accustomed to use hierarchical references in their verification, this limitation can feel frustrating. Class-based environments simply need a different kind of approach. Regardless, the use of hierarchical references is considered as a bad verification practice since it greatly reduces reusability of the verification components, and they should only be used when necessary.

Code coverage can be improved with constrained random stimulus. This is mostly due to large increase in signal bit toggles, and the amount of total test run. Only the high quantity of tests itself is enough to test most conditions, statements and branches found in the source code, giving high code coverage. On the other hand, a good functional coverage is mainly determined whether the test program executes specific functional patterns or not. The most crucial part is to understand the DUT operation and write test patterns that stress the different operation schemes. Randomization itself does not automatically give a good functional coverage, but it can always bring out new bugs in the tested operation scheme since a larger amount of different values are used in the stimulus. For both code and functional coverage, the way how the DUT operates matters a lot. Even with larger designs, if the operation is limited to one specific way, the improvement received from random stimulus is not that great. The DUT used in this thesis partially represents this kind of scheme. On the other hand, if the DUT has data inputs with a wide range of legal values, randomization usually brings major benefits. Yehia A. studied constrained random stimulus for achieving faster coverage closure [34]. In his work, Yehia used a direct memory access (DMA) IP and an Ethernet media access control (MAC) IP, both allowing a high degree of direct input stimuli, to compare constrained random stimulus to directed testing. The results Yehia measured showed that constrained random stimulus provided much faster coverage closure and coverage values with lesser amount of transactions used to stimulate the DUTs.

The different test bench performance results presented in Chapter 6 indicate that UVM environments can provide significantly faster total test bench run times compared to module-based SV environments. With the DUT and test program used in this thesis, the UVM test bench's total run time was between 24 % and 26 % faster than the original module-based SV test bench's. With test cases lasting multiple hours, the time saved was measured in hours. Because no simulator profiling properties were

used, it is hard to pin point the specific reasons for the improvement in the test bench total run time. Since the C-model integration required concurrent processes to implement the additional synchronization and communication between the UVM environment and the C-model, it is possible that the simulation server distributed its work load more efficiently, giving the DUT simulation more computation capacity. To find out whether this or something else causes the speedup, profiling needs to be used to acquire instance specific data, but that falls outside of the scope of this thesis. Söderlund T. also studied the performance of an UVM environment compared to a legacy test bench in his thesis [20]. Söderlund's UVM test bench was around 50 % slower compared to the original test bench, but also had added functionality, making the scenario slightly different than in this thesis.

There are also some downsides when adopting UVM verification. The UVM can be a bit overwhelming in terms of environment complexity. Typically, more time spent with UVM environments is required to be familiar with the common structure and operation of a UVM environment than with traditional, module-based environments. In addition, creating a single UVM environment from scratch is not much more efficient than creating an environment of a different type; sometimes it can be even more time consuming. The real benefit with UVM is acquired when a base set of UVM components exist and the verification engineers have the basic skillset to work with UVM. At this point most of the unnecessary hassle when working with UVM environments has been eliminated, and creating new verification environments for the project's needs requires much less working hours.

The goal of this thesis was to study the validity of UVM in IP verification. The goal was achieved by successfully creating an efficient UVM environment based on an existing SV test bench. The most interesting results got from this experiment were the UVM environment performance gains. Proving that porting versatile test benches to UVM is possible while gaining more code coverage by enabling randomization also serves its purpose. It would be really beneficial to replicate this kind of study, where no additional functionality is added to the UVM test bench, with different IPs. This would provide data regarding whether the performance or coverage improvements would be present with other types of test benches, or not. Nevertheless, based on the results presented in this thesis, UVM is an excellent option for versatile IP verification for any size of a design.

This thesis can serve as a starting point for future experiments regarding class-based IP verification involving existing test benches. When creating a coverage-driven UVM environment, the basic steps should be similar to what was presented in this thesis. In addition, the created UVM agents for different buses can be reused if more UVM environments are desired in the future.

8. SUMMARY

This thesis studies the advantages and disadvantages of UVM in IP verification. This is done by creating a CDV environment using UVM from an already existing module-based SV test bench. The history, concept and main features of UVM is presented, and a look into code and functional coverage is taken. The final conclusions are made based on the coverage and simulation performance results got from the different test benches.

UVM is a widely supported SV class library used for digital design verification. UVM follows the principles of object-oriented programming and utilizes proven OOP features like classes and inheritance. In addition to the OOP principles, UVM has multiple useful built-in properties, like phasing, transactions, message reporting and configuration database, to help with the test bench creation. Typical environments built with UVM have a clear class hierarchy, are able to drive and monitor the DUT, and do functional checking and coverage collection.

Coverage can be divided into two concepts: code and functional coverage. Code coverage is an automatically generated metric used to measure whether specific sections of the source code have been executed or not. Functional coverage is a manually declared model that represents the key functional features of the DUT, and shows whether those features have been tested or not. In SV, functional coverage models can be written with covergroups or assertions. Covergroups can also be used to enable CDV. Both code and functional coverage go hand-in-hand, and both are required to achieve complete coverage closure.

In the practical part, UVM monitor and subscriber components were first created to capture functional coverage from the IP's original test bench. For the full UVM test bench, UVM agents were created to enable driving of the DUT, and the monitors were transferred inside the agents. The original test program was ported to the UVM side, leaving out the original test program. The coverage results were collected in the same manner as with the monitoring test bench.

The results got from the three different test bench setups show that the full UVM environment provided performance improvements of 24 - 26 % to total simulation run time. Also, the constrained random stimulus found in the UVM test bench gave slight improvements to code coverage, but the random stimulus itself did not have a big impact on functional coverage. With functional coverage, randomization can aid the process of creating stimulus with multiple different values, but the final coverage results are determined mainly by the test patterns gone through and the coverage model itself. In this experiment, the DUT's operation flow was quite restricted, which also contributed to the low impact of the randomization. Nonetheless, UVM is an excellent option for IP verification based on the experiment done in this thesis.

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