Methodology of Communication Protocols Development: from Requirements to Implementation

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COMMUNICATION PROTOCOLS DEVELOPMENT
Communication Protocols Development

- **Communication protocol** is a set of rules for the order in which messages of particular types are exchanged.

- Nowadays communication protocols are widely used in different areas. Particularly, in the following areas:
  - Space and aircraft industry;
  - Vehicle systems;
  - Mobile industry (USB, UniPro, etc.);
  - Computing (TCP/IP, etc.);
  - Etc.

- The developed protocol should be *precisely investigated before being implemented*. 
Protocol Design Difficulties

- Increasing complexity of projects
- Demand to speed-up the project design phase
- Increasing requirements to products reliability
- Power consumption

The modern approach to the system design implies the **parallel** execution of some **design tasks**
System General Design Flow:

- **Conceptual system design**
  - Task-level design and choose of the optimal decisions
  - System-level design and choose of the optimal decisions
  - Elaboration of time, energy and board area constraints

- **Specification**
  - Spec. development
  - Functional spec. and research
  - Spec. improvement

- **Verification**
  - Behavioral level modelling
  - Testing

- **Logical design**
  - Choose of technology and library

- **Logical synthesis**

- **Physical verification**

- **Physical design**

**Collecting requirements for the target system**, evaluation of the main system description, analysis of the system mechanisms and development of the first specification draft.

**Translation of the executable project specification** to the register level (in Verilog/VHDL) and further at the gate level.

**This stage begins from the selection of technological and library basis** and it is completed when everything is ready for the final product production.

**Getting the final version of the system specification and the system model in a high-level language** (usually in C/C++, SDL).

**Verification of the design decisions on conformity to the specification and other requirements**.
What do we Cover by our Methodology?

**Generalised design flow**

- Conceptual system design
- Specification
- Logical design
- Verification
- Physical design

**Our approach**

1. Requirements collection, specification draft
2. Development of Formal Specification
3. Modeling and Verification
4. Performance Analysis
5. Implementation
6. Specification Update

- Errors, inconsistencies
- Functional requirements
- Non-functional requirements
- Errors

**SUCCESS**

**FAIL**
Collecting Requirements
Main Problems to Resolve

- Different terminology;
- Unclear requirements;
- Customer who:
  - does not know what they want;
  - wants more than they need;
  - wants to get smth absolutely new and keep all adjacent soft/hardware unchanged;
- Some parameters and requirements should be held in confidence, e.g. in space industry companies.
Main Principles of Collecting Requirements

1. Analyse the technical assignment, find “blank spaces”
2. Create a common vocabulary for both developer and customer
3. Create a draft questionnaire for the customer in accordance with possible functionality for the developed protocol
4. Interact with the customer, discuss every little question
5. Do not ask the questions on which the customer cannot know the answer
6. Do not ask “how” or “what do you need”, but “do you need THIS or THAT”
7. Analyse the answers, are there any inconsistencies or ambiguities?
8. Ask more questions to be sure that the customer understands your questions and his answers.
Specification and Description

Language Formal Spec
Formal Protocol Specification

- **The objective of development**: the target model describes all mechanisms, interactions and functionality which are stated in the specification.

- There is a set of FDT: Spin, Estelle, LOTOS, Petri Nets, SDL, etc.

- In our methodology we widely use **Specification and Description Language (SDL)** for protocol specification

- **Results of this stage**:
  - consistent readable textual specification
  - formalised graphical specification in SDL is produced which can be used as a reference for the textual spec
Specification and Description Language (SDL)

- Standardized between 1976 and 1992 by ITU-T
- High-level general-purpose graphical description language for event-driven, real-time and communicating systems
- SDL provides two representations:
  - Graphical (SDL-GR)
  - Textual (SDL-PR)
- Application fields:
  - telecommunication systems
  - protocols
- Provides strong structuring facilities which give an ability to describe systems of all kinds of difficulties

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The system described by an SDL specification represents the Extending Communicating Finite State Machine (ECFSM)

- It consists of a set of concurrent processes, extended with variables and data space.
- Communication is performed by exchanging control signals on finite-length asynchronous channels. Output signals of one process can be an input signal for the another process.
- Each process consists of a set of states. Transitions from one state to another are performed in accordance with the received signals.
Example of Protocol Stack SDL Specification

Upper Service Access Point

Internal interactions via channels

SpaceWire protocol layer blocks

Bottom Service Access Point

SDL specification of the SpaceWire protocol stack
Protocol Modeling

Main goals of modeling

• Verification of the protocol functional properties;
• Investigation of compatibility and correctness of algorithms and methods deployed in the specification;
• Investigation of protocol operation in case of error occurrence while data transmission.

Modeling and investigation directions

• Specification and Description Language;
• SystemC modeling;
• C++ reference code;
• SDL/SystemC joint model.

Basic approaches

• Protocol stack modeling;
• Network modeling.
**Goals:**
- check the data transmission
- check the routing correctness

**Benefits:**
- The real interest represents here the mechanisms of devices communications in the network which is the key issue for the performance analysis

**We cannot consider:**
- the protocol layers
- the interaction between protocol layers
- the forming of packets
- device’s operation with applications

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**Goals:**
- check the presence of errors in specification
- check the packets generation
- check all internal mechanisms

**Benefits:**
- The set of modules breaks into the layers forming hierarchy;
- Every layer communicates only with directly adjoining layers.

**We cannot consider:**
- Interaction of devices in a network
Approaches for Protocol Modeling (2/2)

Requirements collection, specification draft

Development of Formal Specification

Errors, inconsistencies

Specification Update

Formal spec

Modeling and Verification

SUCCESS

Performance Analysis

FAIL

SUCCESS

Implementation

Two approaches

Protocol stack modeling: SDL, SystemC, C++

Network modeling: SystemC

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Mapping of Modeling Directions to Design Flow Stages

SDL

SDL, SystemC, SDL/SystemC, C++ reference

SystemC network model

Requirements collection, specification draft

Development of Formal Specification

Modeling and Verification

Performance Analysis

Implementation

Specification Update

Errors, inconsistencies

Formal Description Technique

Functional requirements

Non-functional requirements

SUCCESS

SUCCESS

FAIL

Errors

SUCCESS

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SDL Protocol Stack Modeling
SDL Protocol Stack Modeling

- SDL is the most reasonable solution for modeling and validation on per layer basis.
- SDL model formally describes all mechanisms, interactions and functionality stated in the specification.
- Generally, the simulated system consists of two nodes which communicate via a model of a link.

- Such kind of modeling gives an ability to:
  - check and verify all internal mechanisms,
  - validate the consistency of the specification and
  - check functional requirements that were defined for the protocol.
- Furthermore, such SDL models can be used as a part of a tester.
SystemC Network Modeling
SystemC is a C++ library for modeling of embedded systems and communication protocols.

**The objective of development:**
- check the communication protocol operation over the network,
- test the network configuration,
- networking features and conduct the performance analysis.

In our methodology we widely use **SystemC** for network modeling and performance analysis.

**Results of this stage:**
- the final version of the system specification
- the system model in a high-level language.
SystemC Advantages

- SystemC uses
  - such primitives as channels, interfaces and methods,
  - it gives high flexibility in modeling that could be based on various computation models,
  - provides possibility to integrate and use these models in parallel.
- SystemC is C++ based and this point makes cooperation in HW/SW design easier.
- SystemC supports hardware modeling and detailing of a project to the RTL level.
Modeling of Networks

• Generally, the network model consists of the following SystemC modules:
  – Nodes implementing the communication protocol,
  – Switches or routers,
  – Traffic Generators, which operate over the nodes and give ability to launch different tests and generate test sequences.

• Configuration parameters:
  – data transmission speed,
  – number of nodes and switches,
  – time delay and routing table for the switch,
  – number of ports in the switch, etc.

• Ability to simulate operation of:
  – the various numbers of devices
  – networks with different topologies.
SDL/SystemC Co-Modeling. Tester
Protocol Model Tester

- **The objective of development**: verification of the protocol specification, algorithms testing on the basis of the developed protocol model.
- Such a Tester is able to:
  - validate the standard specification itself;
  - validate the model for correspondence to the specification;
  - test prototypes or boards in production;
  - certify products, verify products for conformance with the standard.
SDL/SystemC tester is a flexible tool for:

- setting different configurations;
- generating various test sequences;
- gathering statistics.

The Tester gives the following abilities:

- representation of tested layers by means of finite state machine
- access not to the whole SDL model only but also to certain layers of stack through appropriate Intermediate Blocks
- getting all necessary test results by SystemC implementation of the test environment
Organization of SDL and SystemC Co-Modeling

- SDL and SystemC can be combined in one model so as to:
  - use SDL as a basic FDT for specification, verification and performance analysis
  - use SystemC for creation of complex test sequences and to provide wide facilities to work with time
  - perform all investigations on the basis of one model of the protocol.

- Basic structure of SDL/SystemC co-model:
  - SystemC provides simulation core and test environment
  - SDL provides formal protocol implementation

- General principles:
  - SDL model is compiled into C-code, equivalent to the original model
  - Generated C-code together with the SDL core is integrated into the SystemC project
The Tester contains three parts:

- **Test Engine** – contains conformance tests and Tester control features
- **Modeling Core** – model of the tested protocols or protocol stack which are implemented according to the protocol specification in SDL
- **Medium** – ensures interconnection between tested nodes inside the Modeling Core
The Modeling Core consists of:

- Tested SDL model
- SDL/SystemC Wrapper
- Communication Wrapper

Intermediate blocks of Communication Wrapper

- module implemented in SystemC
- module implemented in SDL
Modeling Core

• Each Intermediate Block can provide the following features:
  – managing data flows transmitted through the Communication Wrapper
  – parsing transmitted data – introduced for getting information about data exchange between two adjacent layers
  – making logs – used for monitoring of results
  – error injection – introduced for testing of error detection and/or error correction possibilities of a tested protocol

• Key issues for SDL model implementation:
  – each layer shall be represented by one SDL block
  – all required layers should be joined to one SDL system
  – each two adjacent layers of one node can be connected in two ways:
    • through an SDL channel only
    • through an appropriate Intermediate Block
The Test Engine module is responsible for control of the SDL model simulation.

The Test Engine tasks:
- Configuration of the SDL model Communication Wrapper before the start of test sequence.
- Configuration of the Medium. During this phase, channel parameters such as the channel delay and the error injection are defined.
- Data exchange with the tested SDL model. The Test Engine operates in accordance with a protocol of the chosen layer and uses services of the layer below.
introduction of delay

set of channels implementing a particular data transfer protocol

error injection

logs

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C++ Reference Model
Reference Code

• The reference code is a software implementation of a protocol in C++ language;

• **The objective of development:** create a reference for the programmers, who will implement the protocol in the software as well as use it as a part of a joint hardware/software tester;

• The C++ reference code describes:
  – the logical structure of the protocol,
  – its interfaces,
  – all internal mechanisms.

• This reference code can be used for:
  – studying of the protocol functionality;
  – translation into the other programming language;
  – implementation of a protocol in the software;
  – hardware/software testing.
Hardware/Software Testing

- A set of test cases for checking DUT operation
- Reference implementation of the tested protocol
- Module for testing non-nominal cases

DUT is a device which shall be checked on conformance to the protocol specification. DUT can be represented by either:
- Hardware
- Software

- Test cases
- C++ reference
- Error Generator
- HW Driver
- HW/SW Tester
- Device Under Test
IP-Core Development
IP-core Development

- IP-core (or IP-block) is a reusable unit of logic, cell, or chip layout design
- **The objective of development:**
  - check the hardware implementation of the protocol,
  - check the operability of the protocol’s mechanisms,
  - evaluate hardware costs.
- In our methodology we use **VHDL** for implementation of IP-blocks
- **Results of this stage:**
  - IP-block area estimation;
  - Clock frequency estimation;
  - Power consumption characteristics;
  - Protocol ready or not for the hardware implementation.
The protocol controller implementation: Typical structure of IP-block

Main concerns on reusability in different network-on-chip (NoC) projects:

- Varied technologies (FPGA, ASIC), different technology process (libraries);
- Different standards of NoC system interface (e.g. AXI, OCP).

- depends on SoC (NoC) interface
- common problem: different standards

**Functional part**

**Controller (IP-block)**

- Block1
- Block2
- Block3
- Block4
- Block5
- Block6
- Block7

**System interface controller**

**RTL model, written in HDL (VHDL, Verilog) – independent from technology library**

**Component from technology library (e.g. – memory block for FIFO implementation)**

• determined by a standard

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Issue of Varied Technologies

1. Separation of technology dependent sub blocks to a particular “tech” block,
2. Development the special “tech” block for used technologies

using “if... generate” for every technology dependent sub block

A_mem: for I in 1 to 1 generate
A_FPGA_Virtex_5: if tech_parameter = fpga_virtex_5 generate
A_buf: xRAMB16_S36_S36
port map(DOB=>QB_copy(31 downto 0),
   DOPB=>QB_copy(35 downto 32),
   ...
end generate

A ASIC 1_90: if tech parameter = ASIC 1_90 generate
A_buf: SRAM16x36
Port map(DB =>QB_copy,
   ...
end generate;
end generate;
Issue of Different NoC System Interface Standards

1. Development of the **special block of a system interface controller** for every communication standard

   - IP-block
     - Functional part
     - System interface controller

   Possible to use an approach similar to the previous issue

2. Utilize a **Bridge** between the IP-block and communication system

   - IP-block
     - Functional part
     - System interface controller
     - AXI bridge
     - AHB bridge
     - OCP bridge
     - WISHBONE bridge

   Possible to implement this bridge either use the ready decision from Design&Reuse

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OUR EXPERIENCE
## Modeling Directions in Projects

### SDL
- UniPro (MIPI Alliance)
- SpaceWire (University of Dundee, ESA)
- SpaceWire-RT (FP7 project)
- STP-ISS protocol (JSC Information Satellite Systems)

### SystemC
- UniPro, PIE (MIPI Alliance)
- SpaceWire, RMAP, STP (University of Dundee, ESA)
- SpaceWire-RT
- STP-ISS protocol, Plug-n-Play (JSC Information Satellite Systems)

### SDL/SystemC
- UniPro
- SpaceWire-RT
- SpaceWire

### C++ reference
- STP-ISS protocol
Thank you!
Questions?