



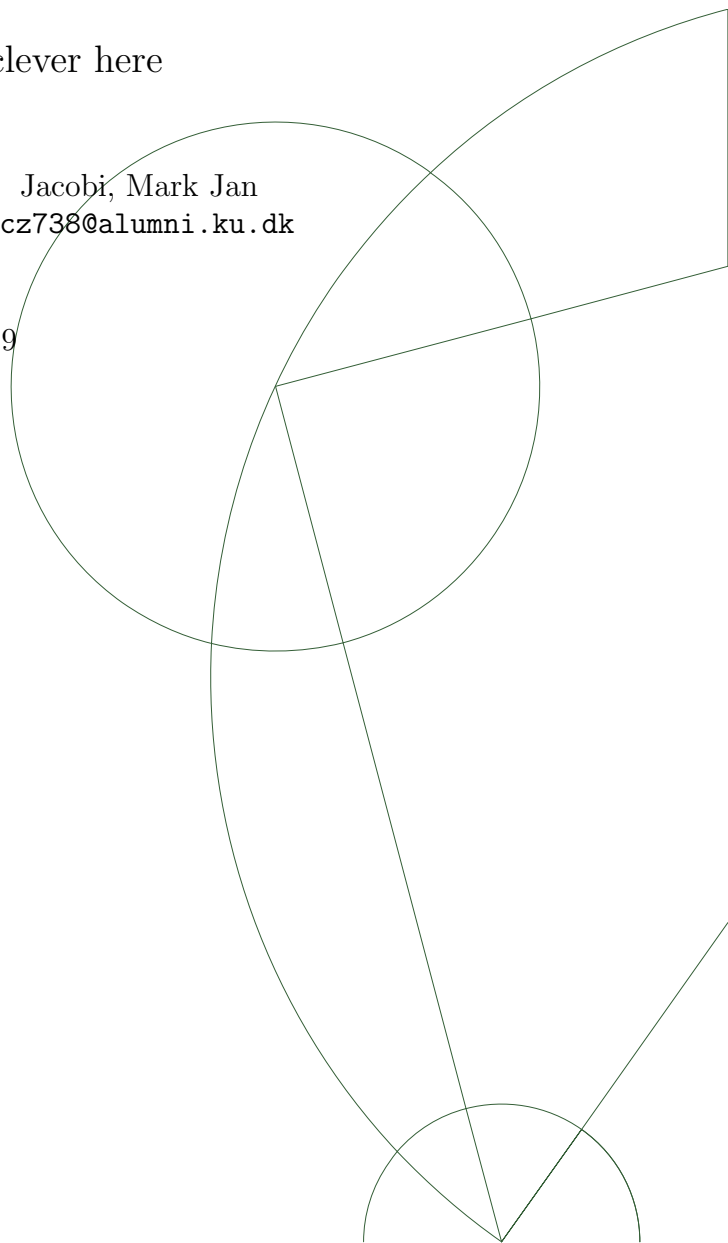
# TCP/IP in hardware using SME

Write something clever here

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Background</b>	<b>2</b>
2.1	Internet Protocol Suite (TCP/IP)	2
2.1.1	Link Layer	2
2.1.2	Internet Layer	2
2.1.3	Transport Layer	2
2.1.4	Application Layer	3
2.2	Hardware	3
2.2.1	Field Programmable Gate Array (FPGA)	3
	Technical specifications	3
	Programming an FPGA	4
2.3	Synchronous Message Exchange	4
2.3.1	The model	4
2.3.2	Process execution flow	5
2.3.3	Using SME	5
<b>3</b>	<b>Design</b>	<b>6</b>
3.1	Overview	6
3.1.1	Design principles	6
3.1.2	Initial requirements	6
3.2	The architecture	7
3.2.1	Initial design	7
	The issues	7
3.3	Pipelined design	8
3.3.1	Internet layer processes	8
3.3.2	Busses	9
3.3.3	Data buffers	9
3.3.4	Interface	10
	Read/Write interface	10
	Interface Control Bus	10
<b>4</b>	<b>Implementation</b>	<b>11</b>
4.0.1	Interface Signal protocols	11
4.0.2	Buffer-Producer data transfer	11
4.0.3	Compute-Producer data transfer	11
4.0.4	Interface Control	11
	<b>Appendices</b>	<b>12</b>

# Chapter 1

## Introduction

This thesis describes the design and implementation of an efficient, high-speed TCP/IP network stack intended to run on custom hardware where performance, responsiveness, and throughput is crucial.

As is the trend with modern automation, computerization, and mechanization, new devices are steadily invented to handle this increasing demand for data and control. With the ever-increasing sophistication of machines generating immense amount of information, the data needs to be transmitted to numerous other machines for further processing, or even simply storage. The most common and the most convenient way of linking multiple devices together is using the internet, and its underlying protocols. However, the networking stack supplied with most major operating systems, while heavily optimised, suffers from considerable penalties due to complexities of a standard computer architecture. For example, heavy network traffic utilizes the computers' internal busses, allocates vast amounts of memory, and spend precious CPU clock-cycles with polling and interrupts. This prevents the machine from using these resources for actual computing tasks.

These issues have been identified and solved by hardware manufacturers by adopting dedicated Network Interface Controllers (NIC) which would employ various techniques to offload the processing. One such offloading technique is called the TCP offload engine (TOE), which usually takes care of the essential parts of networking involved – the Internet Protocol and the Transmission Control Protocol [15].

Modern hardware manufacturers can produce NICs boasting network throughput speeds as high as 100 Gigabits [8]. Unfortunately, these cards are highly specialized for certain applications, and even though they provide basic programmability, they are rarely suitable for rapid prototyping of applications and other custom hardware devices. Furthermore, each NIC manufacturer has a diverse set of hardware with varying interfaces, making it hard to combine and swap and test these cards. Licensed software solutions in the form of IP blocks exist as well. Unfortunately, these blocks are usually distributed as black-boxes of VHDL code, which is hard to maintain, and even harder to debug and extend.

In this thesis, we bridge the gap between the blazingly-fast network offloading devices and their more flexible and malleable software counterparts.

This networking stack is implemented in a fully self-contained fashion so that it is completely independent of any other software running on the machine, while utilizing the performance advantages gained from the lack of overhead in conventional implementations. The use of a high-level programming language in combination with the modern Synchronous Message Exchange model makes the network stack a very versatile implementation with ease of use, debugging, and even extension.

MORE TO COME!!

# Chapter 2

## Background

In this chapter, we will introduce the basic concepts of the Internet Protocol Suite, briefly describe its origin, semantics, and some of its protocols. Furthermore, SME and the hardware it will run on will be introduced as a basis for the implementation.

### 2.1 Internet Protocol Suite (TCP/IP)

Internet Protocol Suite, better known as simply TCP/IP, is a conceptual model providing end-to-end communication between computers. It consists of a collection of protocols specifying the communication between multiple Internet systems [6]. The very early research and development on what would later become the Internet Protocol Suite began in the late 1960s by the Defense Advanced Research Project Agency (DARPA), and was being adopted by DARPA, as well as the public, since 1983 [19]. Although the Internet Protocol Suite predates the newer, arguably more refined Open Systems Interconnection (OSI) model, TCP/IP still remains the popular choice in modern systems. As opposed to OSI 7-layer model [13], the collection of protocols in TCP/IP are organized into 4 abstraction layers, each related to their scope of networking involved.

#### 2.1.1 Link Layer

The link layer is the lowest, bottom-most layer in the Internet Protocol Suite. Link layer addresses methods and protocols operating on the link that the host is physi-

cally connected to<sup>1</sup>. Contrary to the OSI model, this lowest layer in TCP/IP does not regard the standards and protocols of the physical mediums used (the pin layout, voltages, cable specifications etc.), making TCP/IP hardware-independent. As a result, TCP/IP can in theory be implemented on virtually any hardware configuration, emphasizing the flexibility of the model.

#### 2.1.2 Internet Layer

The internet layer mainly concerns itself with sending data from the source network to the destination network. This seemingly simple task requires multiple functions from the layer:

- Addressing and identification
- Packet routing
- *Basic* transmit diagnostic information
- Carrying data for various upper layer protocols

#### 2.1.3 Transport Layer

The transport layer establishes end-to-end data transfer between hosts. Protocols in the transport layer can provide additional services to the user, such as reliability, ordering, error- and flow-control, application addressing (port numbers), error-checking, and so on.

While it is possible to bypass the protocols in this layer on most modern network stacks, the protocols in the transport layer provide such essential and useful services

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<sup>1</sup>Wireless connections are also included under this category.

that it hardly ever makes sense to implement in the application layer.

While there are numerous protocols defined in the Transport Layer, perhaps the most well-known protocol in the stack is the Transmission Control Protocol (TCP). Being one of the most used transport protocol for its reliability and congestion control systems, it is rightly justified to refer to the whole Internet Protocol Suite as simply "TCP/IP".

#### 2.1.4 Application Layer

The application layer protocols are used by applications and services to exchange information over the network. A few of the well-known application layer protocols are the Hypertext Transfer Protocol (HTTP) [3], File Transfer Protocol (FTP) [4], and Simple Mail Transfer Protocol (SMTP) [16]. This layer is usually implemented by the userspace applications themselves, and therefore are not strictly required to actually run a TCP/IP network.

## 2.2 Hardware

The networking stack is intended to be flexible enough to run on just about any configuration of hardware and software. However, this also means that it cannot depend on any major external components, such as an existing memory, a processor, or any form of operating system. Fundamentally, not only the software-part of the networking stack has to be implemented, but the hardware needs to be defined as well. This hardware should be self-contained enough to work well in combination with any additional system, which the user incorporate for networking. A wide variety of hardware types exist for such independent system, such as Application-specific Integrated Circuit (ASIC), Complex Programmable Logic Device (CPLD), Socket on a Chip (SoC), and Field-Programmable Gate Array (FPGA). Each of these integrated circuits have their advantages and disadvantages; some of them are re-programmable, some

are cheap and disposable, and some are excellent for general-purpose applications. In this thesis, only FPGAs will be taken into consideration for its re-programmability, its fairly low-cost, and the compatibility with SME code-generators.

#### 2.2.1 Field Programmable Gate Array (FPGA)

Field Programmable Gate Arrays, or FPGA for short, are devices containing integrated circuits (ICs) consisting of arrays of logic blocks. These logic blocks can be programmed to form arbitrary logic circuit by simply synthesizing a design and then loading it onto the board. This process alone can save the manufacturer months by not having to fabricate a whole new IC. FPGAs can be used for any computational tasks without the need of any additional hardware. Usually, these devices are used for smaller, domain-specific tasks, where the control over the hardware yields significant performance increases. FPGAs are indeed very universal, and can be used in product-design, prototyping, as well as in final products. Products like car driver assistance systems [9], audio decoders [10], or even internet search engines [5] all utilize FPGAs to increase the performance, lower the electrical bill, and boost the development potential.

#### Technical specifications

Field Programmable Gate Arrays consists of a vast number of ICs, which can be re-programmed at any time for a desired application or functionality [12], making the devices very flexible and extensible, even after manufacturing.

These ICs are practically totally independent, and their logic within can be programmed and combined in virtually any way with other ICs. This, however, poses a problem, as signals do not propagate through circuitry, immediately, but rather, they have a slight delay. Sometimes, two events precede each other, while other times, events of distinct timings must occur

simultaneously. Since the order of events is critical for correct and expected execution in digital circuits, a digital clock is used to ensure everything runs in sync. A clock in this context emits a series of pulses in a pre-determined and very precise interval. These pulses are used to control the execution of various elements in the circuitry. When synthesizing to a FPGA, the compiler finds the longest code-path, it finds the required circuitry to perform the calculation, and then it determines the minimal required time for the signals to propagate through the path. In this manner, the fastest possible clock can be found for that particular circuit.<sup>2</sup> With innovations and steady improvements in modern FPGAs, the circuitries within the devices can be clocked at higher than 500 MHz [11].

### Programming an FPGA

Unlike conventional processors with a very sequential nature, the logic blocks in FPGAs are truly parallel in nature. Given the right programming, an FPGA can allocate dedicated sections of the chip for each independent subtask, enabling the circuitry to perform numerous independent calculations at once [12]. Unfortunately, this universality of FPGAs comes at a cost to their performance. Whereas conventional processors are heavily optimised based on the predetermined circuitry, FPGAs programmers must ensure to utilize the parallel nature of the device in order to secure best possible performance. Even worse, the FPGA must be programmed in such a way that all paths in the electrical wiring can be in any time-frame.

Due to this parallel nature of FPGAs, conventional programming languages are next to impossible to use. To define the behavior of an FPGA, Hardware Description Languages (HDL) are used. These programming languages are not easy to learn without a good grasp of electrical engineer-

ing. Even with prior programming knowledge, the unusual approach to concurrency in these languages can be hard to understand for average developers.

To simplify the development process, most manufacturers offer predefined circuits along their FPGAs. These predefined circuits are more commonly known as Intellectual Property (IP) cores, and can provide the hardware designers with pre-made circuitry for a wide variety of functionality. While most IPs provide the functionality of processors for testing on an FPGA, mp3 audio decoding or PCI bus interconnect can be obtained as well [1].

## 2.3 Synchronous Message Exchange

The Synchronous Message Exchange model (SME) is a messaging framework created in order to help model hardware descriptions [17]. It was conceived once the flaws of using Communicating Sequential Processes (CSP) was identified during the modelling of a vector processor with CSP using PyCSP [14]. It turned out that there is a major discrepancy between the way data is propagated in hardware opposed to that of the CSP model. While CSP does not pose any requirements on the communication between processes, in digital hardware, all communication has to be synchronized, driven by a clock. To combat this in the CSP model, a global clock process needed to be implemented, which was connected to all other processes. Additionally, latches had to be introduced in order to not overwrite values during a cycle. This caused an explosion of both channels and latches in the final design, making CSP a much less viable framework for hardware modelling [17].

### 2.3.1 The model

The SME model consists of only a few fundamental concepts. Each SME model is a *network* consisting of one or more *processes*. These processes do not share any memory or storage, but are interconnected

<sup>2</sup> Although many modern FPGAs consist of multiple regions which can have individual clock-rates. While it is a demanding task to propagate signals across these boundaries, a performance increase can be gained.

with *busses*. These busses are perhaps the most interesting units in SME model, as they not only propagate information between processes using the underlying *channels*, but also introduce an implicit clock between the processes.

strong typing system, which better reflects the functionality of the hardware, as well as making the code more readable to the programmer. At the time of writing, the C# implementation currently enjoys the most recent features of the SME model, as it is being the most actively developed version.

### 2.3.2 Process execution flow

The execution flow of a process is fairly simple, and relates very closely to that of the actual hardware. At the beginning of a clock-cycle, the input-ports are read into the busses they are connected to. Then, the process executes its "compute" stage, and the results, if any, are written to the output-port, which will be read by the following bus. A visualization of the execution flow can be seen on figure 2.1. It is im-

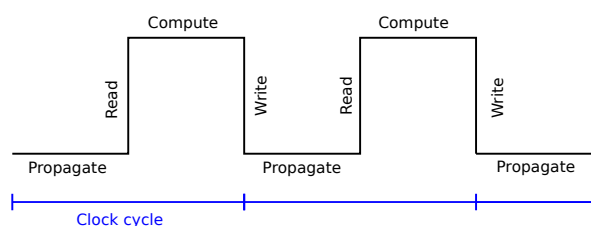


Figure 2.1: An illustration of a typical SME clock-cycle

portant to note that although certain channels might be written earlier than others in a process clock, the subsequent processes connected to said bus will first see the values change in the beginning of the next clock cycle.

### 2.3.3 Using SME

SME has undergone multiple iterations, reworks, and extensions. While it is still under very active testing and development, its core functionalities and features are well-established and stable [18].

SME has concurrent implementations in the C# and Python languages, with promising efforts to unify these under a common intermediate domain-specific language SMEIL [2]. The C# version has exhibited various advantages over the Python counterpart, such as the more error-prone

# Chapter 3

## Design

### 3.1 Overview

The networking stack introduced in this thesis is implemented in the C# programming language with SME. The aim of its design is to capacitate performance, flexibility, and ease of use. In this chapter, the design principles are described, the architecture of the solution is outlined, and the components are outlined.

#### 3.1.1 Design principles

As briefly mentioned in the introduction, the proposed network stack is to provide an alternative to the existing proprietary network offloading engines. While the main goal of this thesis is to research and study the suitability of SME for implementing a TCP/IP stack on an FPGA, there are many other aspects of the system to be studied. The extensibility of the network stack are to be tested by studying the effects of introducing new protocols to the stack. While the network stack should be able to be refined with new and custom protocols, it is to be studied which implications it has for the system. Mainly, it is to be seen how the addition of new protocols affect the performance, scalability, and viability of the system.

In the same vein, the design should be as FPGA-agnostic as possible. While this is mainly guaranteed by the SME framework used to develop the system, the underlying systems, operations, and features should be easily portable across FPGA manufacturers.

Lastly, the design of the networking stack should be interoperable with other systems

on the FPGA, or even FPGAs. It is to be seen how easy it is to modify and extend the versatility of the system without any major modifications or even extensible knowledge of the system. As an example, the networking stack can be expanded with a firewall, developed alongside this project.

#### 3.1.2 Initial requirements

Following our design principles, initial requirements and goals for the networking stack are set so that these can be tested and improved upon.

- **Essential protocols only**

Considering that the SME project is still fairly early in its development, and considering the sheer number of protocols in the internet protocol suite, the networking stack in this thesis is to support only the absolutely essential protocols required to provide the users with a meaningful interface to the internet. These protocols should be picked such that the system can provide the end-user with a network data-stream, which can transport information to and from a remote computer.

The initial protocols chosen may be implemented and supported partially, but they must not deviate from the standard specifications.

- **Support an interface for the end-user**

The system must be controlled by an end-user on the FPGA. Such an interface is very unique in its own way, compared to standard software interfaces,



like the ones defined in the POSIX collection of specifications. By supporting such an external interface gains insight in the way such a networking stack will be used, and which measures must be taken in order to provide the best possible integration and performance considerations.

- **Independent of underlying physical hardware**

By using SME, the underlying hardware description language code can be abstracted away from the actual implementation. This will later provide developers to easily modify and tweak the networking stack without having to consider the target hardware.

Likewise, the networking stack may not rely on using a certain physical layer hardware, and must be designed to be independent of the underlying hardware used for the physical connections. This will ensure that the target hardware can easily swap between physical connectors, such as going from ethernet cables to wireless, or even another FPGA.

## 3.2 The architecture

### 3.2.1 Initial design

The initial architecture focused heavily on the input from the link interface, minimizing hardware memory requirements, and to minimize the latency from the source data-stream to its respective layer handler.

In the initial design, figure 3.1, the link interface, which provides the raw byte-stream from the network, is connected to all of the input parsing layers. The layers are connected in the order in which a network frame is parsed; link- to internet- to transport-layer. This approach aims to utilize the fact that the layers can act immediately upon the packets received directly from the source, avoid having to buffer the whole packet in each stage, as well as easing the logic required to buffer the data across the layers.

This design starts by the Link Interface

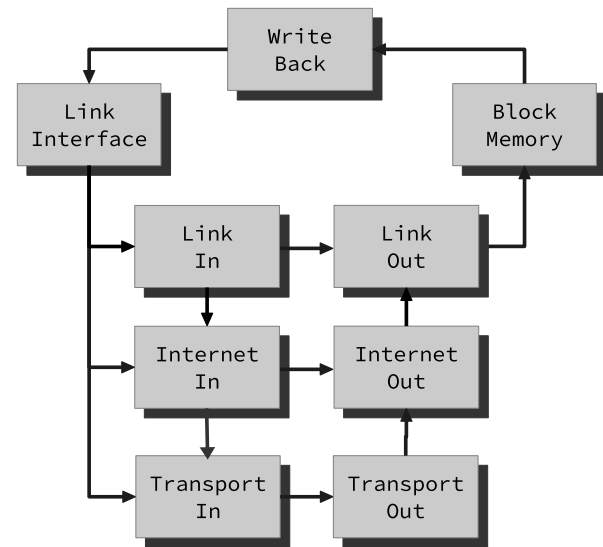


Figure 3.1: The initial design

sending one byte at a time through its bus. The **Link In** will parse the first header, and signal the next layer upon completion. **Internet In** will then start to listen on the **Link Interface** bus and, using the information from **Link In**, parse the internet header accordingly. The same procedure would be applied to the connection between **Internet In** and **Transport In**.

When data is to be sent to the internet, the network frame would be built bottom up from the transport layer through internet to the link layer.

### The issues

The issues quickly surfaced during the implementation of the design. Although the interconnect from the **Link Interface** to all the subsequent layers in parallel promised negligible latency, it came with a great cost to the solution:

1. **Process under-utilization**

Since each "in" process has to wait for the previous layer to signal when to start listening on the data-bus, the layers would in average only be active a third of the time. Since each layer has very little information about the states of the other layers, it would become a

challenge to get any other work done during these phases.

For example, it would be an immense challenge to coordinate an ICMP reply on a faulty packet in the **Internet In**.

## 2. Redundant Link layer

While the Link layer is an essential part of the Internet Protocol Suite, it did not fit well with the functionality of the rest of the stack. Most network interfaces are equipped with buffers, on which integrated circuits perform operations such as error check using cyclic redundancy check, de-noising, timeslot management, etc. Likewise, the Pmod NIC100 Ethernet interface has built-in controller with internal memory suited for buffering the incoming packets [7]. This memory, apart from the cyclic redundancy check, can be used as the initial step for parsing the packet, and only send the data-gram to the stack.

## 3. IPv4 fragmentation and out of order TCP packets

The chaotic nature of internet routing might cause packets to come out of order, or even get fragmented along the way. Since each layer parses the packet immediately as it is written to the bus, it became a challenge for the layers to figure out what to do. On IPv4 fragmentation, if the second half of a dataframe arrived first, the Transport header would not be available to the Transport layer. Although IPv4 fragmentation is an increasingly rare phenomenon, the network design is not able to handle the situation well.

## 4. TCP connection state sharing

With a clear separation between the "in" layers and the "out" layers, the Transport block had to be split as well. Unfortunately, unlike the other stateless layers, the transport layer actually needs to keep track of the connections and their states. On every segment received, the appropriate connection needs to be updated accordingly. In the TCP protocol, the connection

state changes on both receiving and sending. In this case, the **Transport In** and **Transport Out** have to agree on a shared state. As these states can be quite large, and the should support multiple connections at once, one large bus containing all the information is not feasible. To solve this, a negotiation protocol may be introduced, however, as pointed out in item 1, the processes are very limited in their execution time. A negotiation would be very hard to achieve in such circumstances.

While it would be possible to work around these identified issues in code, the added complexity would have additional ramifications on the project as a whole. Upon further analysis of analysis, it is clear that the source of the issues is the parallel arrangement of the process blocks.

## 3.3 Pipelined design

The next iteration of the design utilizes a fairly standard approach to pipelining, albeit with an unusual transfer of data between the stages.

The idea with the pipeline is to enable the processes to receive, compute, and forward data at their own pace, without any major limitation from the other parts of the system.

### 3.3.1 Internet layer processes

The processes performing computation and processing on the actual internet packets, called "layer processes" for brevity, are by large kept intact from the previous design. The fairly simple, but highly sequential nature of packet header parsing turned out to be very complicated to optimise with the additional computing power of the hardware, without introducing too much complication.

Missing from the updated figure 3.2 are the **Link In** and **Link Out** processes, which, for now, are made by the ethernet interface, which can easily parse and strip the first frame headers.

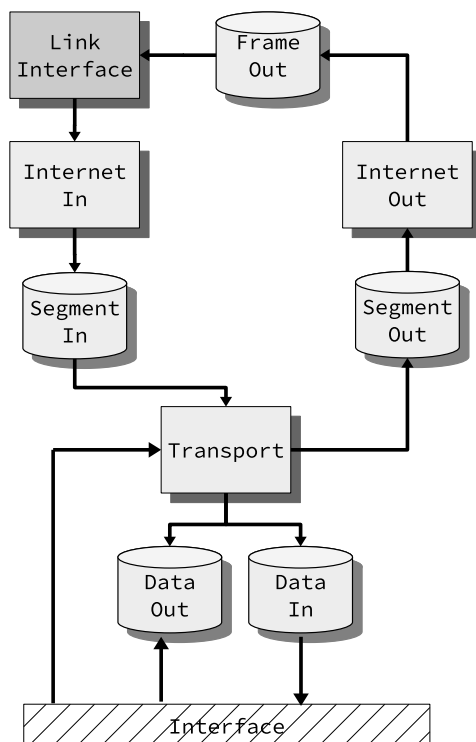


Figure 3.2: The revised design

### 3.3.2 Busses

The busses in the revised pipelined design are devised such that communication is only limited to the immediate neighbours in the logical network. This design is put in place so that the synchronization and the order of execution is much easier to keep track of, so that fewer race-conditions occur, and so that blocks in the network are easier to replace, remove, or modify, without having a large cascade effect on the whole network, as opposed to only the neighbours.

Whereas in the previous design where the busses would simply write new data on every new clock-cycles regardless of the reading processes, now there must be some logic to actually ensure that the reading process is ready to receive new data. While the Data Buffers, as introduced in the next section 3.3.3, solve the issue of blocks reading and writing data at their own pace, the busses must support an interface for sharing the state of both processes. Thus, while the busses are depicted as directional with arrows in figure 3.2, there is naturally a need for a control signal in the opposite direction to control the data-flow. This communication protocol will be discussed further in the implementation section 4.0.1.

### 3.3.3 Data buffers

Illustrated as cylinders on figure 3.2, First-In, First-Out (FIFO) buffers are introduced between each parsing process in order to control the data-flow between the layers. Apart from maintaining a fairly large memory bank through the block-RAM, these buffers also contain logic to store the incoming data intelligently in order to offload the following processes. For example, the **Segment In** buffer ensures that fragmented IPv4 packets are defragmented before leaving the buffer. However, introducing a new "type" of a process — the buffers — poses a new challenge. While the buffers can be read from at any time, the layer-parsing processes do not have this luxury, as they do not have any significant internal buffer. Here again it becomes obvious that a hand-

shake protocol needs to be used in the bus-communication between the buffers and the processes.

### 3.3.4 Interface

Lastly, the Interface is designed so that the end users and system can utilize and use the network stack.

The networking stack is controlled with 3 connections (consisting of bus-pairs): the control-, the read-, and the write-connection. While the last two connections are incredible simple and only transfer data from the **Data** buffers, the last connection controls the whole network-stack.

#### Read/Write interface

In conventional programming languages, the user would usually supply the a function call with an array or a list on which the function can operate. However, in hardware, this is generally not the case, as arrays are costly to transmit at once.

Therefore, the two read and write interfaces would simply stream one byte at a time, and it is up to the user to be prepared to read or write the data.

#### Interface Control Bus

The Interface Control Bus controls all the "business" logic of the network – maintaining the active connections, starting and closing connections, and various other protocol-specific control on each connection.

Currently, all this can be handled by the **Transport** block which has all the necessary information to handle the interface requests.

The design of the Interface is based on the widely adopted Berkeley Sockets library, which saw the first implementation in 4.2BSD, and has been defacto a standard component in the POSIX specification [20]. There are multiple reasons for this decision:

- The Interface will feel more familiar to users accustomed to the Berkely Sockets API commonly found in main-

stream systems such as Linux, OSX, and BSD variants.

- The inner workings of the stack will be more transparent, and the API exposes fairly fine-tuned control over the whole network stack.
- Even with the relatively few functions exposed, the API has thrived in the most used systems as of now. It would be an understatement to say that the Berkeley Sockets API have stood the test of time, and therefore, it is a good basis for the interface used in the network stack.

The first version of the stack should support the following functions:

# Chapter 4

## Implementation

### 4.0.1 Interface Signal protocols

With the introduction of buffers between each parsing processes, a clear pattern emerged. The layer-handling processes are responsible for numerous real-time tasks (parsing, sending, protocol-specific tasks, etc), while also limited by their fixed internal buffers. These processes are not always ready to receive input from preceding processes, while they at the same time must be able to write their output to following processes immediately.

The buffers are a stark opposite, as their large internal block memories enable them to buffer huge chunks of memory, while also being able to wait for the succeeding process to start reading.

With these two established scenarios, protocols for each can be proposed.

### 4.0.2 Buffer-Producer data transfer

### 4.0.3 Compute-Producer data transfer

### 4.0.4 Interface Control

# Appendices

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