

Comparing HLS with VHDL at the example of an FM Radio Receiver

Michael Wurm



MASTERARBEIT

eingereicht am
Fachhochschul-Masterstudiengang

Embedded Systems Design

in Hagenberg

im Juli 2021

Advisor:

DI (FH) Dr. Florian Eibensteiner

© Copyright 2021 Michael Wurm

This work is published under the conditions of the Creative Commons License *Attribution-NonCommercial-NoDerivatives 4.0 International* (CC BY-NC-ND 4.0)—see <https://creativecommons.org/licenses/by-nc-nd/4.0/>.

Declaration

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere. This printed copy is identical to the submitted electronic version.

Hagenberg, July 15, 2021

Michael Wurm

Contents

Declaration	iv
Preface	viii
Abstract	ix
Kurzfassung	x
1 Introduction	1
1.1 Motivation	1
1.2 Broadcast Radio	1
1.3 Goal	1
2 Signal Processing Theory	3
2.1 Modulation from Baseband to RF	3
2.2 Modulation from RF to Baseband	3
2.3 Frequency Modulation in Broadcasting	3
2.3.1 Mathematical description	3
2.3.2 Frequency Band	4
2.3.3 Frequency Spectrum of a Broadcast FM Channel	4
2.4 Algorithms for Digital FM Demodulation	6
2.4.1 Baseband Delay Demodulator	6
2.4.2 Phase-Adapter Demodulator	6
2.4.3 Phase-Locked Loop (PLL)	6
2.4.4 Mixed Demodulator	6
3 HLS	7
3.1 Introduction / State of the Art	7
3.2 Functionality (transform high-level code to HDL)	7
3.3 Language Support	7
3.3.1 C++	7
3.3.2 SystemC	7
3.4 Coding	7
3.4.1 Compiler Directives (#pragma's)	7
3.4.2 Data types	7
3.4.3 Functions	7

3.4.4	Loops	7
3.4.5	Conditional statements	7
3.5	Advantages / Disadvantages	7
4	System Architecture/Concept	8
4.1	Block Diagram (with details)	8
4.1.1	describe blocks	8
4.2	Which parts in HLS and VHDL	8
4.3	Test Environment	8
5	Implementation	9
5.1	Matlab/Python Model	9
5.2	VHDL (no shortcut)	9
5.2.1	Channel Selection (IF to Channel-BB)	9
5.2.2	Phase Detector	9
5.2.3	other Elements	9
5.3	High-Level Synthesis	9
5.3.1	Channel Selection (IF to Channel-BB)	9
5.3.2	Phase Detector	9
5.3.3	other Elements	9
5.4	Common Testbench	9
5.4.1	Architecture (same tb for VHDL and HLS-generated HDL)	9
5.4.2	Framework cocotb, with ghdl compiler	9
5.5	Develop HLS compiler independent code (optional)	10
5.5.1	Challenges	10
6	Deployment on Hardware	11
6.1	Hardware Platform	11
6.1.1	RTL2832u Dongle	11
6.1.2	ZedBoard	11
7	Test Results	12
7.1	Functionality	12
7.1.1	Implementation effort/time	12
7.1.2	Hardware Utilization	12
7.1.3	Others	12
8	Using Literature	13
A	Technical Details	14
B	Supplementary Materials	15
B.1	PDF Files	15
B.2	Media Files	15
B.3	Online Sources (PDF Captures)	15
C	Questionnaire	16

Contents	vii
D LaTeX Source Code	17
References	18
Literature	18
Online sources	18

Preface

Abstract

This should be a 1-page (maximum) summary of your work in English.

Kurzfassung

An dieser Stelle steht eine Zusammenfassung der Arbeit, Umfang max. 1 Seite. ...

Chapter 1

Introduction

1.1 Motivation

FM is a common RF signal that's available everywhere.

The demodulated signal is an audio signal, that can be listened to. This is subjectively more attractive than a generic data stream.

1.2 Broadcast Radio

Evolution from AM to FM because of certain advantages, etc.

Explain FM usage/existence nowadays (geographical; frequencies; devices; new standard DAB, etc)

1.3 Goal

put all knowledge that was accumulated during studies (HSD, ESD, mention subjects such as DSP) together in a project.

practical usage of DSP in an FPGA

develop an FM receiver and explain it, so that it can be followed in a tutorial with an affordable budget in hardware.

show multiple ways of how to implement the same thing, in different levels of abstraction.

Weigh each ways' field of application, efficiency and applicability.

Thesis Design Decisions:

Main focus on system design.

How to achieve the same result in 3 (4?) different levels of abstraction?

1. GnuRadio (?)
2. Matlab/Python
3. HLS

Implementation targeting Xilinx' ZedBoard.

Optionally:

Intel as a comparison (synth only, no HW) - “How platform-independent is HLS?”

4. VHDL

Compare: - Implementation effort (difficulty) - Implementation time - Usefulness on Target Systems (uC, SoC, RasPi, etc) - others?

Chapter 2

Signal Processing Theory

2.1 Modulation from Baseband to RF

2.2 Modulation from RF to Baseband

2.3 Frequency Modulation in Broadcasting

Frequency modulation (FM) is a widely used standard to transmit data streams. The probably best known usecase therefore is commercial broadcast radio, where an audio stream is transmitted. Devices to receive these streams are available for low prices to the public.

This chapter describes the main properties of broadcast FM, such as the mathematical description, frequency bands that are used, or the specific frequency parts within a channel spectrum.

2.3.1 Mathematical description

The mathematical description of an FM baseband signal can be described with the formulas presented in this section. FM encodes the information content in its instantaneous frequency. This means that the measured frequency at any moment in time represents a specific value of a transmitted message. For a general classification, FM belongs to the group of angle, or phase modulated signals (PM). The simple reason therefor is, that a frequency has a direct relationship to an angle, if the signal is seen on a unit circle.

The instantaneous frequency f_i of an FM signal can be described as

$$f_i = f_c + \Delta f \cdot m(t) \quad (2.1)$$

where f_c is the carrier- or center frequency, Δf is the maximum frequency deviation and $m(t)$ is the information or message signal that is to be transmitted. Simply looking at this equation, the frequency deviation, which is sometimes also called the swing, varies in the range between $f_c \pm \Delta f$.

Considering the relationship between frequency and angle, as described above, and after some simple substitutions which will not be described into detail here, the equation

for a generic frequency modulated wave is the following

$$s(t) = A_c \cos\left(2\pi f_c t + 2\pi k_f \int m(t) dt\right) \quad (2.2)$$

where A_c is the amplitude of the resulting FM signal and k_f is the frequency sensitivity factor. This sensitivity factor has a direct relationship with the modulation index β .

$$\beta = \frac{\Delta f}{f_m} = \frac{k_f A_m}{f_m} \quad (2.3)$$

where f_m is the highest existing frequency, or the bandwidth of the information signal.

Formula 2.2 describes a frequency modulated signal with a generic message signal $m(t)$. A widely used example application of FM is broadcast radio, where audio streams are transmitted. An audio stream can be described as a cosine wave. Therefore, the information signal that is to be transmitted in broadcast radio can be represented as a cosine wave in the form of

$$m(t) = A_m \cos(2\pi f_m t). \quad (2.4)$$

By inserting this message signal into the generic FM formula 2.2, the final equation for an FM signal transforms into the following form.

$$y(t) = A_c \cos\left(2\pi f_c t + \beta \sin(2\pi f_m t)\right) \quad (2.5)$$

Several formulas, as well as their derivations are described according to [ref_FM_Maths_Info_1][ref_F

2.3.2 Frequency Band

The frequency band that is used for FM broadcasting is defined worldwide and spans from 87.5 to 108 MHz. However, some countries only partially use the band [ref_itu_regulations]. The range is located within the so-called Very-High-Frequency (VHF) band, which is open to the public in terms of usage. This means, that any transmitter may use the specified frequency range freely. Austria allowed the legal usage in 2006 [ref_austria_rundfunkgesetz_2006]. However, the transmission power needs to be limited, so that neighboring receivers are not disturbed in receiving any existing channels. The European Commission specifies the power limit as 50 nW of effective radiated power (ERP) [ref_eu_commission_radio_spectrum]. Another limitation is, that a transmitter must be capable to transmit on multiple center frequencies within the broadcasting band. It must not be fixed to a single center frequency. Through this specification, a transmitter is capable of switching its transmission center frequency, in order to avoid interference with another transmitters signal.

In a practical usecase this means that a transmitter needs to select a channel or frequency range, that is not already occupied by an official transmitter. If a free range is found, the transmitter may start sending an FM signal with the mentioned power limitations [ref_ebu_fm_modulators_in_europe_power_regulations].

2.3.3 Frequency Spectrum of a Broadcast FM Channel

The entire FM broadcasting band from 87.5 to 108 MHz divides into multiple channels which can be used. In Europe, the European Telecommunications Standards Institute

(ETSI) sets the respective standards for the usage of these frequencies. The main specifications for a single FM broadcasting channel are explained in this section.

Each channel may allocate a bandwidth of 200 kHz. Within one of these channels, the maximum deviation from the center frequency shall not exceed 75 kHz. This leaves a guard band of 25 kHz on either side, to minimize interference with adjacent channels. Center frequencies may be allocated on multiples of 100 kHz. However, neighboring channels need to be considered therefor, since this may result in an overlap in the spectrum.

Fig.2.1 shows the frequency spectrum of a single channel, located at its carrier- or center frequency. For a better overview, only the positive spectrum part is shown. The negative part is an exact mirror, because the transmitted and received signals from the antenna are real signals - they do not have an imaginary part. The spectrum consists of multiple parts, which are described in the following paragraphs.

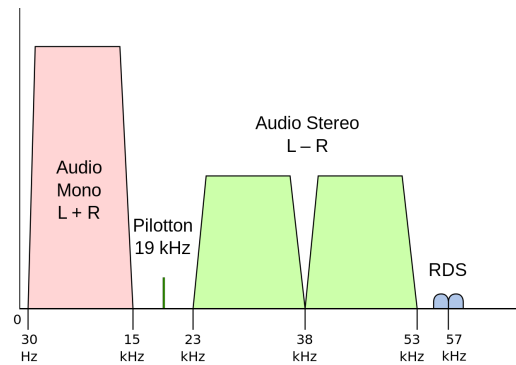


Figure 2.1: Allocation of frequencies in an FM channel [ref_fig_channel_freqs]

Mono Audio Part

The mono audio stream is located between 30 Hz and 15 kHz. This signal is built by the sum of the left and right audio channels. The upper limit at 15 kHz is chosen to maintain a sufficient spacing to the first subcarrier. For audio streaming, as in FM broadcasting, this is not a limitation, since it is unlikely to have frequencies higher than 15 kHz in an audio stream. Also, this already reaches the upper limit of the human ears' bandwidth, so higher spectral parts will not be heard anyway.

Pilot Tone

The first subcarrier is allocated at an offset of 19 kHz from the center frequency. It is also called the 'pilot tone', since it is a continuous signal. The pilot tone is used to be able to demodulate the left and right channel of an audio signal correctly, to generate stereo audio.

Stereo Audio Difference

A signal that is constructed by the difference between left and right audio channel is modulated on a 38 kHz subcarrier. This subcarrier is an integer multiple of 19 kHz for practical reasons. However, the 38 kHz carrier is suppressed and thus not visible in the received spectrum. It can still be recovered, since it is phase coherent with the 19 kHz pilot tone per definition. The bandwidth for this difference-signal spans 15 kHz on either side of the subcarrier. It is used to generate a stereo audio signal, in combination with the mono signal. This process is explained into more detail in chapter ??.

Additional Services

Considering all these parts in the spectrum, there is still bandwidth free to use, up to the maximum channel bandwidth of 100 kHz in one sideband. Because of that, additional services were added to the pure audio transmission, to provide additional data services and information. Services that were implemented are the Data Radio Channel (DARC), which is mostly used in Japan and the USA, the Subsidiary Communication Authorization (SCA) and the Radio Data System (RDS) [ref_rohde_u_schwarz]. Out of these, RDS is the most significant service in Europe. It is used to transmit additional information about the channel, such as the radio stations' name, currently playing songs' title or traffic information.

The information about the frequency spectrum was taken from [ref_fm_broadcast_tutorial_and_bas

2.4 Algorithms for Digital FM Demodulation

see literature/FmDemodulator.pdf (Sect. 3.3) see literature/00476180 Digital FM Demodulator for FM, TV, and Wireless.pdf (Sect. II and III)

2.4.1 Baseband Delay Demodulator

2.4.2 Phase-Adapter Demodulator

2.4.3 Phase-Locked Loop (PLL)

2.4.4 Mixed Demodulator

Chapter 3

High-Level Synthesis

3.1 Introduction / State of the Art

3.2 Functionality (transform high-level code to HDL)

3.3 Language Support

3.3.1 C++

3.3.2 SystemC

3.4 Coding

3.4.1 Compiler Directives (#pragma's)

3.4.2 Data types

3.4.3 Functions

3.4.4 Loops

3.4.5 Conditional statements

3.5 Advantages / Disadvantages

easy and much faster to get complex HDL code, such as image/video processing, through libraries like OpenCV. However, it is less optimized, and a developer still needs to have a strong hardware background, to be able to understand what is being generated in hardware from x lines of code in HLS/Cpp.

Chapter 4

System Architecture/Concept

4.1 Block Diagram (with details)

4.1.1 describe blocks

4.2 Which parts in HLS and VHDL

4.3 Test Environment

Chapter 5

Implementation

5.1 Matlab/Python Model

in fixed point, close to hardware level algorithm

5.2 VHDL (no shortcut)

5.2.1 Channel Selection (IF to Channel-BB)

5.2.2 Phase Detector

5.2.3 other Elements

5.3 High-Level Synthesis

5.3.1 Channel Selection (IF to Channel-BB)

5.3.2 Phase Detector

5.3.3 other Elements

5.4 Common Testbench

5.4.1 Architecture (same tb for VHDL and HLS-generated HDL)

5.4.2 Framework cocotb, with ghdl compiler

Instantiate both HDL models in the testbench.

Display a direct comparison of outputs in graphs. This is practical, since the cocotb framework runs in python and graphs can be generated using Python's matplotlib.

5.5 Develop HLS compiler independent code (optional)

5.5.1 Challenges

Different compilers use different `#pragmas`, etc.

The `#pragmas` need to be within the code, at the appropriate positions, which makes it difficult to write compiler independent code....

Chapter 6

Deployment on Hardware

6.1 Hardware Platform

6.1.1 RTL2832u Dongle

6.1.2 ZedBoard

Chapter 7

Test Results

7.1 Functionality

7.1.1 Implementation effort/time

7.1.2 Hardware Utilization

7.1.3 Others

Chapter 8

Using Literature and other Resources

[1]

Appendix A

Technical Details

Appendix B

Supplementary Materials

List of supplementary data submitted to the degree-granting institution for archival storage (in ZIP format).

B.1 PDF Files

Path: /

thesis.pdf Master/Bachelor thesis (complete document)

B.2 Media Files

Path: /media

*.ai, *.pdf Adobe Illustrator files

*.jpg, *.png raster images

*.mp3 audio files

*.mp4 video files

B.3 Online Sources (PDF Captures)

Path: /online-sources

Reliquienschrein-Wikipedia.pdf [2]

Appendix C

Questionnaire

Appendix D

LaTeX Source Code

References

Literature

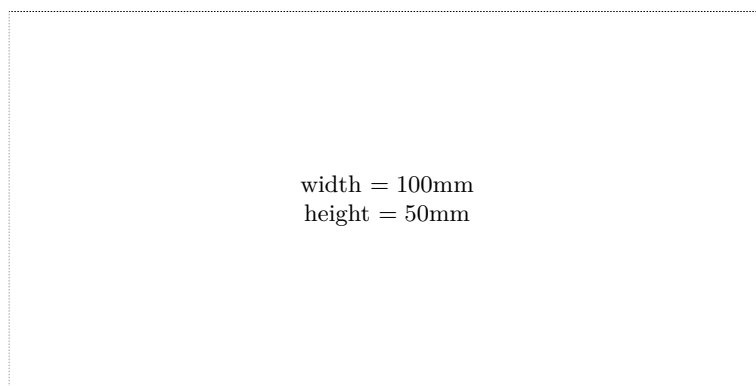
- [1] Hubert M. Drake, Milton D. McLaughlin, and Harold R. Goodman. *Results obtained during accelerated transonic tests of the Bell XS-1 airplane in flights to a MACH number of 0.92*. Tech. rep. NACA-RM-L8A05A. Edwards, CA: NASA Dryden Flight Research Center, Jan. 1948. URL: https://www.nasa.gov/centers/dryden/pdf/87528main_RM-L8A05A.pdf (cit. on p. 13).

Online sources

- [2] *Reliquienschrein*. Sept. 2018. URL: <https://de.wikipedia.org/wiki/Reliquienschrein> (visited on 02/28/2019).

Check Final Print Size

— Check final print size! —



— Remove this page after printing! —