Truck Connectivity Platform Using Software Defined Radios

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Abstract

Hardware updates and feature updates of electronic equipment can take a long time for market implementations. Technology tends to become obsolete by the time the update is launched into the market. In the automotive industry, the service entertainment module (SEM) containing the core logic for Amplitude Modulation (AM), Frequency Modulation (FM), and Digital Audio Broadcasting (DAB) radio tuners lack the facility for software-based updates. One of the major challenges for the infotainment/entertainment modules in the automotive industry is to have a single radio module that can support software updates and multi-standard radio technologies from different countries. Software Defined Radios (SDR) can be used to deal with this problem as SDR is a platform to prototype or develop new communication protocols as well as add new features or capabilities to the existing protocols without requiring major capital expenditures. SDR is a cost-effective radio platform because it can update radio equipment on the fly and provide additional functionality without requiring hardware modifications. By means of software instead of hardware updates, development loops could be shortened and manufacturing costs are reduced. In this thesis, a thorough comparison of a hardware-based tuner and a software-based tuner is performed in the presence of AM/FM/DAB modulated signals based on the metrics specified in ETSI EN 303 345-1 including sensitivity, adjacent channel suppression, far-off channel suppression, cross-modulation, third-order intermodulation, etc. After performance evaluation and comparison, it can be proven that the SDR based system can perform as well as the hardware tuner used in the SEM unit.

Keywords: SEM, AM, FM, DAB, SDR
Sammanfattning


Keywords: SEM, AM, FM, DAB, SDR
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Chapter 1

Introduction

The advancements in wireless technologies have altered the communication habits of consumers. According to a survey presented by the World Wireless Research Forum (WWRF), nearly 7 trillion wireless devices will be deployed for 7 billion consumers by 2020 [1]. With billions of Internet of Things (IoT) devices being developed each year, the challenge is to accommodate as many users as possible by altering the basic connectivity and networking layers. Over the years, a plethora of communication protocols have been developed such as ZigBee, Bluetooth Low Energy (BLE), Long Term Evolution (LTE), and Wireless Fidelity (WiFi) for IoT devices. The Wireless standards are adapting quickly to comply with the user needs and hardware specifications. This has called for a transceiver design with the ability to handle several communication protocols, including the existing ones and those being developed. Software Defined Radio (SDR) offers a flexible, reconfigurable, scalable, and a programmable framework for different communication protocols. SDR is a radio communication system where components that are traditionally implemented in hardware (modulators, demodulators, filters, etc.) are implemented by means of software on a PC or embedded system [2].

The life-cycle of conventional radio equipment is getting shorter day by day. This can be attributed to the fact that these radio equipment are unable to cope up with the rapid rise in technology. Small bugs in these radio equipment result in higher repair costs as the bugs cannot be solved via software. Unlike conventional radios, SDRs enable updating the radio equipment on the fly, just like software updates in a PC. Bugs on the radio equipment can be fixed without any costly device replacements. Moreover, SDR also offers full flexibility, i.e. can modify parameters...
SDRs are implemented through different types of hardware platforms, such as General Purpose Processors (GPP), Digital Signal Processors (DSP), Graphical Processing Units (GPU), and Field Programmable Gate Arrays (FPGA). Each of these platforms has its own set of benefits and challenges. Also, each SDR is unique with regards to the design methodology, performance, and applications. Therefore, before selecting an SDR for an application, it is necessary to understand the hardware specifications and architecture of the radio module.

Section 1.1 mentioned below gives us a comprehensive overview of the various components used in SDR.

1.1 Architecture of SDR

In this section, we analyse the general architecture of the SDR, its components, and their processing requirements. Figure 1.1 shows the general architecture and the components of SDR.

Figure 1.1: Transceiver architecture of Software Defined Radio
As shown in Figure 1.1, a typical SDR consists of a transmitter as well as a receiver. It can be seen that the transmitter and receiver sides of SDR’s are replicas and contain similar components (different specifications) as each other.

The signal processing block takes care of the baseband processing. This block is responsible for signal processing operations like encoding/decoding, interleaving/de-interleaving, modulation/demodulation, scrambling/descrambling, etc. This baseband block forms the heart of the SDR and is usually implemented on top of a hardware circuitry like DSP’s/GPP’s/GPU’s/Application Specific Integrated Circuit (ASIC) which are capable of processing signals efficiently.

The Digital Front End (DFE) performs different sets of operations for the transmitter and receiver part of the SDR. The two major functions of the DFE are sample rate conversion and channelization. The sample rate conversion is important for converting the sample rate from one functionality to another. Channelization performs upconversion or downconversion depending on the mode of operation of the incoming signal.

In the transmitter part, the baseband signal is translated into an intermediate frequency signal using upconversion performed by a Digital Up Converter (DUC). In the receiving side, the digital samples from the Analog to Digital Converter (ADC) are fed into the Digital Down Converter (DDC). The DDC includes a digital mixer and a local oscillator that are responsible for extracting the baseband signal from the ADC.

As the name suggests, ADC and Digital to Analog Converter (DAC) are responsible for converting the signals from one domain to another. The performance of these data converters can be monitored by analysing the signal to noise ratio (SNR), the number of bits per sample (resolution), Spurious Free Dynamic Range (SFDR), and power dissipation [1].

The RF Front End (RFFE) is responsible for translating a signal to/from intermediate frequency. In the transmitter side, the RFFE receives an analog signal from the DAC which is in turn mixed with a pre-set RF frequency, modulated, and finally transmitted at an RF frequency. On the receiver side, when the antenna receives an RF signal, it is passed through a low noise amplifier (LNA) to amplify the weaker section of the received signal. Then, this amplified signal is down-converted to an IF frequency with the help of a local oscillator.
1.2 Background

One of the major problems faced by the infotainment units of the automotive industry is the ever-increasing need for Electronic Control Units (ECU) for providing entertainment based services. The rapid shift from analog to digital technology has imposed a challenging task to chip-set makers and automotive companies on how to accommodate different digital radio standards from different countries. Current radio tuner architecture in the Service Entertainment Module (SEM) alone cannot afford to accommodate these evolving radio technologies in a single chip. The SEM unit in the automotive industry employs a minimum of 3 ECU’s to implement the AM, FM, DAB or HD-Radio technologies. Also, the radio chip-sets present in the SEM lack the facility for software-based updates. Any update/upgrade of a radio chip-set can take nearly 3-4 years to come into serial production. As mentioned above, it is clear that the SEM unit does not support multi-standard radio within a single chip too.

SDR can be the right solution to these problems. For instance, the entire truck connectivity logic for analog or digital radios can be implemented in an SDR. However, the problem lies in selecting suitable SDR for performing these radio operations. Moreover, the selected SDR should match the requirements set by the ETSI standard (for Europe) and perform as well as the current SEM solution.

1.3 Problem

This thesis will investigate the possibility of introducing SDR in the automotive industry. Since hardware and feature updates take a long time for market implementations, technology tends to become obsolete by the time the update is launched into the market. This calls for faster development loops. In the current infotainment units of automobiles, the conventional hardware-based radio tuner (AM/FM/DAB) present inside the SEM unit lacks the facility for software updates. With the current hardware-based tuner being replaced every few years, there is a need for a tuner with minimum hardware updates. Also, the current SEM unit used in the industry does not completely support multi-standard radio technologies. For example, it uses a separate DAB radio module for Europe, HD-Radio module for the USA, and digital radio mondiale (DRM) for India.
To solve this problem, SDR can be the best option as it has the capability to address these problems faced by conventional radio. It can support multi-standard radio and thus help in the reduction of the number of ECU’s required for AM/FM/DAB/HD-Radio reception. However, a thorough comparison of the SDR based radio and the conventional automotive radio is necessary before deeming the selected SDR as the way forward. This thesis will present a detailed comparison of the selected SDR based tuner and the conventional radio tuner based on few KPI’s.

1.4 Motivation

As mentioned in the problem statement, SDRs can prove to be the right solution as it provides a cost-effective radio platform by providing updates and additional functionality with a minimum of hardware updates or modifications. By means of software updates, the development loops are shortened while manufacturing costs are being reduced. With the introduction of SDR, new radio technologies can be rolled out faster and bugs within the radio equipment can be fixed without any device replacements. Moreover, in the SEM unit, separate chip-sets are used for the operation of AM/FM and DAB radio. However, the SDR selected for AM/FM/DAB implementation can perform all three operations using a single chip. By using SDR in place of the hardware tuner, we can reduce the space consumed by the radio tuners in the SEM.

1.5 Goals

The goal of this thesis is to investigate the performance of the selected SDR as opposed to the conventional hardware based radio tuner in the SEM. The performance will be evaluated based on ETSI EN 303 345-1 standard in terms of sensitivity, channel selectivity, intermodulation, etc. To achieve this goal, the following steps are necessary to be performed:

- Conduct a survey on the potential SDR that could be an ideal fit to work as a radio tuner in the SEM unit.
- Implement the AM, FM, and DAB radio technologies in the chosen SDR.
• Setting up the SEM unit and integrating it with the SDR module.

• Compare the performance of SDR based setup with the hardware based setup based on a few KPI’s.

1.6 Research Methodology

In this thesis, we use an empirical and analytical approach as our results are based on observed and measured phenomena. We can divide the entire thesis into 4 phases, namely, the learning phase, implementation phase, integration phase, and evaluation phase. The research process of the thesis is shown in Figure [1.2]. In the learning phase, firstly, we conduct a detailed survey on the potential SDR’s that could be considered to perform the radio tuner operations (AM/FM/DAB). The SDR is selected based on the frequency range supported, the sampling rate of the hardware, ADC resolution, and cost. Secondly, the literature review of the three radio technologies is conducted to allow us to familiarize ourselves with the concepts of AM, FM, and DAB. In the implementation phase, the three radio technologies are realized and implemented in the chosen SDR. In the integration phase, we will set up the SEM unit by preparing the cable harness required for the power supply, speakers, connection to the PC for debugging/troubleshooting SEM applications, etc. Once the harness is prepared, we can integrate the SEM unit with the antennas and LCD display for performance analysis. Finally, in the evaluation phase, the performance of the SDR based setup, as opposed to the conventional hardware-based setup, is evaluated and compared as per the ETSI EN 303 345-1 standard and the pre-defined metrics mentioned for the SEM. Once the testing and evaluation phase is completed, we get a measure of the performance capabilities of the SDR based setup.
1.7 Delimitations

The focus of the thesis is to test and evaluate the performance of SDR setup functioning as a radio tuner with the typical radio tuner in the SEM. In the entertainment and telematics unit of an automobile, there are many ECU’s attached to the SEM and telematics gateway (TGW) respectively. For example, in the SEM unit, there are separate radio tuners for AM and FM, DAB/DRM/HD Radio (based on the country), and satellite radio (SiriusXM). However, in this thesis, our research is confined to testing and evaluating the performance of AM/FM/DAB in SDR as opposed to the traditional radio tuner. As far as AM radio is concerned, there are no AM radio base stations present in Sweden. In order to test the working of the implemented AM radio, we feed the SDR an AM modulated signal generated from the signal generator.

1.8 Research Contributions

In this thesis, a thorough comparison of the SDR based setup implementing AM/FM/DAB and the hardware-based radio tuner in the SEM is performed based on the EN 303 345-1 (General requirements and measurement methods for broadcast sound receivers) and the predefined metrics listed for the SEM unit.
1.9 Thesis Organization

This thesis is organized into six chapters as follows. Chapter 1 deals with the introduction and a little background and SDR and presents a holistic view on why SDRs are important. This chapter also provides a comprehensive list of SDRs that are suitable for implementing the AM, FM, and DAB radio technologies. From the list, it can be found that RTL-SDR, HackRF one, and LimeSDR can be suitable options for implementing the radio technologies. Chapter 2 gives a detailed background study on the history of SDR and provides an overview of the SEM unit used in the automotive industry. This chapter also presents the introduction to RTL-SDR v3 and the various software platforms that can be used for implementing the above-mentioned radio technologies. Chapter 3 deals with the methodology of the thesis including the research process, data collection, hardware & software required, and the test environment used for evaluating the SDR tuner and SEM. Chapter 4 provides the necessary introduction and implementation of the radio technologies. Chapter 5 provides the results and performance analysis of the SDR based setup as opposed to the tuner inside the SEM. Finally, chapter 6 provides the conclusion and future work of the thesis.
Chapter 2

Background

As telematics and infotainment services are becoming more and more prevalent on the roadways, it is imperative for the vehicles to be equipped to support multiple wireless communication standards \[4\]. The conventional way of realizing and implementing different wireless communication standards is through the use of dedicated hardware-based chips. With hardware updates and feature updates taking a long time for market implementations, there is a necessity for faster development loops with a minimum of hardware updates. SDRs could serve as an ideal option as it can provide a convenient platform for designing and evaluating different communication protocols and standards without the need for hardware implementation. Although SDR concepts have been used in military applications for several years, it is only recently that cost-effective SDR solutions have been realized for mobile phones and automotive radios. Advances in the architecture of microprocessors have facilitated SDRs to offer new solutions to vehicle original equipment manufacturers (OEM) \[5\]. With the radio functionality being transferred from hardware-based chips to the software, there can be a considerable amount of cost savings in vehicle production. This advantage of SDR provides complete flexibility on the manufacturing side for future radio features or technologies. One of the major challenges that infotainment units in automotive industries face today is the ability of the receiver to handle analog AM/FM standards and the upcoming digital standards, including HD Radio in the U.S.A, DAB radio in Europe, DRM in India, and china digital radio (CDR) in China. An up to date modern radio receiver must support the simultaneous reception of multiple broadcast channels and incorporate complex DSP algorithms to optimize the radio performance.
As of now, SDR is probably the best approach to achieve flexibility and reconfigurability necessary for automotive radios [6].

Section 2.1 gives us an overview on SDR and its merits/demerits. Sections 2.2, 2.3, and 2.4 provide comprehensive background study on RDS-FM, AM, and DAB respectively. Section 2.5 introduces the SEM unit used in automotive industry. Sections 2.6 and 2.7 deal with introductions to RTL-SDR v3 and HackRF one.

2.1 Software Defined Radios

SDRs have emerged as a popular radio technology in the design of radio communication systems. Due to its implementation in software, they provide a very efficient alternative to the conventional design of radio communication systems. Further, they allow for components of the communication system to be designed in software rather than hardware, thus simplifying the design process and allowing greater flexibility [7]. This feature also enables SDRs to be used as a suitable platform for the development of IoT-specific protocols.

An SDR system may comprise a computer, an analog-to-digital converter, and an RF front end. It is designed such that the components responsible for signal processing are implemented in software to enable the radio to transmit and receive a wide range of protocols based on the underlying software. The processing can either be done by a GPP, a DSP, an FPGA or an ASIC and can be exploited to support concurrent processing.

The most important features of an SDR are its adaptability and flexibility that enables the use of the DSP software to perform the necessary signal processing tasks depending on the modulation scheme used, without the need for modification of the hardware components of the system. This helps to reduce cost, complexity and development effort. Signal processing framework development can be done in software like GNU Radio, RFNoC, LabVIEW, MATLAB and Simulink, which are explained in detail in below sub-sections.

2.2 FM Radio

In the field of telecommunications and signal processing, FM is the process of encoding information in a carrier wave by varying the frequency
of the transmitted wave. Frequency modulation is widely used for FM broadcasting and was invented in 1933 by Edwin Armstrong [8]. The FM broadcast band falls in the very high frequency (VHF) region of 30-300 MHz.

The FM broadcast band used for broadcasting radio differs between different parts of the world. According to International Telecommunication Union (ITU), continents like Europe, Africa, and Australia fall under ITU region 1 and their broadcast frequencies span from 87.5 to 108 MHz. In North America and South America (ITU region 2), the frequency spans from 88-108 MHz. In Japan, the FM broadcast band ranges from 76-95 MHz [9]. The center frequencies of FM carrier frequencies are spaced in increments of 200 kHz. The frequency deviation used for a 200 kHz channel spacing is limited to 150 kHz total (±75) kHz in order to prevent adjacent channel interference on the FM band.

The following sections provide a detailed background on RDS-FM, its message format, coding structure, etc.

### 2.2.1 Radio Data System

The Radio Data System (RDS) is intended for VHF or FM broadcasts in the frequency range between 87.5 to 108 MHz that carry stereophonic or monophonic programmes. The main objective of RDS FM is to provide better end-user experience by displaying text information such as traffic, weather, and radio text information on the user GUI. What started out as a niche feature on a handful of FM receivers in the late ’90s and early 2000s have turned mainstream in this decade. The following are the list of codes that we see in GUI of RDS FM:

- Program identification code (PI)
- Program type (PT)
- Traffic program identification code (TP)
- Traffic announcement (TA)
- Program service (PS)
- Alternative frequencies (AF)
- Music or speech (M/S)
• Radio text
• Decoder information (DI)

The data signal in the RDS is carried on a sub-carrier which is added to the stereo multiplex signal at the input of the VHF/FM transmitter. During the stereo broadcasts, the sub-carrier (data signal) will be locked either in-phase or in quadrature to the third harmonic of the 19 kHz pilot tone. RDS carries data at 1187.5 bits per second on a 57 kHz sub-carrier, which means there are exactly 48 cycles of sub-carrier during each data bit \[10\]. The RDS sub-carrier was set to the third harmonic of the 19 kHz FM stereo pilot tone to minimize interference and inter-modulation between the data signal, the stereo pilot and the 38 kHz stereo double side-band suppressed carrier (DSB-SC) difference signal. The sub-carrier is amplitude modulated by a shaped and bi-phase coded data signal. The modulation can be alternatively called as a two-phase phase-shift keying (PSK) with a phase deviation of \(\pm 90^\circ\). The source data generated at the transmitter are differentially encoded according to Table 2.1 shown below.

<table>
<thead>
<tr>
<th>Previous output (t_{i-1})</th>
<th>New input (t_i)</th>
<th>New output (t_i)</th>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

From Table 2.1, the time instance \(t_i\) is some arbitrary time and \(t_{i-1}\) denotes one message-data clock period \((1/1187.5 \text{ sec})\) earlier. When the new input data is 0, the output remains unchanged from its previous state. While when the input bit is 1, the output becomes the complement of the previous output bit. In the receiver, the inverse process is applied to decode the data \([10]\).

### 2.2.2 Baseband Coding and Group Structure

The largest element in the structure is called a *Group* and it comprises of 104 bits. Each *Group* contains 4 *Blocks* consisting of 26 bits each. Each
Block in turn is made up of an infoword (16 bits) and a checkword (10 bits) while each Group is categorized as either Version A or Version B. The following Figure 2.1 shows us the structure of an RDS frame.

Figure 2.1: Grouping of Inforwords and Codewords

The data transmission is completely synchronous and there are no gaps/spacing between Groups or Blocks. The order of transmission is such that the most significant bits (MSB) of the infoword or checkword or any binary address value is transmitted first.

The 10-bit checkword is primarily intended to enable the receiver/decoder to detect and correct errors that occur during transmission. The checkword is generated by a combination of a generator polynomial $g(x)$ and a 10-bit binary string $d(x)$ called offset word. The addition of offset brings Block and Group synchronization in the receiver/decoder. They are designed in a way that a cyclic shift of the codeword would not give rise to a new codeword [6,7 (standard doc)]. The error-correcting code is attached at the end of each block and it has the following capabilities as mentioned below:

- Detect all single and double bit errors in the Block.
- Detect any single burst error spanning 10 bits or less.
• Detects about 99.8% of bursts spanning 11 bits and 99.9% of other longer bursts.

The blocks within each group are identified by the type of offset words (A, B, C or C’, and D).

2.2.3 Message Format

According to the EN50067 standard document, RDS FM has a few underlying message formats and addressing structure. Different Group types and its Version are responsible for different operations. Some of the salient features of RDS FM are listed below.

• The first block of every Group always denotes the program identification (PI) code

• The first 4 bits of every second block contains the Group Type. There are totally 16 types of groups ranging from 0 to 15. For each Group Type, two Versions can be defined, namely, A & B.

• The program type code (PTY) and traffic program identification (TP) occupy fixed places in the second Block of every group.

For more information regarding the different types of Groups, refer section 3.1.3 of the EN50057 standard.

Program Identification (PI)
The PI code is responsible for enabling the receiver to distinguish between countries, areas in which the same program is transmitted, and the identification of the program itself. The PI code is unique for every radio program in order to differentiate from other radio programmes. One of the major uses of PI is that it would enable the radio to search for radio programmes with the same PI code that are transmitted in alternative frequencies. For instance, if the frequency at which the radio program being played has bad reception, the PI provides us with the option of switching to an alternative frequency.

Program Service name (PS)
It is a label that is used for displaying the name of the program service transmitted by an RDS FM transmitter. It occupies no more than 8 alphanumeric characters. For example, in Sweden, SR P1 is the name
of the program service. PS name informs the end-user on what program service is being broadcasted by the RDS FM transmitter that the user tuned to.

**Program Type** (PTY)
PTY is an identifier code that is transmitted with each radio program and specifies the current program type of the radio program. The PTY identifier code ranges from 0 to 31 where each code represents a unique program type name. For example, PTY code of 4 represents *Sport* as the PTY name.

**Program Type name** (PTYN)
The PTYN label is used to describe the current PTY. PTYN describes a more specific program type description that the radio broadcaster can freely decide upon. For example, a PTY code of 4 represents *Sport* and PTYN can be decided by the broadcaster as to whether the program type is *Football* or *Baseball* or any another sport according to the requirements.

**RadioText** (RT)
When the radio broadcaster wants to transmit longer PS name or any program-related information, the RT label is used to display those messages. For instance, When ‘SR P3’ radio is broadcasting a song, the information regarding the name of the song and the artists involved are displayed in the RT label. In automobiles, the RT label is switched off by default as it can be distracting to the user.

**Alternative Frequencies** (AF)
The AF label describes the list of various transmitters broadcasting the same information on different frequency channels. This feature enables the receivers with memory to store the list of AF to reduce the time for switching from one transmitter to another transmitter.

**Music Speech Switch** (MS)
It is a 2-state signal that is used to describe whether the signal broadcasted is *Speech* or *Music*.

**Traffic Announcement** (TA)
This is a binary switch to indicate when TA is on air. This feature pro-
vides an option to the users to switch from audio mode to TA mode when the TA flag is set.

**Traffic Program Identification Code** (TP)
This flag is used to indicate that the program tuned by the user is capable of receiving traffic announcements. This flag is set only on programs that dynamically switch on TA identification during traffic announcements.

**Decoder Identification** (DI)
They occupy 4 bits and indicate different operating modes to switch individual decoders ON or OFF. For example, if bit $d_0$ is set to 0, then the operating mode is Mono and if $d_0$ is set to 1, then the mode is Stereo.

**Clock Time and Date** (CTD)
One of the important features of RDS FM is that it displays the date and time. In order to avoid ambiguities when different radio data broadcasts are processed at a single point, the broadcast time and date codes follow the Coordinated Universal Time (UTC) and Modified Julian Day (MJD).

## 2.3 AM Radio
AM Broadcasting was the first-ever radio broadcasting technology to transmit audio. It employed the use of amplitude modulation to transmit audio through long distances. The broadcasting of audio using AM modulation started in the 1920s and became the dominating technology for the subsequent decades. Post the introduction of FM and various other digital standards like DAB, HD Radio (USA), DRM, etc. the popularity of AM radio diminished greatly. Although it is one of the oldest forms of modulation technique, it is still used in long, medium, and short wave broadcasting and for some aeronautical point to point communications. The long wave broadcasting, also known as, low frequency (LF) broadcasting is done in the frequency ranges from 148.5 to 283.5 kHz. The medium wave broadcasting is the most common AM broadcasting band and the broadcast frequency ranges from 535-1605 kHz (different in few ITU regions). The shortwave broadcasting (also known as high frequency (HF)) ranges from 2.3 to 26.1 MHz.
2.3.1 Mode of Operation

The ITU divides the world into 3 regions.

- Region 1: Europe, Africa, The Soviet Union, and the Middle East
- Region 2: North America, South America
- Region 3: South and East Asia, Australia, and Japan

In regions 1 and 3, the channel bandwidths are multiples of 9 kHz. In region 2, the channel bandwidth is 10 kHz. Moreover, region 1 uses both the long and medium waves for broadcast transmissions, whereas the other regions use only the medium wave transmissions. One of the major differences between Region 1 and other regions is bandwidth. Region 1 is densely populated and it had many AM bands set until recently. In order to minimize the co-channel interference, the maximum bandwidth allocated to AM audio in Europe is 6.3 kHz. However, in Regions 2 & 3, higher bandwidths are allocated to audio as the amount of interference is lower compared to that of Region 1 [9]. Shortwave broadcasting is generally used only in less developed countries or in tropical regions where medium waves suffer from high interference. In the 20th century, the shortwave bands were used for international radio broadcasting only to be replaced by the internet later in the 21st century. Nowadays, the shortwave radio bands are used only in less developed countries and in tropical zones as MW suffers from high interference.

Unlike FM radio or other digital radio standards, AM radio is not used extensively in all countries. In Europe, there has been a heavy decline in the usage of AM radio. Countries like Andorra, Austria, Belarus, Croatia, Finland, Flanders (in Belgium), Sweden and Switzerland have completely closed their AM radio services. One of the reasons AM radio is dying is because of its inherent technical problems and some unyielding regulations. For example, AM stations lose listeners during the night because the FCC makes them cut power or shut down completely to avoid interference to other stations operating on the same frequency. During the nighttime, the AM signals can travel over hundreds of miles by reflection from the ionosphere, a phenomenon called ‘skywave’ propagation. Since there is higher ionization in the upper layers of the atmosphere, AM signals refract off these higher layers skipping hundreds or thousands of miles [11]. This phenomenon can lead to interference from other stations.
2.3.2 AM radio services - A Short Survey

The decline in AM radio started when programmes were simulcast on FM radio. In Europe, the future of AM radio is bleak as most of the countries have stopped using the AM services for digital radio technologies.

- **France**: France used a combination of AM and FM to broadcast information. AM was primarily used for filling the gaps in FM coverage. However, almost every AM transmitter was closed in the last decade. In 2015, an MW AM transmitter was launched and it is currently the only serving AM radio station.

- **Germany**: Most of the LW and MW AM transmitters were closed by the end of 2014. In 2018, a new local service, Radio Oberfranken was launched in Upper Bavaria. However, it is not known how long this service will survive.

- **Netherlands**: In Netherlands, there are 7 low power AM radio stations, one of which is relying on an FM network in Limburg and six community stations. AM radio is still used in limited quantities in the Netherlands. From 2016, most of the AM frequencies in the Netherlands were re-allocated to local services with about fifty 50W and 100W stations and about 25 1W stations licensed [9].

- **Spain**: It is one of the few countries in Europe to broadcast a full AM radio service. Even though many AM transmitters were closed in 2013, there are still many AM stations that broadcast news, sports, and other regional opt-outs.

- **Italy**: In 2018, the Italian government had advertised licenses for operating more than 100 AM transmitters. Italy is probably the only country in Europe where there can be an increase in AM broadcasting.

- **Albania and Lithuania** have closed short and long wave AM broadcasting but have retained MW transmitters for international broadcasting.

- **Other**: Cyprus, the Czech Republic, Hungary, Iceland, Romania and Slovenia (together with England, Scotland, Wales, Northern Ireland, and Spain) are continuing with a comprehensive AM radio service.
From the above-mentioned information on the usage of AM radio in Europe, it is fair to say that AM radio might cease to exist in the near future. However, it might not be the case in other continents.

- **United States of America**: AM radio is still predominant in the USA. Even though FM radio became the dominant medium for broadcasting music stations, AM radio has found a niche as the home for many sports and talk shows, religious and children stations, and broadcasts Spanish programmes too. The AM band was extended up-to 1700 kHz which clearly shows that MW is holding up very well as compared to other countries.

- **Australia**: AM radio is still widespread all over Australia. The AM band has also been extended up-to 1701 kHz (medium wave). In the major cities, the oldest public and commercial radio stations have stayed on AM, rather than migrating to FM radio. Even though AM radio is the dominant standard for speech-based radio stations, there are still plenty of music stations. Even today, most of the popular stations still broadcast on AM frequency.

- **India**: At the moment, it is not feasible for digital radio to spread its wings in India. The reason for that is AM and FM stations cover about 99.2% of the population and AM and FM broadcasters have spent huge license contracts to the governments for setting up their facilities.

### 2.4 Digital Audio Broadcasting (DAB) radio

DAB is a digital radio standard for broadcasting digital audio radio services. The DAB radio is generally more efficient in the usage of the spectrum as compared to analog FM radio and offers more radio services for the same bandwidth. The transmitted information is spread in both time and frequency domains to eliminate the effects of channel distortions and multipath fading \[12\]. Spectrum is utilized efficiently through interleaving multiple program signals and frequency reuse. Through multiplexing and compression, DAB combines multiple audio streams onto a relatively narrow band centered on a single broadcast frequency called DAB ensemble. For example, in Göteborg, Sweden, the 225.648 MHz (12B) is a DAB ensemble where digital audio feeds from 6 different ra-
dio stations are multiplexed into one single digital transmission. The following Table 2.2 mentioned shows us an example of a DAB Ensemble.

Table 2.2: DAB Radio in Gothenburg

<table>
<thead>
<tr>
<th>DAB Frequency</th>
<th>Radio Station Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>225.648 MHz</td>
<td>SR P1</td>
</tr>
<tr>
<td>(12B)</td>
<td>SR P2 Classical</td>
</tr>
<tr>
<td></td>
<td>SR P2 World</td>
</tr>
<tr>
<td></td>
<td>SR P3 Star</td>
</tr>
<tr>
<td></td>
<td>SR Sisuradio</td>
</tr>
<tr>
<td></td>
<td>SR Radio’s lap channel</td>
</tr>
</tbody>
</table>

The DAB system is a highly rugged, spectrum and power-efficient sound, video, and data broadcasting system. The DAB signal is a multiplex of several digital services with a bandwidth of 1.536 MHz. DAB radio operates in the VHF range of 174-240 MHz and L-band (1.452 - 1.492 GHz). The L-band is reserved for US military purposes, making it unavailable for other purposes in the USA.

DAB uses OFDM with D-QPSK modulation to transmit data. Besides transmitting an audio signal, DAB is capable of transmitting additional data, such as program information, traffic information, and multimedia messages. In 2006, WorldDAB introduced DAB+ as a major upgrade to DAB radio. DAB+ uses HE-AAC v2 audio codec for data compression of digital audio and can carry more stations at a higher quality than DAB. The efficiency of audio codec decides how many radio stations can be carried on a fixed capacity multiplex at a particular level of audio quality. Some of the other benefits of DAB+ include lower transmission cost, lesser utilization of spectrum, and more robust reception quality.

The transmitted DAB signal is built around a conceptual frame consisting of time-multiplexed components comprising of 3 channels: a synchronization channel, a fast information channel (FIC), and a main service channel (MSC). Figure 2.2 below shows the structure of a DAB transmitted frame.

**Synchronization channel:** The synchronization channel incorporates the basic receiver control mechanisms, such as automatic frequency control (AFC), automatic gain control (AGC), channel state estimation,
transmitter identification, etc. The synchronization channel contains the first two OFDM symbols of the transmission frame, namely, the null symbol and phase reference symbol [13].

**Main service channel:** The main service channel (MSC) is the largest portion of the transmitted DAB signal and it carries the audio and data service components. MSC is a time-interleaved data channel divided into a number of sub-channels. Each sub-channel is convolutionally coded with error protection. Each sub-channel may carry one or more service components. MSC carries all user data such as audio, multimedia, etc, and is made up of common interleaved frames (CIF). CIF is a data field containing 55,296 bits. The smallest addressable unit of a CIF is called a capacity unit (CU) and it comprises 64 bits. The maximum number of CU’s that a CIF can contain is 864. An integral number of CU’s are combined to form a single sub-channel [13].

There are two transport modes in MSC: stream mode and packet mode. Stream mode allows the service application to accept and transfer data from source to destination at a fixed data rate. The packet mode allows different data service components to be carried within the same sub-channel.

**Fast information channel:** The fast information channel (FIC) is limited in capacity but is capable of supplying information to the receiver faster than the MSC. In particular, it is used to transfer multiplex configuration information (MCI) and service information (SI). FIC is a non-time interleaved data channel with fixed equal error protection. For

Figure 2.2: Structure of a DAB DAB frame
example, FIC is responsible for carrying the name of the radio station, artist name, song name, multimedia messages, etc.

Section 4.3 explains the implementation and architecture of the DAB radio.

### 2.5 Service Entertainment Module

The service entertainment module (SEM) unit of Volvo Trucks contains the core logic of AM/FM/DAB and software digital audio radio service (SDARS) radio. It is powered up by an Intel Apollo lake platform having 2GB RAM and 8GB eMMC. The SEM works on the Android operating system (version 9). The AM and FM radio modules are controlled by the NXP Dirana 3 chip and the DAB radio module is separately controlled by Telechip TCC 3171. Figure 3.3 below shows us the architecture of the SEM unit.

![Figure 2.3: SEM 2.0 unit](image)
The SEM unit contains the following interfaces in its hardware:

- One AM/FM/DAB antenna connector with phantom power supply (Fakra connector)
- One SDARS Fakra antenna connector with phantom power supply
- One mini-A connector for USB 2.0 interfaces
- One HSD connector for LVDS output to an external display
- One HSD connector for Ethernet.
- One Quadlock connector interface

### 2.6 RTL-SDR

RTL-SDR is a hardware platform that was originally designed for DVB-T and HDTV reception [7]. Later, it was identified by hackers to be useful as a general purpose SDR. Being controlled by the RTL2832u driver, the RTL-SDR’s are commonly connected to a host computer through a USB-A port. Through this USB link, the software installed on the host PC (Eg: GNU Radio or SDR#) is used to control the working of RTL-SDR. The RTL2832u drivers are available from the open-source [os-mocom](https://os-mocom.reposity) repository. The specifications of the RTL-SDR are mentioned in Table 3.1. Figure 2.4 shows us the RTL-SDR v3 dongle used in different applications.

### 2.7 HackRF One

HackRF One is the current hardware platform for the HackRF project. It is an SDR designed for transmission and reception of radio signals in the frequency ranges 1 MHz to 6 GHz. This unit comes with one subminiature version-A (SMA) port, 2 SMA ports for CLK IN and CLK OUT and a USB 2.0 port. The SDR is interfaced with the PC through the USB-A port. Like RTL-SDR, HackRF one also works in SDR# and GNU Radio software applications. The host tools for HackRF one is downloaded from [HackRF-host-tools](https://HackRF-host-tools). Figure 2.4 below shows us an image of the HackRF one.
2.8 GNU Radio

GNU Radio is an open-source software that can be used to develop a signal processing framework. It is a flowgraph based software with a library of many built-in radio signal processing blocks, which can be used with SDR platforms like the USRP to model, run and test complex radio systems. The blocks that are used to create a flowgraph can be developed using either C++ or Python programming language. The developed signal processing blocks are connected block by block, describing a data flow using a graphical tool called GNU Radio Companion (GRC). The advantage of GNU Radio is that it already contains a large number of signal processing blocks that are used for modulation, demodulation, sampling, converters, signal sources and sinks, and many other blocks used in radio signal processing. In addition to the already available signal processing blocks, new blocks can be developed or new functionalities can be added to the already existing blocks using either Python or C++, depending on how computationally demanding they are. These characteristics make GNU Radio a great tool for prototyping and rapid development of real-world applications.
2.9 Other Signal Processing Framework Platforms

In addition to the GNU Radio, there are other signal processing framework development platforms like LabVIEW, MATLAB, and Simulink. Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a system-design platform developed by National Instruments (NI). It offers a graphical programming approach that helps the user to visualize every aspect of the application, including hardware configuration, measurement of data, and debugging. LabVIEW communications system design suite supports USRP motherboard and daughterboard configurations with the goal of accelerating productivity by providing a seamless tool flow from desktop PC to FPGA. SDR# is a simple, intuitive, and fast PC based DSP application for SDR. It is used for demodulating wideband FM (WFM), narrowband FM (NFM), AM, and double sideband carrier radio signals. MATLAB® and Simulink® provide a radio-in-the-loop environment for designing, prototyping, and verification of Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) wireless systems. The Communications System Toolbox™ of MATLAB and Simulink support various SDR USRPs and RTL-SDRs for transmitting and receiving RF signals in real-time.
Chapter 3

Methodology

This chapter provides an overview of the research method used in this thesis. Section 3.1 describes the research process. Section 3.2 focuses on the data collection techniques and the metrics used for evaluation in this project. Section 3.3 describes the experimental design of the host-SDR setup and also the test-bed used for evaluating the SDR performance. Finally, Section 3.4 explains the various hardware and software used throughout the thesis.

3.1 Research Process

This thesis is a performance evaluation and comparison of the SDR based setup with the SEM unit. As the first step of the process, we begin by finding suitable SDR for its application in the SEM unit of vehicles. The selection of SDR is addressed comprehensively in 3.2. This research is done by analyzing and comparing a plethora of SDR based on its frequency range of operation, the sampling rate of the hardware, ADC resolution, software support offered by the SDR, and cost. A thorough literature review of the 3 technologies, namely, FM, AM, and DAB are performed in parallel throughout the thesis. Secondly, once the SDR is selected, the chosen technologies are implemented in the SDR through GNU Radio. Thirdly, the SEM unit is set-up based on its pin configuration specified in the supplier manual. The wiring harness required for the working of the SEM unit is prepared by soldering the power supply cables, speakers, USB-serial connectors, etc. Finally, the performance of the SDR based setup is compared with the hardware based tuner with the help of KPI’s like number of channels available, sensitivity, adjacent channel
suppression, third order inter-modulation, etc.

3.2 Selection of SDR

Since this thesis deals with the Amplitude Modulation (AM), Frequency Modulation (FM), and Digital Audio Broadcasting (DAB) radios, the selection of the SDR should be based on its capability to support the working of these three broadcast radio technologies.

Before selecting an SDR, we analyse the hardware specifications of the SDR based on the following:

- The Frequency range of operation
- The Sampling rate of the device
- Resolution of the ADC
- Transmit and Receive capability
- Cost of the SDR equipment
- Support systems for the SDR (forums, applications, community, etc.)

Firstly, we can start the selection of SDR by considering the frequency range of the technologies that we are going to monitor. We know that AM radio operates in the frequency range of 535 kHz (medium wave) to 26.1 MHz (short wave), FM radio operates on 88 to 108 MHz frequency band, and DAB operates on band-III with a frequency range of 174 to 240 MHz. From the current market, a wide range of SDRs does not operate on the kHz frequency band required for AM operation. So, it is important to find SDRs that can operate on the kHz frequency range.

Secondly, we can focus on the economic aspect of the SDR. Since the conventional radio tuners used in vehicles cost only a few hundred dollars, we need to select an SDR that does not cost more than the radio tuner used in the vehicles.

The current SDR in the market offers an RF bandwidth of at least 1 MHz. Since the implementation of AM/FM/DAB does not require higher RF bandwidth, we do not consider the bandwidth as a metric to select the SDR.
Table 3.1: List of SDRs capable of AM/FM/DAB Reception

<table>
<thead>
<tr>
<th></th>
<th>Crimson TNG</th>
<th>HackRF One</th>
<th>RTL-SDR v3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>DC - 6 GHz</td>
<td>1 MHz - 6 GHz</td>
<td>500 - 1.76GHz</td>
</tr>
<tr>
<td>RF Bandwidth</td>
<td>325 MHz</td>
<td>20 MHz</td>
<td>2.4 MHz</td>
</tr>
<tr>
<td>DAC/ADC</td>
<td>16 bits</td>
<td>8 bits</td>
<td>8 bits</td>
</tr>
<tr>
<td>Sample Rate</td>
<td>325 MSPS</td>
<td>8 - 20 MSPS</td>
<td>2.4 MSPS</td>
</tr>
<tr>
<td>Tx Channels</td>
<td>4</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Rx Channels</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Full / Half Duplex</td>
<td>Full Duplex</td>
<td>Half Duplex</td>
<td>Half Duplex</td>
</tr>
<tr>
<td>Interface</td>
<td>Dual 1/10G SFP+ 1G</td>
<td>High Speed USB 2.0</td>
<td>USB 2.0</td>
</tr>
<tr>
<td></td>
<td>Ethernet USB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD Card</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chipset</td>
<td>ADF4355</td>
<td>RFFC 5071/5072</td>
<td>R820T</td>
</tr>
<tr>
<td>FPGA</td>
<td>Altera Arria V</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Processor</td>
<td>dual-core ARM</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>Cortex-A9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>Firmware</td>
<td>Complete</td>
<td>Complete</td>
</tr>
<tr>
<td>Oscillator Precision</td>
<td>± 10ppm</td>
<td>± 20ppm</td>
<td>± 20ppm</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>Low 30 - 18 dBm</td>
<td>Max power is 15 dBm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High 10 - 15 dBm</td>
<td></td>
<td>Receive only</td>
</tr>
<tr>
<td>Power required</td>
<td>IEC320 cable</td>
<td>USB 2.0 bus power</td>
<td>280 mA, 4.5 V</td>
</tr>
<tr>
<td>Software support</td>
<td>GNURadio</td>
<td>GNURadio, LabVIEW,</td>
<td>GNURadio, LabVIEW,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matlab, SDR#</td>
<td>Matlab, SDR#</td>
</tr>
<tr>
<td>Price</td>
<td>$13500</td>
<td>$245</td>
<td>$25</td>
</tr>
<tr>
<td>AM/FM/DAB</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 3.2: (Contd) List of SDRs capable of AM/FM/DAB Reception

<table>
<thead>
<tr>
<th></th>
<th>LimeSDR</th>
<th>Matchstiq S12</th>
<th>USRP N200/N210</th>
<th>USRP X300/X310</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong></td>
<td>100 kHz - 3.8 GHz</td>
<td>&lt;1 MHz - 6 GHz</td>
<td>DC - 6 GHz</td>
<td>DC - 6 GHz</td>
</tr>
<tr>
<td><strong>RF Bandwidth</strong></td>
<td>61.44 MHz</td>
<td>50 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DAC/ADC</strong></td>
<td>12 bits</td>
<td>12 bits</td>
<td>14 bit ADC</td>
<td>14 bit ADC</td>
</tr>
<tr>
<td><strong>Sample Rate</strong></td>
<td>61.44 MSPS</td>
<td>61.44 MSPS</td>
<td>50 MSPS</td>
<td>200 MSPS</td>
</tr>
<tr>
<td><strong>Tx Channels</strong></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Rx Channels</strong></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td><strong>Full / Half Duplex</strong></td>
<td>Full Duplex</td>
<td>Full Duplex</td>
<td>Full Duplex</td>
<td>Full Duplex</td>
</tr>
<tr>
<td><strong>Interface</strong></td>
<td>USB 3.0</td>
<td>Gigabit Ethernet, USB 2.0, HDMI</td>
<td>Gigabit Ethernet</td>
<td>10 Gigabit Ethernet</td>
</tr>
<tr>
<td><strong>Chipset</strong></td>
<td>LMS 7002M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FPGA</strong></td>
<td>Cyclone IV</td>
<td>Xilinx spartan 6</td>
<td>Spartan 3A-DSP 1 FPGA</td>
<td>USRPX300: XC7K325T USRPX310: XC7K410T</td>
</tr>
<tr>
<td><strong>Processor</strong></td>
<td>Nil</td>
<td>Quad-core ARM A9 cortex</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Complete</td>
<td>Schematic, Firmware</td>
<td>Schematic, Firmware</td>
<td></td>
</tr>
<tr>
<td><strong>Oscillator Precision</strong></td>
<td>± 1ppm</td>
<td>± 1ppm</td>
<td>± 2.5ppm</td>
<td>± 2.5ppm</td>
</tr>
<tr>
<td><strong>Transmit Power</strong></td>
<td>10 dBm</td>
<td>13 dBm</td>
<td>15 dBm</td>
<td>&gt;10 dBm</td>
</tr>
<tr>
<td><strong>Power required</strong></td>
<td>Via USB</td>
<td>&lt; 3W</td>
<td>DC 6V, 2.3A</td>
<td>DC Input 12 V (45 W)</td>
</tr>
<tr>
<td><strong>Software support</strong></td>
<td>GNURadio LimeSuite</td>
<td>GNURadio Matlab RedHawk</td>
<td>GNURadio, LabVIEW, Matlab, Simulink</td>
<td>GNURadio, LabVIEW, Matlab, Simulink</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$299</td>
<td>$4500</td>
<td>N200: 1715</td>
<td>X300: 4,403</td>
</tr>
<tr>
<td><strong>AM/FM/DAB</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Tables 3.1 and 3.2 mentioned below explains the selection of SDR for realizing the AM, FM, and DAB technologies.

From the SDR selection table, it can be seen that RTL-SDR, HackRF one, and LimeSDR can be considered as a suitable option for implementing the above-mentioned technologies. The reason is that these SDR operate in the frequency range of these technologies, have a very good support community, and more importantly is economically viable. Among these SDR we select the RTL-SDR v3 as the chosen hardware due to its cheaper price and comparable specifications as opposed to LimeSDR and HackRF. With LimeSDR and HackRF One, there is a provision for transmission of data as well. Since our focus is towards the reception of the three broadcast radio technologies, a receive-only (half-duplex) SDR will be sufficient to cater to our needs.
3.3 Data Collection

The data collection process for testing the implementation of AM, FM, and DAB in SDR with the hardware-based tuner are explained below. It has to be noted that the radio tuner performance is measured based on the metrics set according to ETSI EN 303 345-1 standard [3]. Performance metrics like sensitivity, adjacent-channel suppression, far-off channel suppression, cross-modulation, and third-order intermodulation indicates the performance of AM, FM, and DAB.

The sensitivity of a radio receiver is defined as the minimum magnitude of the input signal (RF level) needed to produce a specific output having a specified SNR.

The receiver adjacent channel suppression is defined as a measure of how well the receiver can receive the transmitted signal in the presence of a high-level interfering signal in the adjacent channel.

Cross-modulation or blocking is the intermodulation distortion caused by multiple carriers within the same bandwidth. This can happen when strong nearby unwanted AM signals get added with the wanted AM signal.

Intermodulation distortion is defined as the production of new output signals as a result of a combination of non-linear signals. The order of intermodulation products depends on how many signals are mixed and which harmonics of these input signals are mixed. Third-order harmonic products are a major problem in radio reception because they fall close to the signals causing them.

Section 3.3.1 below gives us an overview of how the above-mentioned metrics are calculated.

3.3.1 Metrics used for AM/FM/DAB

To analyze the performance of the implemented AM/FM/DAB radio technologies in SDR and the SEM tuner, we measure parameters such as sensitivity in terms of SINAD, adjacent channel suppression, far-off channel suppression, cross-modulation, third-order intermodulation, etc.

The sensitivity of the radio implementations in SDR and hardware tuner are measured for the standard minimum and ultimate sensitivity values of a broadcast radio receiver. In the case of the three radio technologies, we find the minimum RF levels for which we reach the minimum and ultimate sensitivity values.
The parameter adjacent channel suppression is measured by generating 2 RF signals having a frequency spacing of a minimum $\pm 9 \text{ kHz}$ for AM signals, $\pm 200 \text{ kHz}$ for FM signals, and $\pm 1712 \text{ kHz}$ for DAB signals. This metric is measured as the ratio of audio output as mentioned below:

Adjacent channel suppression $= \frac{\text{RF1 modulation ON, RF2 modulation OFF}}{\text{RF1 modulation OFF, RF2 modulation ON}}$

Similar to adjacent channel suppression, the far-off channel suppression is measured by generating 2 RF signals (wanted and interfering signal) having a frequency spacing of a minimum $\pm 27 \text{ kHz}$ for AM signals, $\pm 600 \text{ kHz}$ for FM signals, and $\pm 5136 \text{ kHz}$ for DAB signals. This metric is calculated as the ratio of audio output as stated below:

Far-off channel suppression $= \frac{\text{RF1 modulation ON, RF2 modulation OFF}}{\text{RF1 modulation OFF, RF2 modulation ON}}$

Cross-modulation is basically the transposition of strong interfering signals with AM components getting added to the wanted signal. The interfering signal containing strong AM content can cause the parts of a radio receiver to move into non-linear regions. This metric is used for evaluating the performance of all radio broadcasting technologies. It is measured as the ratio of audio output in the presence and absence of the interfering signal.

Crossmodulation/Blocking $= \frac{\text{RF1 ON, RF2 OFF}}{\text{RF1 modulation OFF, RF2 ON}}$

Third-order intermodulation is measured by generating X modulated RF signals (X can be AM/FM/DAB) from a signal generator such that the three RF signals are sufficiently spread apart from each other. The frequency spacing between the signals is dependent on the radio technology used. The details about the spacing are mentioned in Chapter 5. This metric is measured as mentioned below:

Third-order intermodulation $= \frac{\text{RF1 ON, RF2 OFF, RF3 OFF}}{\text{RF1 modulation OFF, RF2 ON, RF3 OFF}}$

### 3.4 Experimental Design

This section discusses the test-bed model, hardware, and software necessary to realize the implementation of AM, FM, and DAB. The Figure below shows the experimental setup used to implement the radio technologies. The following subsection below explains the test setup used for implementing the radio technologies in SDR. The subsequent subsection
explains the test-bed necessary for monitoring the performance of the host-SDR setup.

### 3.4.1 Test Environment for AM, FM, and DAB Implementation

The test-bed for implementing the radio technologies is explained in Figure 3.1 below. The radio technologies are implemented in a host PC running GNU Radio. The host PC is connected to the SDR via a USB 2.0 interface. GNU Radio contains the necessary signal processing blocks for the implementation of radio technologies.

![Figure 3.1: Simple Host-SDR setup](image)

### 3.4.2 Test Environment for Performance Monitoring

In order to test the performance of the implemented AM, FM, and DAB radio technologies, we use the below-mentioned test-bed shown in Figure 3.2. To measure the performance metrics mentioned in section 3.2, we use electronic equipment such as signal generators, RF combiners, and a signal analyzer. Using the signal generator, we generate an AM/FM/DAB modulated signal and feed them as an input to the RF combiner. The output of the RF combiner is fed as an input to the host-SDR setup or the SEM unit. Since the metrics mentioned above are measured based on the audio quality of the signal, the signal coming from the audio port of the host-SDR setup or the SEM unit (depending on the operation) is fed as an input to the audio analyzer port of the signal analyzer. For instance, AM or FM radio running in the GNU Radio platform on top of an SDR produces an audio output signal (music or speech) when the SDR encounters an active AM or FM signal in its frequency band of operation. The audio signal produced from the sound card of the PC
(or SEM unit) is fed as an input to the audio analyzer port of the signal analyzer to monitor the distortion and noise contents of the signal.

![Diagram](image)

**Figure 3.2: Test-bed for Performance Evaluation**

### 3.5 Hardware and Software Required

The host PC used for the thesis is a Linux operating system (version 4.15.0-36-generic) powered by an Intel i3-5th generation processor with 8 GB RAM memory. The open-source GNU Radio software is installed on the Linux operating PC. For implementing the AM and FM radio, the pre-installed signal processing blocks in GNU Radio is used to realize the AM and FM flowgraphs. For implementing the DAB radio, we use the signal processing blocks developed by the gr-dab repository. RTL-SDR v3 dongle is used as the SDR for implementing the above-mentioned radio technologies. It is interfaced with the SEM and PC via an USB interface.

The implemented flowgraphs of AM, FM, and DAB can be found in the [radio-tech] repository. In order to run these radio technologies, the following software and packages are necessary to be installed:

- GNU Radio
- RTL-SDR driver
- GR-DAB
The RTL-SDR driver is installed from RTL-SDR tools found in [rtl-specific-tools]. Upon the installation of the driver, we have the necessary software to communicate with GNU Radio.

For testing the performance of the implemented AM, FM, and DAB, we use a variety of hardware as mentioned below:

- Signal Generator
- Signal Analyzer
- RF combiner
- Variable attenuator
- SMA and N connectors

The signal generator used for performance evaluation must be capable of generating AM, FM, and DAB modulated signals. The signal generator used for this thesis is Rohde & Schwarz Broadcast Test Center (BTC). The R&S BTC is capable of acting as a signal generator and spectrum analyzer. For analyzing the receiver characteristics like sensitivity, channel selectivity, cross-modulation, etc we use the Anritsu MS2830A spectrum/signal analyzer.

### 3.5.1 Rohde & Schwarz Broadcast Test center (BTC)

The R&S broadcast test center (BTC) is a reference signal generator that can generate RF signals for all global broadcasting standards, perform transmission simulation, and provide audio and video analysis of device under test (DUT). The R&S BTC provides seamless modification of transport structures based on the audio or video stream. It can also support simultaneous transmission of analog and digital audio broadcasting. The R&S BTC generates the DAB modulated signals according to the EN 300 401 standard in the form of ensembles making it easier for receiver demodulation and decoding. In this thesis project, we use this signal generator for generating the AM, FM, and DAB modulated signals for testing the radio receiver performance.

### 3.5.2 Anritsu MS2830A

The Anritsu MS2830A is a high speed, high performance, and cost-effective signal/spectrum analyzer. It can operate in the frequency range
from 9 kHz to 6 GHz and has signal generation capability as well. It has an audio-analyzer function which helps us to measure the sensitivity (SINAD) of a radio receiver. It can also provide modulation analysis of various communication technologies like GSM, WCDMA, and LTE in software. It works on Windows operating system making it easier for users to work with the unit.

3.6 Setting up the SEM - Hardware

The SEM unit under study works on the Android operating system and is primarily used for entertainment services. Figure 3.3 shows the complete schematic of the SEM unit. The antenna in the schematic is from a public source.

Figure 3.3: Schematic of SEM

In order to get the SEM unit up and running, the following are the components required:

- SEM 2.1 unit of Volvo Trucks
- 1 quadlock connector

1https://www.amazon.in/Authentic-Antenna-Device-Feet-Long/dp/B0197XFMBW
• 2 RS232 (USB <-> Serial) connectors for getting the data from VIP and AP.
• USB-A to USB-A connector
• USB-mini connector
• LCD display (known as the SID)
• 2 speakers
• AM/FM/DAB compatible antenna
• Fakra connectors for antenna
• 12V DC power supply
• LVDS connector for the LCD display

The RS232 connectors are necessary for loading or debugging applications in the SEM. In order to communicate with the SEM, the PC in use should have the android debug bridge (ADB) installed. Putty is used for getting access to the COM port (serial port) of the SEM unit. Figure 3.4 shows the entire setup in lab conditions.

Figure 3.4: SEM unit setup
Chapter 4

Implementation of AM/FM/DAB

In this chapter, we will look into the implementation and working of RDS-FM, AM, and DAB in SDR. Section 4.1 gives us a comprehensive overview of the working of RDS FM in GNU Radio. Section 4.2 provides the implementation details of AM radio and Section 4.3 provides information on the DAB radio implementation.

4.1 RDS-FM Implementation & Architecture

For implementing the RDS FM, GNU Radio is selected as the software platform and RTL-SDR as the suitable hardware. The encoder, decoder, and the message parsing blocks for the RDS FM has been developed by gr-rds as a part of GNU Radio. As mentioned in the introduction section 2.2.1 of RDS FM, the data signal is transmitted through a separate sub-carrier located at the third harmonic to the pilot tone. The following Figure 4.1 shows the implementation of RDS FM in GNU Radio.

From the flowgraph, we can see that RTL-SDR Source is the receiving part of the SDR and is responsible for sniffing/receiving radio signals. The center frequency of the RTL-SDR source can be set to any frequency within the FM frequency band. The RF gain of the RTL-SDR is controlled dynamically. From the RTL-SDR Source block, we can see that the sample rate is 2 MHz and is significantly lower than the center frequency. According to the Nyquist Theorem, the sampling frequency should be at least 2X the center frequency. In order to satisfy the Nyquist theorem, we down-convert the RF signal to the baseband level centered around 0 Hz. The bandwidth of a broadcast FM radio station is typically
Figure 4.1: Flowgraph of RDS FM radio
about 200 kHz which means that we can find a radio signal within 0 to 200 kHz. Signals above 200 kHz are frequencies from other stations. In order to remove the signals from frequencies outside the bandwidth, the cutoff frequency of the low pass filter is chosen to be 200 kHz. For any radio receiver, we need filters and demodulators to bring the RF signal to baseband level. After the demodulation operation performed by WBFM Receive, we try to extract the audio and data from the demodulated signal separately. The extraction of the audio signal is straightforward. We decimate and integrate the signal using a Rational Resampler in order to bring the demodulated signal to PC sound-card frequency.

For the data signal, we need to perform a series of operations as explained below. The sub-carrier is amplitude modulated by a shape and bi-phase coded data signal. The modulation can be thought of as a two-phase phase-shift keying. The demodulated data signal is passed through a series of filters and is fed into a MPSK receiver block. We use a Root Raised Cosine Filter in order to perform pulse shaping [14]. Since the demodulated signal after WBFM Receive has much larger bandwidth than the intended bandwidth for a data signal, we band-limit the signal and also reduce the inter-symbol interference (ISI) from multipath reflections using RRC filter.

Once the filtering operation is done, the data signal is received by the M-PSK Receiver. This block takes care of receiving M-PSK modulated signals through a phase, frequency, and symbol synchronization. It performs phase and frequency synchronization based on a Costas loop. The symbol synchronization is performed using the Mueller circuit [15]. This circuit performs interpolation of the downconverted sample every mu samples and finds the sampling error based on current symbols and previous symbols and the decision made on them.

After receiving the signal from the MPSK Receiver block, the data signal is differentially decoded and sent to the RDS Decoder block to perform the decoding of the RDS FM data. Once, the RDS data is decoded, parsing is done so that the necessary RDS data is displayed in the WX GUI panel.

Figure 4.2 below shows us the FFT details and the RDS information of RDS-FM when it is run from GNU Radio. It has to be noted that GNU
Radio is not a calibrated system and the values that we are outputting are relative values and not absolute ones. This is because GNU Radio does not enforce a strict-hardware interface in which the samples are expected to be exactly calibrated to some standard amplitude by the hardware. In order to measure absolute power, it is advisable to use a calibrated signal generator and signal analyzer.

Figure 4.2: Details of RDS-FM radio

\[1\]https://wiki.gnuradio.org/index.php/FAQ
4.2 AM radio Implementation

For implementing the AM radio in software, we use the signal processing blocks present in GNU Radio. Figure 4.3 shown below explains the AM radio implementation in GNU Radio.

The Osmocom Source block is responsible for receiving the AM signals in the SDR. When the antenna connected to the SMA port of RTL-SDR receives an AM signal, it is processed using the Osmocom Source by setting the sample rate and channel frequency. With the help of the Low Pass Filter, we decimate the signal further in order to bring the signal close to the baseband level. We use a Rational Resampler to fraction sample the received signal even further in order to bring the sample rate to the audio sound card frequency of the PC. Once the signal is fraction sampled, it is fed to the Automatic Gain Control (AGC3). AGC is a circuit design (widely used in AM receivers) to maintain the same level of amplification for a sound or radio frequency. If the input signal to the AGC3 is too low, it will amplify the signal level and if the signal level is too high, it will lower the signal amplitude to maintain a constant level as possible. The gain is updated for each sample using the formula given below.

\[
\text{Gain} = \text{Gain} + \text{Rate} \times (\text{Reference} - \text{abs(Input)})
\]

Further, the signal is fed to the AM Demod block which demodulates the received signal to its baseband frequency. Once the signal is demodulated, it is fed to the Audio Sink which is responsible for playing the signal through the speaker or any other audio device connected.

As mentioned earlier, due to the absence of broadcasting AM stations in Sweden, it was not possible to listen to AM radio. However, AM modulated signals from the signal generator were fed as an input to the RTL-SDR in order to test and verify the correctness of the implementation.
Figure 4.3: Flowgraph of AM radio
4.3 DAB Radio - Implementation and Architecture

For implementing the DAB radio in GNU Radio, we use the gr-dab repository in order to perform the demodulation and decoding process of a DAB signal frame [16]. The Osmocom Source is used for receiving the DAB signal by setting the channel frequency in the DAB frequency range (174-240 MHz). We set a sample rate of 2.048 MHz which is the ideal sample rate at which the RTL-SDR works in the presence of a DAB signal. Once the signal is received, it is demodulated by using the DAB: OFDM Demodulator block from the gr-dab module. Once demodulated, we can separately decode the FIC transmission frame and MSC frame. In order to check whether a particular signal is DAB modulated, we can connect the DAB:OFDM Demodulator block to a QT GUI Constellation Sink to check the DAB constellation. Figure 4.4 below shows us the DAB constellation and its FFT plot centered at 225.648 MHz.

Generally, a DAB ensemble contains many broadcast services and supplies audio and data streams in separate sub-channels. All these sub-channels are together multiplexed into an MSC within a common interleaved frame that occupies the bulk of the channel capacity. In order to provide information about the structure of the MSC data to the receiver, an FIC is used. The FIC Decoder block is responsible for decoding the fast information channel content like the radio station names, program labels, multiplex configuration information, etc; that are required to be displayed to the user in less time as compared to the information carried by the MSC. The DAB+ Decoder is responsible for decoding the MSC content which generally carries audio or data-related services. Once the MSC channel content is decoded, we feed it to the audio sink which is responsible for playing the audio in speakers or any other audio device.

The flowgraph of DAB radio is shown in Figure 4.5.
Figure 4.4: Constellation and FFT of DAB signal
Figure 4.5: DAB flowgraph
Chapter 5

Results and Analysis

In this chapter, we present the results for the SDR based AM, FM, and DAB implementation as compared to the radio tuner used inside the SEM unit. The results and analysis for the SDR based implementation are explained in detail in the section below.

5.1 Results and Analysis of SDR based setup

As mentioned in the previous section, in this thesis, we evaluate and test the performance of the SDR based AM, FM, and DAB radio with the hardware based radio tuner used by the SEM. The following sections will explain the results and analysis obtained for these radio technologies.

The first step for evaluating the performance of the SDR based setup with the hardware tuner will be to compare the number of channels that the SDR based receiver can receive as compared to the hardware tuner. In case of the FM radio, we checked the amount of FM channels received by RTL-SDR and the SEM tuner. Table 5.1 below shows the list of FM radio stations available for reception in the SDR and hardware tuner.

The list of FM channels mentioned in the table are the standard FM stations broadcasting information in Gothenburg [17]. However, there were a few stations that transmitted the music/data in alternative frequency channels. The SDR based setup was able to receive a few of them which weren’t possible with the SEM tuner. For instance, the 97.2 MHz\(^1\) channel can be decoded and demodulated by the SDR based setup but not by the tuner inside the SEM.

\(^1\)Alternate frequency channel located far away from test site
Table 5.1: FM Performance: SDR vs SEM

<table>
<thead>
<tr>
<th>FM (MHz)</th>
<th>Radio Station Name</th>
<th>SEM Tuner</th>
<th>SDR tuner</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.0</td>
<td>Radio 88 Partille</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>89.3</td>
<td>SR P1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>90.2</td>
<td>Rix FM</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>90.7</td>
<td>Radio Plus</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>94.9</td>
<td>GNF 94.9</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>96.3</td>
<td>SR P2</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>97.2[1]</td>
<td>SR P3</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>99.4</td>
<td>SR P3</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>100.2</td>
<td>Radio MNF</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>101.9</td>
<td>SR P4</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>102.6</td>
<td>GNF 102.6</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>103.1</td>
<td>GNF 103.1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>104.8</td>
<td>Rock FM</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>105.3</td>
<td>Rix FM</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>105.9</td>
<td>NRJ</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>107.3</td>
<td>Mix Megapol</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>107.8</td>
<td>Star FM</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

In the case of DAB radio, both the SDR based setup and hardware based tuner were able to receive the 12B ensemble. In Gothenburg (Sweden), data/music was broadcasted only in the 225.648 MHz (12B) frequency which consists of 6 independent broadcasting channels multiplexed to result in an ensemble. The following Table 5.2 shows the ensemble received by SDR and the hardware tuner.

As far as the AM radio is concerned, there are no broadcasting stations in Sweden as AM radio is extinct in Sweden since the late 2000’s.

The next step involved in this performance evaluation will be to test the SDR setup based on the EN 300 345 and the predefined metrics mentioned for the SEM unit.
Table 5.2: DAB Performance : SDR vs SEM

<table>
<thead>
<tr>
<th>DAB Frequency</th>
<th>Radio Station Name</th>
<th>SEM tuner</th>
<th>SDR setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>225.648 MHz</td>
<td>SR P1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(12B)</td>
<td>SR P2 Classical</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>SR P2 World</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>SR P3 Star</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>SR Sisuradio</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>SR Radio’s lap channel</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

5.1.1 FM based setup

For evaluating the performance of FM based radio setup, we monitor and evaluate the following set of parameters, namely, sensitivity (SINAD), adjacent channel suppression, far-off channel suppression, cross-modulation, third-order intermodulation, AM suppression, etc. The details regarding the measurement of these metrics are explained below.

Sensitivity: We measure the sensitivity of a radio receiver in terms of SINAD by varying the RF level of the input signal. For a broadcast radio receiver used in vehicles, the minimum sensitivity of the receiver is 26 dB and the ultimate sensitivity is 60 dB [18]. With this metric, we have to identify the minimum RF level (of the input signal) required to reach the threshold sensitivity values. In order to measure this parameter, we use the setup as mentioned in Figure 3.2. The Rohde & Schwarz BTC is used as the signal generator to generate an FM modulated signal with arbitrary RF levels for measuring the minimum sensitivity and the ultimate sensitivity values of the RTL-SDR radio receiver. We use a frequency deviation of 40 kHz in both the cases and generate a stereo signal with RDS information embedded in the sub-carrier of the generated FM signal. The RF level of the input signal is varied in small steps in order to attain the minimum and ultimate sensitivity values.

Once the signal is received in RTL-SDR, we can monitor the signal at the transmitted RF frequency in GNU Radio and verify it by listening to the 1 kHz audio tone and the RDS data carried by the signal. The RTL-SDR managed to achieve these respective thresholds values for minimum and ultimate sensitivity in lower RF levels.
Adjacent Channel Suppression: Adjacent channel suppression is the interference caused by an extraneous power from a signal in the adjacent channel. We use this metric in order to test how well the radio receiver performs in presence of a strong interfering signal from an adjacent channel. In order to test and evaluate this metric, we generate 2 FM modulated signals with a frequency deviation of 40 kHz and an RF signal level of 80 dBuV. We generate the 2 FM modulated signals from the signal generator in such a way that the 2 signals are separated by a spacing of ±200 kHz.

The signals coming out from the 2 signal generators are combined in the presence of an RF combiner and fed as an input to the SMA port of the RTL-SDR. Upon reception, we tune the RTL-SDR to the wanted RF signal frequency in GNU Radio. In order to check whether we receive the right signal, we can check the RDS data embedded in the signal at that frequency. Since we are also transmitting another RF signal (interference signal) at a frequency ±200 kHz of the wanted RF signal, we can see a strong spike in the adjacent channel. To calculate the adjacent channel suppression, we find the ratio of the audio output when the RF1 (wanted signal) is ON, RF2 Signal (interference) OFF to the ratio RF1 (wanted signal) OFF, RF2 (interference) ON.

With this metric, we also measure the adjacent channel suppression (SINAD < 3 dB) to check how well the SDR reacts to a much stronger interfering signal (power level of interfering signal » wanted signal). The reason why 3 dB is significant because it is the point where the output power level becomes half the input power. This metric is calculated as the ratio of audio output when the interfering signal RF2 is OFF to the audio output when RF2 is ON. The requirement is that the SINAD level in the presence of a strong interfering signal should be no less than 3 dB from the reference SINAD level (in the absence of an interfering signal).

From the table shown below, it is quite clear that the SDR is capable of rejecting the strong interfering signal from the neighbouring FM channels. The SDR produces an adjacent channel suppression of greater than 40 dB and its SINAD level reduces less than 3 dB of the reference signal in the presence of interference, which is the minimum requirement for a broadcast radio receiver.

Far-off Channel Suppression: Far-off channel suppression is the interference caused by an extraneous power from a signal coming from a non-adjacent channel. This metric helps us to monitor the ability of the
radio receiver to reject unwanted signals. We use the same setup as we used for adjacent channel suppression. The signal coming from the interference channel is spaced more than ±200kHz from the wanted signal generated by signal generator.

The 2 FM modulated signals from the signal generator have an RF level of 80 dBuV and 40 kHz frequency deviation with different RF frequencies. This metric is calculated as the ratio of audio output when the RF1 (wanted signal) is ON, RF2 Signal (interference) OFF to the ratio RF1 (wanted signal) OFF, RF2 (interference) ON.

The far-off channel suppression (SINAD < 3 dB) is calculated similar to the adjacent channel suppression (SINAD < 3 dB).

The SDR produces a far-off channel suppression of greater than 50 dB sensitivity and passes the minimum requirement for a broadcast radio receiver.

**Cross-Modulation:** Cross-modulation is a parameter used in radio receivers where strong signals with an amplitude modulated component gets added to the wanted signal. The undesired or interference signal is amplitude modulated with a suitable modulation depth. It is generally found that such a strong signal can cause parts of the radio receiver to become non-linear by transferring to a typically weaker signal that has lesser non-linearities in the receiver chain.

To measure this metric, we generate an FM modulated signal with a frequency deviation of 40 kHz and an RF level of 20 dBuV from a signal generator. We combine this FM modulated signal with an AM modulated signal having a modulation depth of 80% and an RF level higher than the FM modulated signal. Once the 2 signals are combined using an RF combiner, it is fed to the radio tuner for performance evaluation. The cross-modulation metric is measured as the audio output when the RF1 (wanted signal) is ON, RF2 Signal (interference) OFF to the ratio RF1 (wanted signal) OFF, RF2 (interference) ON. The RF level of the unwanted signal is kept based on the frequency of the generated interfering signal. The power levels of the RF signals are selected according to the SEM unit specifications.
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\[
\begin{align*}
65\text{MHz} & \quad \text{RF1 (wanted signal)} \quad 108 \text{MHz} \quad \text{RF1} = 60 \text{ dBuV} \\
0.15\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 26 \text{MHz} \quad X = 117 \text{ dBuV} \\
26\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 28 \text{MHz} \quad X = 123 \text{ dBuV} \\
65\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 108 \text{MHz} \quad X = 116 \text{ dBuV} \\
174\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 230 \text{MHz} \quad X = 107 \text{ dBuV} \\
380\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 480 \text{MHz} \quad X = 101 \text{ dBuV} \\
470\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 698 \text{MHz} \quad X = 99 \text{ dBuV} \\
699\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 960 \text{MHz} \quad X = 96 \text{ dBuV} \\
1710\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 2170 \text{MHz} \quad X = 93 \text{ dBuV} \\
2300\text{MHz} & \quad \text{RF2 (unwanted signal)} \quad 2690 \text{MHz} \quad X = 82 \text{ dBuV}
\end{align*}
\]

The SDR setup has the ability to block strong AM content in the wanted signal bandwidth. Similar to the SEM tuner, SDR setup also achieves the minimum requirement for cross-modulation. The cross-modulation (SINAD < 3 dB) is measured and it satisfies the requirement for automobiles as well.

**Input Third Order Intermodulation:** When 2 or more signals are modulated they produce a form of distortion called inter-modulation products. These inter-modulation products are distortions that result from the non-linearities of the system. They can prove to be a problem because of their close proximity to the fundamental frequency and cannot be filtered out as they are on the same band as the fundamental frequency.

To measure this metric, we generate 3 signals from the signal generator having a spacing of 1 MHz and 2 MHz with respect to the fundamental signal. Let us say the RF power levels of the 3 signals be RF1, RF2, and RF3 respectively. They all follow the condition:

RF1 = fundamental frequency channel
RF2 = RF1 + 1 MHz
RF3 = RF1 + 2 MHz

The third-order intermodulation (TOI) distortion products are formed as a result of the combining of these 3 signals. We generate an FM modulated signal with a frequency deviation of 40 kHz and a RF power level (RF1) of 30 dBuV. Similarly, we generate a carrier wave at a frequency spacing of 1 MHz from the fundamental frequency and an FM modulated signal at a frequency spacing of 2 MHz from the fundamental signal (RF1). This test is done in accordance with the test metric values.
mentioned in the SEM hardware specifications. The TOI is measured as the ratio of the audio output RF1 (wanted signal) is ON, RF2 Signal (unwanted signal) OFF, RF3 (unwanted signal) to the ratio RF1 (wanted signal) OFF, RF2 (unwanted signal) ON, RF3 (unwanted signal) ON.

The TOI (SINAD < 3 dB) passes the test in presence of strong interfering signals. According to the metrics given for the SEM unit, the radio receiver should have a minimum of 50 dB TOI SINAD to be qualified as a broadcast radio receiver in vehicles. The RTL-SDR was successful in achieving the requirement.

**AM Suppression:** In order to realize the complete capability and advantage of FM radio with respect to the SNR or SINAD, it is necessary to suppress any form of amplitude modulation which may be present in the signal. AM suppression can be defined as the ratio of the index of AM in the output signal to the index of AM in the input signal [19]. This metric can give us a fair idea of how well the SDR can suppress the unwanted AM content in the FM signal.

For evaluating this metric, we generate 2 RF signals from the signal generators, where one of them is FM modulated and the other is AM modulated. The FM modulated signal is generated with an RF level (RF1) of 60 dBuV and a FM deviation of 40 kHz. The AM modulated signal is also generated with a RF level (RF2) of 60 dBuV and an AM depth of 90%. The 2 signals are combined using an RF combiner and is fed as an input to the SDR based tuner. The AM suppression is calculated as the ratio of the audio output with RF1 ON and RF2 OFF with respect to audio output with RF1 OFF and RF2 ON.

The following Table 5.3 shows the performance of the SDR in presence of FM modulated signals. It has to be noted that other than the sensitivity measurements (minimum and ultimate), the stimulus is same for SEM and the RTL-SDR v3. This holds for the AM and DAB radio metrics as well. For minimum and ultimate sensitivity, the stimulus is specified explicitly for both SEM and SDR.
Table 5.3: FM Radio Metrics

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Stimulus: RF1 signal is FM modulated with an audio signal (1 kHz) such as speech/music with deviation = 40 kHz</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Sensitivity</td>
<td>26 dB</td>
<td></td>
<td>SDR: RF1 input &lt;5 dBuV, SEM: RF1 input = 5 dBuV</td>
<td>RF1 frequency in FM band</td>
</tr>
<tr>
<td>Ultimate Sensitivity</td>
<td>60 dB</td>
<td></td>
<td>SDR: RF1 input &lt;60 dBuV, SEM: RF1 input = 60 dBuV</td>
<td>RF1 frequency in FM band</td>
</tr>
<tr>
<td>Adjacent Channel Suppression</td>
<td>40 dB</td>
<td></td>
<td>RF1 input 80dBuV, RF2 input 80dBuV, RF1 = wanted signal, RF2 = adjacent channel RF2 = RF1 +/- 200 kHz</td>
<td>RF1 = wanted signal, RF2 = adjacent channel, RF2 = RF1 +/- 200 kHz</td>
</tr>
<tr>
<td>Adjacent Channel Suppression (SINAD &lt;3 dB)</td>
<td>3 dB</td>
<td>RF1 input 30dBuV, RF2 input 80dBuV, RF1 = wanted signal, RF2 = adjacent channel RF2 = RF1 +/- 200 kHz</td>
<td>RF1 = wanted signal, RF2 = adjacent channel, RF2 = RF1 +/- 200 kHz</td>
<td></td>
</tr>
<tr>
<td>Far-off Channel Suppression</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 80dBuV, RF2 input 80dBuV, RF1 = wanted signal, RF2 = interfering signal RF2 = RF1 +/- 600 kHz</td>
<td>RF1 = wanted signal, RF2 = interfering signal, RF2 = RF1 +/- 600 kHz</td>
</tr>
<tr>
<td>Far-off Channel Suppression (SINAD &lt;3 dB)</td>
<td>3 dB</td>
<td></td>
<td>RF1 input 20dBuV, RF2 input 90dBuV, RF1 = wanted signal, RF2 = interfering signal RF2 = RF1 +/- 600 kHz</td>
<td>RF1 = wanted signal, RF2 = interfering signal, RF2 = RF1 +/- 600 kHz</td>
</tr>
<tr>
<td>Cross-Modulation</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 20dBuV, RF2 input X dBuV, AM 1.3kHz, depth 80%, RF1 = wanted signal, RF2 = interfering signal RF2 = 26 MHz &lt;RF2 &lt;28 MHz</td>
<td>RF1 = wanted signal, RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>Cross-Modulation (SINAD &lt;3 dB)</td>
<td>3 dB</td>
<td></td>
<td>RF1 input 20dBuV, RF2 input X dBuV, AM 1.3kHz, depth 80%, RF1 = wanted signal, RF2 = interfering signal RF2 = 26 MHz &lt;RF2 &lt;28 MHz</td>
<td>RF1 = wanted signal, RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>Input Third Order Intermodulation</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 30 dBuV, RF2 input 80 dBuV, CW carrier, RF3 input 80 dBuV, RF1 = wanted signal, RF2 = RF1 + 1 MHz, RF3 = RF1 + 2 MHz</td>
<td>RF1 = wanted signal, RF2 = RF1 + 1 MHz, RF3 = RF1 + 2 MHz</td>
</tr>
<tr>
<td>Input Third Order Intermodulation (SINAD &lt;3 dB)</td>
<td>3 dB</td>
<td></td>
<td>RF1 input 30 dBuV, RF2 input 85 dBuV, CW carrier, RF3 input 85 dBuV, RF1 = wanted signal, RF2 = RF1 + 1 MHz, RF3 = RF1 + 2 MHz</td>
<td>RF1 = wanted signal, RF2 = RF1 + 1 MHz, RF3 = RF1 + 2 MHz</td>
</tr>
<tr>
<td>AM Suppression</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 60 dBuV, RF2 input 60 dBuV, AM 1kHz, depth 50%, RF1 = wanted signal, RF2 = wanted signal</td>
<td>RF1 = wanted signal, RF2 = wanted signal</td>
</tr>
</tbody>
</table>
5.1.2 DAB based setup

The metrics used for evaluating the performance of FM radio is used for DAB radio as well. Only the modulation and other signal characteristics are modified accordingly for evaluating DAB performance in SDR based tuner. The RF signals generated by the signal generators are in the frequency range 174-240 MHz. The DAB modulated signal is transmitted in the form of an ensemble. The ensemble comprises of 6 radio channels each containing an audio/speech signal. The following metrics are used for the evaluation of DAB radio performance in the SDR tuner.

**Sensitivity:** As mentioned in FM radio setup, the minimum and ultimate sensitivity values of a radio receiver for any broadcast signal is 26 dB and 60 dB respectively. Like FM radio, Figure 3.2 is used as the test-bed for DAB performance evaluation in SDRs. To find the minimum RF levels required to achieve the minimum and ultimate sensitivity values, we use a signal generator to broadcast a DAB modulated signal (modulation 50%) with an arbitrary RF level. The RF level of the transmitted signal is varied until we reach the minimum and ultimate sensitivity values. The lower the RF level of the transmitted signal, better is the receiver performance.

The DAB modulated signal generated from the signal generator is fed as an input to the SDR and we monitor the DAB signal and its constellation at the transmitted RF frequency. The transmitted DAB signal is in the form of an ensemble and we can measure its audio quality by feeding it to the Anritsu MS2830A signal analyzer.

The SDR was able to achieve the minimum and ultimate sensitivity values for RF levels of -95 dBm and -70 dBm respectively. However, by adjusting the gain of the DAB signal, the threshold values can be obtained slightly below these RF levels as well.

**Adjacent Channel Suppression:** In order to test and evaluate this metric, we generate 2 DAB modulated signals from the Rohde & Schwarz BTC with both the signals separated by a minimum of ±1.712 MHz. The spacing between 2 ensemble centers is 1712 kHz, of which 1536 kHz is taken by the DAB signal which comprises of 1536 OFDM carriers spaced at 1 kHz. The remaining 176 kHz is the spacing between the top of one ensemble and the bottom of the next. The wanted DAB signal is generated at an RF level of -70 dBm (RF1) with modulation of 50%.
The interfering DAB signal is generated at a higher RF level (RF2) of -20 dBm in the adjacent channel. This metric will give an idea of how well the SDR performs in the presence of a strong interfering signal from an adjacent channel.

The 2 DAB modulated signals coming out from the signal generator is fed to the SDR via a RF combiner. Upon reception, the DAB signal is monitored in the PC and its audio quality is measured using the signal analyzer. This metric is calculated as the ratio of the audio quality when the interfering signal RF2 is OFF relative to RF2 is ON.

Along with this metric, we also measure the adjacent channel suppression (SINAD < 3 dB). This metric is evaluated by measuring the SINAD of the DAB signal with RF2 signal ON relative to RF2 signal OFF.

The RTL-SDR was able to reject the interference from the DAB ensemble in the adjacent channel by producing an adjacent channel suppression SINAD of greater than 40 dB [20]. This indicates that the SDR has passed the requirement for minimum adjacent channel suppression.

**Far-off Channel Suppression:** For measuring this metric, we generate 2 DAB modulated signals with an RF frequency spacing of ±5136 kHz. In order to measure the effect of the interfering signal from a far-off channel on the wanted frequency channel, we generate the 2 DAB modulated signals from the signal generator and feed it to the SDR via an RF combiner. The resulting signal is fed to the Anritsu MS2830A signal analyzer for measuring the audio quality of the DAB signal. The audio distortion quality in SINAD is calculated as the ratio of audio output when RF1 (wanted signal) is ON and RF2 (interfering signal) is OFF to the ratio of audio output when RF1 is OFF and RF2 is ON.

The far-off channel suppression (SINAD < 3 dB) is calculated similar to the adjacent channel suppression and is measured as the ratio of audio output in the presence and absence of the interfering signal.

The far-off channel suppression SINAD of the radio equipment has to be a minimum of 45 dB to be used in vehicles [20]. The SDR was successful in achieving that value showing its ability to reject the interference from non-adjacent channels too.

**Cross-Modulation:** Cross-modulation is the transposition of the AM content from an interfering signal to the wanted signal. This metric is measured by generating a DAB modulated signal with 50% max modu-
lation level and generating a CW signal from the signal generator. The 2 signals are combined with the RF combiner and fed to the SDR tuner. The audio output is measured by feeding the signals from the SDR to the Anritsu signal analyzer. Cross-modulation is calculated as the ratio of audio output when RF1 (wanted signal) is ON and RF2 (interfering signal) is OFF to the ratio of audio output when RF1 is OFF and RF2 is ON. The RF level of the wanted signal is kept as -70 dBm and the RF level of unwanted cross-modulating signal is kept accordingly depending on the frequency of unwanted signal.

The SDR was successful in achieving the threshold value achieved by the SEM unit indicating that it has passed the test.

Input Third Order Intermodulation: For measuring the TOI, we generate 3 DAB modulated signals from the Rohde & Schwarz BTC signal generator. As per the common convention, the RF level of the wanted DAB modulated signal (RF1) is kept as -70 dBm [20]. The RF power levels of the interfering signals (RF2 and RF3) are kept to higher values as compared to the wanted signal. The frequency spacing between the wanted and interfering signals are shown below.

RF1 = fundamental frequency channel
RF2 = RF1 + 1.712 MHz
RF3 = RF2 + 1.712 MHz

The wanted and interfering signals generated from the R&S BTC is combined using a RF combiner and is fed as an input to the SDR tuner. Upon reception, the DAB ensembles are viewed in the operating system and the audio quality of the DAB speech/music signal is measured by feeding its audio output to the Anritsu signal analyzer. The TOI metric is calculated as the ratio of audio output with RF1 ON, RF2 OFF, RF3 OFF to the audio output when RF1 OFF, RF2 ON, RF3 ON. The TOI (SINAD < 3 dB) is calculated similar to the way it was calculated for the FM radio. It is measured as the audio output in the presence and absence of the interfering signals RF2 and RF3.

From the DAB metrics table, it indicates that the SDR has passed the minimum requirement set for the TOI metric.

Table 5.4 mentioned below gives us the performance metrics for the DAB radio in SEM and SDR.
Table 5.4: DAB Radio Metrics

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Stimulus: RF1 signal is DAB modulated with an audio signal (1 kHz) such as speech/music and modulation = 50%</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Sensitivity</td>
<td>26 dB</td>
<td></td>
<td>RF1 input -95 dBm, 50% modulation</td>
<td>174 &lt;RF1 &lt;240 RF1 in MHz</td>
</tr>
<tr>
<td>Ultimate Sensitivity</td>
<td>60 dB</td>
<td></td>
<td>RF1 input -70 dBm, 50% modulation</td>
<td>174 &lt;RF1 &lt;240 RF1 in MHz</td>
</tr>
<tr>
<td>Adjacent Channel Suppression</td>
<td>40 dB</td>
<td>3 dB</td>
<td>RF1 input -70 dBm, RF2 input -30 dBm,</td>
<td>RF1 = wanted signal RF2 = adjacent channel RF2 = RF1 +/- 1712 kHz</td>
</tr>
<tr>
<td>Adjacent Channel Suppression</td>
<td></td>
<td></td>
<td>RF1 input -70 dBm, RF2 input -20 dBm,</td>
<td>RF1 = wanted signal RF2 = adjacent channel RF2 = RF1 +/- 1712 kHz</td>
</tr>
<tr>
<td>(SINAD &lt;3 dB)</td>
<td></td>
<td></td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
</tr>
<tr>
<td>Far-off Channel Suppression</td>
<td>50 dB</td>
<td>3 dB</td>
<td>RF1 input -70 dBm, RF2 input -30 dBm,</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
</tr>
<tr>
<td>(SINAD &lt;3 dB)</td>
<td></td>
<td></td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
</tr>
<tr>
<td>Cross-Modulation</td>
<td>50 dB</td>
<td></td>
<td>RF1 input -70 dBm, RF2 input X dBm, CW carrier (no DAB)</td>
<td>RF1 = wanted signal RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>Cross-Modulation</td>
<td></td>
<td>3 dB</td>
<td>RF1 input -70 dBm, RF2 input X dBm, CW carrier (no DAB)</td>
<td>RF1 = wanted signal RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>(SINAD &lt;3 dB)</td>
<td></td>
<td></td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 5136 kHz</td>
<td>RF1 = wanted signal RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>Input Third Order Intermodulation</td>
<td>50 dB</td>
<td></td>
<td>RF1 input -70 dBm, RF2 input -20 dBm, RF3 input -20 dBm</td>
<td>RF1 = wanted signal RF2 = RF1 + 1.712 MHz RF3 = RF2 + 1.712 MHz</td>
</tr>
<tr>
<td>(SINAD &lt;3 dB)</td>
<td></td>
<td>3 dB</td>
<td>RF1 input -70 dBm, RF2 input -16 dBm, RF3 input -16 dBm</td>
<td>RF1 = wanted signal RF2 = RF1 + 1.712 MHz RF3 = RF2 + 1.712 MHz</td>
</tr>
</tbody>
</table>


5.1.3 AM based setup

We use the same set of metrics that we used for evaluating the performance of FM and DAB radio in SDR. Only the modulation and other signal characteristics (e.g., AM depth) are changed accordingly for the AM radio performance evaluation in SDR. The same test-bed mentioned in Figure 3.2 is used for AM radio as well. The following metrics are used for analyzing the AM radio performance in SDR.

**Sensitivity:** The sensitivity of the radio receiver for the incoming AM radio signals is measured in terms of SINAD. Similar to FM and DAB radio, we have to find the minimum RF level for which we get a particular value of SINAD. The minimum sensitivity value for a broadcast receiver is 26 dB. To find the required RF level for a particular SINAD value, we generate an AM modulated RF signal at an arbitrary RF power level and feed it as an input to the RTL-SDR. Upon reception, we analyze the AM radio signal in GNU Radio. In order to measure the audio distortion content, we feed the audio output to the Anritsu signal analyzer. Once the SINAD reading is shown on display, we adjust the RF level of the generated signal in the signal generator to achieve a particular value of SINAD.

Since the minimum sensitivity of the broadcast receiver is 26 dB and the ultimate sensitivity is 60 dB, we find the corresponding minimum RF levels required to achieve this value of SINAD. The lower the RF level for a particular SINAD, better is the radio receiver performance.

**Adjacent Channel Suppression:** This metric is calculated in the same way as in FM and DAB radio. We generate 2 AM modulated signals from the signal generator with an RF level of 60 dBuV and a modulation depth of 50%. The signals are combined with a RF combiner and fed to the SDR. The interfering signal (RF2) is generated from the adjacent channel of the wanted signal. Since the bandwidth of the AM signal is 9 kHz in European regions, we generate the RF2 signal at a channel spacing of $\pm 9$ kHz from the wanted signal. The audio distortion content is analyzed using the audio function present in Anritsu MS2830A. This metric is calculated as the ratio of audio output when RF1 ON, RF2 OFF to the audio output when RF1 OFF, RF2 ON.

Along with this metric, we also measure the adjacent channel suppression (SINAD < 3 dB) by keeping the RF power level of the interfering
signal higher than the wanted signal. This metric is calculated as the ratio of audio output when the interfering signal is ON to the audio output when the interfering signal is OFF.

**Far-off Channel Suppression:** This metric gives us the effect of interference from non-adjacent channels on a radio receiver. This measurement is quite similar to the adjacent channel suppression except that the interference signal is generated at a non-adjacent channel. For our measurements, we generate the interfering signal (RF2) with a frequency spacing of $\pm 27\, \text{kHz}$ from the wanted AM modulated signal (RF1). In this case, the RF power levels of both the signals are kept to be 60 dBuV. The metric is calculated as the ratio of audio output when RF1 ON, RF2 OFF to the audio output when RF1 OFF, RF2 ON.

For radio broadcast receivers, it is important that the SINAD of the receiver should not fall below 3 dB from its original SINAD value (without interference from other channels) when a strong interfering signal mixes with the desired signal. We measure the Far-off channel suppression (SINAD < 3 dB) as the ratio of audio output when the RF2 is ON to audio output when RF2 is OFF.

**Cross-Modulation:** We calculate this metric by generating 2 AM modulated signals with a modulation depth of 50% from the signal generator. Similar to how we measured this metric for FM and DAB radio, the interfering signal with the AM content is generated with a 1.3 kHz AM tone. Once the signals are combined in the RF combiner, it is fed to the SDR and its audio distortion content is visualised in the Anritsu signal generator. Cross-modulation is calculated as the ratio of audio output when RF1 in ON, RF2 is OFF to the audio output when RF1 is OFF and RF2 is ON. The RF level of the interfering signal is kept according to the frequency of the interfering signal.

The Cross-modulation (SINAD < 3 dB) is measured as the ratio of audio output when RF2 is ON to the audio output when RF2 is OFF.

**Input Third-Order Intermodulation:** Since the third-order intermodulation products fall quite close to the wanted frequency signal, it is important to find the capability of the receiver in the presence of these interfering distortion products. The wanted AM modulated signal is generated with a modulation depth of 50%. The interfering signals RF2 and RF3 are spaced according to this condition.
RF1 = fundamental frequency channel
RF2 = RF1 + 27 kHz
RF3 = RF2 + 27 kHz

This metric is measured as the ratio of audio output with RF1 ON, RF2 OFF, RF3 OFF to the audio output when RF1 OFF, RF2 ON, RF3 ON.

The TOI (SINAD < 3 dB) is evaluated in a way that the RF levels of the interfering signals transmitted by the signal generator are increased to much higher values as compared to the wanted signal. It is measured as the audio output in the presence and absence of the interfering signals RF2 and RF3.

The following Table 5.5 shows the performance of the SDR based setup for AM radio.
Table 5.5: AM Radio Metrics

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Stimulus: RF1 signal is AM modulated with audio signal (1 kHz, 50 % depth) such as speech/music</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Sensitivity</td>
<td>26 dB</td>
<td></td>
<td>SDR: RF1 input &lt;= 16 dBuV, SEM: RF1 input = 16 dBuV</td>
<td>RF1 frequency in FM band</td>
</tr>
<tr>
<td>Ultimate Sensitivity</td>
<td>70 dB</td>
<td></td>
<td>SDR: RF1 input &lt;= 60 dBuV, SEM: RF1 input = 60 dBuV</td>
<td>RF1 frequency in AM band</td>
</tr>
<tr>
<td>Adjacent Channel</td>
<td>40 dB</td>
<td></td>
<td>RF1 input 60dBuV, RF2 input 60dBuV</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 9 kHz</td>
</tr>
<tr>
<td>Suppression</td>
<td></td>
<td>3 dB</td>
<td>RF1 input 16dBuV, RF2 input 60dBuV</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 9 kHz</td>
</tr>
<tr>
<td>Far-off Channel</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 60dBuV, RF2 input 60 dBuV</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 27 kHz</td>
</tr>
<tr>
<td>Suppression</td>
<td></td>
<td>3 dB</td>
<td>RF1 input 16dBuV, RF2 input 60dBuV</td>
<td>RF1 = wanted signal RF2 = interfering signal RF2 = RF1 +/- 27 kHz</td>
</tr>
<tr>
<td>Cross-Modulation</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 60dBuV, AM 1kHz, depth 50% RF2 input X dBuV, AM 1.3kHz, depth 80%</td>
<td>RF1 = wanted signal RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>(SINAD &lt;3 dB)</td>
<td></td>
<td>3 dB</td>
<td>RF1 input 60dBuV, AM 1kHz, depth 50% RF2 input X dBuV, AM 1.3kHz, depth 80%</td>
<td>RF1 = wanted signal RF2 = interfering signal 26 MHz &lt;RF2 &lt;28 MHz</td>
</tr>
<tr>
<td>Input Third Order</td>
<td>50 dB</td>
<td></td>
<td>RF1 input 60 dBuV, RF2 input 80 dBuV, CW carrier RF3 input 80 dBuV</td>
<td>RF1 = wanted signal RF2 = RF1 + 27kHz RF3 = RF1 + 54kHz</td>
</tr>
<tr>
<td>Intermodulation</td>
<td></td>
<td>3 dB</td>
<td>RF1 input 16 dBuV, RF2 input 80 dBuV, CW carrier RF3 input 80 dBuV</td>
<td>RF1 = wanted signal RF2 = RF1 + 27kHz RF3 = RF1 + 54kHz</td>
</tr>
</tbody>
</table>
5.2 Performance Analysis - SDR vs SEM

The three tables mentioned above give us the performance of AM, FM, and DAB based radio in SDR. It has to be noted that the values given for these metrics are the bare minimum values that the radio receiver needs to achieve in order to comply with the ITU standards for vehicular radios.

The RTL-SDR was able to achieve the minimum requirements set for AM, FM, and DAB based radio. This can prove to us that the RTL-SDR is as good as the hardware-based tuner used by SEM. Moreover, the RTL-SDR has a better capability in receiving weaker signals from radio stations proving that is has good receiver sensitivity. The performance of the SDR is hugely influenced by the software we use for demodulating and decoding the signals. One of the major advantages of the SDR is that by tweaking the software of the SDR we can detect the weaker signals in the spectrum. For instance, the 97.2 MHz is the alternate frequency channel of SR P3 (99.4 MHz). The radio transmitter broadcasting information in that channel (97.2 MHz) is located at a far-off distance to our testing area as compared to the primary channel (99.4 MHz). The SEM unit was unable to detect this channel while the SDR was able to receive information from this frequency due to tweaking in the software. This highlights one of the major merits of using an SDR.

On the other hand, RTL-SDR v3 also has certain drawbacks. For instance, in the case of measuring the adjacent channel suppression and intermodulation distortion for AM, FM, and DAB, when we increase the RF level of the interfering signals to a much higher level (higher than the RF values mentioned in the table), the SDR struggled to reach the minimum requirements. This struggle can be attributed to the architectural constraints in RTL-SDR v3.

The RTL-SDR v3 dongle uses an R820T2 tuner chip with an ADC bit resolution of 8 bits and a dynamic range of 48 dB. The relatively lower ADC bit resolution can result in intermodulation distortion and spurs due to the lower dynamic range. This aspect of RTL-SDR can put it at a disadvantage among 12-bit ADC tuners. However, in our case, the lower ADC resolution did not cause many problems in our performance analysis. The TOI metric for AM and FM radio implementation in SDR barely passed the requirement of 50 dB sensitivity due to the injection of spurs and intermodulation distortion content near the frequency of interest. This performance can be largely due to the lack of a sub-octave
band-pass filter and a lower dynamic range.

Based on the stimulus set for each metric in the SEM unit and ITU standards for broadcast receivers, the RTL-SDR dongle was able to achieve the minimum requirements for each performance metric suggesting that it is as good as the radio tuner used in SEM unit. However, this performance comparison alone cannot claim RTL-SDR to be a worthy contender as a radio tuner in automobiles. It has to be mentioned that the performance analysis done to check the effectiveness of the SDR implementation was in presence of static conditions. It would be really interesting to see how the RTL-SDR would perform in the presence of fading (dynamic conditions). RTL-SDR performance in dynamic environmental conditions can decide its potential usage in the automotive industry.

One of the other major advantages of RTL-SDR is its ability to support multi-standard radio technologies in a single chip. The SEM unit has 2 separate radio tuner circuitry for AM/FM and DAB respectively. The SDR dongle performs all the 3 operations with a single R820T2 chip. If the RTL-SDR dongle were to be used in the SEM unit, it would occupy a lesser area as compared to the tuner circuitry used currently.

The performance results that we have obtained for the RTL-SDR v3 is highly encouraging and it only suggests how good the SDR can perform as opposed to the standard radio tuner in the SEM.
Chapter 6

Conclusion and Future Work

This thesis is organized into 4 phases. In the first phase, the objective was to identify the suitable SDR that can be used as a radio tuner in the automotive industry. In order to identify the suitable SDR, a detailed comparison of many SDRs was performed based on their frequency range of operation, sampling rates, ADC resolution, software support, cost, etc. Ultimately, the cost of the radio becomes the deciding factor as a plethora of SDRs supports the operation of AM, FM, and DAB radio. RTL-SDR v3 was selected as the suitable SDR for implementing the mentioned radio technologies as it complies with the requirements set for each metric.

In the second phase of the project, the radio technologies including AM, FM, and DAB were implemented in GNU Radio software on top of an RTL-SDR. For implementing the DAB radio receiver, the blocks developed in the gr-dab repository were used. In the case of FM and AM, the pre-existing signal processing blocks in GNU Radio was used.

In the third phase, the SEM unit was set up which involved forming the wire harness necessary for connecting the SEM unit with the power supply, USB to serial connectors, speakers, and the display unit. Once the harness was prepared, the SEM unit was ready for performance evaluation.

Finally, we test the performance of the SDR based radio setup as compared to the radio tuner in the SEM 2.1. In order to test the performance, we use a test-bed as mentioned by [EN 303-345]. The metrics used for performance evaluation were sensitivity, adjacent channel suppression, far-off channel suppression, cross-modulation/blocking, third-order inter-modulation, etc. After monitoring the SDR setup based on these metrics, it is found that the RTL-SDR performs as well as the hardware-
based tuner of Volvo Trucks. The SDR setup is able to achieve the requirements set for each metric evaluation.

However, the results obtained from the tests were inconclusive to decide whether RTL-SDR v3 is a suitable fit for the automotive industry. The SDR barely manages to achieve the minimum requirements set for cross-modulation and third-order intermodulation due to its lower dynamic range and lack of an input sub-octave band-pass filter.

As a part of the future work, I am planning to conduct performance evaluation tests for the AM, FM, and DAB implementations in SDR and the hardware-based tuner in the presence of fading. This test would give us a thorough estimate of how the SDR based setup will perform in dynamic environments. Additionally, the SEM unit under study also has other radio technologies like DRM and HD-Radio which can be implemented in the SDR and compared with the traditional hardware tuner. The perception evaluation of the audio quality algorithm (PEAQ) specified in ITU BS.1387-1 provides the objective difference grade (ODG) which corresponds to subjective difference grade used in human-based audio tests. This metric can support our results obtained earlier to prove that the SDR based tuner can perform as good as the hardware tuner. Since the RTL-SDR v3 does not have an inbuilt sub-octave band-pass filter, we could try using such a filter to check if the RTL-SDR is able to limit the TOI and adjacent channel suppression from other signals.
Bibliography


# Appendix A

## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEM</td>
<td>Service Entertainment Module</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>DAB</td>
<td>Digital Audio Broadcasting</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Radio</td>
</tr>
<tr>
<td>WWRF</td>
<td>World Wireless Research Forum</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>BLE</td>
<td>Bluetooth Low Energy</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>WiFi</td>
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<tr>
<td>GPP</td>
<td>General Purpose Processors</td>
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<td>DSP</td>
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<tr>
<td>GPU</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Arrays</td>
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<tr>
<td>DFE</td>
<td>Digital Front End</td>
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<tr>
<td>DUC</td>
<td>Digital Up Converter</td>
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<tr>
<td>DDC</td>
<td>Digital Down Converter</td>
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<td>ADC</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>SFDR</td>
<td>Spurious Free Dynamic Range</td>
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<td>RFFE</td>
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<td>TGW</td>
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<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<td>ITU</td>
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<td>RDS</td>
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