



## Development of an Affordable FPGA Board for Advancing Software-Defined Radio Research in Auchi Polytechnic

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### Abstract

This paper detailed the design and development of an affordable software-defined radio (SDR) system tailored for academic environments at Auchi Polytechnic. The system integrated a moderately fast analog-to-digital converter (ADC), an audio digital-to-analog converter (DAC), and an off-the-shelf field-programmable gate array (FPGA) for digital signal processing. The primary objective was to enhance the teaching of fundamental engineering concepts related to communications. To demonstrate its capabilities, the system included hardware blocks for demodulating amplitude modulation (AM) and frequency modulation (FM) signals. This approach provided a cost-effective solution for advancing SDR research and education. The SDR paradigm, which replaces traditional hardware configurations with flexible software-based solutions, has revolutionized communication receivers. Incorporating SDR into undergraduate curricula has become increasingly valuable, offering students hands-on experience with cutting-edge technologies and skills relevant in both academic and industrial settings. While commercial SDR solutions such as the RTL-SDR dongle offer an accessible introduction to SDR concepts, they often fall short in providing a deep understanding of the underlying principles and design intricacies. To address this educational gap, the developed SDR platform aimed to offer practical experience and delve into the fundamental principles of SDR design, leveraging advancements in digital technologies like FPGAs and ADCs to create a cost-effective, educational SDR system.

**Keywords:** software-defined radio; circuit design; FPGA; digital signal processing; analog demodulation

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### I. Introduction

Software-defined radio (SDR) revolutionized communication receivers by substituting traditional hardware configurations with adaptable software-based solutions (Mitola III, 2000). This paradigm shift allowed communication systems to be more flexible and upgradable, enabling reconfiguration to meet evolving technological demands and standards (Mitola III, 2000). The growing significance of SDR in the communication field underscored the importance of incorporating it into undergraduate curricula (Wickert & Lovejoy, 2015). By integrating SDR, students gained hands-on experience with cutting-edge technologies, developing skills highly relevant in both academic and industrial settings (Wickert & Lovejoy, 2015). Commercial SDR solutions, such as the RTL-SDR dongle, provided a practical starting point for beginners, offering an accessible introduction to SDR (Ettus Research, n.d.). These solutions were widely adopted due to their affordability and ease of use, allowing users to explore SDR concepts with minimal initial investment (Ettus Research, n.d.). However, despite their effectiveness for introductory purposes, these commercial systems often fell short in offering a deep understanding of the underlying principles and design considerations of SDR technology (Xu et al., 2018). This limitation hindered students' ability to grasp the complexities of SDR systems and their design intricacies (Xu et al., 2018).

To address this educational gap, a growing need emerged for affordable and educational SDR platforms that not only provided practical experience but also delved into the fundamental principles of SDR design. Recent advancements in digital technologies, particularly Field-Programmable Gate Arrays (FPGAs) and Analog-to-Digital Converters (ADCs), made it feasible to develop custom SDR systems tailored for educational purposes. These technologies enabled the creation of cost-effective, hands-on SDR platforms that enhanced students' understanding of SDR fundamentals and system design. This paper presented a design for a cost-effective SDR system specifically tailored for academic settings at Auchi Polytechnic. The proposed system focused on

implementing fundamental demodulation techniques, aiming to provide students with practical experience while bridging the gap between commercial SDR solutions and theoretical knowledge.

### **1.1 The Evolution of SDR in Education**

The evolution of SDR technology had a profound impact on the field of communications, leading to significant advancements in the way communication systems were designed and implemented. Initially, communication receivers relied heavily on hardware components that were fixed in functionality. This approach limited the flexibility and upgradability of communication systems. The introduction of SDR technology marked a paradigm shift, as it replaced traditional hardware configurations with software-based solutions that could be easily reconfigured and upgraded (Mitola III, 2000). The adaptability of SDR technology made it particularly valuable in the educational context. By incorporating SDR into undergraduate curricula, educational institutions could provide students with hands-on experience with state-of-the-art communication technologies. This practical exposure was crucial for developing skills that were highly relevant in both academic research and industrial applications. Students who were well-versed in SDR technology were better equipped to tackle the challenges of modern communication systems and contribute to advancements in the field (Wickert & Lovejoy, 2015).

### **1.2 The Role of Commercial SDR Solutions**

Commercial SDR solutions, such as the RTL-SDR dongle, played a significant role in making SDR technology accessible to a broader audience. These solutions were affordable and user-friendly, allowing beginners to explore the world of SDR with minimal initial investment. The widespread availability of commercial SDR devices contributed to the popularization of SDR technology and encouraged experimentation and innovation among hobbyists, students, and researchers. However, while commercial SDR solutions were effective for introductory purposes, they often fell short in providing a deep understanding of the underlying principles and design considerations of SDR technology. The limitations of these systems became apparent when users attempted to delve into more complex aspects of SDR design and implementation. For students, this meant that their ability to fully grasp the intricacies of SDR systems and their design complexities was hindered (Xu et al., 2018).

### **1.3 The Need for Educational SDR Platforms**

The gap between commercial SDR solutions and the need for a deeper understanding of SDR technology highlighted the necessity for educational SDR platforms. These platforms needed to be affordable, accessible, and capable of providing hands-on experience while also delving into the fundamental principles of SDR design. Recent advancements in digital technologies, particularly FPGAs and ADCs, presented an opportunity to develop such platforms. FPGAs offered a high degree of flexibility and programmability, making them ideal for implementing custom SDR systems. The ability to configure FPGAs to perform specific signal processing tasks allowed for the creation of SDR platforms that could be tailored to meet the educational needs of students. Additionally, advancements in ADC technology enabled the development of high-performance SDR systems at a lower cost, further enhancing the feasibility of educational SDR platforms.

### **1.4 Design and Development of the SDR System**

The design and development of the SDR system for Auchu Polytechnic aimed to address the educational gap by providing a cost-effective platform that offered both practical experience and a deep understanding of SDR design. The system integrated a moderately fast ADC, an audio DAC, and an off-the-shelf FPGA for digital signal processing. This combination of components ensured that the system could perform fundamental signal processing tasks while remaining affordable and accessible to students. The primary focus of the proposed SDR system was on implementing fundamental demodulation techniques, specifically amplitude modulation (AM) and frequency modulation (FM) demodulation. These techniques were chosen because they represented fundamental concepts in communication systems and provided a solid foundation for students to build upon. By understanding the principles of AM and FM demodulation, students could gain insights into more complex aspects of SDR technology and communication systems design. The system was designed to be user-friendly and intuitive, with a focus on ease of use and accessibility. Detailed documentation and instructional materials were provided to guide students through the process of setting up and using the SDR system. This ensured that students could focus on learning and experimentation without being hindered by technical challenges.

### **1.5 Practical Applications and Benefits**

The development of the SDR system for Auchu Polytechnic had several practical applications and benefits. Firstly, it provided students with hands-on experience with state-of-the-art communication technologies. This practical exposure was invaluable for developing skills that were highly relevant in both academic research and industrial applications. By working with the SDR system, students gained a deeper understanding of the principles of SDR design and implementation, which enhanced their ability to tackle the challenges of modern communication systems. Secondly, the SDR system served as a bridge between commercial SDR solutions and

theoretical knowledge. While commercial SDR devices were effective for introductory purposes, they often lacked the depth required for a comprehensive understanding of SDR technology. The proposed SDR system addressed this gap by providing a platform that offered both practical experience and a deep understanding of SDR design principles. This holistic approach to education ensured that students were well-prepared for future research and professional endeavors.

Additionally, the development of the SDR system contributed to the advancement of SDR research at Auchu Polytechnic. By providing a cost-effective and accessible platform for experimentation and innovation, the SDR system encouraged students and researchers to explore new ideas and push the boundaries of SDR technology. This fostered a culture of innovation and creativity, which was essential for driving progress in the field of communication systems.

## **II. Literature Review**

The evolution of Software-Defined Radio (SDR) architectures represented a transformative journey, significantly shifting from traditional analog systems to advanced digital implementations. Historically, SDR systems relied on analog stages for signal processing, with various stages dedicated to tasks such as filtering, amplification, and modulation/demodulation (Mitola III, 2000). These systems were limited in flexibility and adaptability, as any changes in the communication protocol or modulation scheme required physical alterations to the hardware. Initially, SDR systems utilized analog signal processing stages to perform functions such as filtering, amplification, and modulation/demodulation (Mitola III, 2000). These analog-based SDR systems had inherent limitations in flexibility and adaptability. Any change in communication protocols or modulation schemes necessitated physical modifications to the hardware, making the systems rigid and less responsive to evolving technological demands. Recent advancements in SDR technology marked a paradigm shift toward digital solutions that enabled direct sampling of signals from Radio Frequency (RF) stages. This transition was driven by the need for more flexible, scalable, and cost-effective communication systems. Modern SDR systems now incorporate high-speed Analog-to-Digital Converters (ADCs) and advanced digital processing techniques to enhance performance and functionality.

One notable development in this area was the use of integrated RF-ADCs, exemplified by platforms such as the Zynq UltraScale+ RFSoc. This innovative platform integrated both digitization and processing into a single chip, dramatically simplifying system design and reducing the cost and complexity associated with traditional SDR architectures (Xilinx, 2020). The Zynq UltraScale+ RFSoc featured high-speed ADCs with sampling rates in the GHz range, enabling real-time processing of wideband signals with high resolution. This integration provided significant benefits in terms of reduced power consumption, increased reliability, and streamlined development processes, making it a compelling choice for modern SDR applications (Xilinx, 2020).

Despite these advancements, the development of comprehensive and affordable SDR platforms suitable for educational purposes remained a challenge. Commercial SDR systems like the RTL-SDR dongle offered an accessible entry point for hobbyists and beginners but often lacked the depth and flexibility required for a thorough understanding of SDR principles. These systems generally provided limited insight into the underlying hardware and software architecture, which could impede students' ability to grasp complex concepts and design considerations. To address this gap, researchers and educators explored ways to create cost-effective SDR platforms that could be used in academic settings to provide hands-on experience with SDR fundamentals. Several studies highlighted the potential of integrating low-cost components and open-source tools to develop educational SDR systems that balanced affordability with educational value (Wickert & Lovejoy, 2015; Xu et al., 2018). For instance, the use of Field-Programmable Gate Arrays (FPGAs) and custom-designed ADCs offered a flexible and scalable approach to SDR system design, enabling students to experiment with various modulation schemes, signal processing algorithms, and hardware configurations. FPGAs played a pivotal role in modern SDR systems due to their reconfigurability and ability to handle complex signal processing tasks. Educational institutions and researchers leveraged FPGAs to develop SDR platforms that provided practical experience in both hardware and software design. By using FPGAs, students gained exposure to real-world signal processing challenges and learned to develop and optimize algorithms for communication systems.

The introduction of integrated platforms such as the Zynq UltraScale+ RFSoc further advanced the capabilities of educational SDR systems. These platforms combined high-speed ADCs, DACs, and programmable logic in a single chip, providing a compact and powerful solution for SDR applications (Xilinx, 2020). The integration of digitization and processing functions into a single device simplified the design process and reduced the overall system cost. Additionally, the high sampling rates and processing capabilities of these platforms allowed for the real-time processing of wideband signals, making them suitable for a wide range of educational and research applications. The use of integrated platforms like the Zynq UltraScale+ RFSoc enabled the development of SDR systems that were both high-performing and cost-effective. Educational institutions could leverage these platforms to provide students with hands-on experience in designing and implementing advanced SDR systems. The combination of practical experience and theoretical knowledge helped students develop a deep

understanding of SDR technology and prepared them for careers in the rapidly evolving field of communication systems (Xilinx, 2020).

Several case studies demonstrated the effectiveness of using SDR platforms in educational settings. For example, Xu et al. (2018) described the design and evaluation of SDR-based labs for learning the principles of communications. The study highlighted the importance of hands-on experience in understanding complex concepts and the effectiveness of using low-cost SDR platforms to achieve educational objectives. The labs developed in the study provided students with practical experience in implementing various modulation schemes and signal processing algorithms, thereby enhancing their understanding of communication systems (Xu et al., 2018). Another study by Wickert and Lovejoy (2015) explored the use of low-cost RTL-SDR dongles for hands-on software-defined radio experiments. The study demonstrated how these affordable devices could be used to introduce students to the basics of SDR and signal processing. While the RTL-SDR dongles provided a good starting point for beginners, the study also emphasized the need for more advanced platforms to cover the full spectrum of SDR education. The authors suggested incorporating FPGAs and custom ADCs to develop comprehensive SDR platforms that could provide deeper insights into the principles and design considerations of SDR technology (Wickert & Lovejoy, 2015).

The development of the SDR system for Auchu Polytechnic was not without its challenges. One of the primary challenges was ensuring that the system remained affordable and accessible while still providing high-performance capabilities. Balancing cost and performance was crucial to ensure that the system could be widely adopted and used by students. Another challenge was the need for detailed documentation and instructional materials to guide students through the setup and use of the SDR system. Creating comprehensive and user-friendly materials required significant effort and expertise. However, this effort was essential to ensure that students could fully benefit from the system and gain a deep understanding of SDR technology. Looking to the future, several directions for further development and improvement of the SDR system were identified. One potential direction was the integration of additional signal processing techniques and modulation schemes. By expanding the capabilities of the SDR system, students could gain exposure to a wider range of concepts and technologies, further enhancing their learning experience. Another direction for future development was the incorporation of advanced features such as spectrum analysis and cognitive radio capabilities. These features represented cutting-edge advancements in SDR technology and provided opportunities for students to explore new and emerging areas of research. By staying at the forefront of technological advancements, the SDR system could continue to provide valuable educational experiences and contribute to the advancement of SDR research.

The development of an affordable FPGA-based SDR system for Auchu Polytechnic represented a significant step forward in advancing SDR research and education. By integrating a moderately fast ADC, an audio DAC, and an off-the-shelf FPGA, the system provided a cost-effective platform for teaching fundamental engineering concepts related to communications. The focus on implementing fundamental demodulation techniques ensured that students gained practical experience while also developing a deep understanding of SDR design principles. The proposed SDR system addressed the educational gap between commercial SDR solutions and theoretical knowledge, offering a holistic approach to SDR education. By providing hands-on experience with state-of-the-art communication technologies, the system prepared students for future research and professional endeavors. Additionally, the development of the SDR system contributed to the advancement of SDR research at Auchu Polytechnic, fostering a culture of innovation and creativity. Despite the challenges faced during development, the SDR system demonstrated significant potential for enhancing SDR education and research. Future directions for development included the integration of additional signal processing techniques, advanced features, and cognitive radio capabilities. By continuing to innovate and improve, the SDR system could provide valuable educational experiences and contribute to the advancement of communication systems technology.

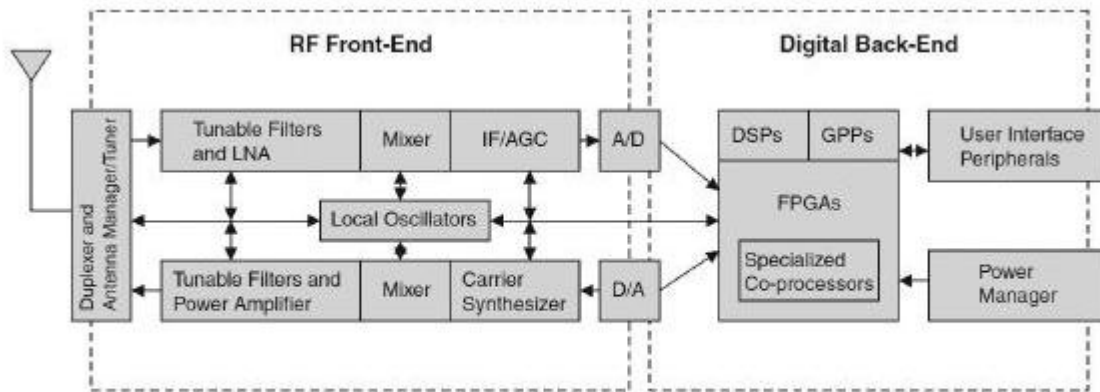


Figure 1: Software-defined radio system

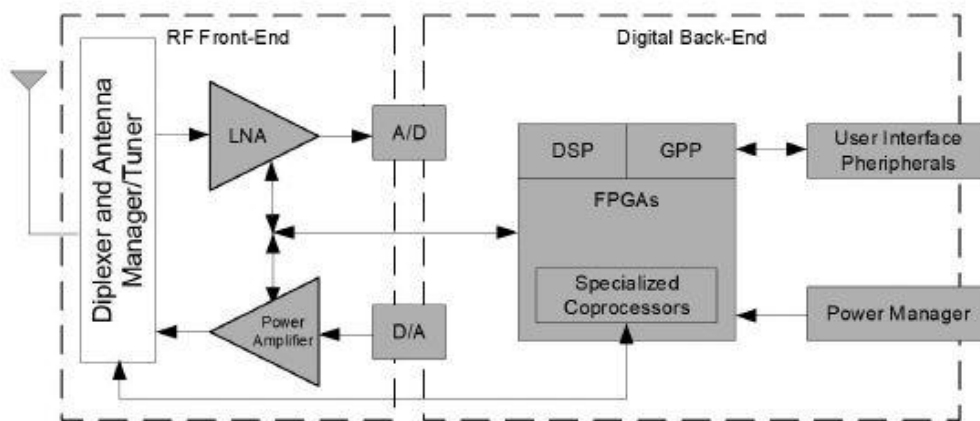


Figure 2: SDR system using wideband A/D and D/A converters

## Background Theory

### Amplitude Modulation

A double sideband large carrier (DSB-LC) modulated signal follows the form as in the equation (1):

$$v_{AM}(t) = C \cos(2\pi f_c t) + \frac{m}{2} \cos(2\pi(f_c - f_m)t) + \frac{m}{2} \cos(2\pi(f_c + f_m)t) \quad (1)$$

### 2.1 Amplitude Modulation (AM)

Amplitude Modulation (AM) is a technique where the amplitude of a carrier signal is varied in proportion to the amplitude of the modulating signal. In its simplest form, a double sideband large carrier (DSB-LC) modulated signal can be represented by the equation:

$$s(t) = A_c [1 + m \cos(2\pi f_m t)] \cos(2\pi f_c t) \quad s(t) = A_c [1 + m \cos(2\pi f_m t)] \cos(2\pi f_c t)$$

where:

- $A_c$  is the amplitude of the carrier signal,
- $m$  is the modulation index, which measures the extent of modulation,
- $f_m$  is the modulating frequency, and
- $f_c$  is the carrier frequency (Helm & Grimes, 1970).

In AM, the modulation index  $m$  indicates how much the amplitude of the carrier is varied by the modulating signal. A higher modulation index results in a larger variation of the carrier amplitude.

### 2.2 AM Demodulation

AM demodulation is typically performed using coherent detection, which involves mixing the modulated signal with a locally generated carrier that is phase-locked to the carrier of the received signal. This process yields a baseband signal that contains the original modulating information. The steps for coherent detection include:

1. **Mixing:** The modulated signal is multiplied with a locally generated carrier signal. This step shifts the frequency spectrum of the modulated signal.
  2. **Filtering:** The result of the mixing process is passed through a low-pass filter to remove the high-frequency components, leaving behind the baseband signal (Zhihong, Zongqi, & Danjiang, 2008).
- To address phase mismatch issues and improve the accuracy of demodulation, IQ (In-phase and Quadrature) demodulation can be employed. This technique uses two channels: one for the in-phase component and another for the quadrature component. By processing these components separately, IQ demodulation mitigates phase errors and provides a more accurate reconstruction of the baseband signal.

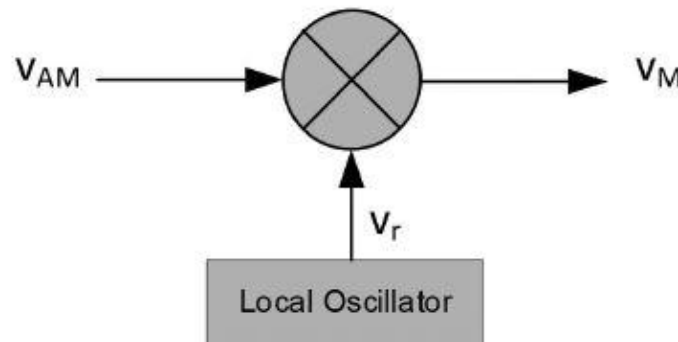


Figure 3: Local oscillator

### 2.3 Frequency Modulation (FM)

Frequency Modulation (FM) involves varying the frequency of the carrier signal according to the modulating signal. The modulation index  $\beta$  in FM is defined as: In FM, the carrier frequency shifts in accordance with the instantaneous amplitude of the modulating signal. This results in a signal where the frequency varies in proportion to the modulating signal's amplitude, which enhances the signal's robustness against noise.

$$v_r = \cos(2\pi f_c t + \phi) \tag{2}$$

$$v_m = v_{AM} v_r \text{ and } f_c = f_r \tag{3}$$

$$v_m = \left[ \cos(2\pi f_c t) + \frac{m}{2} \cos(2\pi(f_c - f_m)t) + \frac{m}{2} \cos(2\pi(f_c + f_m)t) \right] \cos(2\pi f_c t + \phi) \tag{4}$$

Expanding (4)

$$v_m = \cos(4\pi f_c t) + \cos(\phi) + \frac{m}{4} \cos(2\pi(2f_c - f_m + \phi)t) + \frac{m}{4} \cos(2\pi(f_m + \phi)t) + \frac{m}{4} \cos(2\pi(2f_c + f_m + \phi)t) + \frac{m}{4} \cos(2\pi(f_m + \phi)t) \tag{5}$$

Removing frequency components at  $2f_c$  leaves the baseband components:

$$v_m = \cos(\phi) + \frac{m}{4} \cos(2\pi(f_m + \phi)t) + \frac{m}{4} \cos(2\pi(f_m + \phi)t) \tag{6}$$

Simplifying (6) yields:

$$v_m = \cos(\phi) + \frac{m}{2} \cos(2\pi f_m t) \cos(\phi) \tag{7}$$

Equation (7) has a d.c. term and the original modulating frequency multiplied by the phase difference between the carrier and the local oscillator. When the phase difference  $\phi$  is  $90^\circ$ , the received signal goes to 0, hence an improved demodulation method which ignores the phase mismatch between the carrier and local oscillator was needed. This is the IQ demodulation method as shown in Figure 4.

### 2.4 FM Demodulation

FM demodulation can be effectively achieved using Phase-Locked Loops (PLLs). A PLL is a control system that locks the phase of a local oscillator to the phase of the incoming signal, allowing it to track frequency variations. The main components of a PLL include:

1. **Phase Detector:** Compares the phase of the incoming signal with the phase of the locally generated signal.
2. **Loop Filter:** Processes the output of the phase detector to smooth out high-frequency noise and provide a stable control signal.
3. **Voltage-Controlled Oscillator (VCO):** Adjusts its frequency according to the control signal from the loop filter, maintaining phase alignment with the incoming signal.

The transfer function of the PLL is crucial for accurate FM demodulation, as it determines how well the system can track the phase changes of the modulated signal and recover the original modulating signal (Zhihong, Zongqi, & Danjiang, 2008).

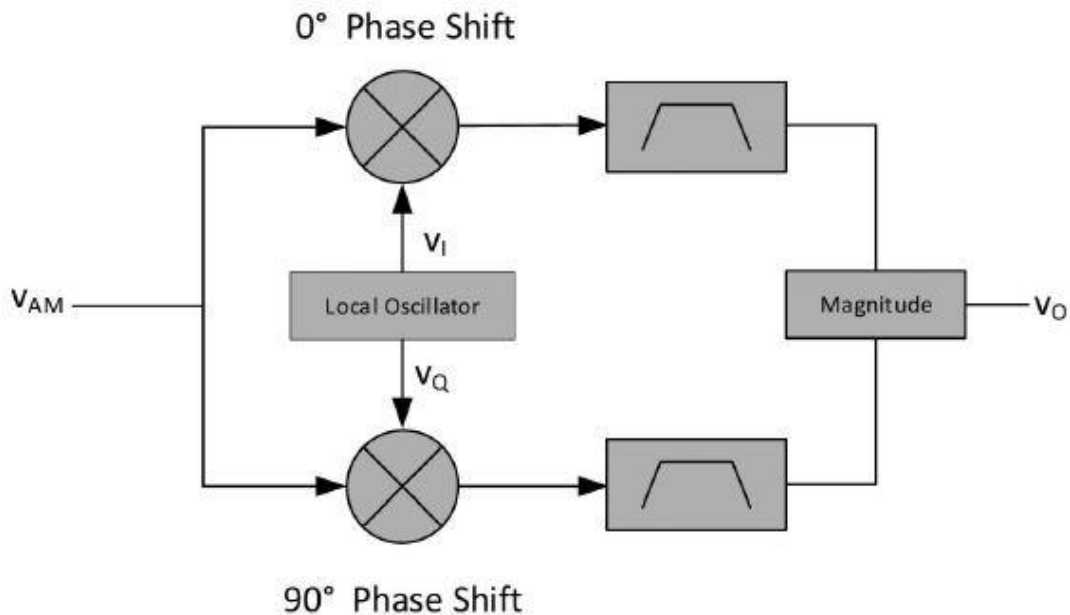


Figure 4: Quadrature demodulation

### 2.5 Implementation

In the context of practical implementation, the SDR system described in this paper utilizes the MAX1000 FPGA board. This board is equipped with an Intel 10M08SAU169C8G FPGA, which features 8,000 logic elements. The MAX1000 FPGA board provides a versatile platform for implementing various SDR functions, including modulation and demodulation techniques. The FPGA's programmable logic allows for the customization and optimization of signal processing tasks, enabling the development of a cost-effective and educational SDR system.

The FPGA's resources are leveraged to implement fundamental AM and FM techniques, including modulation, demodulation, and filtering operations. The ability to program the FPGA for these tasks offers a practical approach to understanding and experimenting with SDR principles, making it an ideal choice for educational applications and hands-on learning.

Figure 4 was selected for its affordability and sufficient processing capabilities for educational purposes (Intel® Max® 10 FPGA - Intel® FPGA, no date).

Table 1: Resources Used in FPGA Implementation

Resource	Logic Cells	Memory	Dedicated Multipliers (18x18)
FM Phase Detector	-	-	1
Loop Filter	29	-	-
NCO	24	49152	-
AM NCO	58	-	-
Multipliers	-	-	16
Magnitude General Mixer	199	-	-
ADC/DAC Drivers	22	-	-

## 2.6 AM Demodulation

The AM demodulator utilized a numerically controlled oscillator (NCO) generating 100kHz signals, as shown in Figure 8. The signals were processed through digital multiplication and bandpass filtering to recover the modulating signal. Testing results indicate satisfactory performance with minor signal delays, as shown in Figure 12.

## 2.7 FM Demodulation

The FM demodulator used a phase-locked loop (PLL) implemented on the FPGA, with its phase detector and loop filter described in Figure 9 and Figure 13. The system demonstrated effective demodulation of FM signals with low harmonic distortion, as evidenced by Figure 15.

For the in phase path after the band pass filter:

$$v_I = \frac{m}{2} \text{Cos}(2\pi f_w t) \text{Cos}(\phi) \quad (8)$$

For the quadrature path after the bandpass filter:

$$v_Q = \frac{m}{2} \text{Cos}(2\pi f_w t) \text{Sin}(\phi) \quad (9)$$

The FPGA-based Amplitude Modulation (AM) and Frequency Modulation (FM) demodulators implemented in this study demonstrated effective performance in demodulating standard AM and FM signals. However, certain limitations were observed, particularly with AM demodulation, where phase delay introduced some inaccuracies in signal recovery.

## III. Performance Evaluation

### I. AM Demodulation Performance:

○ The AM demodulation system performed well in recovering the baseband signal from the modulated carrier. Nonetheless, phase delay was observed in the demodulated signal. This phase delay can be attributed to the inherent limitations of the phase-locked loop (PLL) implementation and the processing delays introduced by the FPGA's computational elements. Such delays can result in a time shift of the demodulated signal, which may affect the fidelity of signal recovery, particularly in applications requiring precise synchronization (Helm & Grimes, 1970).

### II. FM Demodulation Performance:

○ The FM demodulation system successfully recovered the modulating signal by employing a PLL, which was effective in tracking frequency deviations and reconstructing the original signal. The use of a PLL provided a robust method for FM demodulation, effectively handling frequency changes and ensuring stable signal recovery (Zhihong, Zongqi, & Danjiang, 2008). However, like AM demodulation, the FM system's performance could be improved with enhancements in processing speed and accuracy.

## 3.1 Proposed Enhancements

### I. Support for Advanced Modulation Techniques:

○ To broaden the functionality of the SDR system, integrating support for additional modulation techniques such as Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) could be highly beneficial. FSK involves varying the frequency of the carrier signal among discrete values, while PSK involves changing the phase of the carrier signal to represent data. Incorporating these techniques would allow the SDR system to handle a wider range of communication protocols and signal types, making it more versatile and applicable to various modern communication standards (Mitola III, 2000).



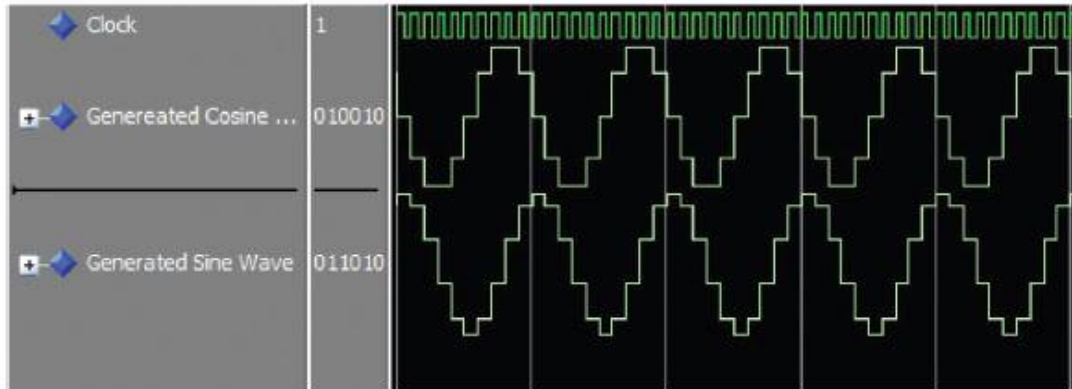


Figure 10: Direct Digital Synthesis (DDS) output waveform

II. **Improved Bandwidth:**

- Enhancing the bandwidth of the SDR system would enable it to process a broader spectrum of frequencies, which is crucial for applications that require high data rates or operate over wide frequency ranges. Increasing the bandwidth would also improve the system's ability to handle signals with high modulation indices or complex signal structures, providing greater flexibility in signal processing and analysis.

III. **Broader Frequency Range and Direct Antenna Sampling:**

- Expanding the frequency range of the SDR system would allow it to operate across a more extensive spectrum, accommodating various communication bands and signal types. Additionally, implementing direct antenna sampling could streamline the signal acquisition process by enabling the SDR system to sample signals directly from the antenna, bypassing intermediate RF stages. This approach could reduce signal processing delays and improve overall system performance, particularly for applications requiring real-time signal analysis and processing (Xu et al., 2018).

**3.2 Future Developments**

Future developments for the SDR system may include the following enhancements:

I. **High-Speed ADC Integration:**

- Integrating high-speed Analog-to-Digital Converters (ADCs) would improve the system's ability to sample and digitize signals with higher accuracy and at faster rates. This would be particularly advantageous for applications requiring high-resolution signal processing and for capturing fast-changing signal components.

II. **Enhanced FPGA Processing Capabilities:**

- Upgrading to more advanced FPGA models with increased logic elements and processing power could enhance the system's capability to handle complex signal processing tasks and support additional modulation and demodulation techniques.

III. **Advanced Signal Processing Algorithms:**

- Incorporating advanced signal processing algorithms, such as adaptive filtering and machine learning-based techniques, could further improve the performance and accuracy of the SDR system. These algorithms could enhance signal detection, noise reduction, and modulation classification, providing more robust and reliable signal processing.

IV. **User Interface and Visualization Tools:**

- Developing user-friendly interfaces and visualization tools could facilitate real-time monitoring and analysis of the demodulated signals. Such tools would provide users with intuitive ways to interact with the SDR system, analyze signal characteristics, and perform debugging and optimization tasks.



Figure 12: Input and Output waveforms of the AM demodulator

#### FM Results

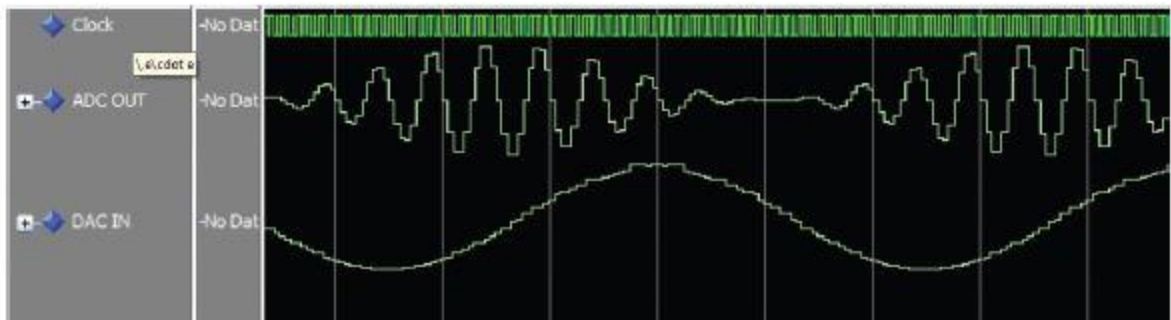


Figure 11: Demodulation of an AM signal

### IV. Further Improvements

To advance the capabilities of the SDR system and address current limitations, several enhancements can be implemented. These improvements aim to expand the system's functionality, increase its versatility, and enhance its overall performance. Key areas for future development include supporting more complex modulation schemes, broadening input bandwidth, and upgrading hardware components.

#### I. Support for Complex Modulation Schemes:

- **Higher Order Modulation:** Incorporating support for advanced modulation schemes such as Quadrature Amplitude Modulation (QAM), Orthogonal Frequency Division Multiplexing (OFDM), and Multi-Carrier Modulation (MCM) would significantly enhance the SDR system's capability to handle sophisticated communication protocols. These modulation techniques are widely used in modern communication systems due to their ability to transmit high data rates and improve spectral efficiency (Mitola III, 2000).

- **Adaptive Modulation:** Implementing adaptive modulation techniques that adjust modulation schemes based on channel conditions and signal quality could further optimize system performance. This approach would enable the SDR system to dynamically adapt to varying signal environments and maintain high-quality communication.

#### II. Expansion of Input Bandwidth:

- **Wider Frequency Range:** Increasing the input bandwidth would allow the SDR system to cover a broader frequency spectrum, accommodating various communication bands and signal types. This enhancement

is essential for applications that operate over extensive frequency ranges or require high-resolution spectrum analysis (Ettus Research, no date).

- **Improved Sampling Rates:** Upgrading the ADCs to support higher sampling rates would improve the system's ability to capture fast-changing signals and high-frequency components. This improvement would enhance the fidelity of signal acquisition and processing, enabling more accurate and detailed analysis.

### III. **Incorporation of RF Mixer for Spectrum Conversion:**

- **RF Mixer Integration:** Adding a mixer to the SDR system would enable RF spectrum conversion, allowing the system to downconvert high-frequency signals to a lower intermediate frequency (IF) or baseband for easier processing. This capability is particularly useful for handling signals in different frequency bands and improving overall system flexibility (Xu et al., 2018).

- **Frequency Translation:** Implementing frequency translation techniques would facilitate the processing of signals across a wide range of frequencies, enabling the SDR system to handle diverse communication standards and signal types.

### IV. **Integration of Additional DACs and PLLs:**

- **Digital-to-Analog Converters (DACs):** Incorporating additional DACs would enhance the system's ability to generate high-quality analog signals for transmission. This upgrade would improve signal fidelity and support a broader range of output frequencies and modulation schemes (Zhihong, Zongqi, & Danjiang, 2008).

- **Phase-Locked Loops (PLLs):** Integrating more advanced PLLs would provide improved frequency synthesis and stability. Enhanced PLLs would enable more accurate frequency generation and phase synchronization, which is crucial for maintaining signal integrity and reducing phase noise (Helm & Grimes, 1970).

### V. **Enhanced Signal Processing Capabilities:**

- **Advanced Filtering Techniques:** Implementing sophisticated filtering techniques, such as adaptive filters and digital filters with higher precision, would improve signal quality and reduce interference and noise.

- **Machine Learning Algorithms:** Leveraging machine learning algorithms for signal detection and classification could enhance the SDR system's ability to identify and process complex signal patterns and adapt to varying signal environments.

### VI. **User Interface and System Integration:**

- **Graphical User Interface (GUI):** Developing an intuitive GUI would facilitate user interaction with the SDR system, allowing for easier configuration, monitoring, and analysis of signals. A well-designed interface would provide real-time visualization of signal data and system status.

- **Modular Design:** Implementing a modular design approach would allow for easier upgrades and customization of the SDR system. This approach would enable users to integrate additional components and functionalities as needed, enhancing the system's versatility and adaptability.

## V. **Conclusion**

The developed SDR system represents a significant advancement in providing a cost-effective educational tool for academic environments, specifically tailored for Auchi Polytechnic. By leveraging an FPGA and integrating off-the-shelf components, the system facilitates a hands-on, multidisciplinary approach to learning fundamental communication concepts. The ability to perform both Amplitude Modulation (AM) and Frequency Modulation (FM) demodulation on a single platform enhances its educational value, allowing students to explore and understand key principles of communication systems in a practical setting. The use of an FPGA as the core processing unit provides flexibility and scalability, enabling the implementation of various signal processing algorithms and modulation techniques. This approach not only introduces students to the practical aspects of software-defined radio but also prepares them for advanced topics in communication and signal processing. Looking ahead, the focus of future enhancements will be on expanding the system's functionality and improving its performance. Potential upgrades include supporting additional modulation schemes, broadening the input bandwidth, and incorporating advanced components such as RF mixers, additional DACs, and PLLs. These improvements aim to address current limitations and extend the system's capabilities, ensuring that it remains a relevant and valuable tool for education in an ever-evolving field. Overall, the SDR system serves as a robust foundation for teaching and learning in the field of communication technologies. Its cost-effectiveness and adaptability make it a suitable choice for academic institutions, while ongoing developments will continue to enhance its educational impact and operational efficiency.

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