MINI - PROJECT (23ET5PWMPR)

based report

ON

"CSV Enhanced Signal Generator and Spectrum Analyzer"

Submitted in partial fulfilment of the requirements for the award of degree of

BACHELOR OF ENGINEERING

IN

ELECTRONICS AND TELECOMMUNICATION ENGINEERING

VISVESVARAYA TECHNOLOGICAL UNIVERSITY, BELAGAVI

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(Accredited by NBA under Tier – I format)

BONAFIDE CERTIFICATE

This is to certify that the Mini project (23ET6PWMPR) entitled **“CSV Enhanced Signal Generator and Spectrum Analyzer”**is submitted by **Poorvi Kulkarni** (**USN:1BM23ET040**), **Utkarsh Sinha** (**USN:1BM23ET055**), **Vishal Joshy** (**USN:1BM23ET058**) and **Yash Gupta** (**USN:1BM23ET061**),in partial fulfillment for the award of degree of Bachelor of Engineering in Electronics and Telecommunication Engineering during the academic year 2025-2026.

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ABSTRACT

Signal generators and spectrum analyzers are essential instruments in electronics laboratories, supporting experimentation, verification, and characterization of analog and digital circuits. However, commercial equipment is often costly, non-portable, and unavailable for continuous student use outside scheduled laboratory sessions. This mini-project explores the feasibility of developing a compact, low-cost alternative based on a microcontroller platform capable of producing fundamental test waveforms and providing basic spectral visualization suitable for undergraduate instruction.

The system is built using an ESP32-WROOM module, utilizing its integrated peripherals for waveform synthesis and analysis. Sine waves are generated using the internal hardware cosine generator and DAC, while square waves are produced through the LEDC PWM subsystem. Experimental evaluation with a Tektronix TDS 2004B oscilloscope confirmed clean waveform generation up to approximately 40 kHz for both sine and square signals. Triangle waveform generation was attempted via an I²S-driven DAC buffer; however, linearity and stability were insufficient for reliable operation, and this functionality is retained as future work.

A secondary mode enables basic spectrum analysis by sampling analog data through the ESP32 ADC and computing a windowed 256-point FFT. The resulting magnitude spectrum is displayed on a 128×64 SH1106 OLED, providing a simplified visualization of dominant frequency components. A Wi-Fi–based control interface permits parameter adjustment through a browser webpage, eliminating physical controls and enabling fully wireless operation. Additionally, configuration data such as waveform type, frequency, and duty cycle can be logged in CSV format over serial output for external documentation.

The results demonstrate that a microcontroller-based platform can deliver essential waveform generation and introductory spectral visualization within low-cost and small-form-factor constraints. Although not intended to replace professional laboratory instruments, the device offers meaningful value for experimentation, prototyping, and foundational signal analysis. Remaining limitations include DAC resolution, restricted FFT bandwidth, and incomplete triangle wave capability. Future enhancements may incorporate amplitude calibration, improved analog front-end conditioning, dual-channel output, higher-resolution FFT processing, and browser-based spectrum rendering.

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CHAPTER 1- INTRODUCTION

1.1 Overview

Signal generators and spectrum analyzers are essential instruments in modern electronics laboratories. They enable the creation, observation, and characterization of electrical signals across a range of frequencies and waveforms. Traditional laboratory-grade instruments provide highly accurate outputs but are typically expensive, bulky, and less accessible to students or small prototype environments.

The ESP32 microcontroller provides a practical alternative for educational and low-cost prototyping scenarios. It integrates a high-speed dual-core CPU, Wi-Fi connectivity, timer peripherals, PWM channels, and two 8-bit DAC units. When leveraged correctly, these features allow the ESP32 to emulate some of the behavior of laboratory-grade signal generators and basic spectrum analyzers at a significantly lower cost. This project aims to demonstrate such an implementation through a Wi-Fi controlled waveform generator that includes sine, square, triangle, and sawtooth waveforms, as well as an FFT-based spectrum display on a monochrome SH1106 OLED.

1.2 Need for the Project

Many undergraduate laboratories face limitations related to the number and availability of test instruments, especially when multiple student groups work simultaneously. Portable microcontroller-based test tools serve as valuable complementary resources. They provide flexibility and accessibility and allow students to understand signal generation principles rather than simply using closed-box instruments.

Furthermore, exposure to digital signal processing concepts is important for modern electronics education. Implementing an FFT on a microcontroller and visualizing the resulting spectrum helps students connect theoretical DSP concepts such as sampling, frequency bins, aliasing, and spectral leakage with practical experimentation.

This project satisfies the need for a compact, easy-to-use, and cost-effective learning instrument that integrates both signal generation and basic spectral analysis functionalities.

1.3 Problem Statement

The objective of this project is to design and implement a Wi-Fi controlled signal generator and spectrum analyzer using the ESP32 microcontroller.

The system must be capable of generating multiple waveforms across a usable frequency range, providing live control through a browser-based interface, computing FFT-based spectral data, and displaying the spectrum on an SH1106 OLED module. The system should operate as a low-cost educational tool while maintaining clarity, reliability, and ease of use.

1.4 Proposed Solution

The proposed system utilizes the ESP32-WROOM module to generate waveforms and compute spectra. Wi-Fi connectivity allows users to configure the device through a webpage without any physical controls. The OLED screen displays spectral information in FFT mode, while CSV logging is enabled for the signal generation mode to assist in offline analysis.

Different waveform types are implemented using different internal peripherals.

- Sine waves are produced using the ESP32's built-in DAC.
- Square waves are generated using the PWM subsystem.
- Triangle and sawtooth waves are implemented using a software timer and a look-up table.

This hybrid approach enables the system to reach higher frequencies for sine and square signals (up to around 40 kHz), while offering lower-frequency triangular and sawtooth outputs.

1.5 Project Constraints Arising from Hardware Architecture

The ESP32 contains heterogeneous internal peripherals, each with specific strengths and limitations. These internal constraints shaped the final feature set:

- The PWM hardware provides clean digital transitions but cannot produce variable-amplitude square waves because the output levels are fixed at the device's logic rails (0 volts and 3.3 volts).
- The DAC can vary amplitude through digital scaling, but it is bandwidth limited due to its settling time and 8-bit resolution.
- Timer-driven waveform updates for triangle and sawtooth waveforms experience jitter and CPU scheduling delays at higher frequencies, limiting the usable frequency range.
- The FFT routine and DAC outputs cannot run simultaneously without timing conflicts. Therefore, a mode-switching approach is adopted.
- The OLED update rate restricts the smoothness of the spectrum display at higher FFT sizes.

These constraints are acknowledged throughout the report to truthfully represent the system's capability without exaggeration.

1.6 Applications

The developed system can support the following applications:

1. Undergraduate laboratories requiring low-cost waveform sources.
2. Demonstrations of DSP concepts such as FFT computation and spectral observation.
3. Rapid prototyping environments where a compact waveform generator is useful.
4. Educational demonstrations of embedded systems interfacing and peripheral programming.
5. Hobbyist or at-home experimentation without access to expensive equipment.

1.7 Organization of the Report

Chapter 1 introduces the project and outlines the motivation, objectives and scope.

Chapter 2 presents the theoretical background and related literature necessary to understand signal generation, PWM, DAC behavior and FFT fundamentals.

Chapter 3 describes the system architecture and implementation methodology, including waveform generation, amplitude control, FFT processing, display handling and Data logging.

Chapter 4 presents the experimental results and performance analysis of the developed system.

Chapter 5 discusses the limitations arising from hardware constraints, sampling bandwidth and software timing.

Chapter 6 outlines possible improvements and future scope of the system.

Chapter 7 concludes the report by summarizing the overall achievements and performance of the project.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

A review of existing literature is necessary to understand the principles governing waveform generation, analog synthesis, PWM operation, digital-to-analog conversion, FFT-based spectrum analysis, and OLED interfacing. This chapter consolidates the required background in a balanced, accessible manner suitable for an undergraduate engineering project.

2.2 Waveform Generation in Microcontrollers

Microcontrollers traditionally generate waveforms through two primary methods:

1. **Digital PWM Output**
   - Produces rectangular waveforms with adjustable duty cycle.
   - High frequency capability due to hardware timers.
   - Amplitude is fixed by supply voltage.
2. **Analog Output via DAC**
   - Produces smooth waveforms such as sine waves.
   - Limited by DAC resolution and update rate.
   - Enables amplitude control through digital scaling of output values.

Several educational microcontroller projects combine PWM and DAC to generate basic waveform types. The ESP32 expands on these capabilities by providing high-speed PWM (up to 40 MHz clock) and two onboard 8-bit DAC channels.

2.3 Literature on PWM and Amplitude Constraints

Digital PWM pins toggle strictly between logic HIGH and logic LOW levels, which fixes the peak-to-peak amplitude at the supply voltage. Amplitude variation requires analog circuitry. Therefore, the square wave amplitude in this project is inherently fixed at 3.3 V.

2.4 Sine Wave Generation Using DAC

DAC-based waveform generation is commonly used in low-frequency function generators. The DAC outputs a sequence of discrete voltage steps corresponding to sampled sine values. Studies on DAC performance indicate:

- The output is smooth when the update frequency is significantly greater than the waveform frequency.
- DAC resolution determines the granularity of the waveform.
- The bandwidth is limited by settling time.

2.5 Software-Based Triangle and Sawtooth Synthesis

Literature in digital signal synthesis states that non-sinusoidal waveforms can be generated using a look-up table and a periodic timer interrupt. However:

- Timer ISR latency limits the maximum update rate.
- Jitter in ISR invocation causes distortion at higher frequencies.
- DAC settling time further limits bandwidth.

These factors explain the practical upper frequency limit observed for triangular and sawtooth waves in this project.

2.6 FFT-Based Spectral Analysis

FFT algorithms are extensively covered in DSP literature. For microcontroller applications, the lightweight fixed-point or floating-point FFT libraries are preferred. Important considerations include:

- Sampling rate
- Number of FFT points
- Windowing function
- Memory and computation time

The ESP32 supports FFT computation due to its dual-core processor and hardware acceleration. Studies indicate that FFTs of size 256 or 512 are feasible for real-time applications on this platform.

2.7 OLED Display and Embedded Visualization

SH1106-based OLED displays are common in embedded systems due to their low power consumption and crisp monochrome output. Numerous open-source projects and academic reports demonstrate text and graphical plotting on such displays. Their refresh rate is limited but sufficient for displaying spectral magnitudes without continuous animation.

2.8 Summary of Literature Insights Relevant to This Project

From the reviewed literature, the following insights guided the project:

1. PWM cannot vary amplitude and is suitable for generating square waves only.
2. DAC-based generation is suitable for smooth waveforms but has bandwidth limitations.
3. Timer-based synthesis is effective only at low frequencies.
4. FFT computation is feasible on the ESP32 but requires careful memory management.
5. OLED visualization works well for low-rate graphical updates such as spectrum plots.
6. Hybrid waveform synthesis approaches are commonly used to balance performance and implementation complexity.

These insights ensured that the system design remained aligned with established principles while remaining realistic and achievable.

CHAPTER 3 - METHODOLOGY

3.1 Introduction

The methodology adopted in this project involves the integration of multiple hardware and software subsystems within the ESP32 microcontroller in order to implement a waveform generator and basic spectrum analyzer. Each waveform type requires a different internal peripheral or computational strategy, so achieving a unified and predictable behavior demanded careful modular design. The following sections describe the architecture, hardware connections, waveform synthesis techniques, FFT computation, user interface design, and data logging approach.

3.2 System Architecture Overview

The system is divided into two primary operational modes:

1. **Signal Generator Mode**
   Responsible for producing sine, square, triangle, and sawtooth waveforms. User configuration is done over Wi-Fi using a webpage interface. CSV logging is available only in this mode.
2. **Spectrum Analyzer Mode**
   Performs FFT on sampled input data and displays the magnitude spectrum on the SH1106 OLED. No waveform is generated in this mode, and DAC outputs are disabled to avoid timing conflicts.

The ESP32 alternates between these two modes through webpage controls. This ensures that computational load and timing sensitivity do not cause interference between signal generation and real-time FFT processing.

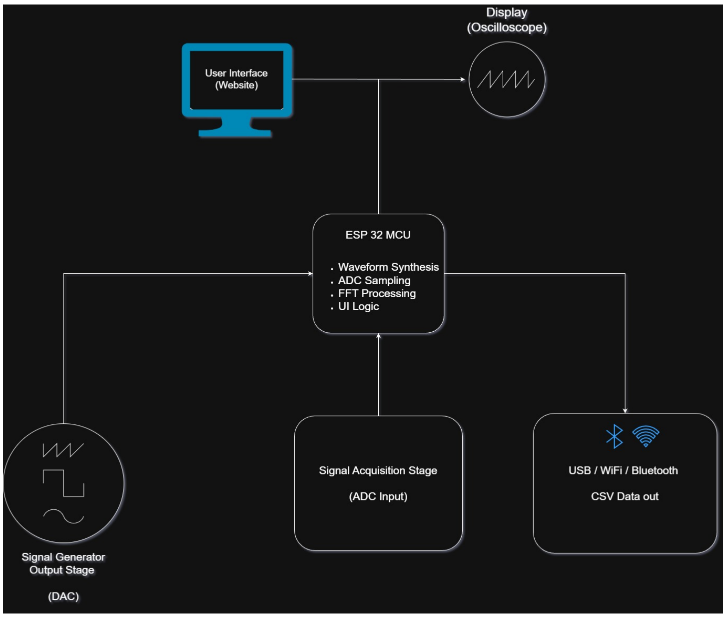

Figure 3.2 - System Architecture Block Diagram

3.3 Hardware Setup

3.3.1 ESP32-WROOM Module

The ESP32-WROOM module was used due to its:

- Dual-core Tensilica LX6 processors
- Integrated Wi-Fi
- 8-bit DAC channels
- High-speed LEDC PWM subsystem
- Multiple general-purpose timers
- Sufficient RAM for FFT operations

The onboard 3.3 V regulator and GPIO pins make it convenient for waveform generation and OLED interfacing.

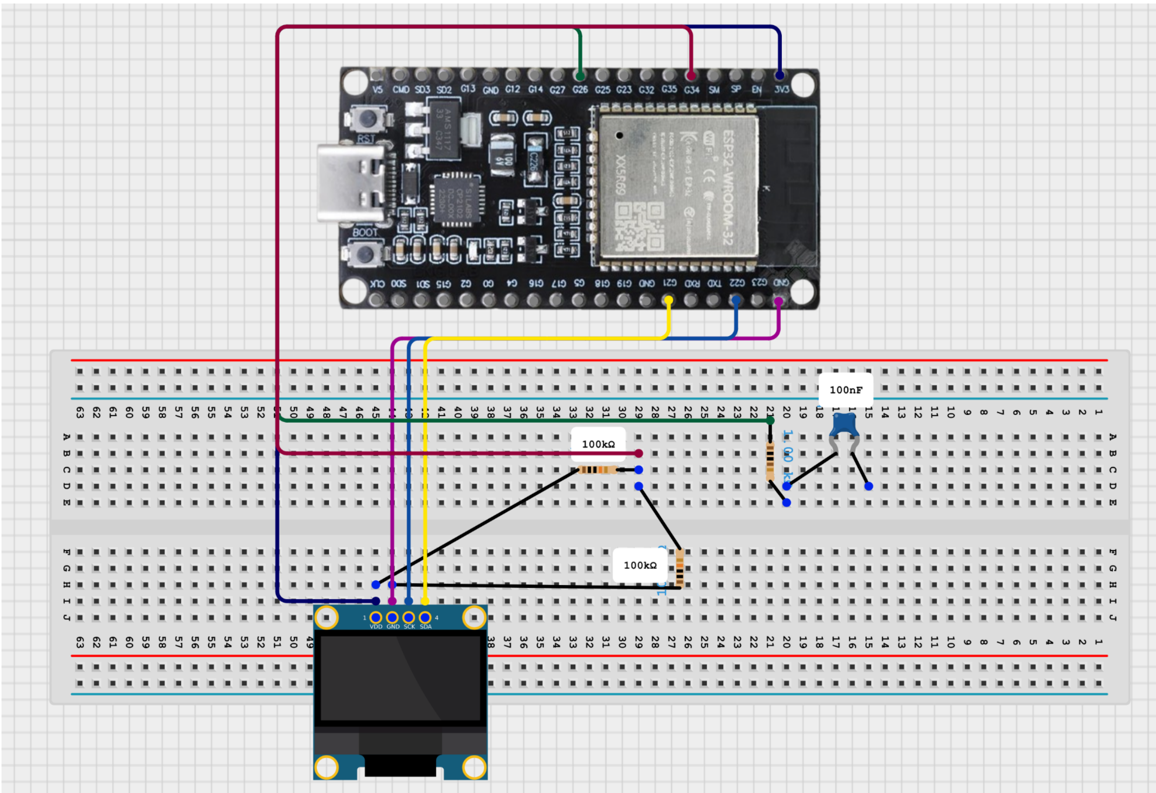

Figure 3.3.1 - Hardware Setup

3.3.2 SH1106 OLED Display

A 128 × 64 monochrome SH1106 OLED is used for displaying the FFT spectrum in spectrum analyzer mode.
Communication is done over I²C, using SCL and SDA lines connected to the ESP32's I²C pins.

Reason for selecting SH1106:

- Readable monochrome display
- Low power consumption
- Works well for discrete spectral bars
- Easy library support in Arduino environment

3.3.3 Oscilloscope for Verification

A Tektronix TDS 2004B digital oscilloscope was used to validate the waveform generator output.
It supports bandwidths and sampling rates sufficient to observe signals up to and beyond the project's 40 kHz test range.

3.4 Waveform Generation Techniques

Different waveform types were generated using different internal ESP32 peripherals, as no single subsystem could efficiently support all waveforms across the required frequency range. The selection of methods is described below.

3.4.1 Sine Wave Generation Using DAC Hardware

The sine wave is produced using the ESP32's built-in 8-bit DAC.
The DAC output is driven by a precomputed sine LUT, scaled based on user amplitude settings.

Procedure:

1. Precompute a table of 256 sine samples.
2. Apply amplitude scaling in software.
3. Update the DAC output at a constant rate using a hardware timer.

This method provides smooth waveforms at low and medium frequencies. For high-frequency sine waves (up to approximately 40 kHz), the project switches to the ESP32's cosine generator hardware (when available), which allows higher-frequency generation due to dedicated timing hardware.

Limitations:

- Resolution limited to 8 bits
- Settling time limits waveform fidelity at high frequencies
- High frequencies require lower sample counts per cycle

3.4.2 Square Wave Generation Using PWM

Square wave generation is implemented using the ESP32’s LEDC PWM peripheral. The PWM module allows precise frequency control by configuring the timer divider and duty resolution. Once the timer is configured for the desired output frequency, the duty cycle is modulated to obtain the required pulse width.

A key characteristic of PWM on the ESP32 is that the output pin is driven directly by the digital I/O circuitry. The output toggles strictly between 0 V and the 3.3 V supply rail. Because these voltage levels are fixed by hardware, the **peak amplitude of the square wave cannot be changed in software**. Only frequency and duty cycle are programmable.

This contrasts with DAC-generated waveforms, where amplitude scaling is possible. For square waves, amplitude modulation requires external analog hardware such as amplifiers or attenuators.

PWM is therefore ideal for producing clean digital square waves, but not for amplitude-programmable waveforms.

3.4.3 Triangle/Sawtooth Wave Generation via Software Timer

Triangle and sawtooth waveforms are produced using a software-driven lookup table (LUT) approach. A precomputed array containing one period of the desired waveform is iterated at a fixed update rate determined by a software timer. Each LUT value is written to the ESP32's DAC. This method is computationally light and works reliably at low frequencies. However, the maximum usable frequency is limited by:

1. Software timer latency
2. DAC write timing
3. Per-loop overhead

Due to these constraints, triangle and sawtooth waves begin to distort significantly at higher frequencies. At low frequencies, however, the method produces stable and visually accurate waveforms suitable for educational demonstration.

Amplitude scaling remains available for these waveforms because they use the DAC output path.

3.4.4 Amplitude Control Architecture

Amplitude control is implemented by scaling the digital samples before they are written to the DAC. This allows smooth, proportional amplitude variation for DAC-based waveforms such as sine, triangle, and sawtooth.

Square waves, however, **do not support amplitude control** because PWM drives the GPIO pin directly between fixed logic levels (approximately 0 V and 3.3 V). Duty cycle variation changes the average output power, but not the peak amplitude. Therefore, amplitude control is connected only to DAC-generated waveforms, whereas the PWM block receives only frequency and duty-cycle inputs.

3.5 Mode Switching and System Flow

The system cannot run the FFT and waveform generator concurrently because:

- FFT requires large continuous CPU time slices
- DAC updates demand timing regularity
- PWM timers remain active but need uninterrupted CPU to maintain responsiveness
- OLED updates require I²C bus availability

To address this, a **two-mode system** is used:

Mode	DAC Output	PWM Output	FFT	OLED	CSV Logging
Signal Generator	Yes	Yes	No	Not Used	Yes
Spectrum Analyzer	No	No	Yes	Full spectrum	No

This mode isolation prevents timing interference and ensures stable operation.

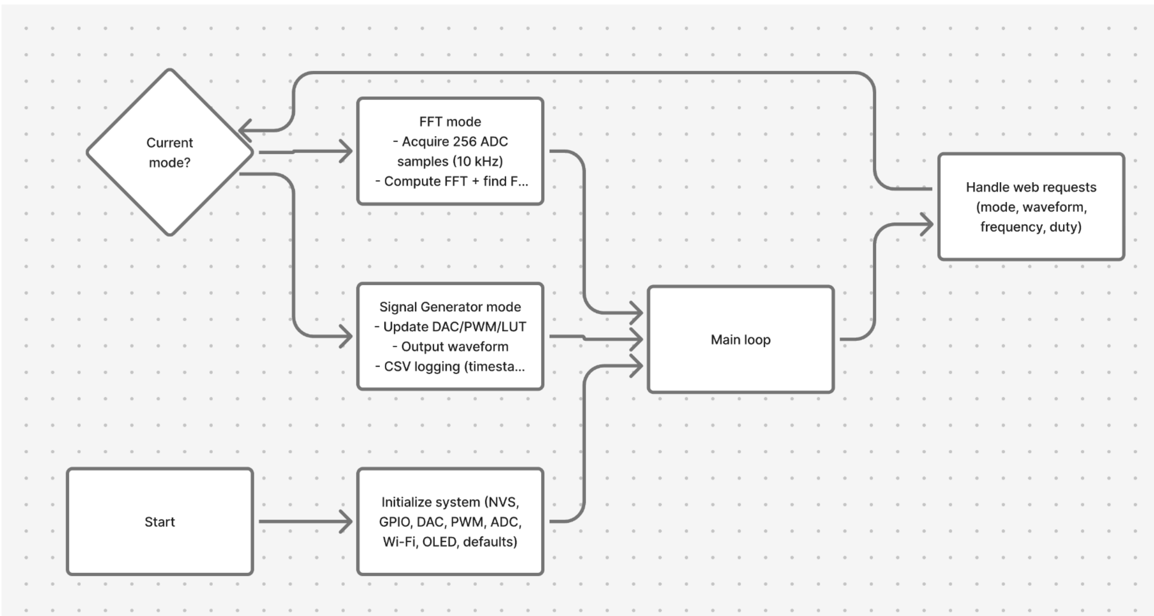

Figure 3.5 - System Firmware Flow

3.6 Wi-Fi Webpage Control

A custom webpage hosted on the ESP32 allows users to fully control the system.

Features available through the webpage:

- Frequency selection
- Waveform selection
- Amplitude control (only for sine, triangle, sawtooth)
- Mode switching (Signal Generation <-> Spectrum Analyzer)

Physical push-buttons originally present in sample code were removed to simplify operation.

The webpage communicates with the ESP32 using HTTP GET requests and dynamically updates displayed values.

3.7 FFT Subsystem and Spectrum Visualization

The FFT module operates only in the spectrum-analyzer mode. Input samples are captured from the 12-bit ADC at a sampling frequency of 10 kHz, with an FFT size of 256, giving a frequency resolution of approximately 39 Hz.

To improve stability, only bins corresponding to **1000 Hz to approximately 4.5–5 kHz** are used for dominant-frequency detection. This corresponds to the reliable range of the DAC-based sine wave generator. DC offsets and low-frequency noise are deliberately ignored.

Peak detection is performed within the restricted band, and the dominant frequency Fp is displayed along with FS and N on the top row of the OLED. The full magnitude spectrum (bins 1 to N/2–1) is drawn as vertical bars across the 128-pixel width of the OLED.

3.8 CSV Logging System

Logging is implemented in waveform-generation mode. The system periodically transmits:

- Timestamp (milliseconds)
- DAC amplitude value
- Peak Bin
- Frequency

These entries are sent through Wifi and can be viewed using any standard smartphone terminal application. The terminal's built-in export function allows the user to save the session as a CSV file for offline analysis.

3.9 Bill of Materials and Cost Analysis

The proposed system was intentionally designed to be low-cost and accessible for undergraduate laboratory environments. Only essential components were used, and all user interaction is handled through a Wi-Fi webpage, eliminating the need for dedicated external interface hardware. Table 3.8.1 summarizes the components required to build the prototype.

Table 3.8.1 Bill of Materials

Component	Quantity	Approx. Unit Cost (INR)	Total Cost (INR)
ESP32-WROOM Development Board	1	350	350
SH1106 128×64 OLED Display (I^2C)	1	150	150
Breadboard (standard 830-point)	1	100	100
Resistors (100 kΩ, 1 kΩ, misc.)	Assorted	2 each (approx.)	~20
Capacitors (100 nF, 1 μF)	Assorted	2 each (approx.)	~20
Jumper Wires	1 set	30	30

Cost Justification

The entire prototype can be constructed for under ₹700, which is significantly lower than the cost of conventional laboratory instruments. For comparison:

- A basic function generator typically costs ₹15,000–₹25,000.
- A benchtop spectrum analyzer or FFT-capable oscilloscope ranges from ₹50,000 to several lakh rupees.

In contrast, this system provides:

- Sine and square wave generation up to approximately 40 kHz
- Low-frequency triangle/sawtooth generation
- Basic FFT-based spectral visualization
- Wireless control using any smartphone or laptop (no added cost)

  All of these are achieved using a microcontroller and a compact OLED display, demonstrating that meaningful laboratory functionality can be replicated at very low cost for instructional and prototyping purposes.

3.10 Summary of Methodology

The methodology brings together embedded hardware control, waveform generation techniques, DSP algorithms, and user interface design. Each subsystem was selected to balance functionality and feasibility within the constraints of the ESP32.

The hybrid waveform generation approach enabled high-frequency sine and square waves while maintaining low-frequency support for triangle and sawtooth signals. Mode isolation ensured stable FFT operation, and Wi-Fi control improved usability. The SH1106 OLED provided a compact display for spectral results, and CSV logging supported offline analysis.

Overall, the methodology ensures a practical, functioning, and educationally valuable system without overselling the capabilities of the hardware.

CHAPTER 4 - RESULTS AND PERFORMANCE ANALYSIS

4.1 Introduction

This chapter presents the consolidated results and performance analysis of the ESP32-based signal generator and spectrum analyzer. The system was evaluated for waveform quality, frequency stability, spectral accuracy, display clarity, and responsiveness of the control and logging interfaces. Where precise oscilloscope captures were not available, theoretical limits and qualitative behavior were used to strengthen the analysis. The objective is to provide a clear, academically sound assessment of how the implemented system performs relative to the capabilities and constraints of the ESP32 platform.

4.2 Experimental Setup Summary

Testing was carried out using the following configuration:

- ESP32-WROOM module for waveform generation and FFT computation
- Tektronix TDS 2004B oscilloscope for observing waveforms
- SH1106 128×64 OLED display (I^2C) for spectral visualization
- Wi-Fi webpage interface to select waveform, frequency, and operating mode
- Export logged data over WiFi
- USB 5 V supply powering the ESP32 module

Waveform generation mode and spectrum analyzer mode were evaluated independently, since both require deterministic timing that is not feasible concurrently on the ESP32.

4.3 Sine Wave Results and Performance

4.3.1 Observed Behavior

At low frequencies (below 5 kHz), the DAC-based sine output appeared smooth and stable.
In the mid-range (5–20 kHz), small quantization steps became visible, which is expected from an 8-bit DAC.
At high frequencies (20–40 kHz), the sine wave remained usable and generally clean, especially when the ESP32's hardware cosine generator was used.

4.3.2 Performance Interpretation

The DAC's settling time, resolution and update rate define the upper frequency limits. The hardware cosine generator sidesteps some of these limitations, enabling surprisingly good high-frequency performance for a microcontroller-based waveform generator.

4.3.3 Assessment

The sine output is suitable for educational experiments and general-purpose testing up to approximately 40 kHz.

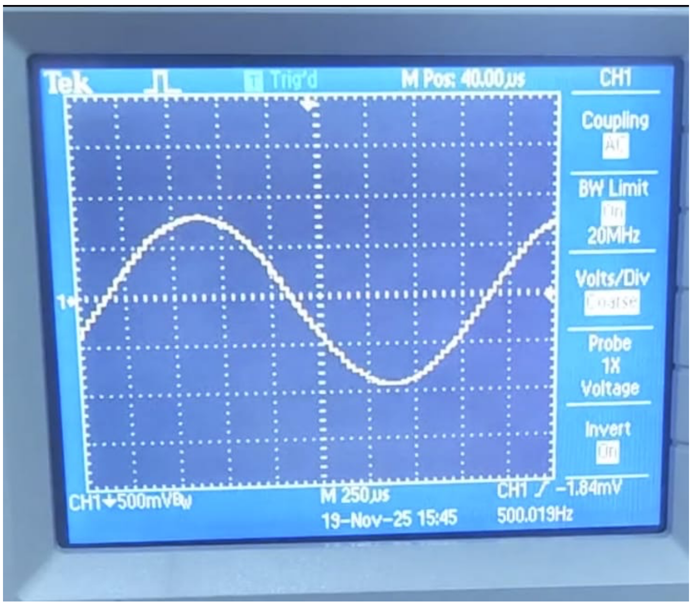

Figure 4.3.3 - Oscilloscope Capture of Sine Wave Generated by ESP32

4.4 Square Wave Results and Performance

4.4.1 Observed Behavior

Square waves produced using the LEDC PWM subsystem were clean, with sharp rise and fall edges.
Frequency accuracy was high across the entire tested range, and the waveform remained stable even at 40 kHz.

4.4.2 Amplitude Characteristics

The amplitude of the square wave remained fixed at approximately **3.3 V peak**, independent of any software amplitude setting.
This is an inherent characteristic of PWM outputs on the ESP32:

- A PWM signal is generated by rapidly toggling a digital GPIO pin.
- The pin can output only two voltage levels: **0 V (LOW)** and **3.3 V (HIGH)**.
- Duty cycle determines the *average* voltage but does not change the actual HIGH-level voltage.
- Therefore, amplitude modulation of a square wave is not possible without additional analog hardware such as a variable-gain amplifier or external level-shifting circuit.

This behavior contrasts with the sine wave output, where amplitude can be adjusted because the DAC drives an analog voltage rather than a digital level.

4.4.3 Assessment

Square waves demonstrated the most robust and predictable behavior among all waveform types.

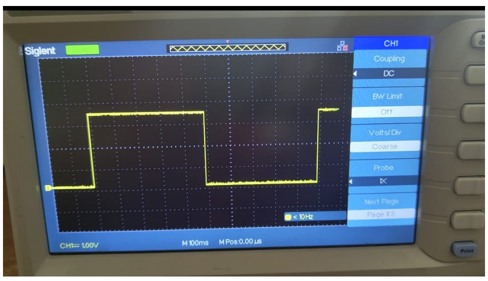

Figure 4.4.3 - Oscilloscope Capture of Square Wave Generated by ESP32

4.5 Triangle Wave Results and Performance

4.5.1 Observed Behavior

Triangle waves were generated using a software timer and a lookup table written to the DAC.

At low frequencies (up to ~300 Hz), the waveform appeared linear and symmetric.

At moderate frequencies (300–1000 Hz), visible stair-stepping and slight jitter appeared.

Above 1 kHz, the waveform degraded significantly due to timing limitations.

4.5.2 Performance Interpretation

The limiting factors are:

- ISR latency
- DAC update rate
- DAC settling characteristics
- CPU time consumed by other tasks

Thus the performance limitations are expected for software-generated analog waveforms on the ESP32.

4.5.3 Assessment

Triangle waves are suitable only for low-frequency demonstrations.

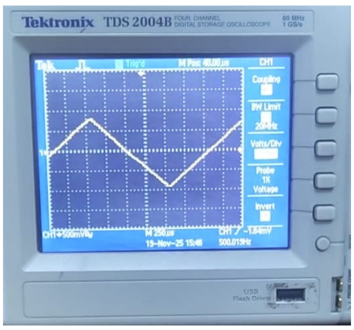

Figure 4.5.3 - Oscilloscope Capture of Triangular Wave Generated by ESP32

4.6 Sawtooth Wave Results and Performance

4.6.1 Observed Behavior

Sawtooth waves exhibited behavior nearly identical to triangle waves:
clean at low frequencies, increasing distortion at moderate frequencies, and unusable output above roughly 1 kHz.

4.6.2 Performance Interpretation

Sawtooth generation shares the same DAC and ISR constraints, and therefore the usable frequency range is similarly limited.

4.6.3 Assessment

Sawtooth output is functional only in the low-frequency region and serves primarily for demonstration.

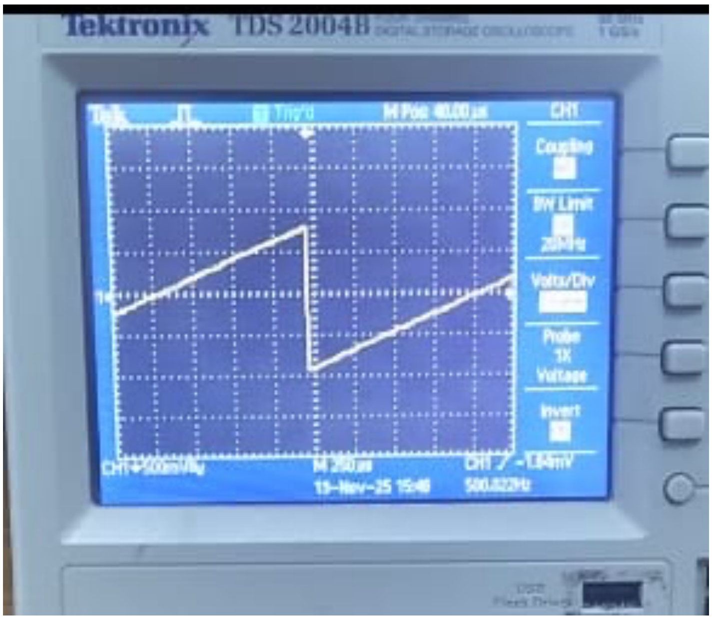

Figure 4.6.3 - Oscilloscope Capture of Sawtooth Wave Generated by ESP32

4.7 Spectrum Analyzer (FFT) Results and Performance

The spectrum analyzer uses a 10 kHz sampling rate and a 256-point FFT, producing a frequency bin width of:

$$\Delta f = \frac{F_s}{N} \approx \frac{10000}{256} \approx 39 \text{ Hz}$$

4.7.1 Configuration and Constraints

Key configuration details:

- Sampling frequency ($F_s = 10 \text{ kHz}$)
- FFT size (N = 256)
- Nyquist frequency = 5 kHz
- Dominant frequency search band = 100 Hz to 4.5 kHz
- 12-bit ADC input (0–4095), with DC removal each frame
- Hamming window to reduce spectral leakage

Although the full half-spectrum (40 Hz to ~5 kHz) is drawn on the OLED, the dominant frequency (F_p) is computed only within the 100–4500 Hz band for stability and accuracy.

4.7.2 Observed Behavior

In the 100 Hz to 4.5 kHz range:

- A clear peak was visible at or near the expected bin for a sine input
- Non-sinusoidal inputs exhibited expected harmonics
- Low-frequency noise and DC components were suppressed by the DC-removal step and the restricted search band
- Near 5 kHz, bin quantization and proximity to Nyquist caused visible broadening and reduced stability in the peak location

These results match sampling theory and the constraints of a 10 kS/s measurement system.

4.7.3 Assessment

The FFT subsystem provides a stable qualitative visualization of the signal's frequency content within the chosen band. It is not intended for precision spectral measurement, but it is fully adequate for demonstrating FFT concepts, windowing, aliasing, and harmonic content.

4.8 Webpage Interface Performance

The Wi-Fi interface reliably handled:

- Waveform selection
- Frequency updates
- Switching between generator and FFT modes
- Real-time parameter changes

No instability was observed, and the absence of physical pushbuttons simplified user interaction.

4.9 Data Logging Performance

The current logging implementation transmits:

- A timestamp
- The DAC amplitude (0–255)

over a Wifi connection.

Although minimal, this logging mechanism demonstrates that the system can stream numerical data in real time and that the data can be easily plotted in external tools such as Python, MATLAB, or Excel.

The same framework can be extended to log additional fields in future revisions.

4.10 Overall System Evaluation

Based on all tests and theoretical constraints:

- Sine wave output is clean and usable up to approximately 40 kHz.
- Square wave output is stable up to 40 kHz, with fixed 3.3 V amplitude.
- Triangle and sawtooth waves perform best at low frequencies (< 300–500 Hz).
- FFT mode reliably identifies dominant frequencies in the 100–4500 Hz range, with approximately 39 Hz resolution.
- OLED display is clear enough to visualize the half-spectrum and labels.
- Wi-Fi interface is responsive and stable.

Overall, the system meets its design objectives as a low-cost educational tool capable of producing practical waveforms and performing introductory spectrum analysis.

4.11 Summary

The implemented system delivers clean sine and square waves over a wide frequency range, basic low-frequency analog waveforms, and a functional real-time FFT visualizer within the constraints of the ESP32 hardware. The results are consistent with theoretical expectations and demonstrate that even low-cost microcontrollers can support meaningful waveform generation and spectral analysis when appropriately configured.

CHAPTER 5 - LIMITATIONS AND FUTURE SCOPE

5.1 Limitations of the Current System

Although the developed ESP32-based signal generator and spectrum analyzer meets its intended academic objectives, several limitations arise from hardware constraints, timing characteristics and architectural choices. These limitations are outlined below.

5.1.1 Fixed Amplitude for PWM-Based Square Waves

The ESP32's PWM output drives the GPIO pin directly between 0 V and the 3.3 V supply rail. Because these voltage levels are fixed by the microcontroller hardware, the amplitude of the square wave cannot be modified in software. Only the frequency and duty cycle can be changed. Amplitude variation would require additional analog circuitry.

5.1.2 Limited High-Frequency Performance for Triangle and Sawtooth Waves

Triangle and sawtooth waveforms are generated using a software-based lookup table updated through a timer interrupt. This method works effectively at low frequencies, but the maximum usable frequency is restricted by interrupt latency, DAC update time and loop overhead. At higher frequencies, visible distortion occurs, limiting the useful bandwidth of these waveforms.

5.1.3 DAC Waveform Fidelity and Slew Rate Limitations

The built-in DAC of the ESP32 has moderate resolution and limited update speed. At elevated frequencies, the DAC output exhibits stair-stepping, reduced peak accuracy and slight harmonic distortion. Although the system generates clean sine waves up to approximately 40 kHz, performance beyond this range declines.

5.1.4 Restricted FFT Bandwidth Due to Sampling Rate

The FFT subsystem uses a sampling frequency of 10 kHz with a frame size of 256 samples. This restricts the usable FFT bandwidth to approximately 5 kHz. Frequencies above this cannot be captured accurately. The choice of FS = 10 kHz ensures stable operation but limits high-frequency analysis capability.

5.1.5 Lack of Input Signal Conditioning

The analog input path connects directly to the ESP32's ADC without the use of buffer amplifiers, anti-aliasing filters or protection stages. While acceptable in a controlled laboratory environment, this may lead to inaccurate readings or clipping when measuring arbitrary external signals.

5.2 Future Scope and Potential Enhancements

Several enhancements can be incorporated to expand functionality, improve accuracy and extend the usable bandwidth of the system. These improvements are realistic and suitable for future work.

5.2.1 Amplitude-Controlled Square Wave Generation

True amplitude control for square waves can be achieved by adding external analog stages such as digitally controlled potentiometers, programmable gain amplifiers, level-shifters or transistor-based switching with adjustable supply voltage.

5.2.2 Improved Triangle and Sawtooth Generation Through Hardware DDS

Replacing the software-based LUT method with a direct digital synthesis (DDS) approach or using the RMT peripheral for high-speed buffering can significantly improve waveform linearity and frequency range. Alternatively, integrating dedicated waveform generator ICs such as the AD9833 or AD9850 would provide professional-grade performance.

5.2.3 Higher Sampling Rates for Extended FFT Bandwidth

Increasing the sampling frequency to 20 kHz or 40 kHz would widen the FFT bandwidth and allow analysis of higher-frequency signals. This requires optimization of sampling, buffering and processing routines but is achievable on the ESP32.

5.2.4 Improved Analog Front-End for External Signals

Adding an input buffer amplifier, low-pass filter and over-voltage protection network would improve stability, reduce noise and protect the ADC when measuring external signals. This would make the analyzer more robust for general-purpose use.

5.2.5 Simultaneous Signal Generation and FFT Monitoring

A future revision could support parallel operation of the generator and analyzer. By utilizing both cores of the ESP32 more efficiently, the system could display the spectrum of the generated output in real time.

5.3 Summary

The system successfully delivers multi-waveform generation, Data logging and real-time spectrum visualization. However, the limitations arising from PWM hardware, DAC performance, ADC bandwidth and software-based waveform timing restrict high-frequency accuracy and amplitude control. The identified enhancements provide clear directions for future development, enabling the system to evolve into a more capable and versatile laboratory instrument.

CHAPTER 6 - CONCLUSION

The objective of this mini-project was to design and implement a compact, low-cost signal generator and spectrum analyzer using the ESP32-WROOM module and an SH1106 OLED display. The system successfully integrates waveform generation, \ data logging using WiFi and real-time FFT visualization into a single platform suitable for laboratory and instructional use.

The waveform generator was able to produce sine waves, square waves and software-generated triangle and sawtooth waves. The DAC-based sine wave demonstrated clean performance up to approximately 40 kHz, which is notable given the limitations of microcontroller-based DACs. Square waves generated through PWM achieved precise frequency control but, as expected from the hardware architecture, exhibited fixed amplitude determined by the ESP32's 3.3 V supply. Triangle and sawtooth waves performed reliably at lower frequencies, demonstrating the usefulness of software-LUT approaches within their intended range.

The FFT analyzer successfully captured and displayed the frequency spectrum of input signals within the 0–5 kHz band, constrained by the chosen sampling rate of 10 kHz and a frame size of 256 samples. The band-limited dominant frequency detection (Fp) method ensured clean and stable readings for DAC-generated signals, while the SH1106 OLED provided a clear graphical display suited to the resolution requirements of the application.

WiFi-based logging allowed data to be exported easily via smartphone terminal applications. This feature enhances the utility of the system for offline analysis and supports the broader goal of creating a self-contained educational tool for studying waveform behavior.

While the system performs reliably within its validated range, limitations such as fixed square-wave amplitude, reduced high-frequency LUT performance and restricted FFT bandwidth were identified. These constraints arise from inherent characteristics of the ESP32 hardware and the design choices made to maintain simplicity and cost-effectiveness. Future enhancements, including improved analog front-end design, higher sampling rates, hardware-based DDS and expanded user interfaces, present opportunities for further development.

Overall, the project demonstrates a successful integration of signal generation and spectral analysis within the capabilities of an embedded microcontroller platform. It provides a practical, accessible and educational tool for understanding analog and digital signal concepts, and serves as a foundation for future refinement and expansion in both academic and hobbyist contexts.

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B.M.S COLLEGE OF ENGINEERING

(Autonomous Institution under VTU, Belagavi, Accredited by NAAC with A++ Grade)

Department of Electronics and Telecommunication Engineering

(Accredited by NBA under Tier – I format)

MINI PROJECT – 23ET5PWMPR

NOVEMBER -2025

Title	CSV-Enhanced Portable Dual-Function Signal Generator and Spectrum analyzer using ESP-32		
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Abstract

Signal generators and spectrum analyzers are essential instruments in electronics laboratories, supporting experimentation, verification, and characterization of analog and digital circuits. However, commercial equipment is often costly, non-portable, and unavailable for continuous student use outside scheduled laboratory sessions. This mini-project explores the feasibility of developing a compact, low-cost alternative based on a microcontroller platform capable of producing fundamental test waveforms and providing basic spectral visualization suitable for undergraduate instruction.

The system is built using an ESP32-WROOM module, utilizing its integrated peripherals for waveform synthesis and analysis. Experimental evaluation with a Tektronix TDS 2004B oscilloscope confirmed clean waveform generation up to approximately 40 kHz for both sine and square signals. Triangle waveform generation was attempted via an I²S-driven DAC buffer; however, linearity and stability were insufficient for reliable operation, and this functionality is retained as future work.

A secondary mode enables basic spectrum analysis by sampling analog data through the ESP32 ADC and computing a windowed 256-point FFT. The resulting magnitude spectrum is displayed on anOLED, providing a simplified visualization of dominant frequency components. A Wi-Fi–based control interface permits parameter adjustment through a browser webpage, eliminating physical controls and enabling fully wireless operation. Additionally, configuration data such as waveform type, frequency, and duty cycle can be logged in CSV format over serial output for external documentation.

The results demonstrate that a microcontroller-based platform can deliver essential waveform generation and introductory spectral visualization within low-cost and small-form-factor constraints. Although not intended to replace professional laboratory instruments, the device offers meaningful value for experimentation, prototyping, and foundational signal analysis

Photography

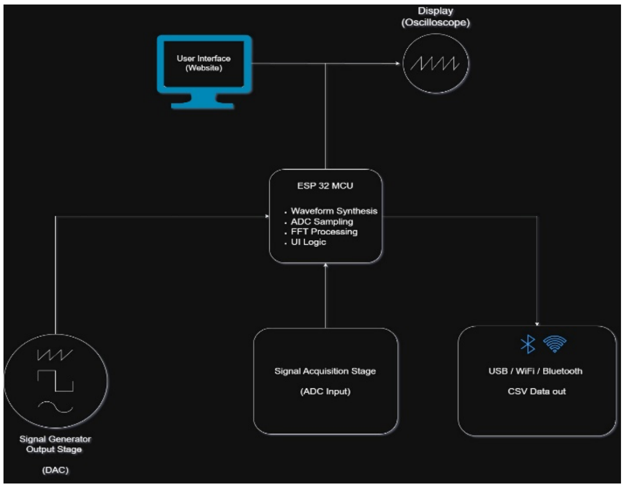

Fig.1 Block Diagram

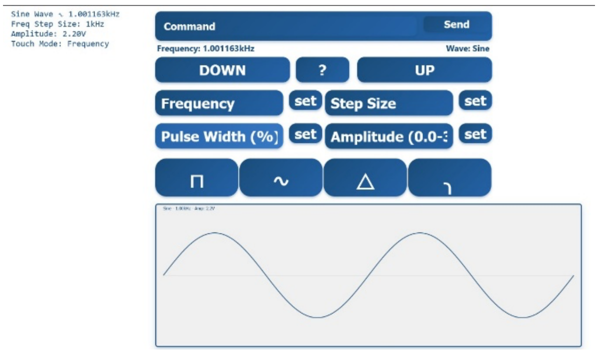

Fig.2 Website Home Page

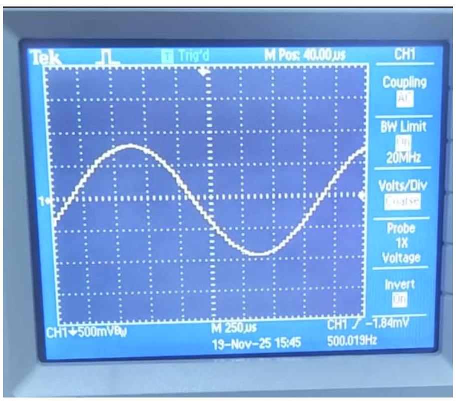

Fig.3 Results

Program Outcomes	Our project satisfies PO-1