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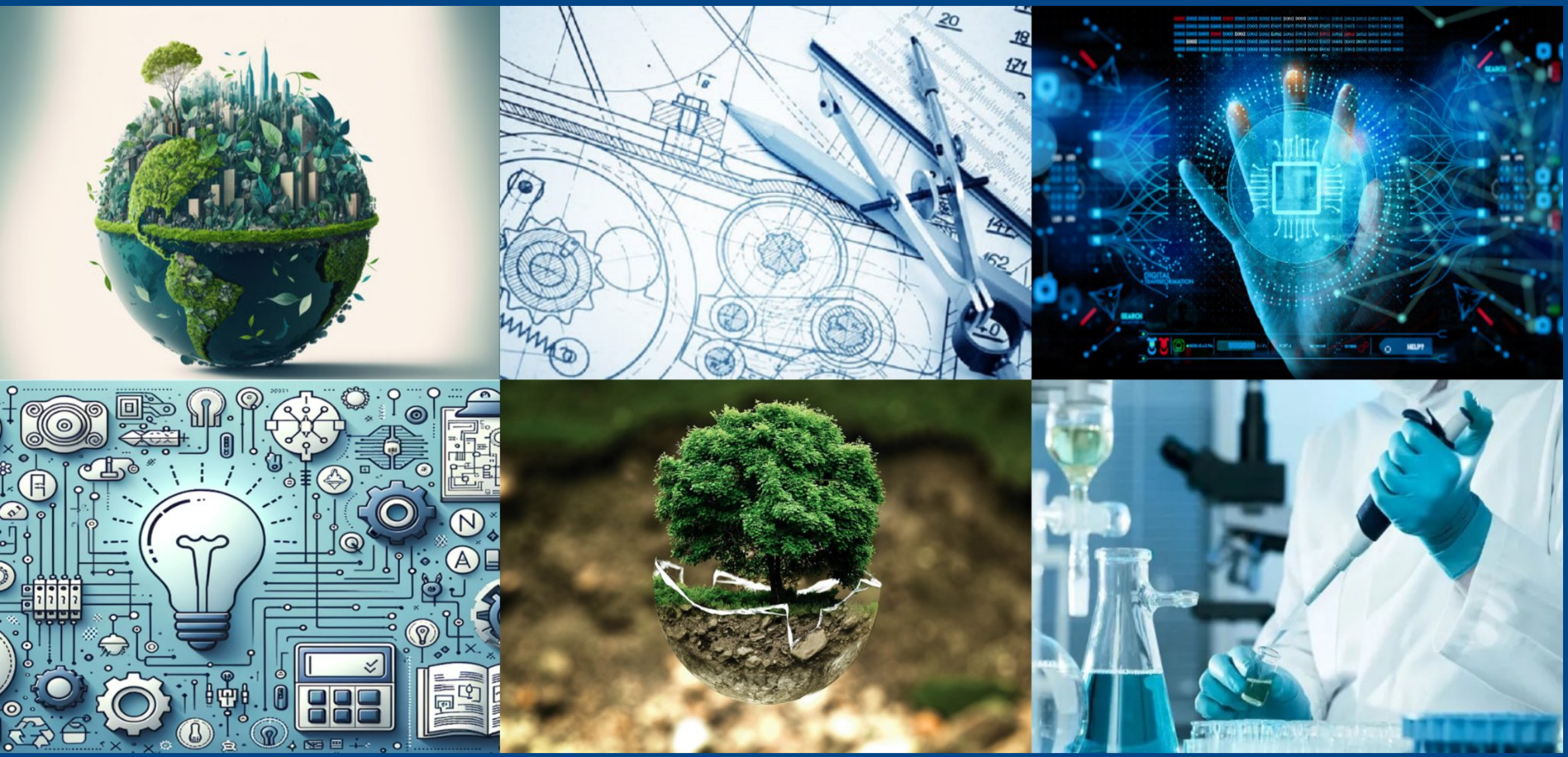

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Design and Implementation of a Low-Cost, Low Frequency, Wi-Fi-Enabled Digital Oscilloscope Using ESP32 Microcontroller

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ABSTRACT: This project presents a low-cost, portable digital oscilloscope using the **ESP32 microcontroller**, addressing the high cost and limited accessibility of traditional DSOs. By leveraging the ESP32's integrated Wi-Fi and ADC, the system enables users to visualize electrical signals in real time on any device with a web browser.

The device acquires signals through the ESP32's ADC and streams the data wirelessly via a **WebSocket server** to a simple web-based interface. This project offers an affordable and practical tool for basic signal analysis, demonstrating how embedded systems can be used to create user-friendly solutions.

KEYWORDS: ESP32, Digital Oscilloscope, Wi-Fi, WebSocket, Real-time Visualization, ADC.

I. INTRODUCTION

Oscilloscopes are essential instruments used in electronics and communication systems to observe and analyze electrical signals in real time [1]. They are widely used in circuit debugging, signal processing, and system design applications [2]. However, traditional oscilloscopes are expensive and bulky, making them less accessible for students and hobbyists [3].

With the rapid advancement of embedded systems and IoT technologies, compact and cost-effective solutions have emerged. Microcontrollers such as the ESP32 provide integrated features including Wi-Fi connectivity, analog-to-digital conversion, and sufficient processing capability, making them suitable for developing portable measurement systems [5].

Wireless communication technologies such as WebSocket enable real-time data transfer between devices with minimal latency [6]. This allows waveform visualization on web browsers without requiring dedicated display hardware [7].
This work aims to design a low-cost, portable oscilloscope using ESP32 that enables real-time signal acquisition and wireless visualization, making it suitable for educational and basic diagnostic applications [2].

II. LITERATURE REVIEW

- Several research efforts have focused on developing low-cost oscilloscopes using embedded systems [1]. Early implementations used microcontrollers with external ADCs and wired communication interfaces, which limited portability and performance [10].
- With advancements in wireless technology, ESP32-based systems have gained popularity due to their integrated Wi-Fi and processing capabilities [3]. These systems enable real-time signal acquisition and wireless transmission, making them suitable for IoT-based applications [6].
- Wireless oscilloscope designs using ESP32 and sensor modules have been proposed for real-time waveform visualization [2]. However, these systems are often limited in frequency range and accuracy, restricting their practical applications [7].

- Signal conditioning techniques such as voltage scaling, filtering, and protection circuits are essential to ensure safe and accurate measurements [8]. Additionally, digital signal processing methods enhance waveform analysis and visualization [12].
- Despite these advancements, many systems lack flexibility, user-friendly interfaces, and customization options. Therefore, there is a need for a low-cost, wireless, and efficient oscilloscope with real-time visualization capabilities [6].

III. PROPOSED METHOD

Problem Statement:

Traditional oscilloscopes provide high accuracy and bandwidth but suffer from significant drawbacks such as high cost, bulky design, and lack of portability, making them unsuitable for students and field applications [5]. Additionally, many low-cost alternatives either lack wireless communication or fail to provide real-time visualization capabilities [7].

Moreover, the limited flexibility and closed architecture of commercial oscilloscopes restrict customization for specific applications such as remote monitoring, embedded system debugging, and IoT-based measurements [6]. These challenges highlight the need for a low-cost, portable, and wireless oscilloscope capable of real-time signal acquisition and visualization.

Objectives:

- To design a cost-effective digital oscilloscope using ESP32.
- To enable wireless transmission of acquired signals.
- To implement real-time waveform visualization using a web interface.
- To ensure safe signal acquisition using proper conditioning circuits.
- To provide a user-friendly and customizable platform System Architecture

System Architecture

The overall architecture of the proposed ESP32 Wi-Fi Oscilloscope system is shown in Fig. 1. The proposed system architecture is divided into three major stages:

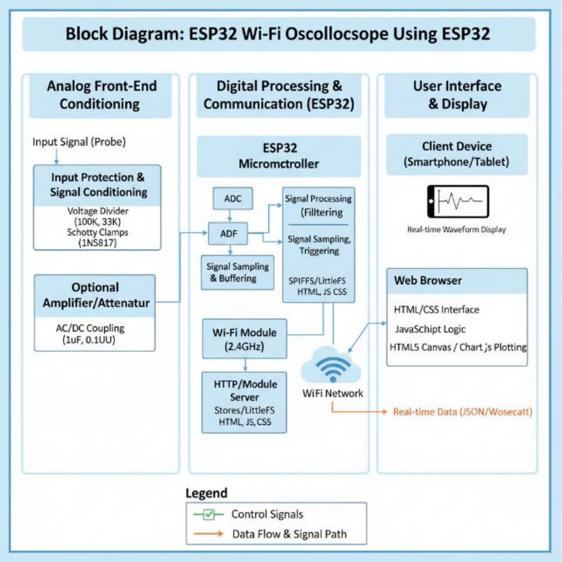


Fig.1: System Architecture Block Diagram

1. Analog Front-End (Signal Conditioning Stage):

The analog front-end is responsible for preparing the input signal for safe and accurate measurement.

- **Voltage Divider:** Reduces high input voltages (±20V) to a safe range compatible with ESP32 (0–3.3V) [8].

- **Protection Circuit:** Zener and Schottky diodes are used to clamp voltage spikes and prevent damage to the microcontroller [8].
- **Level Shifting:** Since ESP32 ADC cannot read negative voltages, an operational amplifier is used to shift the signal into a positive range [4].

This stage ensures signal integrity, safety, and compatibility with ADC input.

2. Processing Unit (ESP32 Microcontroller):

The ESP32 acts as the core processing unit of the system.

- **ADC Sampling:** The built-in 12-bit ADC converts analog signals into digital values. Typical sampling rate: 10–100 kSPS [3].
- **Data Buffering:** Samples are stored in buffers to ensure continuous data flow and avoid loss during transmission.
- **Wi-Fi Communication:** ESP32 operates in Access Point or Station mode and transmits data using WebSocket protocol [14].

This stage handles data acquisition, processing, and transmission**.**

3. User Interface (Web-Based Visualization):

The visualization is implemented using a browser-based interface.

- **Real-Time Plotting:** JavaScript (Canvas API) is used to draw waveform dynamically
- **User Controls:**
  - Time/Div
  - Volt/Div
  - Start/Stop
  - AC/DC mode
- **Measurement Display:**
  - Vmax, Vmin
  - Frequency
  - Time Period
  - RMS Voltage

This stage provides interactive and real-time user experience [6].

IV. IMPLEMENTATION

Hardware Implementation:

The hardware design focuses on ensuring accurate signal acquisition and system safety.

- **ESP32 Microcontroller:** Acts as the central unit for signal sampling and wireless transmission [3].
- **Signal Conditioning Circuit:**

Includes**:**

  - Voltage divider
  - Protection diodes
  - Filtering capacitors
- **Operational Amplifier:** Used for level shifting and buffering to maintain signal quality [4].
- **Power Supply:** The system operates at 3.3V/5V, ensuring low power consumption**.**

Software Implementation:

The software is divided into two main components:

1. Embedded Firmware (ESP32 Side)

- Developed using Arduino IDE [9]
- Configures ADC for continuous sampling
- Implements WebSocket server
- Handles real-time data transmission

Optimization techniques:

- Efficient buffering
- Reduced latency communication

- Lightweight JSON data transfer

2. Web Interface (Client Side)

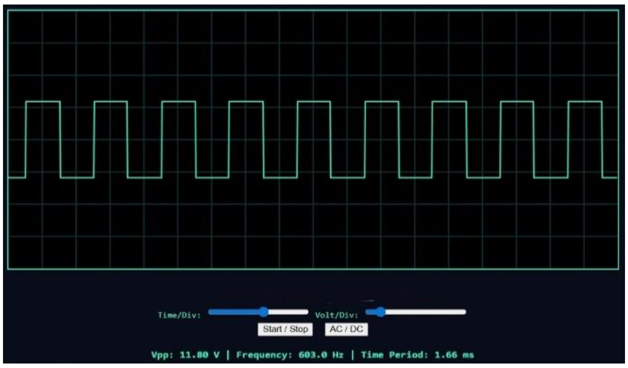
- Built using HTML, CSS, JavaScript
- Uses Canvas API for waveform plotting
- Implements real-time data update via WebSocket

Features:

- CRO-style grid display
- Auto-scaling
- Measurement calculations

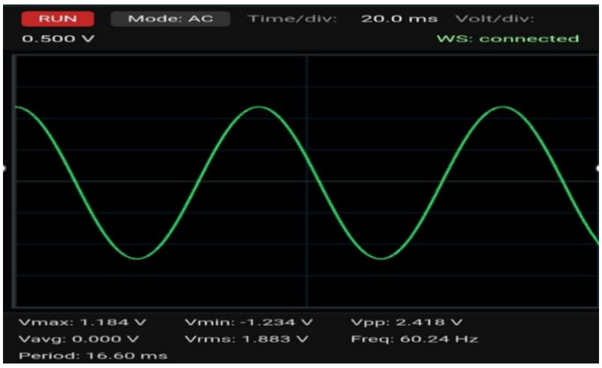
Working Methodology

1. Input analog signal is applied
2. Signal is conditioned and scaled
3. ADC samples the signal
4. Data is stored in buffer
5. ESP32 transmits data via Wi-Fi
6. Browser receives and plots waveform
7. User interacts with controls
8. Digital signal processing algorithms are used to compute parameters like frequency and RMS value [12].



```
Vpp: 11.80 V | Frequency: 603.0 Hz | Time Period: 1.66 ms
```

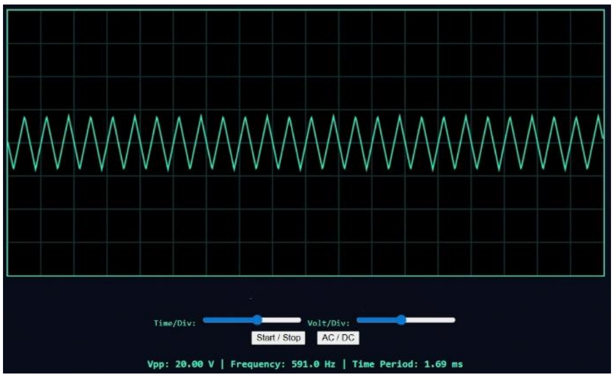
Fig.1 : Triangular Waveform



Mode: AC
Time/div: 20.0 ms
Volt/div: 0.500 V
WS: connected

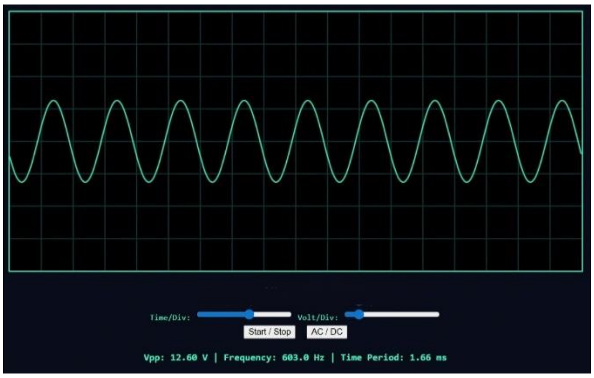
```
Vmax: 1.184 V      Vmin: -1.234 V      Vpp: 2.418 V
Vavg: 0.000 V      Vrms: 1.883 V       Freq: 60.24 Hz
Period: 16.60 ms
```

Fig.2 : GUI Display Interface



```
Vpp: 20.00 V | Frequency: 591.0 Hz | Time Period: 1.69 ms
```

Fig.3 : Sinusiodal Waveform n



```
Vpp: 12.60 V | Frequency: 603.0 Hz | Time Period: 1.66 ms
```

Fig.4 : Square Waveform

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V. RESULTS

The system was tested with different input signals generated using a function generator, successfully visualized various waveforms.

The system successfully displays different waveforms including sinusoidal, square, and triangular signals.
Performance Observatio

- Real-time visualization achieved
- Stable wireless transmission

Frequency measurement in low kHz range

Parameter	**Value**
Sampling Rate	~10–50 kHz
Voltage Range	+20 to –20V
Resolution	12-bit
Frequency Range	Up to few kHz

Table 1: Performance Analysis

Feature	**Proposed ESP32 Oscilloscope**	**Traditional DSO**
Cost	Very Low	Very High
Portability	High (Compact & Lightweight)	Low (Bulky)
Bandwidth	Low (kHz range)	Very High (MHz–GHz)
Sampling Rate	Limited (~100 kSPS)	Very High (MSPS–GSPS)
Display	Web Browser	Built-in Screen
Wireless Capability	Yes (Wi-Fi)	Usually No
Multi-channel	No (Single channel)	Yes
Accuracy	Moderate	High
Customization	High (Open-source)	Low
Ease of Use	Simple	Complex

Fig.4 : Square Waveform

Table 2: Comparison with Traditional Oscilloscopes

Comparison with Traditional Oscilloscope:

Traditional digital storage oscilloscopes (DSOs) offer high bandwidth, accuracy, and multi-channel support, but they are expensive and bulky [5]. In contrast, the proposed ESP32-based oscilloscope is low-cost, compact, and highly portable, making it suitable for educational and field applications [3]. The system enables wireless waveform visualization through a web browser, eliminating the need for dedicated display hardware [14]. However, it is limited by lower sampling rate and bandwidth, restricting its use to low-frequency signals [3]. Additionally, advanced features such as precise triggering and high-resolution measurements are not available. Despite these limitations, the proposed system provides a flexible and cost-effective alternative for basic signal analysis [6].

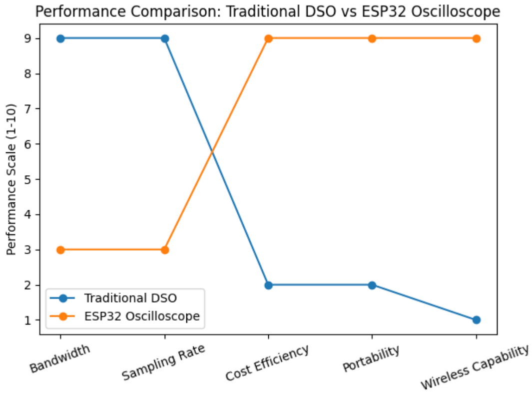

Fig. 5 illustrates the performance comparison

The graph compares key performance parameters between traditional oscilloscopes and the proposed ESP32-based system. Traditional oscilloscopes perform better in terms of bandwidth and sampling rate, while the proposed system excels in cost efficiency, portability, and wireless capability. This highlights the suitability of the ESP32 oscilloscope for low-cost and portable applications.

VI. CONCLUSION

This paper presented the design and implementation of a low-cost, Wi-Fi-enabled digital oscilloscope using the ESP32 microcontroller. The system successfully demonstrates real-time signal acquisition, wireless transmission, and browser-based visualization.

The integration of embedded systems and web technologies provides a flexible and user-friendly solution for signal analysis. Although limited in bandwidth and accuracy, the system is highly suitable for educational purposes, hobby applications, and low-frequency diagnostics.

Future work can focus on improving sampling rate using external ADCs, enabling multi-channel acquisition, and integrating advanced signal processing techniques such as FFT analysis [12].

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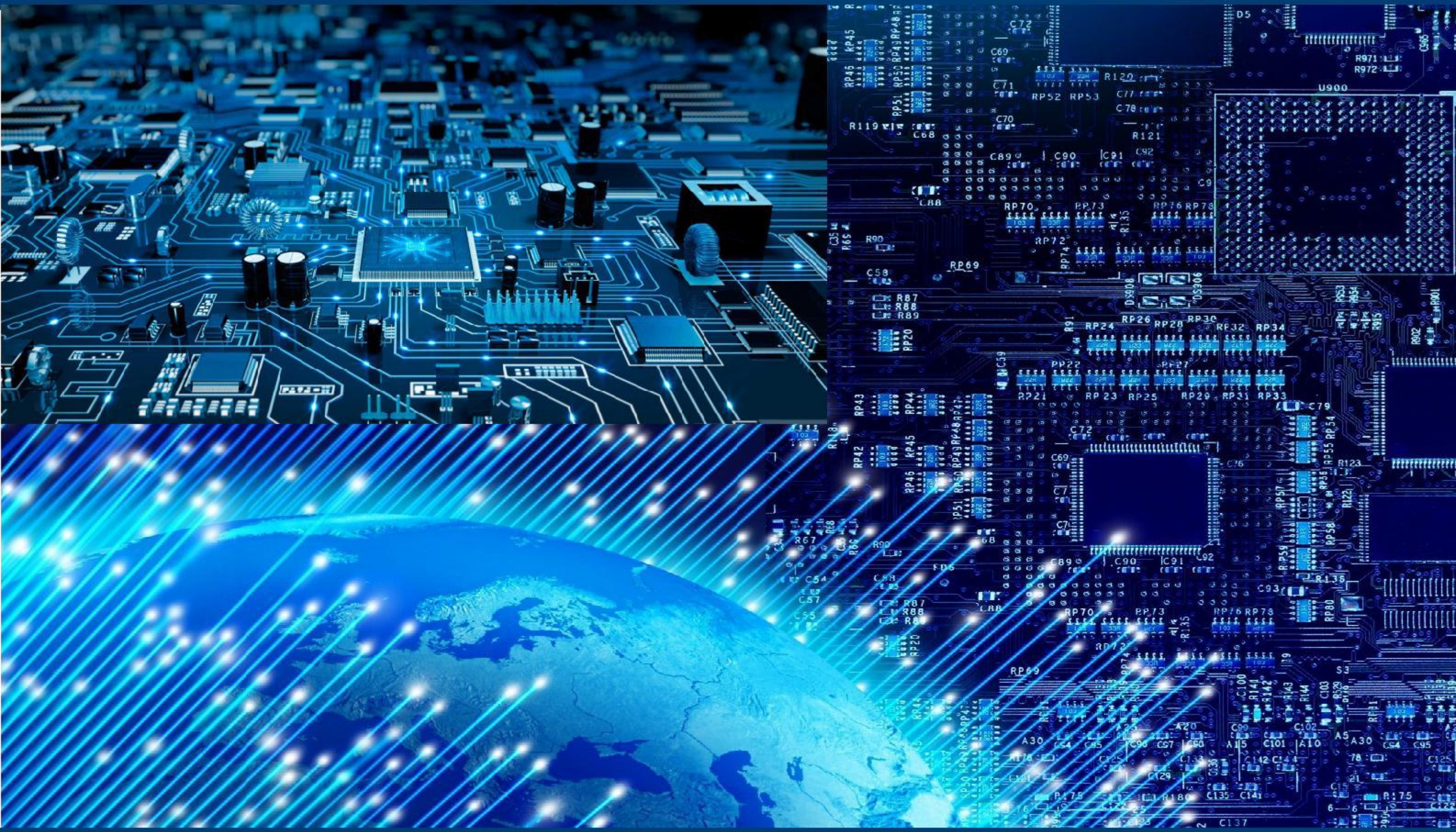

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