Design and Architecture of wireless ECG monitoring system

Alexander Alexandrov[1],
[1 Institute of Robotics, Sofia,
Bulgaria

Abstract— **Portable electrocardiogram (ECG) monitoring systems, such as Holter monitors, have revolutionized the diagnosis and monitoring of cardiovascular diseases. These devices allow for continuous ECG recording over extended periods, making them indispensable in detecting sporadic cardiac abnormalities. One of the most advanced technologies utilized in the development of modern ECG monitors is the developed by Texas Instruments USA chip ADS1293. It is a highly integrated, low-power analog front-end (AFE) specifically designed for multi-channel ECG monitoring.**

This paper presents a comprehensive analysis of the new developed design and architecture based on a Texas Instruments wireless electronic analog front-end device ADS1293. The research covers key aspects of the system, including hardware and software design, signal acquisition, power management, data storage, and communication architecture. The paper also discuss the challenges and considerations involved in designing a reliable, efficient, and user-friendly wireless ECG monitor for long-term remote cardiac monitoring.

Keywords—ECG, wireless, AFE, cardiac monitor

I. INTRODUCTION

A. *Importance of Cardiac Monitoring*

Cardiovascular diseases (CVDs) remain a leading cause of death globally. Continuous monitoring of cardiac activity provides critical information for diagnosing and managing heart conditions. A Holter monitor is a wearable medical device that records the heart's electrical activity (ECG) over an extended period, typically 24 to 48 hours [1]. These devices allow clinicians to detect intermittent arrhythmias or other cardiac anomalies that may not be evident during a standard ECG recording performed in a clinical setting.

B. *Holter Monitor Overview*

Traditional Holter monitors comprise multiple electrodes placed on the chest to measure ECG signals. These signals are stored on the device's internal memory, which is then analyzed by medical professionals.

However, modern advancements in sensor technology, integrated circuits (ICs), and communication methods are enabling more compact, efficient, and precise devices. At the heart of these modern designs is the analog front-end (AFE) IC, responsible for amplifying, filtering, and digitizing the weak bioelectrical signals generated by the heart [2].

C. *ADS1293: A High-Precision AFE for ECG Monitoring*

The ADS1293 is an AFE designed specifically for ECG acquisition and is known for its low power consumption, high resolution, and multiple channels. It integrates essential signal conditioning functions, including low-noise amplifiers, programmable gain amplifiers (PGAs), and analog-to-digital converters (ADCs), into a single chip. With its features, the ADS1293 serves as an ideal solution for implementing Holter monitors that require continuous operation over extended periods with minimal power consumption.

This paper proposes a design and architecture of an autonomous wireless real time ECG monitor built around the ADS1293 analog front-end electronic device, addressing the challenges and solutions involved in developing a compact, low-power, and accurate cardiac monitoring system.

II. THE ROLE OF HOLTER MONITORS IN CARDIAC HEALTH

A. *Monitoring Cardiac Activity*

Holter monitors play a crucial role in diagnosing and managing heart conditions by continuously recording the heart's electrical activity outside clinical settings [3]. Commonly used for detecting arrhythmias, ischemic changes, or silent myocardial infarctions, the Holter monitor provides a more comprehensive picture of a patient's cardiac health [4],[5].

B. *Limitations of Traditional ECG Methods*

While a standard 12-lead ECG is the gold standard for cardiac diagnosis, it is only a snapshot of the heart's activity at a given moment. Many cardiac events, such as paroxysmal arrhythmias, are transient and may not be detected during a brief clinical examination. ECG monitors overcome this limitation by providing long-term, continuous ECG monitoring. However, traditional Holter monitors have drawbacks, such as size, limited battery life, local ECG data storage and patient discomfort [6],[7].

C. *Requirements for Modern autonomous ECG Monitors*

Modern autonomous wireless real time ECG monitors must meet several technical and ergonomic requirements:

- Low Power Consumption: To ensure long-term use without frequent recharging or battery replacement.
- Compact Size and Lightweight Design: For patient comfort and ease of wear.
- High Signal Fidelity: To capture accurate ECG signals that can be used for reliable diagnosis.
- Multi-Channel Recording: To capture signals from multiple leads, providing more comprehensive data.
- Wireless Communication: For real-time data transmission and remote monitoring.
- Data Storage: Sufficient capacity to store high-resolution ECG data over the monitoring period.
- Reliable wireless communication to send real time data to the medical control center.
- Local or remote based Machine Learning analytical system to automate typical ECG disfunctions.

The ADS1293 addresses many of these needs with its low power, multi-channel design, and integrated signal conditioning[8],[9].

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III. The Architecture of the ADS1293

Overview of the ADS1293

The ADS1293 is an AFE designed specifically for ECG applications. It integrates the key elements required for ECG signal acquisition, including three channels for simultaneous measurement, internal low-noise programmable gain amplifiers (PGA), and a 24-bit delta-sigma analog-to-digital converter (ADC).

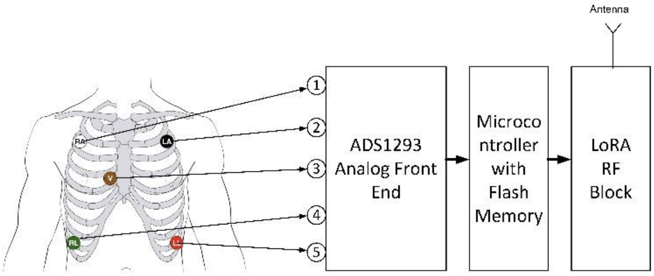


Fig. 1 Typical usage of ADS1293 based ECG monitor

These features allow the ADS1293 to accurately amplify and digitize weak bioelectrical signals from the heart.

The Key features of the ADS1293 include:

- Three ECG Channels: Each channel supports high-precision measurement with programmable gain settings.
- Low Power Consumption: Optimized for battery-powered wearable devices.
- Integrated Signal Processing: Includes filters and amplifiers to condition raw ECG signals.
- Digital Interface: A standard serial peripheral interface (SPI) for communication with external microcontrollers.

A. *Internal Architecture*

The internal architecture of the ADS1293 consists of several key blocks shown on Fig.2

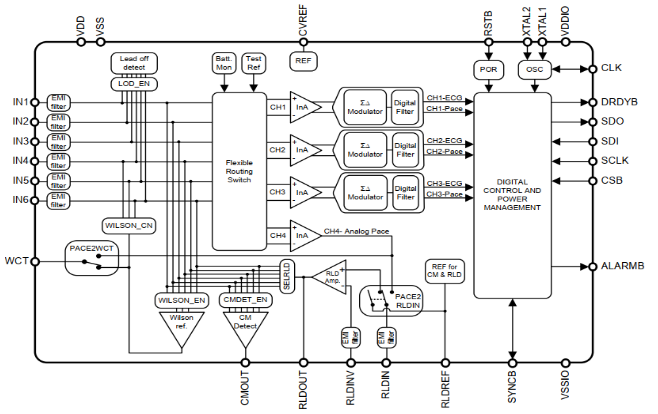


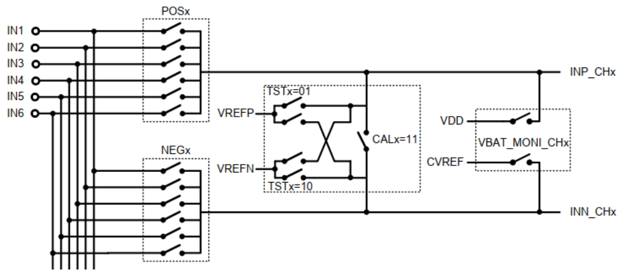
Fig.2 Functional Block Diagram of TI ADS1293

1) *Input Multiplexer*

The ADS1293 features a fully differential input multiplexer that allows it to connect to different electrodes and channels. It supports a variety of electrode configurations, including three-electrode and five-electrode setups, which are common in autonomous ECG monitoring.

On the Fig.3 is shown the switch path for a single channel. All channels are completely identical. The switches are controlled by the registers FLEX_CH1_CN, FLEX_CH2_CN, FLEX_CH3_CN, and FLEX_VBAT_CN, which are described in the Input Channel Selection Registers.

Fig.3 ADS1293 Input Mult9plexer functional design



2) *Programmable Gain Amplifier (PGA)*

The weak signals from the heart are first amplified by a programmable gain amplifier. The ADS1293 offers multiple gain settings to accommodate different signal amplitudes, ensuring that the digitization process is both accurate and efficient. The PGA provides a high input impedance to interface with signal sources that may have relatively high output impedance, such as ECG electrodes. The maximum differential input voltage range of the Sigma-Delta Modulator (SDM) behind the PGA is ±1.4 V, and the gain of the PGA is 3.5x. Therefore, the maximum differential input voltage of the PGA is ±400 mV.

3) *Sigma-Delta Modulator (SDM)*

The amplified signal is then fed into the integrated 24-bit sigma-delta Analog to Digital Converter (ADC). The high resolution of the ADC ensures that even subtle features of the ECG waveform are captured with precision. This is critical for identifying small, transient cardiac events.

The Sigma-Delta Modulator (SDM) takes the output signal of the PGA and converts this signal into a high resolution bit stream that is further processed by the digital filters.

The SDM can operate at clock frequencies of 102.4 kHz or 204.8 kHz; these frequencies are generated internally. Running the SDM at 204.8 kHz results in a larger oversampling ratio, which improves the resolution of the signal recovered by the digital filters behind the SDM. However, running the SDM at a higher clock frequency will increase its power consumption, resulting in a tradeoff between resolution and power consumption.

The 102.4-kHz or 204.8-kHz clock frequency can be selected for each channel individually by programming the FS_HIGH_CHx bits in the AFE_RES register. The SDM also features dithering to reduce tones in the system, a known by-product of Sigma-Delta converters. The dithering circuit is active by default and is automatically turned OFF when the input signal is larger than 40 mV.

4) *On-Chip Filters*

To remove noise and unwanted signal components, the ADS1293 includes several filters, such as a high-pass filter for removing baseline drift and a low-pass filter for eliminating high-frequency noise. These filters help to ensure that the digitized ECG signal is clean and suitable for further analysis. A programmable digital filters behind the Sigma-Delta Modulator (SDM) reconstructs the signal from the SDM output bit stream. The filter up consist of three programmable SINC filters as shown in Figure 4.

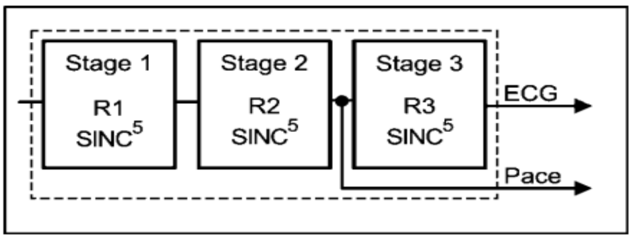


Fig.4 ADS1293 On-chip SINC Filters

The decimation rates (R1, R2, and R3) of the SINC filters are programmable. Each of the three stages further filters and decimates the bit stream so that the output data rate (ODR) and bandwidth (BW) of the signal is reduced, and at the same time, the resolution is enhanced. A 16-bit digital signal with relatively high ODR and BW, but with somewhat limited resolution, is available after the second stage; this signal can be used for PACE pulse detection. That signal is further decimated by the third stage and results in a very high-resolution filtered 24-bit digital signal that is an accurate representation of the ECG signal.

5) Power Management

The ADS1293 has many features that allow the optimization of power consumption. The common-mode detector and right-leg drive amplifier can be configured to achieve the optimum AC performance to power consumption ratio in a given application environment. Almost all internal circuit blocks can be powered down to reduce power consumption. The ADS1293 drawing less than 300 µA during normal operation. This makes it ideal for portable devices like autonomous ECG monitors, where power efficiency is paramount.

IV. System Design of ADS1293-Based Autonomous Monitor

Design of autonomous wireless real time ECG Monitor

A typical autonomous ECG monitor system includes several key components in addition to the ADS1293, including electrodes, microcontroller, data storage, wireless communication module, and a power management system. These components must work together seamlessly to provide continuous, accurate, and reliable ECG monitoring.

1) Electrodes

The electrodes are responsible for capturing the bioelectrical signals generated by the heart. These signals are then transmitted to the ADS1293 for amplification and digitization. The quality of the electrodes and their placement on the body are crucial for obtaining accurate ECG data.

2) Microcontroller

The microcontroller serves as the central processing unit of the ECG monitor system. It interfaces with the ADS1293 through a standard serial peripheral interface (SPI) to receive digitized ECG data. The microcontroller also handles data storage, communication, and user interface tasks.

3) Data Storage

Since autonomous ECG monitors record ECG data over extended periods, they require sufficient storage capacity. Typically, a microSD card or onboard flash memory is used to store the digitized ECG signals. Data compression techniques can also be employed to reduce the amount of storage required without sacrificing signal quality.

4) Power Management

A crucial aspect of the design is the power management system, which ensures that the device can operate continuously for 24-48 hours on a single battery charge. Low-power components, including the ADS1293 and energy-efficient microcontrollers, are essential for achieving this goal. Rechargeable lithium-ion batteries are commonly used, and power-saving techniques, such as sleep modes, are implemented to conserve energy during periods of inactivity.

5) Wireless Communication

In proposed design of autonomous real time ECG monitor, wireless communication is incorporated to enable real-time data transmission and remote monitoring. The communication protocols include Bluetooth Low Energy (BLE) and Wi-Fi. These technologies will allow healthcare providers to monitor a patient's ECG data remotely, providing faster response times in case of an emergency.

The prototype block diagram of the ADS1293 based autonomous wireless ECG monitor is shown on Fig. 5

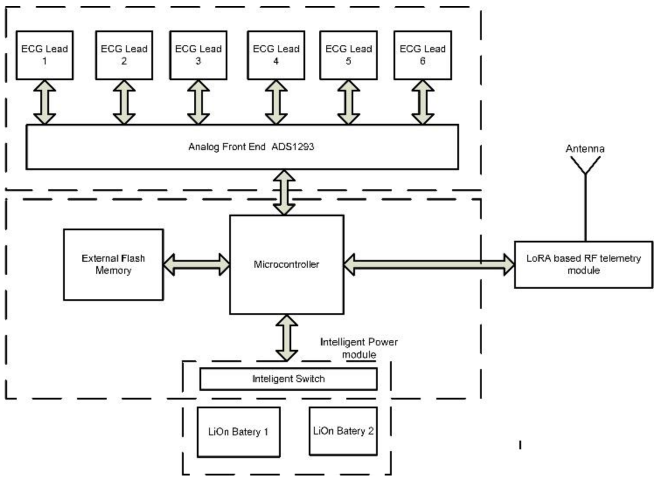


Fig.5 Block diagram of the ADS1293 based autonomous wireless ECG monitor

The prototype of the ADS1293 based autonomous wireless ECG monitor is shown on Fig 6

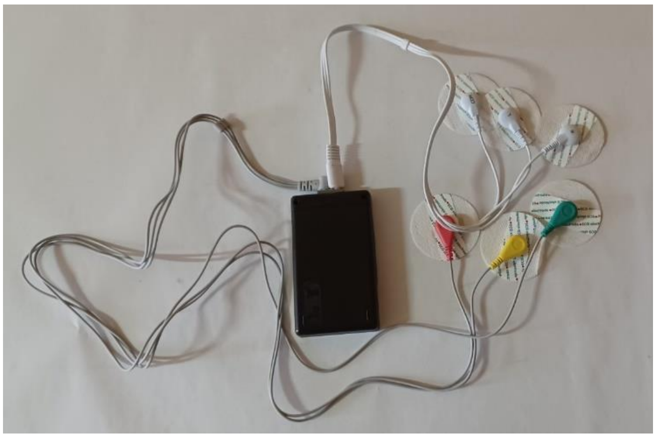


Fig.6 prototype of the ADS1293 based autonomous wireless ECG monitor

B. Signal Acquisition and Processing

1) ECG Signal Acquisition

The ECG signal is captured by the electrodes and fed into the ADS1293. The ADS1293 amplifies and digitizes the signal, with the programmable gain amplifier (PGA) ensuring that the signal is properly conditioned for conversion by the 24-bit ADC. The digitized signal is then sent to the microcontroller for further processing.

2) Signal Processing and Filtering

The ADS1293 includes built-in filtering to remove baseline drift and high-frequency noise from the ECG signal. However, additional digital filtering can be implemented in the microcontroller to further refine the signal. For example, a moving average filter can be used to smooth the ECG waveform, while a notch filter can be used to remove 50/60 Hz power line interference.

3) Detection of Cardiac Events

The processed ECG signal is transmitted to a remote server for analysis. Algorithms can be implemented to detect specific cardiac events, such as arrhythmias, premature ventricular contractions (PVCs), or ST-segment deviations. The servers receiving real time data from the ECG monitors may also incorporate machine learning models to improve the accuracy of event detection.

V. 5. Power Management Considerations

A. Low-Power Design

One of the primary design challenges for the proposed design of the ECG monitor is ensuring that it can operate for extended periods on a limited power source. The ADS1293 is designed with low power consumption in mind, drawing less than 300 µA during normal operation. However, additional strategies are needed to optimize the overall power efficiency of the system.

B. Sleep Modes and Power Gating

The embedded in the ECG monitor microcontroller and LoRA wireless communication modules support low-power sleep modes, which significantly reduce power consumption during periods of inactivity. By implementing an intelligent power management system that dynamically switches between active and sleep modes, the overall energy efficiency of the autonomous ECG monitor is improved significantly.

1) Battery Selection

Two rechargeable lithium-ion batteries are used due to their high energy density and low self-discharge rate. The battery capacity is carefully selected to ensure that the autonomous ECG monitor can operate continuously for at least 120 hours without need to stop sending data.

2) Power Supply Regulation

The ADS1293 based wireless ECG monitor uses two LiON batteries intelligently managed by custom design power switch. Low-dropout (LDO) regulators is implemented to provide a clean, regulated voltage to the all the modules part of the ECG monitor. The efficiency of the power supply system plays a critical role in determining the overall power consumption of the device.

VI. Data Storage and Communication

A. Onboard Data Storage

Autonomous ECG monitors require sufficient onboard storage to record ECG data continuously for extended periods. The ADS1293 produces high-resolution data, which can lead to large storage requirements. Data compression algorithms, such as run-length encoding (RLE) or differential pulse code modulation (DPCM), can be implemented to reduce the storage footprint without compromising signal quality.

B. Wireless Communication

Modern autonomous ECG monitors often include wireless communication capabilities, such as Bluetooth Low Energy (BLE) or Wi-Fi, to enable real-time data transmission and remote monitoring.

BLE is preferred for low-power applications, while Wi-Fi is suitable for higher-bandwidth communication. A key consideration is the trade-off between power consumption and communication range, as wireless modules can be power-hungry.

1) Bluetooth Low Energy (BLE)

BLE is widely used in wearable medical devices due to its low power consumption and short-range communication capabilities. BLE can be used to transmit ECG data to a nearby smartphone or tablet, which then forwards the data to a remote server for analysis.

2) Wi-Fi

For autonomous ECG monitors that require long-range communication, Wi-Fi can be used to transmit data directly to a remote server. However, Wi-Fi modules consume more power than BLE, so they must be used sparingly to avoid depleting the device's battery.

3) LoRa

The autonomous wireless ECG monitors can implement also the LoRA based standard and communication protocol.

LoRa is long range, low power platform. The LoRa wireless modules are highly integrated and cost-effective, boasting a notable battery life of up to 5 years, a 3- kilometer range in urban environments and around 20-kilometer range outdoors.

VII. 7. Challenges and Future Directions

A. Noise and Interference

One of the biggest challenges in designing a autonomous ECG monitor is dealing with noise and interference. The ECG signals are very weak, making them susceptible to interference from external sources such as power lines, muscle artifacts, and motion artifacts. While the ADS1293 includes several features to minimize noise, additional filtering and signal processing techniques are needed to ensure accurate signal acquisition.

B. Miniaturization

As the demand for smaller, more discreet autonomous ECG monitors increases, there is a need to further miniaturize the components. The ADS1293 already integrates many functions into a single chip, reducing the overall size of the device. However, continued advancements in microelectronics and packaging technologies will be required to make even smaller and more comfortable autonomous ECG monitors.

C. Integration of AI and Machine Learning

With the increasing availability of powerful microcontrollers and cloud-based computing platforms, there is growing interest in integrating artificial intelligence (AI) and machine learning (ML) algorithms into autonomous ECG monitors [10]. These algorithms can analyze ECG data in real-time, identifying patterns that may indicate cardiac abnormalities. AI and ML could improve the accuracy and efficiency of cardiac event detection, reducing the burden on healthcare providers [11],[12].

D. Extended Battery Life

Although modern autonomous ECG monitors can operate for 24-48 hours on a single charge, there is a growing need for longer battery life. In the proposed design this is achieved through by intelligent power management and two LiON battery farm.

VIII. Conclusion

The autonomous ECG monitors represents a significant advancement in wireless portable cardiac monitoring technology. By integrating high-precision signal acquisition, low power consumption, and multiple ECG channels into a single chip, the proposed hardware design based on ADS1293 enables the development of compact and efficient autonomous ECG monitors that can provide continuous real time ECG monitoring for longer periods. The proposed design and architecture of the ADS1293 AFE based, combined with low power microcontrollers, LoRa based wireless communication technology, and embedded data storage solutions, make it an perspective choice for next-generation autonomous ECG monitors.

As technology continues to evolve, future improvements of the proposed design of the autonomous wireless real time ECG monitor will incorporate features such as AI-driven event detection and smaller form factor.

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