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Secure and Resource-Efficient MIMO-OFDM-Based Wireless ECG Transmission Using Lightweight Cryptography on Spartan-6 FPGA

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Abstract:

Secure transmission of Electrocardiogram (ECG) signals is critical in modern health monitoring systems, where protecting patient confidentiality and ensuring data integrity are essential. This study presents a hardware-efficient approach that integrates Lightweight Cryptography (LWC) with a Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) framework to protect ECG signal transmission. The proposed method leverages minimal logic resources and a simplified key schedule to achieve robust security with low computational overhead. To further improve reliability, turbo coding is applied to combat burst errors and Inter-Symbol Interference (ISI) inherent in wireless channels.

Performance evaluation of the LWC-MIMO-OFDM system is carried out using ECG signals from the MIT Arrhythmia Database, with implementation and testing on a Spartan-6 FPGA platform. Results demonstrate the effectiveness of the proposed architecture in terms of area utilization, latency, power efficiency, and overall security performance, making it suitable for secure biomedical applications.

Keywords: *Lightweight Cryptography, MIMO-OFDM, ECG Transmission, Health Monitoring, Turbo Coding, Data Security, FPGA Implementation.*

1. Introduction

MIMO-OFDM has established itself as a fundamental technology in advanced wireless communication due to its ability to deliver high data rates and improved performance across a variety of fading environments. By employing multiple antennas at both the transmitter and receiver, MIMO systems significantly enhance throughput when compared to traditional single-input single-output (SISO) systems.

The combination of MIMO with Orthogonal Frequency Division Multiplexing (OFDM) harnesses the latter's ability to handle flat fading through narrowband subcarriers, thereby reducing interference and enabling efficient multi-user access [1, 2]. Key components of OFDM, such as the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT), are essential for implementing flexible and scalable signal processing architectures, particularly in MIMO-OFDM-based communication platforms [3, 4]. In time-varying and frequency-selective environments, precise channel estimation is essential, as it provides both spatial and frequency diversity—critical for maintaining spectral efficiency [5]. Synchronization of frequency across multiple receivers is also crucial to maintain data integrity. Approaching the theoretical capacity of MIMO channels relies on the use of capacity-approaching codes, which are often supported by advanced decoding algorithms like turbo decoders at the receiver end [6, 7]. Furthermore, the secure transmission of biomedical signals, particularly ECG data, has become increasingly important. The implementation of dynamic binary key streams ensures encrypted, secure communication—an essential requirement in real-time healthcare monitoring systems [8, 9].

This study delivers a consolidated analysis of MIMO-OFDM enhancements for high-performance wireless communication, with a specific focus on the secure and efficient transmission of ECG signals using lightweight cryptographic methods in healthcare environments [10, 11].

2. METHODS AND MATERIAL

This section outlines the architectural design, signal processing techniques, cryptographic integration, and hardware implementation used to develop the proposed secure MIMO-OFDM system for ECG signal transmission. The proposed system integrates Lightweight Cryptography (LWC) into a MIMO-OFDM wireless communication framework for secure and efficient transmission of Electrocardiogram (ECG) signals. The system is designed to operate under typical wireless channel conditions, including multipath fading and noise, and aims to ensure data integrity, confidentiality, and robustness.

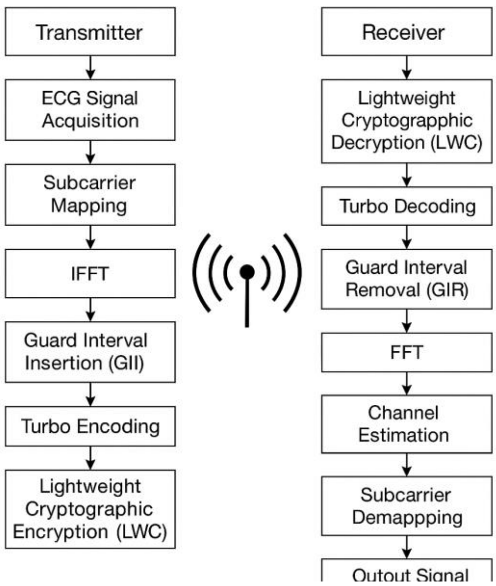

Figure 1: MIMO-OFDM ECG transmission block diagram

Figure 1 illustrates a secure wireless system for transmitting ECG signals using a MIMO-OFDM architecture enhanced with turbo coding and lightweight cryptography. At the transmitter side, ECG signals are first acquired and digitized. These signals are then modulated and mapped onto OFDM subcarriers, followed by the insertion of pilot symbols to facilitate channel estimation at the receiver. The mapped data undergoes an Inverse Fast Fourier Transform (IFFT) to convert it from the frequency domain to the time domain. A guard interval is inserted to mitigate inter-symbol interference (ISI), and turbo encoding is applied to improve error correction capability. To ensure data confidentiality, a lightweight cryptographic algorithm encrypts the encoded signal before wireless transmission.

The encrypted OFDM signals are transmitted through a MIMO wireless channel that employs multiple antennas at both the transmitter and receiver ends to exploit spatial diversity and increase data throughput. he behavior of this MIMO channel is mathematically represented by the equation

$$Y = H \cdot X + N$$

where

Y is the received signal matrix,

X is the transmitted signal matrix,

H is the channel matrix, and

N represents additive noise. This equation forms the foundation of signal detection and recovery in the MIMO system.

At the receiver, the signal is first decrypted using the corresponding lightweight cryptographic key. Turbo decoding is then applied to correct any transmission errors. The guard interval is removed, and the signal is transformed back to the frequency domain using the Fast Fourier Transform (FFT). Channel estimation is performed using the pilot symbols, allowing compensation for channel distortions. The subcarriers are demapped to retrieve the original data, and the ECG signal is reconstructed for further medical analysis. This integrated approach ensures secure, reliable, and efficient wireless transmission of biomedical signals in real-time healthcare applications.

3. RESULTS AND DISCUSSION

The study presents the implementation and simulation of a secure and efficient method for wireless Electrocardiogram (ECG) signal transmission, utilizing MIMO-OFDM technology enhanced with LWC. MATLAB was used for ECG signal capture and preprocessing, while Xilinx 14.4 software was used for the implementation. ECG datasets sourced from the MIT arrhythmia database provided a diverse range of signals for analysis.

An examination of 4x4 MIMO-OFDM setup is used to transmit secure signals. In particular, the proposed technique is examined, which uses four sending and four receiving antennas for communication. The performance of this proposed technique is evaluated using three different FPGA devices: Virtex 4 Virtex 5 and Spartan 6,. A number of metrics are examined in order to evaluate the LWC-MIMO-OFDM technique, including slice registers, slice LUTs (Look-Up Tables), slices, frequency, and latency. These metrics provide insights into the resource utilization, computational efficiency, and overall performance characteristics of the system when implemented on the selected FPGA devices. By analyzing slice registers and slice LUT, the utilization of key FPGA resources for storing and processing data is determined. The number of slices utilized offers a measure of the overall FPGA resource consumption. Additionally, the operating frequency of the system and the associated delays provide crucial information regarding the system's speed and responsiveness.

Through this comprehensive evaluation across different FPGA platforms, the effectiveness and feasibility of the LWC-MIMO-OFDM method can be assessed, aiding in the selection of the most suitable FPGA device for practical deployment and optimizing system performance.

Table 1. Hardware utilization of Spartan 6 FPGA.

Parameters	Available resources	Occupied resources	% of utilization
Slice LUT	5720	1659	29%
Slice registers	11440	378	3%
Slices	1430	577	40%

Table 2. Hardware utilization of Virtex 4 FPGA.

Parameters	Available resources	Occupied resources	% of utilization
Slices	5472	938	17%
Slice LUT	10944	1622	14%
Slice registers	10944	396	3%

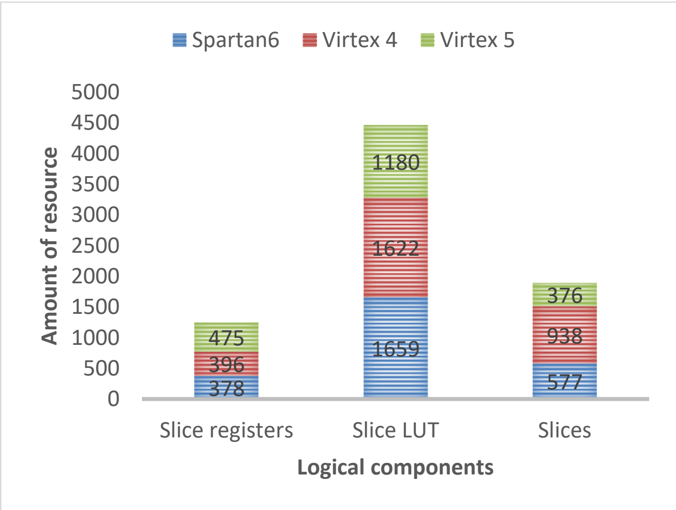

Figure 2. Graphical illustration of Hardware utilization

The hardware utilization of the LWC-MIMO-OFDM technique for various FPGA devices, including the Spartan 6, Virtex 4, and Virtex 5, is displayed in Tables 2, 3, and 4. Next, Figure 4 displays the resource usage for Spartan 6, Virtex 4, and Virtex 5. The Spartan 6, Virtex 4, and Virtex 5 employ 378, 396, and 475 slice registers, in that order. According to the analysis, the Virtex 4 uses 938 slices, which is more than the Spartan 6 and Virtex 5 combined. The hardware consumption investigation reveals that the secure ECG signal transfer with LWC implementation utilizes little resources.

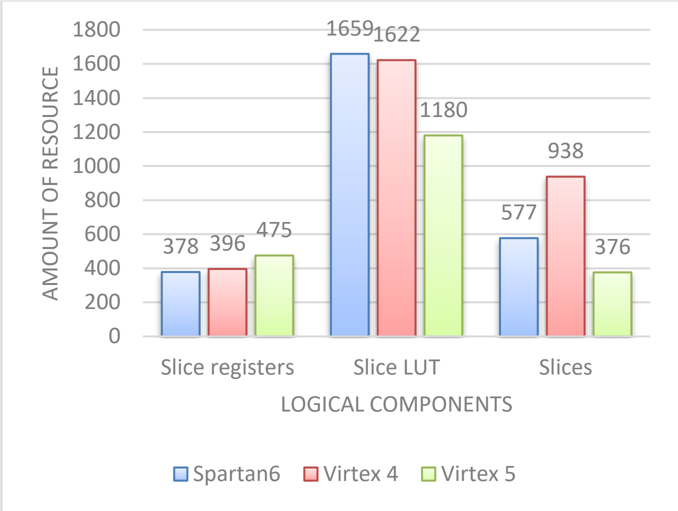

Figure 3. Graphical illustration of Hardware utilization

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4. CONCLUSION

This work presents a secure and efficient architecture for wireless ECG signal transmission using a MIMO-OFDM system integrated with turbo coding and lightweight cryptography. The proposed design ensures both the reliability and confidentiality of biomedical data, which is crucial in healthcare monitoring applications. By employing turbo codes, the system effectively mitigates transmission errors caused by multipath fading and inter-symbol interference. The integration of lightweight cryptographic algorithms enhances data security without imposing significant resource overhead, making the solution suitable for real-time FPGA-based implementation. The hardware realization on a Spartan-6 FPGA demonstrates the feasibility of the proposed system in terms of area utilization, latency, and power consumption. Overall, the approach provides a robust framework for secure and high-performance ECG signal transmission, contributing to the advancement of telemedicine and wireless health monitoring technologies. Future work may explore optimization techniques for power efficiency and the integration of more advanced cryptographic schemes to further enhance data protection in dynamic wireless environments.

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