

Development and Diagnostic Performance Evaluation of A Wireless Digital Fetal Heart Rate Monitoring System Using Ultrasonic Doppler with Digital Filter-Based Noise Reduction

Muhammad Ridha Mak'ruf¹, Roichatun Nashichah², Lusiana³, Verry Angriawan⁴
^{1,2,3,4} Department of Medical Electronics Technology, Poltekkes Kemenkes Surabaya, Surabaya, Indonesia

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ABSTRACT

Early fetal heart rate (FHR) monitoring is essential for assessing fetal well-being and enabling the early detection of fetal distress during pregnancy. However, existing fetal Doppler systems commonly rely on wired communication and remain susceptible to signal noise, limiting monitoring flexibility and measurement reliability. This study aimed to develop and evaluate a wireless fetal heart rate monitoring system with enhanced signal quality and reliable real-time communication. The proposed system integrates an ultrasonic Doppler sensor, ESP32 microcontrollers communicating through the ESP-NOW protocol, and digital signal processing using a Butterworth low-pass filter and a smoothing algorithm to suppress noise and improve signal clarity. System performance was evaluated using sampling frequencies ranging from 200 to 1000 Hz and baud rates from 300 to 250,000 bps. Communication reliability was assessed by transmitting 1,500 ADC packets for each sampling-frequency configuration and 1,000 ADC packets for each baud-rate configuration while monitoring packet sequence numbers to identify transmission loss. Experimental results showed that no packet loss was observed under all tested configurations. The developed system achieved BPM measurement errors ranging from 0.56% to 0.89% and improved signal quality, with the highest signal-to-noise ratio of 18.70 ± 0.17 dB obtained using a 0.5–20 Hz Butterworth filter. Higher sampling frequencies produced more detailed waveform representations, whereas higher baud rates improved transmission responsiveness without affecting waveform integrity within the tested range. These findings demonstrate that the proposed system provides an accurate, reliable, and portable solution for real-time wireless fetal heart rate monitoring.



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Corresponding Author:

Muhammad Ridha Mak'ruf

Department of Medical Electronics Technology, Poltekkes Kemenkes Surabaya, Surabaya, Indonesia

Email: ridha@poltekkes-surabaya.ac.id

1. INTRODUCTION

Fetal heart rate (FHR) is one of the most important physiological indicators used to assess fetal well-being during pregnancy. Continuous and accurate FHR monitoring enables early detection of fetal abnormalities and distress, thereby supporting timely clinical intervention. Despite advances in maternal

healthcare, infant and perinatal mortality rates remain relatively high in many developing countries, including Indonesia [1][2]. A considerable proportion of neonatal deaths is associated with delayed identification and management of fetal complications. Therefore, reliable FHR monitoring systems are essential for improving prenatal care and supporting preventive healthcare strategies. The availability of monitoring devices that are accurate, responsive, and convenient to use is increasingly important in both healthcare facilities and home-based monitoring environments[3][4].

Fetal Doppler technology is widely utilized for fetal heartbeat detection by employing the Doppler effect to capture blood flow movement in the fetal heart and convert it into audible signals [5][6][7]. Various studies have developed fetal monitoring systems using microcontroller-based platforms to improve portability and reduce system complexity [8][9]. Signal amplification circuits and display modules have been integrated into these systems to provide real-time fetal heart rate information. Furthermore, recent developments have introduced wireless communication technologies and digital signal processing methods to enhance data transmission efficiency and signal quality [10][11]. These advancements have contributed to the development of more practical and accessible fetal monitoring systems.

However, several limitations remain unresolved in existing fetal Doppler monitoring systems. Many systems still rely on wired communication, which restricts user mobility and reduces monitoring flexibility[12], [13], [14]. In addition, beats-per-minute (BPM) measurements may become unstable due to noise contamination and inadequate signal processing techniques [1], [15], [16]. Environmental interference, electromagnetic disturbances, and motion artifacts generated by body movement can further degrade signal quality and reduce measurement reliability [17][18]. Consequently, there is a need for a fetal monitoring system that provides reliable wireless communication, improved signal quality, and stable real-time BPM measurements[19].

To address these limitations, this study proposed a wireless fetal Doppler monitoring system integrated with digital signal processing techniques. The system utilized ESP32 microcontrollers and the ESP-NOW communication protocol to enable fast and efficient wireless data transmission without requiring Wi-Fi infrastructure. Fetal heart rate signals acquired from the Doppler sensor were processed using a digital low-pass filter and a smoothing algorithm to suppress noise and improve signal clarity[16]. By combining wireless communication and digital filtering, the proposed system was expected to enhance both transmission reliability and measurement accuracy.

This study aimed to develop and evaluate a wireless fetal Doppler-based fetal heart rate monitoring system capable of providing reliable real-time signal acquisition, wireless transmission, and improved signal quality. Unlike previous fetal Doppler systems, which primarily focused on either wireless communication or signal processing separately, the proposed system integrates ESP-NOW-based wireless communication with digital signal processing using a Butterworth low-pass filter and a smoothing algorithm within a single real-time monitoring platform. In addition, this study provides a comprehensive performance evaluation by investigating the effects of baud rates (300–250,000 bps) and sampling frequencies (200–1,000 Hz) on communication reliability and signal quality. The proposed system was further validated using a fetal simulator through packet transmission analysis, BPM measurement accuracy, and signal-to-noise ratio.

2. RESEARCH METHOD

Research Methods: This study employed a research and development approach to design and evaluate a wireless digital fetal heart rate (FHR) monitoring system based on the ultrasonic Doppler method. The system consisted of a Doppler ultrasound sensor, signal conditioning circuit, digital noise reduction filter, and ESP32-based wireless communication modules for real-time data transmission. The acquired Doppler signals were processed using digital filtering techniques to reduce noise and motion-related artifacts before fetal heart rate extraction. System performance was evaluated through experimental testing using multiple fetal heart rate conditions. The measured FHR values were compared with reference values to determine measurement accuracy. Communication performance was assessed by analyzing transmission reliability, baud rate stability, packet delivery, and communication range. Signal quality was evaluated based on waveform clarity and noise suppression effectiveness.

Sampling frequency analysis was also conducted to determine its influence on BPM measurement accuracy and real-time monitoring performance. The collected data were analyzed quantitatively using percentage error and transmission success rate metrics to assess the overall effectiveness of the proposed system. Wireless communication performance was evaluated by transmitting 1,000 ADC packets for each baud-rate configuration (300–250,000 bps). Each experiment was conducted for 30 s in an indoor laboratory environment with transmitter–receiver separation distances of 1 m and 3 m under line-of-sight conditions. Packet loss was determined by comparing the sequence numbers of transmitted and received packets at the end of each transmission session.

2.1. Dataset

This study aims to evaluate the effectiveness of a wireless fetal Doppler system in improving the accuracy and reliability of fetal heart rate monitoring data, particularly for clinical decision-making applications. By analyzing the performance and limitations of the proposed system, this research is expected to provide an effective solution for minimizing data loss, thereby enhancing safety and efficiency in practical use. Furthermore, this study aims to ensure that innovations in fetal monitoring technology not only emphasize portability and ease of use, but also maintain high standards of data accuracy and transmission reliability, as illustrated in Figure 1.

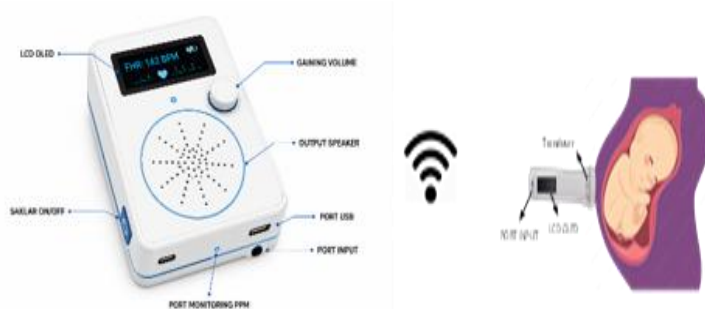


Figure 1. Implementation of fetal heart rate (FHR) monitoring using a wireless fetal doppler with FHR sound enhancement and digital filter for noise reduction

During the system design process, a piezoelectric sensor was used to detect fetal heart rate signals, while an ESP32 microcontroller served as the main processing unit. The measurement results were displayed on an OLED screen. To ensure accurate BPM measurements, system calibration was performed using a fetal simulator with predefined BPM variations. Data observations were conducted by comparing the BPM values obtained from the transmitter and receiver units to evaluate data consistency. The system was tested under five BPM conditions, namely 60, 90, 120, 150, and 180 BPM. Furthermore, data loss analysis was carried out by comparing ADC values between the transmitting and receiving units to determine the presence of any mismatch or information loss during wireless data transmission under different sampling frequency and baud rate configurations.

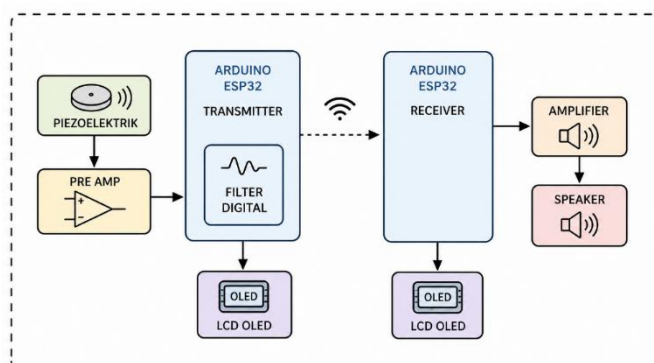


Figure 2. Block diagram of wireless fetal doppler with Djj Voice Enhancement and digital filter for noise reduction

Figure 2 shows a block diagram of the system that starts with a piezoelectric transducer attached to the pregnant woman's abdomen. This transducer functions to send ultrasonic waves into the body, which

are then reflected by the fetal heart and received back as reflected waves. These reflected waves are converted into electrical signals, then processed by a demodulator circuit to extract the information signal from the carrier signal. After that, the signal is amplified using a pre-amplifier circuit, converted from analog to digital, then digitally filtered to remove noise. Furthermore, the signal that has been processed by the ESP32 microcontroller on the sending side is converted into BPM data and displayed on the OLED screen. The BPM data is also sent wirelessly to the receiving ESP32 to be displayed again for comparison. In addition, the data is converted back into an analog signal, amplified using the main amplifier, and finally output through the speaker as an audio signal.

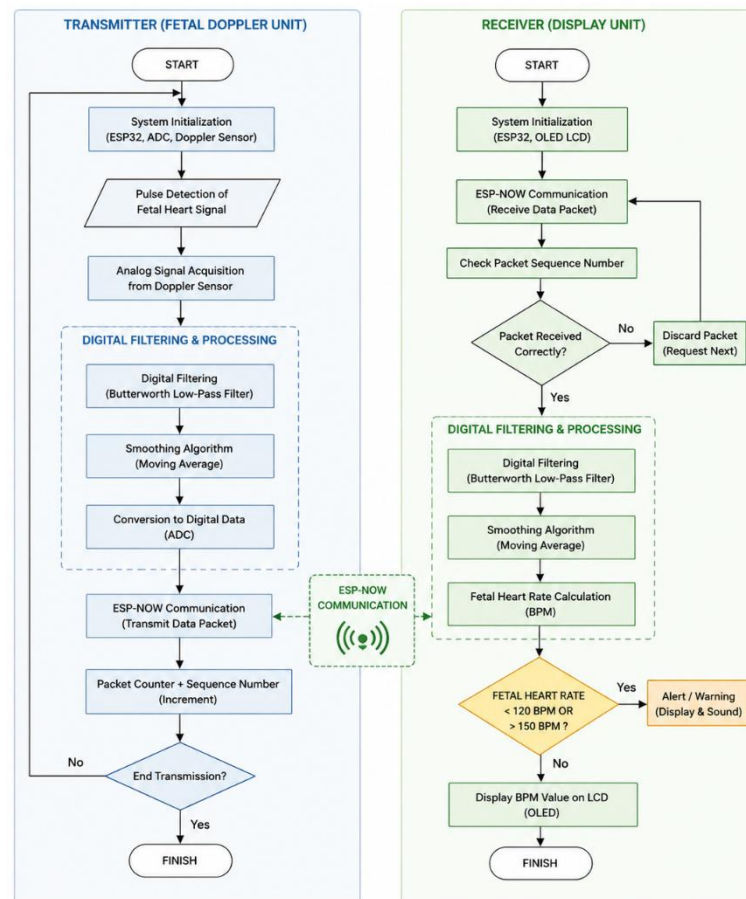


Figure 3. Flowchart of the ESP-NOW-Based wireless fetal heart rate monitoring system

Figure 3 illustrates the operational flow of the proposed wireless fetal heart rate monitoring system, which consists of separate transmitter and receiver processes. The process begins when the Doppler transducer is placed on the pregnant woman's abdomen to acquire fetal heart signals. In the transmitter unit, the ESP32 is initialized, and the analog Doppler signal is acquired and converted into digital data through the analog-to-digital converter (ADC). The acquired signal is then processed using a Butterworth low-pass filter followed by a smoothing algorithm to suppress noise and improve signal quality. The processed digital data are subsequently transmitted wirelessly to the receiver unit using the ESP-NOW communication protocol. At the receiver side, the received data are used to calculate the fetal heart rate in beats per minute (BPM). The calculated BPM value is compared with the predefined normal range (120–160 BPM). If the measured value falls outside this range, the system identifies the condition as abnormal; otherwise, it is considered normal. Finally, the BPM value is displayed on the OLED LCD for real-time monitoring.

2.2. Data Processing

The acquired fetal heart rate (FHR) data were analyzed offline to evaluate the performance of the proposed wireless monitoring system. For each fetal simulator setting (60, 90, 120, 150, and 180 BPM),

six repeated measurements were performed to assess the accuracy and repeatability of the system. The measured BPM values obtained from the receiver unit were compared with the corresponding reference values provided by the fetal simulator.

The arithmetic mean of the repeated measurements was calculated using Equation (1):

$$\bar{x} = \frac{X_1 + X_2 + \dots + X_n}{n} \quad (1)$$

where $\bar{x}$ is the average of the measured BPM values, X_i represents each individual measurement, and n is the total number of measurements.

The percentage error between the measured BPM and the simulator reference value was calculated using Equation (2):

$$\text{Error \%} = \frac{BPM_{ref} - BPM_{meas}}{BPM_{ref}} \times 100\% \quad (2)$$

where BPM_{ref} is the reference value generated by the fetal simulator and BPM_{meas} is the average BPM measured by the proposed system. Measurement repeatability was evaluated using the sample standard deviation, calculated as follows:

$$stdev = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{x})^2}{n - 1}} \quad (3)$$

where SD denotes the standard deviation, $\bar{x}$ is the mean value, and X_i represents each measurement.

To evaluate the effectiveness of digital signal processing, the signal-to-noise ratio (SNR) was calculated before and after filtering using Equation (4):

$$SNR = 10 \log_{10} \left(\frac{P_{signal}}{P_{noise}} \right) \quad (4)$$

where P_{signal} is the power of the useful fetal heart signal and P_{noise} is the power of the noise component. The calculated SNR values were used to compare the performance of different cutoff frequencies and determine the optimal filtering configuration for fetal heart rate monitoring.

3. RESULTS AND DISCUSSION

The developed wireless fetal heart rate monitoring system was successfully implemented and evaluated to analyze its performance in detecting fetal heart signals, transmitting data wirelessly, and improving signal quality through digital filtering techniques. Several tests were conducted to assess system performance, including BPM measurement accuracy, data transmission reliability, baud rate performance, and sampling frequency evaluation. The experimental results demonstrated that the proposed system was capable of transmitting data reliably without significant loss while maintaining stable and clear fetal heart rate signals. Furthermore, the implementation of digital filtering and wireless communication using the ESP-NOW protocol contributed to improved signal clarity and overall system effectiveness for real-time fetal heart rate monitoring applications.

3.1. Accuracy

The module is designed using a piezoelectric sensor to detect the fetal heart rate, using an ESP32 microcontroller and displaying the readings on an OLED LCD. Figure 4. shows the entire circuit used to create the tool module.

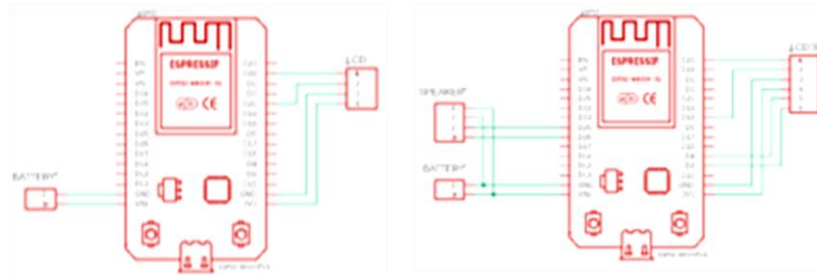


Figure 4. Wireless fetal doppler system circuit with Djj Voice Enhancement and digital filter

Tabel 1. Test results and calculation of percentage of data loss with different F sampling

No	F sampling	Jumlah Paket ADC Dikirim	Jumlah Paket ADC Diterima	Paket Hilang	Persentase Loss (%)
1	200 hz	1500	1500	0	0%
2	400 hz	1500	1500	0	0%
3	600 hz	1500	1500	0	0%
4	800 hz	1500	1500	0	0%
5	1000 hz	1500	1500	0	0%

To find out if any data is lost during the wireless transmission process using ESP-NOW, a test is conducted where each data sent from the sending device is given a sequence number (packet number) that keeps increasing one by one. For example, the first packet is numbered 1, then 2, 3, and so on. The receiving device will display the successfully received packet number along with the ADC (analog-to-digital converter) data value sent. If the receiving device skips a number, for example from packet 101 directly to 103 (without receiving packet 102), then this is considered a lost packet. This test was conducted using different sampling frequencies and baud rates.

In Table 1, Based on the tests I tried, the system was tested using several variations of sampling frequency (F sampling) to determine its effect on transmission performance and the quality of the resulting signal. I tried F sampling ranging from 200 Hz to 1000 Hz to ensure that the system can transmit and receive data stably at various sampling rates. As a result, all tests showed no data loss (0% loss), indicating that the transmission was running well. However, the sampling frequency still affects the shape and sharpness of the signal. At low sampling frequencies such as 200 Hz, the signal looks less detailed and does not capture rapid changes as a whole, because the amount of data sent per second is less. Conversely, at high sampling frequencies such as 1000 Hz, the signal looks more detailed and sharp because more data points are recorded, so the waveform looks clearer and closer to the original shape. Therefore, although the system is able to transmit data stably at various sampling frequencies, choosing the right sampling frequency is still important to ensure that the signal remains accurate and does not lose important details.

Table 2 presents the packet transmission performance of the proposed ESP-NOW communication system under different baud-rate configurations. For each baud rate, 1,000 ADC data packets were transmitted from the ESP32 transmitter to the ESP32 receiver over a testing period of 30 s. The communication tests were conducted in an indoor laboratory environment with transmitter–receiver separation distances of 1 m and 3 m under line-of-sight conditions. Packet loss was evaluated by comparing the sequence numbers of transmitted and received packets after each transmission session. As shown in Table 2, all 1,000 transmitted packets were successfully received at every tested baud rate, resulting in no observed packet loss (0%) across all communication configurations. These results demonstrate that the proposed ESP-NOW communication system provides reliable wireless data transmission for real-time fetal heart rate monitoring within the tested indoor distances.

Tabel 2. Packet transmission performance at Different Baud Rates using the ESP-NOW protocol

No	Baud Rate	ADC Packets Sent	ADC Packets Received	Lost Packets	Packet Loss (%)
1	300 bps	1000	1000	0	0
2	1200 bps	1000	1000	0	0
3	2400 bps	1000	1000	0	0
4	4800 bps	1000	1000	0	0
5	9600 bps	1000	1000	0	0
6	19200 bps	1000	1000	0	0
7	38400 bps	1000	1000	0	0
8	57600 bps	1000	1000	0	0
9	115200 bps	1000	1000	0	0
10	230400 bps	1000	1000	0	0
11	250000 bps	1000	1000	0	0

Although no packet loss was observed, the baud rate affected the responsiveness of real-time data visualization. At lower baud rates (300–9600 bps), data transmission was slower, causing the waveform to appear intermittent on the display. Increasing the baud rate to 115,200 bps and 250,000 bps enabled smoother and more continuous waveform visualization without affecting signal integrity. However, preliminary experiments at baud rates higher than 250,000 bps (500,000 and 1,000,000 bps) produced corrupted data, most likely due to hardware communication limitations. Therefore, baud rates of 115,200 bps and 250,000 bps are recommended because they provide an appropriate balance between transmission speed and communication reliability.

Figure 5. shows the display of BPM values read by the fetal doppler device when connected to the fetal simulator. In this process, the fetal simulator is used as a source of artificial heartbeat signals that can be adjusted for testing and calibration purposes. In the example in the figure, the fetal simulator is set at 60 BPM, then the probe of the fetal doppler is placed directly on the output port of the fetal simulator to detect the signal. The fetal doppler device will read the signal from the simulator and display it in the form of a BPM value on the device screen.

The data collection process is carried out systematically with variations in BPM settings on the fetal simulator, ranging from 60 BPM, 90 BPM, 120 BPM, 150 BPM, to 180 BPM. For each BPM value, measurements were taken six times to ensure the accuracy and stability of the readings, in accordance with standard medical device calibration procedures. The results of each measurement are then averaged and compared with the reference value of the simulator, so that it can be seen how much error or deviation occurs in each BPM setting. The average error value of each BPM setting is presented in the Table 3 as a result of the device performance evaluation.



Figure 5. Measurement results with different bpm settings using fetal simulator

Tabel 3. Test results and calculation of percentage of data loss with different F sampling

Setting (BPM)	Error (Mean $\pm$ SD)
60	0.84 $\pm$ 0.96
90	0.56 $\pm$ 0.61
120	0.83 $\pm$ 0.55
150	0.89 $\pm$ 0.66
180	0.56 $\pm$ 0.47

From the data Table 3 presented, it can be seen that system was tested at five different BPM settings, namely 60, 90, 120, 150, and 180. The test results show that the resulting error rate is quite small and within a narrow range, which is between 0.56% and 0.89%. In detail, at BPM 60, an error of 0.84% was recorded, BPM 90 was 0.56%, BPM 120 was 0.83%, BPM 150 was 0.89%, and BPM 180 was 0.56%. From these data, I can conclude that although there is a slight variation, all error values are still relatively low and show the stability of the system's performance in detecting BPM in various conditions.

3.2. Performance

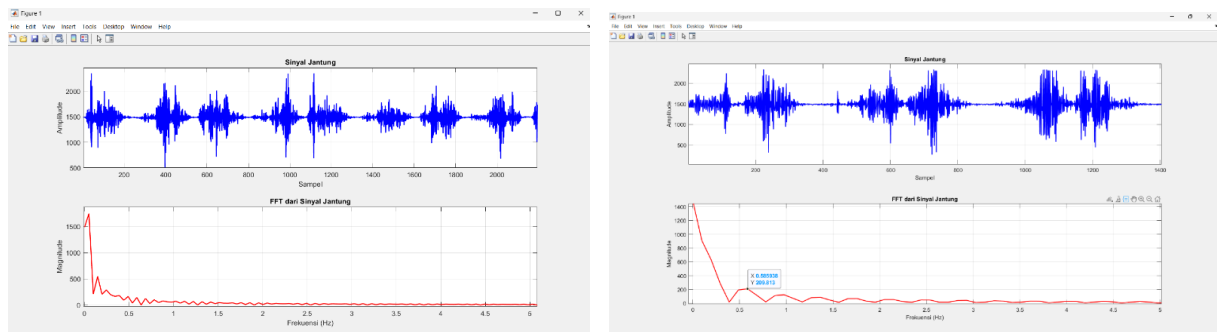


Figure 6. Heartbeat signal analysis using FFT on signals before and after filtering

In the graphic image shown in Figure 6. I performed the acquisition and analysis of the heart signals displayed in two domains, time and frequency. The upper signal shows the shape of the heart signal that I acquired based on the number of samples against the amplitude, while the lower part is the result of analyzing the frequency spectrum using fast Fourier transform (FFT). In processing this signal, I applied an IIR Butterworth bandpass filter with a cutoff frequency of 0.5 Hz to 20 Hz. I used this filter to eliminate low-frequency noise such as baseline wander below 0.5 Hz and also eliminated high-frequency noise above 20 Hz that is irrelevant to the main information of the heart signal.

From the FFT results I obtained, it can be seen that the dominant frequency component of the heart signal is at a frequency below 2 Hz, which corresponds to the physiological range of normal human heart rate, which is about 60-120 beats per minute (bpm)[20]. In the second graph, I marked one of the dominant frequency peaks at about 0.58 Hz with a magnitude of about 209.313, which shows the success of the filter in retaining the main components of the signal. By using the IIR Butterworthfilter, I got a smoother and cleaner spectrum shape as it has gradual transition characteristics as well as a stable frequency response within the bandpass I specified. Through this filtering process, I managed to improve the quality of the heart signal so that it is easier to analyze and more representative of real conditions. This is very important for further analysis, such as peak detection heart rate calculation.

Table 4. Test results and calculation of percentage of data loss with different F sampling

FC filter	Mean $\pm$ SD (dB)
0.5-20hz	18.70 $\pm$ 0.17
0.5-50hz	16.16 $\pm$ 0.08
0.5-100hz	10.83 $\pm$ 0.12
0.5-150hz	8.13 $\pm$ 0.37
0.5-200hz	6.19 $\pm$ 0.48

Table 4 is a the measurement results show that the application of a digital filter with a variation in

cutoff frequency (FC) affects the SNR value. At a narrower FC, such as 0.5–20 Hz, the SNR increases to 18.70 ± 0.17 dB, indicating that noise is effectively suppressed. Conversely, when the FC range is expanded to 0.5–200 Hz, the SNR decreases drastically to 6.19 ± 0.48 dB due to the entry of high-frequency noise. The low standard deviation value (0.08–0.48 dB) indicates that the filtering process is stable and consistent. The decreasing trend in SNR as the FC increases reflects the working principle of the low-pass filter, which only passes low-frequency signals and reduces noise outside that limit. Overall, these data indicate that the digital filter is able to effectively improve signal quality through selective and efficient noise suppression. The performance of the digital filter is proven to be effective in reducing noise. At narrow FC (0.5–20 Hz), high SNR (18.70 ± 0.17 dB) indicates noise is successfully suppressed, while at wide FC (0.5–200 Hz), SNR drops drastically (6.19 ± 0.48 dB) because high-frequency noise is also included. The pattern of decreasing SNR as FC increases is consistent with the working principle of the low-pass filter. The small standard deviation value reflects the stability of the results. This indicates that the filter works optimally in improving signal quality through selective and consistent noise suppression.

4. CONCLUSION

This study successfully developed and evaluated a wireless ultrasonic Doppler-based fetal heart rate (FHR) monitoring system integrating ESP32 microcontrollers, ESP-NOW wireless communication, and digital signal processing using a Butterworth low-pass filter and a smoothing algorithm. The proposed system demonstrated reliable wireless communication, with no packet loss observed during the transmission tests conducted at sampling frequencies of 200–1000 Hz and baud rates ranging from 300 to 250,000 bps. The system achieved BPM measurement errors between 0.56% and 0.89% and improved signal quality, obtaining the highest signal-to-noise ratio (SNR) of 18.70 ± 0.17 dB using a 0.5–20 Hz Butterworth filter. Furthermore, higher sampling frequencies produced more detailed waveform representations, whereas higher baud rates improved transmission responsiveness without compromising communication reliability within the tested range. These findings demonstrate that the proposed system provides an accurate, reliable, and portable solution for real-time wireless fetal heart rate monitoring. Future work will focus on integrating cloud-based monitoring, IoT connectivity, and automatic fetal heart rate abnormality detection to further enhance the system's clinical applicability.

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