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Design and Implementation of an 8-Channel Wireless Transmitter and Receiver System Using STM32 Microcontroller

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Abstract: *Multi-channel communication systems are essential in industrial automation, remote control, robotics, and embedded applications where multiple signals must be transmitted reliably and simultaneously. This paper presents the design and implementation of an 8-Channel Wireless Transmitter and Receiver system using STM32F103C8T6 (Blue Pill) microcontrollers paired with NRF24L01+ 2.4 GHz transceiver modules. The system enables concurrent transmission and reception of eight independent digital channels through structured data framing, unique channel identification, and CRC-based error detection. Experimental results demonstrate data accuracy exceeding 99.5%, an average response latency below 55 ms, and robust wireless operation in indoor environments up to 15 meters. The modular hardware and firmware architecture ensures scalability, low power consumption, and practical deployment across automation, robotics, home control, and remote monitoring applications.*

Keywords: STM32F103C8T6, NRF24L01+, 8-channel wireless, embedded systems, SPI protocol, multi-channel control, industrial automation, real-time communication

I. INTRODUCTION

The rapid growth of industrial automation, robotics, and smart systems has fuelled a growing demand for robust multi-channel communication platforms capable of transmitting several independent control signals in real time. Where older single-channel or wired systems once sufficed, modern applications — from unmanned aerial vehicles to smart factory floors — require simultaneous control of multiple actuators with minimal latency and high reliability.

Conventional approaches based on the 8051, Arduino, or basic parallel-wiring schemes often hit hard ceilings in processing speed, peripheral variety, and power efficiency. The STM32F103C8T6 (Blue Pill) breaks through these constraints with its ARM Cortex-M3 core at 72 MHz, rich GPIO complement, multiple hardware communication buses, and disciplined low-power modes — all at a competitive price point suited to student projects and industrial prototypes alike.

This paper describes the end-to-end design of an 8-Channel Wireless Transmitter and Receiver (TX/RX) system built on the STM32F103C8T6 and the NRF24L01+ 2.4 GHz transceiver. From hardware schematic through firmware logic, communication protocol, and experimental evaluation, the work demonstrates eight fully independent digital channels managed with greater than 99.5% data accuracy and average round-trip latency below 55 ms.

II. LITERATURE REVIEW

Research on multi-channel embedded communication has progressed in three broad waves. Early systems used mechanical switching and parallel wiring, which proved brittle at scale and impractical for wireless operation [1]. A

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second wave leveraged 8051- and Arduino-based designs with RF or infrared modules; these improved flexibility but were constrained by limited CPU throughput and coarse timing control [2].

The arrival of high-performance 32-bit microcontrollers transformed the field. Studies by Zhao et al. [3] and Chen et al. [4] demonstrated STM32- and NRF24L01-based sensor nodes achieving reliable 2.4 GHz links at 250 kbps over 800 m, though their designs topped out at four channels and focused on telemetry rather than real-time actuator control. Parallel investigations into data-framing strategies — checksum and CRC-based error detection, rolling frame counters, structured start/stop delimiters — showed measurable reductions in false outputs and channel cross-talk [5].

The NRF24L01+ PA+LNA variant extended wireless range dramatically while keeping power consumption modest [6]. More recent work explored DMA-driven SPI transfers on STM32 to free the CPU during radio bursts, enabling simultaneous ADC scanning and radio communication without scheduling conflicts [7]. Power-management studies confirmed that interrupt-driven GPIO polling combined with STM32 sleep modes significantly extends LiPo battery life without sacrificing channel responsiveness [8].

A review of the literature identifies two persistent gaps: (a) no prior work presents an experimentally validated 8-channel real-time wireless control system on the STM32 + NRF24L01+ platform, and (b) the integration of joystick analog inputs, structured CRC framing, low-power operation, and modular receiver output control has not been treated holistically. This paper addresses both gaps.

III. SYSTEM ARCHITECTURE

The system comprises two mirror-image hardware units — Transmitter (TX) and Receiver (RX) — each centred on an STM32F103C8T6 microcontroller and an NRF24L01+ radio module. The overall pipeline follows a clean sense → encode → transmit → receive → decode → actuate loop.

3.1 Transmitter Module

The TX unit reads eight independent input channels — physical joystick axes, push buttons, and toggle switches — via GPIO pins and the 12-bit ADC. The STM32 processes these readings, packages them into a structured 26-byte data frame, computes a CRC-16 checksum, and forwards the frame to the NRF24L01+ via SPI at a 250 Hz refresh rate. The NRF24L01+ is configured to operate on channel 76 (2.476 GHz) at 250 kbps in long-range mode.

3.2 Receiver Module

The RX unit listens continuously on the designated NRF24L01+ pipe address. On successful frame arrival, the STM32 validates the CRC-16, extracts the eight channel IDs and their states, and drives the corresponding output pins — LEDs, relay coils, or servo PWM signals — through appropriate driver circuitry. An interrupt-driven reception model keeps latency deterministic and frees the CPU for continuous frame monitoring.

3.3 Communication Link Parameters

Key NRF24L01+ radio settings used in this implementation:
Frequency: 2.476 GHz (ISM channel 76)
Data rate: 250 kbps (long-range mode)
TX power: 0 dBm (configurable to -18/-12/-6/0 dBm)
CRC: 16-bit hardware CRC; auto-retransmit 15 retries, 500 µs delay
Payload: 26 bytes fixed; address width: 5 bytes

IV. HARDWARE DESIGN AND COMPONENTS

Table I summarises the hardware components used in each module. The STM32F103C8T6 (Blue Pill) was selected for its ARM Cortex-M3 core, 72 MHz clock, 64 KB flash, 20 KB SRAM, and rich peripheral set — all in a compact, low-cost 48-pin package. The NRF24L01+ PA+LNA variant was chosen over the standard module for its superior range.

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Component	TX	RX	Role in System
STM32F103C8T6 (Blue Pill)	1	1	Core MCU — processing & control
NRF24L01+ Module	1	1	2.4 GHz wireless link
Dual-axis Joystick	2	—	Analog channel input
Toggle Switch	1	—	Master control / mode select
Push Button	2	—	Manual input / reset
LiPo Battery 7.4V	1	1	Portable power supply
Type-C Charging Module	1	1	Safe battery charging
OLED Display (SSD1306)	opt	—	Status feedback display

Table I. Hardware Components and Their System Roles

Both boards draw power from a 7.4 V (2S) LiPo cell through an AMS1117-3.3 LDO, supplying 3.3 V to the STM32 and NRF24L01+. A 100 µF electrolytic capacitor in parallel with a 100 nF ceramic capacitor, placed within 5 mm of the radio module's power pins, suppresses voltage spikes during transmission bursts — a common source of erratic wireless behaviour.

4.1 SPI Interface

The STM32 communicates with the NRF24L01+ over SPI1 at 8 MHz. Pin mapping: PA5 → SCK, PA6 → MISO, PA7 → MOSI, PA4 → CSN (active-low chip select), PA3 → CE (chip enable), and PA2 → IRQ (active-low interrupt). The PA+LNA module requires a 3.3 V supply capable of sourcing 115 mA peak; the AMS1117-3.3 (rated 1 A) meets this comfortably.

4.2 Input and Output Interfaces

Joystick axes feed into STM32 12-bit ADC inputs (PA0–PA3), scanned continuously by DMA in circular mode at roughly 12,000 samples/second. Digital switches use internal pull-up resistors with EXTI interrupt detection. At the receiver, eight output pins drive LEDs, relay coils (via transistor drivers), or servo PWM lines using STM32 hardware timers TIM1–TIM4, providing 1 µs PWM resolution.

V. FIRMWARE DESIGN

Firmware for both units was developed in STM32CubeIDE v1.14 using the HAL library, with STM32CubeMX generating peripheral initialisation code and an ST-Link V2 used for debugging.

5.1 Data Frame Structure

Every transmitted payload is a 26-byte fixed-size frame: byte 0 carries a start marker (0xA5); byte 1 a rolling counter (0–255) for sequence tracking; bytes 2–17 encode the 16-bit values of the eight channels (two bytes each); bytes 18–21 carry flag bits and a telemetry tag; bytes 22–23 are reserved; and bytes 24–25 hold a CRC-16/CCITT checksum over all preceding bytes, enabling the receiver to detect errors before updating any output.

5.2 Transmitter Firmware

A TIM3 interrupt fires every 4 ms (250 Hz). Each cycle the firmware: (1) reads the eight ADC DMA buffer entries, (2) maps 12-bit values to 16-bit channel words, (3) samples digital GPIO inputs, (4) assembles the 26-byte frame, (5) computes CRC-16, and (6) triggers an SPI DMA write to the NRF24L01+. Because DMA handles the SPI transfer autonomously, the CPU immediately returns to ADC monitoring — no busy-wait cycles wasted.

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5.3 Receiver Firmware

The receiver polls the NRF24L01+ IRQ pin in a tight loop. On assertion it reads the 26-byte payload via SPI DMA, validates the CRC, and dispatches channel values to the appropriate output routines — PWM timer compare registers, GPIO write, or relay state. Frames failing CRC are silently discarded, preventing false actuator movement. A watchdog timer resets the MCU if no valid frame arrives within 500 ms, providing a safe fail-state.

5.4 Power Management

Between transmissions the STM32 enters Sleep mode, waking only on TIM3 tick or EXTI edge. The NRF24L01+ is held in Standby-I between bursts, reducing radio current from 11.3 mA (active TX) to 26 µA. Combined, these measures keep average transmitter draw in the 50–65 mA range, supporting several hours of runtime on a 2000 mAh LiPo cell.

VI. RESULTS AND DISCUSSION

The system was tested indoors with 10–15 m line-of-sight. Each channel was exercised independently and simultaneously to stress the framing, error-detection, and output-mapping logic under realistic multi-channel load.

Ch.	Input Type	Acc. (%)	Latency (ms)	Status
1	Push Button	100.0	45	Synced
2	Toggle Switch	100.0	48	Synced
3	Joystick X	99.8	50	Synced
4	Joystick Y	99.9	52	Synced
5	Push Button	100.0	46	Synced
6	Joystick X	99.7	51	Synced
7	Joystick Y	99.9	49	Synced
8	Toggle/Custom	100.0	47	Synced

Table II. Channel-wise Data Accuracy and Timing Results

6.1 Data Accuracy

All eight channels achieved greater than 99.5% data accuracy. The small gaps on channels 3, 4, 6, and 7 (joystick axes) arise from sub-LSB mechanical jitter on the potentiometers at very slow movement speeds — a hardware-level phenomenon, not a communication error. CRC frame validation ensured no corrupted frame ever triggered a false output during testing.

6.2 Latency and Real-Time Performance

End-to-end latency — from physical input change to observable output change — ranged from 45 ms to 55 ms across all channels, dominated by the 4 ms transmission interval and the NRF24L01+ acknowledgement cycle. No channel showed cross-talk or priority starvation during simultaneous eight-channel activation. The system comfortably meets the sub-100 ms threshold cited for real-time human-in-the-loop control.

6.3 Error Rate and Reliability

The observed raw frame error rate was below 0.5% during continuous indoor operation, with all errors caught by CRC validation. Introducing a co-located 2.4 GHz Wi-Fi transmitter at one metre raised the error rate to approximately 1.2%, still well within acceptable bounds for automation control.

6.4 Power Consumption

Measured average current draw was 52 mA for the transmitter and 68 mA for the receiver (including relay loads). Sleep-mode transitions reduced idle transmitter consumption to approximately 18 mA — equivalent to 38+ hours of runtime on a 2000 mAh LiPo cell.

VII. PRACTICAL APPLICATIONS

Industrial Automation: Remote control of conveyor belts, pneumatic actuators, and robotic arms across multiple motion axes without physical tethering.

Robotics and UAVs: Full-authority flight controller input — throttle, pitch, roll, yaw, and four auxiliary channels — or multi-joint robotic arm control.

Home and Building Automation: Wireless switching of lighting zones, HVAC dampers, and security alerts from a single handheld transmitter.

Agricultural Robotics: Remote irrigation valve control across large open fields, leveraging the extended NRF24L01+ PA+LNA range.

Emergency Response: Safe remote activation of alarms, sprinklers, or lockdown systems in hazardous areas.

VIII. LIMITATIONS AND FUTURE WORK

Despite solid performance, several limitations remain. The NRF24L01+ standard module is limited to 10–15 m indoors; the PA+LNA variant extends this to 300–1000 m outdoors but adds RF certification considerations. The STM32F103C8T6's 20 KB SRAM constrains simultaneous data logging, display rendering, and ADC oversampling — a STM32F4 or STM32H7 would alleviate this.

Planned enhancements include: (a) Frequency Hopping Spread Spectrum (FHSS) for improved co-existence in congested 2.4 GHz environments; (b) AI-driven anomaly detection to flag unusual channel patterns before they reach actuators; (c) OLED-based status dashboards; (d) OTA firmware updates via BLE; and (e) CAN bus integration for direct connection to industrial PLC networks.

IX. CONCLUSION

This paper has presented the design, firmware, and experimental evaluation of a complete 8-channel wireless transmitter and receiver system built on the STM32F103C8T6 microcontroller and the NRF24L01+ 2.4 GHz transceiver. The system achieves greater than 99.5% data accuracy across all channels, average end-to-end latency below 55 ms, and reliable indoor wireless operation — all on a compact, battery-powered platform. The modular hardware and firmware architecture makes channel expansion, communication interface swaps, and AI-enhanced control integration straightforward without redesigning the core system.

The work demonstrates that cost-effective embedded components, when combined with thoughtful system design and disciplined firmware engineering, can deliver multi-channel wireless performance genuinely competitive with commercial RC and industrial automation solutions. The design is well-suited for academic research, industrial prototyping, and real-world deployment across automation, robotics, and smart infrastructure applications.

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