*Engineering Experiences 3, Electronics-ICT, May 2025, Bruges, Belgium*

# Low-energy backup communication system for hydrogen racecar

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**Abstract**

*Summary of the research and conclusion, Problem, method, results, conclusion....*

**Keywords—**Low power, Long-range wireless, Embedded systems

## I. Introduction

In hydrogen-powerd endurance racing, uninterupted telmetry and communication between the pitwall and the car are essential for both competitive performance and for driver safety. As systems could fail due to multiple reasons, and cause a loss of communication costing laps or even endager lives, a dedicated low-power backup is required. This paper therefore proposes a long-range wireless solution capable of transmitting and receiving both critiacal sensor data and messages to the driver over distances up to 2km (the approximate diameter of the Le Mans circuit) while only consuming a few milliwatts. By combining a encrypted LoRa-based RF link with embedded speech synthesis and WAV playback on an ultra-low-power STM32U5 microcontroller, our design ensures that even in the event of primary-system failure, the pit-crew retains awareness of the car's most critical data and issue instructions to the driver.

## II. Firmware Design and Implementation

This section describes the firmware developed for the STM32U5 microcontroller [1], which forms the core of our low-energy backup communication system. It handles real-time LoRa communication, sensor data acquisition, and voice output via speech synthesis or WAV playback. To guarantee deterministic timing, we build on FreeRTOS [2], as illustrated in Figure 1. Task isolation and priority levels make the codebase modular and maintainable.

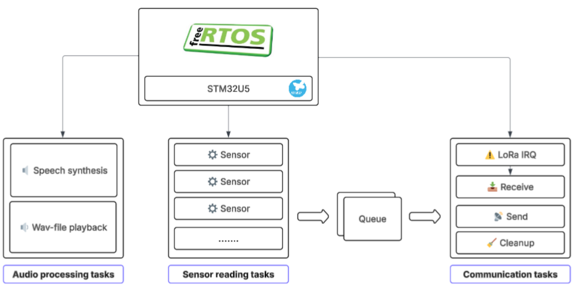


**Fig. 1.** Overview of the FreeRTOS-based firmware architecture

### A. Overall Architecture

Figure 1 shows three primary functional domains, each implemented as one or more FreeRTOS tasks communicating via inter-task communication mechanisms provided by FreeRTOS.

### B. LoRa Communication

- **IRQ Handler** Waits on the SX1276 [3] interrupt line to detect packet RX/TX completion, then gives a binary semaphore.
- **Receive Task** Blocks on that semaphore, retrieves incoming packets, decrypts them with hardware-accelerated AES-128 in CTR mode, and forwards them for processing.
- **Transmit Task** Pulls outgoing messages from a FreeRTOS queue, encrypts and formats them, then issues the LoRa send command.
- **Cleanup Task** Periodically scans stored packet buffers for timeouts and frees associated heap memory.

The message formatting steps mentioned above, including encryption, fragmentation, and encapsulation, are detailed in Section II-F.

### C. Sensor Management

Each sensor (e.g. temperature, pressure, speed) runs its own task at a low priority. Tasks periodically sample the hardware interface, package readings, and enqueue them for transmission.

### D. Audio Processing

- **Speech Synthesis Task** A port of `espeak-ng` [4] with all file I/O replaced by in-memory C arrays. Which dequeues strings from a FreeRTOS queue, synthesises, streams audio to I2S hardware.
- **WAV playback Task** Streams hard-coded WAV data (e.g. racing flags, standard phrases) to the I2S hardware.

### E. Power and Memory Management

All tasks are assigned carefully chosen priorities (Table I) so that time-critical communication tasks preempt lower-priority work. We enable FreeRTOS tickless idle to allow the STM32U5 to enter deep sleep whenever the system is idle.

**TABLE I.** Task priorities and stack usage

| Task | Priority | Stack (bytes) |
|---|---|---|
| LoRa IRQ Handler | 8 | 128 |
| Speech Synthesis | 7 | 48 000 |
| WAV Playback | 7 | 256 |
| LoRa Transmit | 5 | 128 |
| Cleanup | 5 | 128 |
| Sensor (each) | 3 | 256 |

### F. Fragmentation and Reassembly of Encrypted Messages

The transmission process, illustrated in Figure 2, begins with raw message data assigned a unique ID. This data is then processed through the following steps:

**Message Transmission Pipeline**

1) The raw message is padded using PKCS#7 to ensure its length is a multiple of 16 bytes, satisfying the requirements of the hardware-acelerated AES module.
2) The padded message is encrypted using AES-128 in CTR mode.
3) The resulting ciphertext is fragmented into fixed-size chunks. Each fragment is encapsulated in a packet containing the meassage ID, fragment index, and total number of fragments.
4) Packets are enqueued for transmission via LoRa.

**Message Reception Pipeline**

5) Recieved packets are collected in a queue.

6) Each packet is decapsulated and sorted by message ID. Once all fragments of a message are received, they are reassembled into the full encrypted message.
7) The complete ciphertext is decrypted to recover the padded plaintext.
8) Padding is removed, restoring the original raw message.

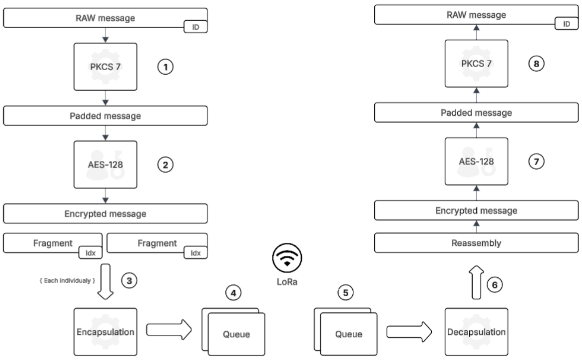


**Fig. 2.** Flowchart illustrating the message encryption fragmentation process prior to LoRa transmission.

## III. Backend and graphical user interface Design and Implementation

## IV. Hardware Design and Implementation

### A. System overview

The hardware functionalities can be divided into six main components: power supply, microcontroller, audio recording, audio playback, wireless communication, and power switching. Apart from the microcontroller, these components are implemented on a custom PCB designed as a shield compatible with an STM32 Nucleo board. All components are designed to be low-power and operate from a 12V power source. The power supply includes a switching regulator that generates both 3.3V and 5V rails to power the remaining circuitry. Audio input is handled via an external analog-to-digital converter (ADC), while audio output is managed through an external digital-to-analog converter (DAC). The power to these audio components can be switched on or off by the microcontroller using MOSFETs, allowing the system to conserve energy when the components are not in use. Processed speech data can be transmitted or received via a LoRa module, and subsequently played back if needed.

### B. PCB

To implement a system that supports all required functionalities, a custom printed circuit board (PCB) was developed. This PCB is designed as a shield, an add-on board with headers that mate with a host PCB. In this project, the shield interfaces with an STM32 Nucleo-144 development board. The Nucleo board features a microcontroller integrated with an onboard programmer and debugger. This board was selected to avoid the complexity of manually soldering fine-pitch microcontroller packages. The Nucleo board brings out all microcontroller signals to accessible headers, enabling the shield to supply power and utilize the full range of I/O capabilities.

The shield offers a wide range of I/O capabilities. UART, I²C, and SPI buses, as well as two digital input lines, are accessible via screw terminals. In the audio section, connectors are available both before and after the amplifier stage. Small surface mount device (SMD) jumper pads allow PCB traces to be manually connected or disconnected. These jumpers are used to configure ADC settings and to isolate the I²S lines from the microcontroller when operating with digital audio instead of analog.

Each functional section: audio input, audio output, LoRa, and the microcontroller are isolated from power via pin header jumpers. These headers can also accommodate current meters, allowing current consumption to be measured per subsystem. In addition, voltage test points are provided near each jumper, enabling accurate power and voltage measurements during debugging.

For the connection between the LoRa module and the antenna, the characteristic impedance of the PCB trace does not need to be matched, as the trace length satisfies the condition $l < \frac{\lambda}{10}$.

### C. Power supply

The power supply uses two buck converters to step down the 12 VC input to 5 V and 3.3 V, based on the TPS629203. This converter supports input voltages up to 17 V and delivers up to 300 mA of output current [5]. Thanks to its high switching frequency, it achieves excellent efficiency, which is further enhanced by dynamically adjusting both the switching frequency and operating mode according to the load. It operates in either pulse-width modulation (PWM) or pulse-frequency modulation (PFM), depending on the current demand. This feature, known as Automatic Efficiency Enhancement (AEE), maintains high efficiency even at very low duty cycles, making the device particularly suitable for low-power applications.

### D. Microcontroller

The STM32U5 microcontroller was selected for this design. This latest generation of STM32 ultra-low-power microcontrollers is well-suited for applications that require minimal energy consumption. Despite its low power profile, certain variants offer up to 4 MB of Flash memory and 3 MB of SRAM, enabling complex processing and data storage [1]. The microcontroller supports multiple low-power modes, allowing it to significantly reduce power consumption during periods of inactivity, such as while waiting to send or receive messages. Wake-up from these modes is achieved using Low-Power General-Purpose Input/Output (LPGPIO) pins. In this setup, an LPGPIO pin is connected to both the LoRa module and a digital input. This configuration enables the microcontroller to wake up upon receiving incoming LoRa data or when the talk button connected to the digital input is pressed.

### E. LoRa

For wireless communication over distances exceeding 2 km, three primary options were considered: LoRa, NB-IoT, and Sigfox. LoRa was selected due to its independence from public infrastructure, which may not always be available or reliable. This technology functions as the physical layer for the widely adopted LoRaWAN protocol. The selected transceiver module, the RFM96W by HopeRF [6], is readily available and well-supported by a broad range of example implementations and open-source libraries, facilitating straightforward integration and development. This compact PCB can be hand-soldered and includes all the necessary hardware for LoRa communication, except for the antenna. Communication with the module is established via the SPI bus and GPIO pins. Data to be transmitted is sent to the module via the SPI interface, while incoming data is signaled through a dedicated I/O pin. The antenna is connected to the PCB using an SMA connector. Both $\frac{\lambda}{2}$ and $\frac{\lambda}{4}$ antennas can be used. A $\frac{\lambda}{2}$ antenna may also be placed remotely using a coaxial cable, allowing for more flexible antenna positioning.

### F. ADC

Audio acquisition was performed using an external ADC, the PCM1808 [7]. This integrated circuit was selected based on its availability and ease of soldering. The ADC provides an I²S output, which can be readily interfaced with the microcontroller. Audio input to the ADC is supplied by a microphone. The microphone signal is amplified and filtered using an operational amplifier (op-amp) circuit powered by a DC supply. To change the sensitivity the volume can be adjusted with a potentiometer. This amplifier is based on a reference schematic provided by Texas Instruments [8].

### G. DAC

Speech output is generated using an external DAC, the PCM5100A [9]. This DAC was selected based on its availability and ease of soldering. It is driven via the I²S interface from the microcontroller. Following the DAC, an op-amp is used to amplify the audio signal to a power level of 50 mW, suitable for headphone use.

### H. Power switching

The audio hardware does not need to remain continuously active. Audio output is only required upon receptionof a speech message, and audio input is only needed when the talk button is pressed. To accommodate this, power to both the input and output audio sections is switchable. This involves controlling the 5 V and 3.3 V supply rails to these sections. Power switching is achieved using MOSFETs, which are controlled by a digital output pin of the microcontroller. The use of MOSFETs ensures minimal voltage drop across the switches during conduction.

## V. Testing

### A. Test Setup

The system was evaluated primarily in a laboratory environment. Key aspects such as power consumption, LoRa communication integrity, and audio output functionality were tested. Most tests were conducted manually, involving the transmission of periodic test messages and monitoring system responses via serial output and audio feedback. Power draw was observed using an inline current measurement tool, and LoRa transmissions were validated using logic analyzers and debug logs.

### B. Communication Testing

To verify LoRa communication, encrypted packets were periodically transmitted and received between two system nodes. Tests confirmed successful decryption, CRC validation, and end-to-end data integrity.

### C. Audio Output Testing

WAV file playback was validated by connecting the system's analog output to external speakers and assessing the clarity of preloaded audio samples. Speech synthesis was tested by transmitting predefined sentences to the device and evaluating intelligibility through blind listening tests. Testers rated intelligibility qualitatively. While overall clarity was sufficient for basic commands, future improvements may include tuning output filters and optimizing speech synthesis parameters for better naturalness.

### D. Audio Input Testing

### E. Power measuring

After connecting the microphone, an oscilloscope was used to verify that the audio waveform was properly amplified and routed to the ADC. The ADC includes an onboard crystal oscillator that generates a clock signal, causing it to continuously transmit data. All I²S bus data lines were probed and analyzed using the oscilloscope. These measurements confirmed the correct operation of the I²S interface.

### F. LoRa on PCB

range limited to 440m ?

### G. Power measurement

#### *1) LoRa power consumption*

Power consumption was measured during transmission at maximum output power. For comparison, NB-IoT, a wireless protocol with similar range, is considered. LoRa shows significantly lower power consumption than NB-IoT. External data indicate that NB-IoT consumes about 65% more energy than LoRa [10].

The measured power consumption of the LoRa device is shown in Table II.

**TABLE II.** Power consumption in different states

| idle | receiving | sending |
|---|---|---|
| 5.8 mW | 38.3 mW | 382 mW |

#### *2) Power supply efficiency*

Due to testing issues and time constraints, it was not possible to measure the efficiency of the buck converter. Therefore, only data provided by the manufacturer can be referenced. These values are listed in Table III [5].

**TABLE III.** Efficiency based on current consumption

| 0.1 mA | 1 mA | 10 mA |
|---|---|---|
| 75% | 87% | 89% |

#### *3) Audio power consumption*

lorem dat niet werkt

## VI. Conclusion


## Acknowledgment

The authors would like to thank the supervising professors for their guidance throughout the development of this project. Special thanks go to the Hydro Team KU Leuven for providing valuable context and support related to the vehicle's communication needs.

Additionally, the authors used generative AI tools to assist with language refinement and grammar correction during the preparation of this paper.


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