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.

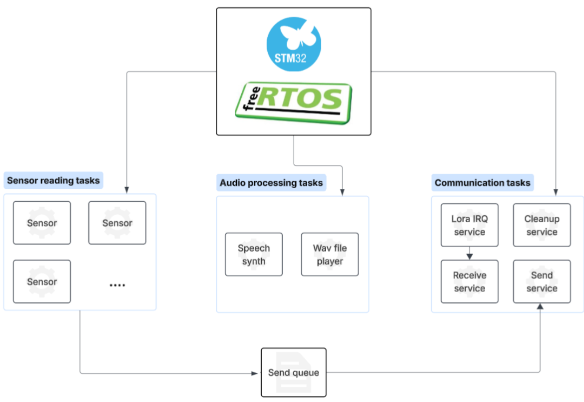

Fig. 1. Overview of the FreeRTOS-based firmware architecture

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.

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 reacdings, and enqueues them for transmission.

D. Audio Processing

- **Speech Synthesis Task** A port of `espeak-ng` [4] with all file I/O replaced bu in-memory C arrays. Wich 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

III. Backend and Graphical User Interface Design and Implementation

IV. Hardware Design and Implementation

A. System overview

The PCB is divided into six sections: power supply, microcontroller, audio recording, audio playback, wireless communication, and power control. All components are designed to be low power and operate from a 12V source. A switching regulator generates 3.3V and 5V for the rest of the logic. Audio is processed by the microcontroller via an external ADC and played back through an external DAC. Power to the audio circuitry can be controlled by the microcontroller using MOSFETs, allowing unused parts to be completely powered down to save energy. Processed speech can be transmitted or received via a LoRa module and played back as needed.

B. Power supply

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

bron: https://www.ti.com/product/TPS629203

C. Microcontroller

als microcontroller werd gebruik gemaakt van de STM32U5. Deze meest recente generatie van STM32 ultra low power microcontrollers is ideaal voor applicaties waar een minimaal stroomverbruik vereist is. Ondanks het ultra lage stroomverbruik zijn er uitvoeringen met 4Mb flash memory en 3 Mb SRAM.
bron [1]

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.

VI. Conclusion

Acknowledgment

The authors would like to thank the supervising professors and lab instructors for their guidance throughout the development of this project. Special thanks go to the hydrogen race team 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 manuscript.

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