Design of radio communication modules for UAVs using atypical frequencies

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Abstract. The ongoing conflict in Ukraine has demonstrated a significant transformation in warfare, as traditional military strategies are increasingly supplemented by digital technologies, particularly unmanned aerial vehicles (UAVs). This article explores the design of radio communication modules for UAVs operating on non-standard frequencies, addressing the challenges posed by Russian electronic warfare (EW) tactics, which systematically disrupt conventional civilian radio frequencies. By leveraging alternative frequencies, UAVs can maintain reliable communication even in electronically hostile environments. The paper provides an overview of current UAV communication systems, such as ExpressLRS (ELRS), and their limitations in modern combat scenarios. It further details the technical process of designing custom transmitter (TX) and receiver (RX) modules using LoRa (Long Range) technology and components like the LILYGO® TTGO LoRa32 V2 board. Emphasis is placed on the importance of selecting appropriate RF chips, amplifiers, antennas, and filters to optimize performance in frequencies, such as 433 MHz, less affected by electronic warfare. This approach enables the development of robust, adaptive communication systems, offering greater flexibility and independence for UAVs in critical operational contexts. The article concludes by highlighting the potential for further system refinements and future scalability for military use.

Keywords: UAVs, radio communication modules, non-standard frequencies, electronic warfare, LoRa technology.

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INTRODUCTION

Russia's large-scale invasion of Ukraine has become an example of how classical forms of warfare are being transformed by digital technologies. The conflict, which began with the use of traditional military methods, has become a digital age war. The use of the latest technologies, cyber operations and drones, has become a key aspect of modern warfare. This is not the first conflict in which unmanned aerial vehicles (UAVs) have played an important role, nor is it the first where they have been used by both sides. However, the use of drones in Ukraine is a dramatic change. Never before have so many drones been used in a military conflict. Recently, the active use of UAVs has faced new challenges. Russian invaders, using electronic warfare equipment, systematically jam conventional civilian radio frequencies traditionally used to control drones. This significantly limits the effectiveness of standard radio communication solutions, increasing the need for new approaches to protecting and ensuring the continuous operation of UAV control systems. In a rapidly changing warfare context, developing flexible and adaptive radio communication solutions is becoming a priority. The design of radio communication modules at non-standard frequencies opens up opportunities to ensure communication stability in the face of intense electronic warfare. This article discusses the design of radio communication modules for drones on non-standard radio frequencies, their potential and effectiveness for ensuring communication reliability, and the prospects for integration into modern UAV control systems.

PROBLEM FORMULATION

Radio systems for UAVs have evolved significantly over the past two decades, providing pilots with flexible and reliable systems to control their drones at different distances and in obstacle conditions. Among the main systems for FPV drones are TBS Crossfire, ExpressLRS (ELRS), FRSky, and FlySky. TBS and ELRS use the same data transmission protocol - LoRa (Long Range) technology, which provides a stable signal over a long distance, low latency, and high resistance to interference. The key difference between the two is that ELRS is an open source platform that is actively developed and supported by a community from around the world. This allows you to quickly integrate new features, adapt the system to the needs of users, and even change the firmware on the modules to suit your tasks. FRSky is a popular UAV control system that operates at 2.4 GHz using FHSS (Frequency Hopping Spread Spectrum) technology, which ensures signal immunity to interference. While this system is well suited for most civilian flights, its range and immunity to radio interference are inferior to TBS Crossfire and ELRS. The FlySky also operates at 2.4 GHz and is aimed primarily at beginners. It provides basic signal reliability and sufficient communication range for less complex flights. However, it is not suitable for professional tasks or use in electronic warfare due to its limited range and simple design. Thanks to its openness and accessibility, ELRS is gaining popularity among pilots looking for ruggedized systems. Of course, in civilian conditions, changing standard frequencies is a violation of radio frequency legislation, but not when used by the armed forces in an existential struggle against a superior enemy.

BASIC PRINCIPLES OF ELRS OPERATION

The ExpressLRS operates on a classic UAV control scheme, using a transmitter (TX) and receiver (RX) connected via a radio channel. The operator transmits commands using the remote control, to which either an external ELRS module is connected via the appropriate port or an internal built-in compatible module is used. From there, the signal is transmitted over the radio channel and received by the receiver installed on board the UAV. The RX, in turn, is connected to the flight controller, which interprets the received commands and executes them in real time. The ELRS is based on microcontrollers and RF modules from Semtech, Espressif, and STMicroelectronics. Semtech's RF modules (SX127x, SX1280, LR1121) support LoRa modulation methods and are the basis for signal transmission and reception [1]. They operate in the frequency bands 433 MHz, 868/915 MHz (SX127x, LR1121) and 2.4 GHz (SX1280). The LR1121 features support for multiple frequency bands and greater sensitivity, which expands its application capabilities. Espressif's ESP32/ESP8285 microcontrollers are computing cores that provide data processing and user interaction (e.g., parameter settings). They also provide the ability to update firmware via Wi-Fi. STM32s are often used in ELRS receivers for signal processing and communication with other components. They are no longer supported as of version 3.5.0, as well as the ESP8285, and communication with other components. They are no longer supported as of version 3.5.0, as well as the ESP8285, and it is recommended to use the more modern ESP32 and ESP32C3.

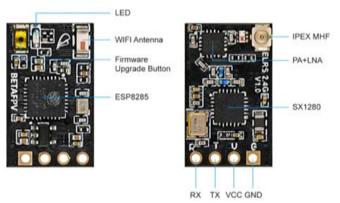

Fig. 1. ELRS receiver from BetaFPV with ESP8285 and SX1280 [3]

Fig. 2. ELRS transmitter from BetaFPV with ESP32 and SX1280 [3]

As illustrated in Figure 2, the ELRS transmitter integrates an ESP32 microcontroller with an SX1280 RF module, demonstrating a setup suitable for UAV control.

LoRa (Long Range) is a wireless modulation technology developed by Semtech. Its main feature is the ability to transmit data over long distances with low power consumption, using an extended signal spectrum and low data rate. LoRa uses Chirp Spread Spectrum (CSS), which broadens the spectrum of the transmitted signal, allowing for significant immunity to interference, very useful in military applications. LoRa can work with very weak signals, which allows it to function effectively even with low transmitter power. LoRa also supports a relatively low data rate (within a few kilobits per second), which is acceptable for radio control systems, where the main task is to provide reliable communication with low latency.

DESIGNING RX/TX PAIR

Today, there are a lot of off-the-shelf solutions that can be converted to other frequencies by reassembling the firmware. This option allows you to experiment with frequencies, but it is important to note that although ELRS software allows you to customize frequency bands through the firmware, the hardware of the TX or RX module may not meet the requirements of the new frequency. RF components, such as filters, amplifiers, and antennas, are usually tuned to a specific frequency band. Moving the module to a frequency for which its hardware was not designed can result in reduced signal efficiency, increased noise, or even damage to the equipment. For our purposes, it is advisable to consider designing your own modules. This will allow us to select the optimal components that will meet the necessary technical requirements. In addition to choosing the most suitable RF chip for our tasks, it is important to choose an amplifier that operates in the desired frequency range. It is also important to select the right antennas and filters that will be tuned to the selected frequency range to minimize signal loss and ensure optimal performance. At the moment, the upper frequency range (700-1000 MHz) is saturated with electronic warfare (EW) interference, making it unsuitable for stable operation of radio control systems. Therefore, this article will highlight the process of developing a working prototype of the module in the lower frequency range, focusing on frequencies around 433 MHz. This will allow for more stable and reliable communication. This development is an important step towards creating an efficient radio system, and these developments can be used for further modernization. In the future, based on this “proof of work,” a factory solution with a full printed circuit board (PCB) and factory production can be developed, which will allow the project to be scaled up for wider use.

The selection of components for this particular case was carried out to speed up the process of creating a “proof-of-concept” and demonstrating the work [2]. The main ones are two LILYGO TTGO LoRa32 V2 boards - one for the transmitter and the other for the receiver. You will also need a 3D printer and material (PLA or PETG) to make a case and antenna for 433 MHz or another frequency you define. We recommend using a moxon antenna for the transmitter and a dipole for the receiver. An important element is also the BEC (Battery Eliminator Circuit), which reduces the voltage to power the transmitter to 5 V. First, you need to prepare the LILYGO TTGO LoRa32 V2.1

board. It must be installed in a case printed with a 3D printer. When choosing the material for the case, PLA or PETG are the best solutions, as they provide strength and heat resistance. The case should be designed to provide adequate ventilation to avoid overheating of the board during operation. Next, you need to provide power for the transmitter. The LILYGO TTGO requires 5 V for reliable operation, so a BEC should be connected to reduce the input voltage from the battery (VBat) to the required 5 V. The BEC can be connected directly to the battery or to the JR bay of the equipment. Next, you need to connect pin 13 of the microcontroller to the lower pin of the equipment, this is the information line. The next step is to connect the antenna. The Moxon antenna must be securely installed and connected to the TTGO board. It is important to place the antenna as far away from other components as possible to minimize electromagnetic interference and improve signal quality. The amplifier and/or filter can be integrated into the system between the TTGO board and the antenna. To connect, connect the antenna output connector of the TTGO board to the input of the amplifier, and connect the amplifier output to the Moxon of the antenna. It is important to pay attention to proper cooling of the amplifier, as it can heat up at high power. This can be solved by installing the amplifier in a well-ventilated enclosure or by adding a passive heat sink to dissipate heat. The addition of an amplifier will significantly increase the range of the UAV and improve the reliability of radio communication in electronic warfare or when operating in difficult conditions. With the receiver, the scheme is a bit simpler, you need to connect the TX of the TTGO board to the RX of the flight controller, and the RX of the TTGO to the TX of the flight controller, which will allow the control panel and the drones to exchange signals via the radio channel. The 5V source and ground can be taken from the dedicated pins on the flight controller.

As illustrated in Figure 2, the ELRS transmitter integrates an ESP32 microcontroller with an SX1280 RF module, demonstrating a setup suitable for UAV control.

Fig. 3. Example of the transmitter assembly inserted into the Radiomaster TX16 remote control [2]

Fig. 4. Example of receiver assembly [2]

CREATING THE FIRMWARE

The process of compiling the ExpressLRS firmware for the TTGO LoRa32 433 MHz board requires the use of Visual Studio Code (VSCode) with the PlatformIO plug-in. First, you need to install VSCode by downloading it from the official website. After installation, add the PlatformIO IDE plugin in the Extensions section of VSCode. The PlatformIO platform provides an integrated development environment for embedded systems, which is necessary for working with ExpressLRS firmware. After that, the user must download the ExpressLRS source code from GitHub. This can be done through the command line built into VSCode using the command "git clone https://github.com/ExpressLRS/ExpressLRS.git", which will download the entire repository to the project. First, you edit the configuration file, specify the module parameters, including the connection key, wifi auto-interval, and radio frequency domain. Next, you need to go to the lib folder, and in it to FHSS. Open the FHSS.cpp file and adjust the frequency of the previously selected domain. When all the parameters are set, you can proceed to compile the firmware. PlatformIO provides the ability to compile by clicking the "Build" button located in the plug-in menu. The compilation process may take several minutes, depending on the computing power of the computer. After the compilation is complete, the “Upload” button can be used to download the firmware to the microcontroller. After downloading, the user can check the system's performance by connecting the module to the transmitter and checking the data transmission over the selected frequency.

As illustrated in Figure 2, the ELRS transmitter integrates an ESP32 microcontroller with an SX1280 RF module, demonstrating a setup suitable for UAV control.

```
const fhss_config_t domains[] = {
    {"AU915",  FREQ_HZ_TO_REG_VAL(915500000), FREQ_HZ_TO_REG_VAL(926900000), 20},
    {"FCC915", FREQ_HZ_TO_REG_VAL(400000000), FREQ_HZ_TO_REG_VAL(410000000), 10},
    {"EU868",  FREQ_HZ_TO_REG_VAL(865275000), FREQ_HZ_TO_REG_VAL(869575000), 13},
    {"IN866",  FREQ_HZ_TO_REG_VAL(865375000), FREQ_HZ_TO_REG_VAL(866950000), 4},
    {"AU433",  FREQ_HZ_TO_REG_VAL(433420000), FREQ_HZ_TO_REG_VAL(434420000), 3},
    {"EU433",  FREQ_HZ_TO_REG_VAL(433100000), FREQ_HZ_TO_REG_VAL(434450000), 3},
    {"US433",  FREQ_HZ_TO_REG_VAL(433250000), FREQ_HZ_TO_REG_VAL(438000000), 8},
    {"US433W",  FREQ_HZ_TO_REG_VAL(423500000), FREQ_HZ_TO_REG_VAL(438000000), 20},
};
```

Fig. 5. Example of changing the FHSS.cpp file

TECHNICAL LIMITATIONS

The LR1121 operates in the 150 MHz to 960 MHz, 1.9-2.1 GHz satellite band and 2.4 GHz ISM band. The SX128x is capable of low power operation in the 2.4 GHz ISM band. It is important that the antennas and amplifiers support the selected frequency bands to ensure optimal system performance. Improperly selected components can significantly reduce signal transmission efficiency, increase noise levels, or even cause equipment damage. Therefore, when designing a radio communication system, special attention should be paid to ensuring that the antennas and amplifiers are compatible with the frequencies at which the transmitter and receiver operate, providing maximum sensitivity and immunity to interference.

Table 1. Characteristics of Semtech SX127x chips [1]

Part Number	Frequency Range	Spreading Factor	Bandwidth	Effective Bitrate	Est. Sensitivity
SX1276	137 - 1020 MHz	6 - 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to -148 dBm
SX1277	137 - 1020 MHz	6 - 9	7.8 - 500 kHz	0.11 - 37.5 kbps	-111 to -139 dBm
SX1278	137 - 525 MHz	6- 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to -148 dBm
SX1279	137 - 960MHz	6- 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to -148 dBm

CONCLUSIONS

In the current environment of electronic warfare and the growing requirements for the reliability of unmanned systems, the issue of designing custom radio communication modules at atypical frequencies is becoming critical. The use of open-source technologies such as ELRS makes it possible to flexibly adapt the system to the needs of the operator, in particular, to change frequencies to bypass jamming in combat. At the same time, to ensure effective operation of the system, it is necessary to carefully select components, such as antennas, amplifiers, and filters, which must support the selected frequency range to achieve a stable and clear signal. Working with frequencies around 433 MHz offers significant potential for providing robust communications in a saturated electronic environment. Creating your own TX/RX modules based on affordable solutions such as LILYGO® TTGO LoRa32 opens up new horizons in the development of radio systems for unmanned aerial vehicles. This approach avoids the limitations inherent in standard frequencies and provides independence and flexibility in critical environments, which is an important factor for the successful completion of combat missions.

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Проектування модулів радіозв'язку для БПЛА з використанням нетипових частот

Юрій Хлапонін, Володимир Мироненко

Анотація. Триваючий конфлікт в Україні продемонстрував значну трансформацію у веденні війни, де традиційні військові стратегії все більше доповнюються цифровими технологіями, зокрема безпілотними літальними апаратами (БПЛА). У цій статті досліджується проєктування радіокомунікаційних модулів для БПЛА, що працюють на нестандартних частотах, з акцентом на виклики, спричинені російською тактикою радіоелектронної боротьби (РЕБ), яка систематично порушує роботу традиційних цивільних радіочастот. Використовуючи альтернативні частоти, БПЛА можуть підтримувати надійний зв’язок навіть в умовах електронного протистояння. У статті подано огляд сучасних систем зв’язку для БПЛА, таких як ExpressLRS (ELRS), та їхніх обмежень в умовах сучасних бойових дій. Далі детально розглядається технічний процес розробки індивідуальних модулів передавача (TX) і приймача (RX) із використанням технології LoRa (Long Range) та компонентів, таких як плата LILYGO® TTGO LoRa32 V2. Особливу увагу приділено вибору відповідних мікросхем RF, підсилювачів, антен і фільтрів для оптимізації роботи на частотах, таких як 433 МГц, які менше піддаються впливу радіоелектронної боротьби. Такий підхід дозволяє створювати надійні, адаптивні системи зв’язку, забезпечуючи більшу гнучкість і незалежність для БПЛА в критичних операційних умовах. У висновку статті висвітлюються перспективи подальшого вдосконалення системи та її масштабування для військового використання.

Ключові слова: БПЛА, радіокомунікаційні модулі, нестандартні частоти, радіоелектронна боротьба, технологія LoRa.