

Application of FPGA in Software-Defined Radio (SDR): Architecture, Advantages and Prospects

Oleksandr Vorgul
Scientific adviser

ORCID 0000-0002-7659-8796
dept.Microprocessor Technologies and System
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
oleksandr.vorgul@nure.ua

Oleh Shuniborov

dept.Microprocessor Technologies and System
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
oleh.shuniborov@nure.ua

Abstract— The paper examines the role of programmable logic integrated circuits (FPGAs) in software-defined radio (SDR) systems. The key advantages of the SDR/FPGA combination are considered: low latency, parallel signal processing, and energy efficiency. The architectural solutions of modern SDR boards (including budget RTL-SDR and professional USRP) are analyzed, as well as the specifics of implementing modulation-demodulation algorithms on FPGAs. Particular attention is paid to the use of the technology in 5G/6G, cognitive radio, and space communications. The prospects for integrating SDR with artificial intelligence and quantum communications are outlined

Keywords— SDR, FPGA, Signal Processing, Adaptive Modulation, RTL2832, Hardware Acceleration, Cognitive Radio.

I. INTRODUCTION

Software-defined radio (SDR) has revolutionized wireless communications by replacing hardware components with software algorithms. Integrating SDR with programmable logic integrated circuits (FPGAs) creates high-performance platforms for real-time signal processing. The relevance of the topic is due to the growing requirements for speed and flexibility in telecommunication systems (5G/6G, IoT), where the SDR/FPGA bundle provides unprecedented adaptability. The purpose of the work is to analyze architectural solutions, advantages and prospects for using FPGAs in SDR systems.

II. PURPOSE OF SDR AND ITS APPLICATION

SDR (Software-Defined Radio) is a radio system where traditional hardware components (filters, modulators) are implemented in software. Key advantages:

- Flexibility: Supports multiple standards (Wi-Fi, LTE, LoRa) on one platform [1].
- Versatility: Works in a wide frequency range (from kHz to GHz).
- Cost-effectiveness: Upgradeable via software update without replacing the hardware.

Application :

- Testing wireless networks (5G, IoT) [2].

- Radio monitoring and satellite communications.
- Military systems with adaptive radio channels

III. BRIEF HISTORY OF ORIGIN FOR SDR

- 1991: The term "Software" Radio" was introduced by Joseph Mitola [3].
- 1996: First military SDR system *Speakeasy* (DARPA).
- 2000s: The GNU Radio opensource platform is released.
- 2010s: Mass production of low-cost SDR receivers (RTL-SDR).
- 2020s: Development of SDR for quantum communication and AI signal processing

IV. PROSPECTS FOR THE DEVELOPMENT OF SDR TECHNOLOGIES

The evolution of software-defined radio is characterized by several strategic directions that determine its future application:

1. Integration with artificial intelligence (AI): There is a growing adoption of machine learning algorithms to automatically classify radio signal types, suppress noise, and predict channel quality [4]. This approach allows for the creation of self-adapting communication systems that optimize transmission parameters (modulation type, power, coding scheme) in real time based on the analysis of signal propagation conditions. This is especially relevant for complex environments such as industrial IoT networks or dense urban developments.

2. Supporting 5G and 6G development: The flexibility of SDR platforms, especially when combined with the computing power of FPGAs, makes them an indispensable tool for prototyping and testing new wireless technologies. Researchers use SDRs to validate complex modulation schemes (OFDMA, FBMC), massive MIMO (Multiple Input Multiple Output), medium access protocols and network architectures such as OpenRAN [4].

3. Space Communications Applications: SDR technologies, enhanced by FPGA capabilities, significantly lower the barrier to receiving and processing signals from low-orbit satellites (LEO), including telemetry from scientific microsatellites (CubeSats) and signals from commercial satellite Internet constellations (Starlink).

Hardware acceleration on FPGAs is critical to handling the wide bandwidths and complex protocols inherent in modern space communications systems.

4. Implementation of cognitive radio concepts: SDR is the technological basis of cognitive radio, capable of dynamically analyzing the radio frequency environment. Functionality includes automatic detection of free frequency channels (for example, in the TV White ranges Spaces), avoiding interference to legitimate spectrum users and adaptive selection of optimal transmission parameters. This direction is aimed at increasing the efficiency of using limited radio frequency resources.

5. Growing open-source ecosystem: There is a steady growth of the community developing open-source hardware (LiteSDR , RISC-V projects) and software (GNU Radio , gr-osmosdr) solutions for SDR. This helps democratize access to advanced signal processing technologies and accelerates innovation.

6. Research in the field of quantum radio communication: SDR platforms with FPGAs are used in experimental work on quantum communication and post-quantum cryptography, where high-precision signal processing and the implementation of specialized algorithms that are efficiently executed at the hardware level are required.

Thus, the prospects for SDR are associated with its transformation towards intelligent, self-optimizing and highly adaptive communication systems capable of solving the problems of future generations of wireless technologies .

V. POPULAR SDR BOARDS

Table 1 – Comparative characteristics of key platforms:

Device	Frequency range	Price	Peculiarities
RTL-SDR (RTL2832)	24–1766 MHz	\$20–30	Budget option. Bandwidth 2.4 MHz
ADALM-Pluto	70 MHz–6 GHz	\$200–300	Zynq-7000, MATLAB support
USRP B210	70 MHz–6 GHz	\$1500+	2×2 MIMO, professional solution
LimeSDR	100 kHz–3.8 GHz	\$400–600	5G support. Bandwidth 61.44 MHz

VI. RTL-SDR PLATFORM (RTL2832U)

1. Origin and architecture:

- The key component of the system is the Realtek RTL2832U integrated circuit . This chip was initially developed as a controller for USB tuners of digital terrestrial television of the DVB-T standard .
- In 2012, it was discovered that the RTL2832U was capable of outputting raw quadrature data (I/Q samples) directly over the USB interface, bypassing the standard video stream decoding process . This discovery, made by enthusiasts, formed the basis of the rtl-sdr.org project [5].
- Typical hardware configuration:

- Antenna input: The signal goes to the tuner module (Rafael chips are often used) Micro R820T/2, R828D or Fitipower FC0013). The module functions: signal amplification, filtering of the required frequency band and conversion (lowering) of the frequency of the received signal to an intermediate frequency (IF).
 - A/D conversion and I/Q generation: The IF signal is fed to the RTL2832U chip , which performs the digitalization of the analog signal. A critical feature is the ability of the chip to output raw quadrature data (I and Q components) from the ADC before the DVB-T transport stream demodulation and decoding stage.
 - Data transfer interface: The digitized I/Q samples are transferred to the host computer via a USB 2.0 interface . USB bandwidth limits the maximum effective bandwidth of the device to approximately 2.4 MHz (the theoretical limit is approximately 3.2 MHz).
2. Operating principle and signal processing:
- The entire process of demodulation and decoding of signals is carried out programmatically on the central processor of the host computer .
 - Specialized software (SDR#, GNU Radio , CubicSDR , HSDR, etc.) receives I/Q data stream via USB.
 - The software implements the necessary digital signal processing (DSP) algorithms: digital filtering, demodulation (AM, FM, SSB, various digital modulations), decoding of specialized protocols.
3. Areas of practical application:
- Reception of signals in VHF/LW ranges: Radio broadcasting (FM, AM), aviation communications (air traffic, ACARS).
 - Reception of satellite signals: Meteorological images from NOAA (APT) and Meteor-M (LRPT) satellites, telemetry.
 - Transportation Systems Monitoring: Receives Automatic Dependent Surveillance-Broadcast (ADS-B) signals on 1090 MHz to track aircraft.
 - Reception of meteorological data from meteorological balloons (Radiosonde): Search and decoding of telemetry.
 - Receiving paging system messages: Decoding POCSAG, FLEX protocols.
 - Educational Objectives: Learn the fundamentals of RF engineering, digital signal processing (DSP), and SDR principles at a low cost and with extensive documentation.
4. Platform limitations:
- Operating mode: Receive signals only (no transmission capability).
 - Bandwidth: Limited bandwidth (~2.4-3.2 MHz) does not allow receiving wideband signals (e.g. full DVB-T/T2 channels, 4G LTE or 5G NR signals).
 - Computational load: All signal processing is performed by the computer's central processing unit, which can lead to high load when implementing complex DSP algorithms or working with multiple virtual receivers.
 - Dynamic characteristics: The sensitivity and dynamic range of RTL-SDR are inferior to more expensive professional SDR receivers. The efficiency of

receiving weak signals depends significantly on the quality of the antenna used.

VII. SDR WITH FPGA: SPECIFICS AND ADVANTAGES

Advantages of SDR/FPGA combination:

- Low Latency: Hardware modulation processing (QPSK, OFDM) without CPU.
 - Parallelism: Simultaneous processing of MIMO channels.
 - Power efficiency : Lower power consumption than GPU/CPU [6].
- Application :
- Adaptive modulation : Dynamic QAM/OFDM switching depending on SNR (as in 5G OpenRAN).
 - Hardware acceleration : Implementation of FIR filters, FFT and FEC on FPGA is 10-100 times faster than CPU.
- Cases:
- USRP X310 (Kintex-7 FPGA): 5G Wideband Signal Processing.
 - PlutoSDR (Zynq-7000): Hardware PSK demodulation with Costas loop .
- Problems:
- Complexity of development under HDL (VHDL/ Verilog).
 - High cost of professional solutions (USRP X310).

VIII. CONCLUSIONS

FPGA integration with SDR creates high-performance platforms for real-time signal processing. Key benefits — flexibility, low latency, and energy efficiency — make this combination indispensable in 5G/6G, cognitive radio, and space communications. The development of open-source projects (LiteSDR) and AI algorithms lowers the entry barrier, expanding the application of the technology. Prospects are aimed at quantum radio communications and further optimization of hardware accelerators.

REFERENCES

- [1] Mitola J. *Software Radio Architecture: Object-Oriented Approaches to Wireless Systems Engineering*. Wiley, 2000.
- [2] Reed JH *Software Radio: A Modern Approach to Radio Engineering*. Prentice Hall, 2002.
- [3] Mitola J. The Software Radio Architecture // *IEEE Communications Magazine* . 1995. Vol . 33(5). P. 26–38.
- [4] Wang Z. et al . FPGA-based SDR Platform for 5G Prototyping // *IEEE Access* . 2021. Vol . 9. P. 118 949–118 963.
- [5] Osmocom. *RTL-SDR Documentation* . URL: <https://osmocom.org/projects/rtl-sdr> (accessed: 01.10.2023).
- [6] Farhang-Boroujeny B. *Adaptive Filters : Theory and Applications* . Wiley , 2013.
- [7] Ettus Research. *USRP X310 Product Sheet* . URL: https://www.ettus.com/wp-content/uploads/2019/01/X310_DS.pdf (accessed: 01.10.2023).
- [8] Balanis CA *Antenna Theory: Analysis and Design* . 4th ed . Wiley, 2016.