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Review article

The application of software defined radios in unmanned aerial vehicles

Marek Błachut[1]*, Piotr Pogorzelec[2]

[1] Institute of Command,
General Tadeusz Kościuszko Military University of Land Forces, Wrocław, Poland,
e-mail: marek.blachut@awl.edu.pl

[2] 133[rd] Light Infantry Battalion, Cieszyn, Poland,
e-mail: pogorz@wp.pl

INFORMATION

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ABSTRACT

The article addresses the application of software defined radios (SDR) on modern battlefields. Above all, it focuses on the application of the SDR technology in communication with unmanned aerial vehicles. It also reviews some solutions applied in the armed forces of Finland, United States, Poland, Turkey, and Israel. It outlines the potential of these solutions and considers the main direction of development of the SDR technology, which is the cognitive radio.

KEYWORDS

software defined radio, unmanned aerial vehicle, troposcatter communications, cognitive radio, spectrum occupancy

* Corresponding author

Introduction

The incredibly fast development of radio communications observed in recent years necessitates the introduction and application of more effective methods of management of the increasingly crowded radio spectrum. It is especially important for the army or, to be more precise, in the environment of ever-increasing demand for free radio frequency bands. Scientists, both civilian and military, are constantly looking for new technological methods to meet this demand. Innovative solutions are to be found in the application of smart software-defined systems, i.e. SDR-type radios[1]. Devices of this type are subject to continuous evolution which, above all, lead to the development of the so-called cognitive radio (CR) technology. The cognitive network allows for radio interfaces to be optimised under specific local, temporal, and operational conditions (for example, in difficult, often urbanised areas). Cognitive systems with in-built "intelligence" learn from the environment, which enables them to

[1] SDR stands for the software-defined radio, which is a system of radio communications, in which the operation of essential electronic components (mixers, filters, modulators, demodulators, and detectors) relies on a computer programme.

update the best transmission parameters at any given time to ensure reliable operation. They play an especially important role in the building of the co-called MANET network (mobile ad-hoc network), where the users include the operator, as well as vehicles, such as helicopters, aircraft, unmanned ground vehicles, unmanned underwater vehicles, and unmanned aerial vehicles (UAVs), commonly referred to as drones. The latter are very often used on the battlefield, especially in reconnaissance and strike activities conducted to support operations on the ground. This is why SDR radio stations are most often used to operate UAVs.

Research objectives

The aim of this article is to outline the potential for applying software defined radios in unmanned aerial vehicles. The authors have formulated the research problem as the question: To what extent SDR radios can be applied in unmanned aerial vehicles? The authors decided to solve the main research problem by formulating the following specific problems:

1. How can a software defined radio (SDR) be applied in UAVs during military operations?
2. What are the types of UAVs?
3. What was the evolution of SDR radios as cognitive radio?

1. Selected types of UAVs

UAVs are an extensive group of devices that provide a wide range of solutions. They are dedicated to various tasks. They differ in terms of structure, or technical parameters, which determines specific features of a given UAV. The parameters determine the assumed characteristics and depend on the type of constructions, which include [1, p. 60]: range, lifting capacity, handling capacity, type of take-off and landing. The basic types of UAV structures constructed in Poland and their general characteristics are listed in Table 1.

Table 1. Classification of UAVs by structure type

Structure type/ manufacturer		Advantages	Disadvantages	General view of the device
Unmanned Aerial Vehicle airframe (fixed-wing)	Silesian Aviation Cluster (Śląski Klaster Lotniczy) [2]	– long range, – high resistance	– a horizontal take-off requires a sufficient amount of space, – inferior manoeuvrability compared to vertical take-off and landing drones	
	Polska Grupa Zbrojeniowa [3]	– long range, – high resistance	– an inclined take-off requires a launcher, – inferior manoeuvrability compared to vertical take-off and landing drones	

Structure type/ manufacturer		Advantages	Disadvantages	General view of the device
Unmanned Aerial Vehicle airframe (fixed-wing)	PW-100 Warsaw University of Technology Faculty of Power and Aeronautical Engineering	– long range, – high resistance	– an inclined take-off requires a launcher, – inferior manoeuvrability compared to vertical take-off and landing drones	
Unmanned Aerial Vehicle airframe (fixed-wing)	FT-5 Łoś Flytronic by WB Group [4]	– long range, – high resistance	– an inclined take-off requires a launcher, – inferior manoeuvrability compared to vertical take-off and landing drones	
Unmanned airframe aircraft with rotor rotation capability	ekoSKY built by the Wrocław University of Science and Technology [5]	– combines an unmanned aircraft and the benefits of vertical takeoff and landing	– technologically complex, – relatively expensive	
Unmanned helicopter	ILX-27 Institute of Aviation in Warsaw, the Military Aviation Works No. 1 [6]	– vertical take-off and landing, – high manoeuvrability	– maintenance requirements	
Unmanned helicopter	UAVS Poland [7]	– vertical take-off and landing, – high manoeuvrability	– maintenance requirements	
Unmanned helicopter	Wabik Warsaw University of Technology, Faculty of Mechatronics and Aviation [8]	– vertical take-off and landing, – high manoeuvrability	– maintenance requirements	
Multicopter	Atrax Air Force Institute of Technology [4]	– affordable, – easy to steer, – low weight	– limited load capacity, – may be susceptible to wind	

Source: Own elaboration based on [2-8].

2. Application of SDR technology in UAVs during military operations

The progressing development of UAVs, as well as the growing requirements and demand of the battlefield have resulted in the combining of functions with specific tasks. The classification of UAVs has been illustrated in Figure 1. UAVs are designed to perform diverse tasks. The main requirements are that they cover significant distances to achieve pre-determined goals, for example, reconnaissance [9, p. 10-11].

The application of UAVs focuses on the following types [9, p. 11]:

1. Micro (weight up to 150 kg) – with mission range up to 5 km and Line of Seeing (LOS) – up to 60 m:
   – Mini (weight up to 150 kg) – with mission range up to 25 km and LOS up to 305 m, e.g. Aladin, Orbiter, Raven;
2. Small (weight up to 150 kg) – with mission range up to 50 kg and LOS up to 366 m:
   – Tactical (weight between 150 and 600 kg) – with mission range up to 200 km and LOS up to 915 m, e.g. Scan Eagle, Aerostar, RQ-7 Shadow 2000,
   – MALE – Medium Altitude Long Endurance (weight over 600 kg) – with unlimited mission range BLOS (Beyond Line of Seeing) and line of seeing up to 12192 m, e.g. Predator R/MQ-1, MQ-9 Reaper, Heron,
   – HALE – High Altitude Long Endurance (weight over 600 kg) – with unlimited mission range (BLOS) and line of seeing up to 19812 m, e.g. Global Hawk.

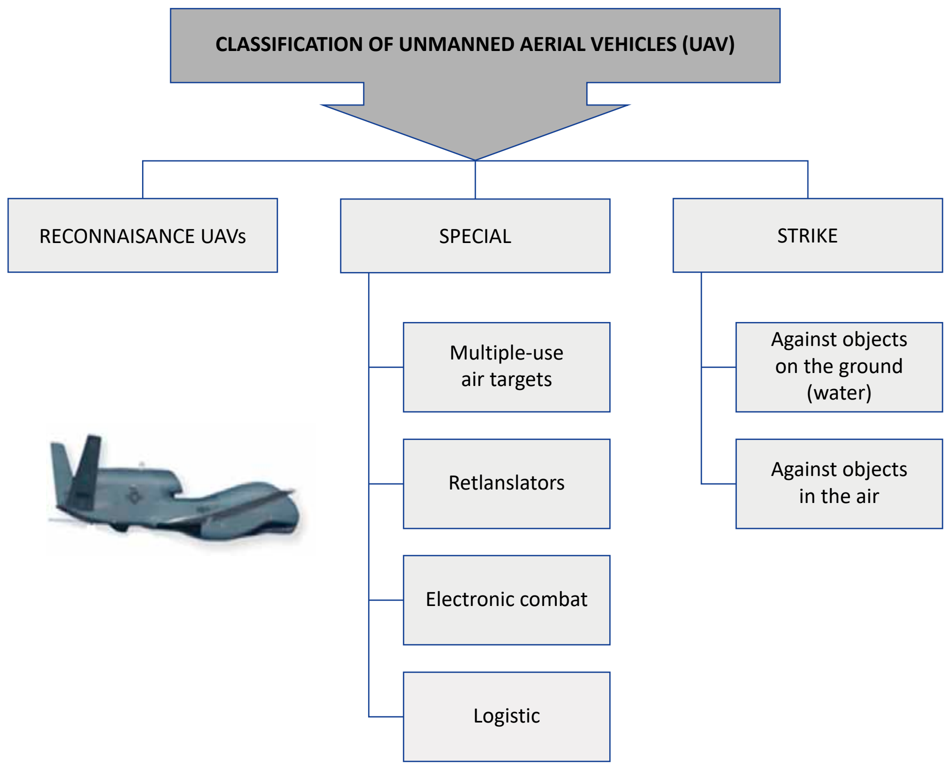

Fig. 1. UAV: classification according to purpose
Source: [9, p. 10-11].

The application of appropriate transmission (radio communication) in the above-mentioned types of UAVs is dependent on the environment in which they are expected to perform their tasks. In communication with UAVs (medium category) operating on distances of a few hundred metres, long range communication is the preferred solution. It is based on X or Ku bands, as in, for example UAVs of the Predator or Raptor type. Additionally, UAVs are equipped with the RC FPV (Remote Controlled First-Person View) function. The function means that the operator has a real time view from the camera (which is usually situated at the front of the model). The image is displayed on a portable monitor or video goggles [10, p. 22-23]. It is worth noting that the SDR technology is quite often used for this purpose.

The satellite communication system in UAVs that relies on devices supplied by the Israeli company Elbit Systems consists of devices using the Starlite Data-Link (SDL) SDR. SDR provides flexible and highly efficient digital wireless communication systems. Moreover, it is completely secure, as it supports encryption as well as frequency hopping. It also enables communication in multiple frequency bands and offers simultaneous support for up to two video sources [11]:

1) H.264 video encoding-decoding for PAL/NTSC,
2) HD-SDI and high definition video and audio transmission from the platform to ground.

The SDL system ensures seamless integration with tactical video systems (vehicle mounted or portable-hand-held), existing and future applications, and cross-layer interoperability [11]. Depending on the purpose, the system is made up of platforms which were presented in Table 2.

In addition to satellite communications, tropospheric communications are also used for UAVs. This solution is exemplified by the US communications system AN/TRC-170, the latest version of which uses the SDR technology for the delivery of communication. Version 1 of the AN/TRC-170 communications system is illustrated in Figure 2.

This type of communication enables data transmission and *semi* real-time exchange of information over the distance of up to 1000 km. It is worth noting the use of tropospheric radio, which is equipped with a very large antenna that enables the detection of very weak signals. This makes it possible to receive data directly from UAVs flying at a distance of 150-200 km (with a guarantee of adequate capacity) [16]. Domo Tactical Communication is the leader in the US market for communications and COFDM (Coded Orthogonal Frequency Division Multiplexing) transmission systems for UAVs, offering the SDR technology, i.e. SOLO8 devices. High speed of data transmission in the applied solutions is ensured through increased range, which means that in drones it is achieved through the so-called Beyond Visual Line of Sight (BVLOS) using the Tactical IP Mesh network. It was presented in detail in Figure 3 downlink COFDM Point-to-Point solution was shown in Figure 4.

The above-mentioned solutions are characterised in Table 3.

The delivery of the so-called video stream transmission is in both cases based on SDR SOLO8 devices. The devices form a flexible, miniature digital COFDM digital transceiver platform, designed for transmitting from UAVs, as well as unmanned vehicles. The system (devices) is available in many sizes The platform can be configured as:

– transmitter,
– receiver,
– double encoder,
– standard IP network,
– MIMO IP Mesh.

Table 2. Platforms forming the Starlite Data-Link system

STARLITE DATA-LINK SYSTEM				
	STARLITE SR	**STARLITE MR**	**STARLITE ER**	**ELAD-10**
Core functionalities	– advanced short-range digital data link system, – designed for small manned and unmanned platforms, – the lightweight system is suitable for mini-UAVs and hand-held trans-mitter-receivers	– advanced mid-range digital data link system, – designed for manned and un-manned aerial, maritime, and mid-range land platforms, including medium UAVs, – lightweight, com-pact system	– advanced digital wireless communi-cation system with an extended range, in sight, – designed for long range manned and unmanned aerial, maritime, and land platforms, including MALE type UAVs	– designed for large manned and un-manned platforms, – LOS wireless com-munication system for MALE/HALE type UAVs, – the system enables flawless long range communication in the air, on sea, and on land
PARAMETERS				
Data trans-mission	up to 8 Mbps (full duplex)		up to 12 Mbps (full duplex)	up to 45 Mbps (full duplex)
Transmission encryption	AES-256 bit (COMSEC) (TRANSEC)			double encryption AES-256 bit (COMSEC) (TRANSEC)
Range	around 70 km	around 150 km	around 250 km	over 300 km
Communication bands	L S C	S C	L S C	S C X Ku
				
				

Source: [11-15].

Fig. 2. Tropospheric communications system AN/TRC-170
Source: [16].

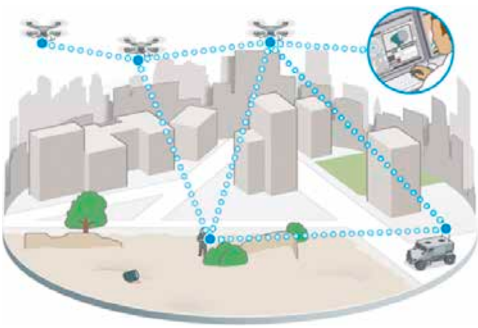

Fig. 3. Tactical IP Mesh – technology for UAVs
Source: [17].

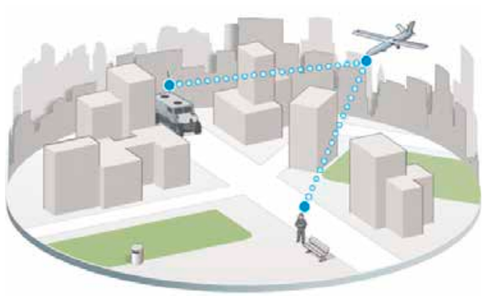

Fig. 4. Downlink COFDM Point-to-Point solutions for tactical UAVs
Source: [17].

Table 3. Communications technologies for UAVs applied in devices produced by Domo Tactical Communication

TECHNOLOGIES AND THEIR CHARACTERISTICS	
Tactical IP Mesh	**Downlink COFDM Point-to-Point**
– excellent range and no line of sight option, – up to 80 nodes operating simultaneously on a single frequency in the network, – bandwidth of up to 87 Mb/s, – each node can operate as a source of data and as repeater, – IP network allows for connecting any general IP device, – optional full AES encryption	– one-way transmission of video, audio, and RS232 data through COFDM RF, – excellent range and NLOS capacity, – Narrowband type (2.5 MHz, 1.25 MHz, 0.625 MHz) ensures excellent spectrum efficiency, – low latency (below 25 ms) for critical applications, – optional full AES encryption, – applying solutions with low power consumption levels ensure longer mission life

Source: [17].

Specific devices making up the SOLO8 systems are characterised in Table 4.

Table 4. SDR SOLO8 devices forming the system for data and video transmission from UAV

SDR SOLO8 RADIO SYSTEM				
	SOL8SDR2x2W-P	**SOL8SDR-R (C)**	**SOL8SDR-H**	**SOL8NNVHDR**
PARAMETERS				
Output capacity (CODFM)	2×2 W	2×100 mW	2×2 W	
Output capacity (telemetrics)	+11 dBm (dependent on frequency)			
Core functionalities	– telemetric transceiver in the ISM band for control, PTZ, and standby with low power consumption, – dual SD/HD-SDI inputs for recording, transmission, and analysis, – USB support for peripheral devices, such as 3G/4G/Wi-Fi cards, – Ethernet, RS232, and RS485 connectivity, – in-built 128 GB memory, – power consumption: approx. 12.5 W	– dual, independent HD H.264 video encoders, – telemetric transceiver in the ISM band for control, PTZ, and standby with low power consumption, – dual SD/HD-SDI inputs for recording, transmission, and analysis, – USB support for peripheral devices, such as 3G/4G/Wi-Fi cards, – Ethernet, RS232, and RS485 connectivity, – in-built 128 GB memory, – IP66 protection rating, – power consumption: approx. 7.5 W	– dual, independent HD H.264 video encoders, – low latency – less than 180 ms for video, less than 20 ms for data, – USB support for peripheral devices, such as 3G/4G/Wi-Fi, – Ethernet, RS232, and RS485 connectivity, – in-built 128 GB memory, – low power consumption, between 7.5 W and 10 W, – battery life – 5 hours for 12 Mb/s; data only (12 hours for sound), – NLOS range: max 15 km	– configurable reception method, – DTC COFDM support, – DTC Mesh support, – two-way telemetry option, – recording storage option, – IP68 protection rating
				

Source: [17, 18].

The outcome of the work on tropospheric communication in Poland is the project entitled *Use of tropospheric communications to increase the range of unmanned aerial vehicles – UAVs*. Its purpose is to conduct industrial research and development work to expand the communication range for unmanned aerial vehicles (UAVs). It was initially assumed that the range would be extended to 150 km, however, research trials showed that it would definitely be much greater than that [16]. The Digital Troposcatter Modem MTR – 700A-01 manufactured by Transbit is an element of that system. It is depicted in Figure 5.

The device is a modem that operates on the basis of the SDR technology and implements advanced digital processing methods, while enabling the bandwidth up to 20 Mb/s. It uses a range of technologies to guarantee reliable connectivity. Detailed technical parameters of the device are presented in Table 5.

Fig. 5. Digital Troposcatter Modem MTR – 700A-01
Source: [19].

Table 5. Parameters of the Digital Troposcatter Modem MTR – 700A-01

PARAMETERS	
Frequency range	4400-5000 MHz
Tuning step	1 MHz
Number of TX levels	2 (TX-1, TX-2)
Number of RX levels	2 (TX-1, TX-2)
Modulation	BSK, QPSK
Power consumption	<200 W
Connection interfaces	10/100Base-T/TX, 10/100Base-FX
User interfaces	SNMPv3, WWW, Command line
BASIC FUNCTIONAL CAPACITIES	
– adaptive control of received signal (ALPC – Adaptive Link Power Control), – corrective coding with 1, 1/2, 2/3, 3/4, 7/8 efficiency (FEC – Forward Error Correction) – automatic adjustment of bandwidth to propagation conditions (ACR – Automatic Code Rate), – built-in non-linearity correction path for "Predistortion" type power amplifier	

Source: [19].

The use of the tropospheric system for long-range UAV communication can expand the range from 10-20 km to 60-70 km for small-sized models, from 20-35 km to 120-130 km for middle-sized ones, and from 35-40 km to 150-170 km for large-sized models. This type of communication seems to have special significance in the operation of coastal missile squadrons and HIMARS missile batteries. They require the UAV to identify targets located over 200 km away.

Transbit has presented another solution for UAV connectivity, namely, the PAXLINK-M series of aircraft radio lines shown in Figure 6.

Fig. 6. PAXLINK-M radio line antenna
Source: [20].

This radio line is based on SDR technology and allows two-way telemetry communication and real-time video transmission from UAVs to the ground station. The PAXLINK-M radio line architecture is based on SDR technology, which makes it possible to implement any waveform[2] in accordance with the requirements of the user. The flexible design of the device enables the implementation of additional functionalities, such as cryptography and security in the field of electronic warfare (frequency hopping). Also, the radio line allows the transmission of compressed PAL-type video. The hardware solution makes it possible to connect to three sources of analog PAL-type signal "composite" or one source working in the "component" mode. The second type of video source is the digital HDMI interface. Two HDMI digital inputs are available on the platform-mounted module, which makes it possible to connect a day or IR camera that operates in FULL HD or lower resolution. The video stream is compressed in the H-264 standard and the user can select compression parameters, such as [20]:

1) resolution,
2) frame rate,
3) keyframe interval,
4) jitter-delay.

The telemetry data channel is independent (to minimise delay) of the video channel and the maximum telemetry data rate is over 40 kb/s [20].

Detailed parameters of the PAXLINK-M platform are presented in Table 6.

The PAXLINK-M platform is used by NeoX unmanned aerial vehicles and mini-planes as well as Atrax-type rotorcraft [21]. Both Atrax and NeoX operate based on the same operator consoles, they share a communication, control and data exchange system. Both systems are also highly automated [22]. NeoX and Atrax devices are shown in Figure 7.

In SDR radio communication, Turkish Baykar TB2 is used, manufactured by Baykar. The system is presented in Figure 8.

[2] Means software – an application with which the SDR hardware platform can make a connection in a specific communication standard. For example, GSM waveform running on SDR hardware enables the connection to be made in the standard of GSM cellular system.

Table 6. PAXLIN-M radio parameters

PARAMETERS	
Frequency range	any frequency sub-band within the 200-6000 MHz range
Operating mode	time-division (TDD), mixed FDM and TDD
Transmission encryption	based on AES256 algorithm
Data transmission range	in open terrain, video transmission from a distance of over 20 km (at 500 m ceiling)
Video and telemetry streaming	in real time
Power consumption	up to 10 W
Communication interface	Ethernet, USB 2.0, serial port, HDMI

Source: [20].

Fig. 7. NeoX Squadron, Atrax and PAXLINK-M communications system
Source: [22].

The communication system is based on the BSI-101 device and it depends on the type of waveform used in it. Everything is based on a software-defined radio architecture. The BSI-101 device can be adapted to the specific needs of ELINT and COMINT systems. The parameters of the device may vary depending on the need (type) of application. The device and the differences resulting from the application are presented in Table 7.

Fig. 8. UAV control system Baykar TB2
Source: [23].

Table 7. Basic parameters and a photo of the BSI-101 device

BASIC PARAMETERS		
	System for ELINT	**System for COMINT**
Frequency range	10 MHz to 40 GHz	10 MHz to 6 GHz
Inter-channel spacing	500/100/80/40/20/10/5/1 MHz	200/100/80/40/20/10/5/1 MHz
		

Source: [23].

The device enables UAVs to achieve a range of up to 150 km and an operating altitude of 7 km. Moreover, it enables the real-time transmission of high-resolution images from day/night cameras and infrared cameras [23]. Having analysed publications and press sources, it can be noticed that the latest versions of UAVs are marked as Baykar TB2S. The latest device uses a satellite connection from the Turkish company CTech, which makes it possible to transfer data at a level exceeding 20 Mb/s. This enables transmission of, inter alia, high-resolution real-time images from on-board optoelectronics and other data from on-board systems. The range of radio systems has also doubled technically [24].

Another example solution is the Tough SDR Vehicular radio by Bittium from Finland. The device can be installed on vehicles. This model is a tactical 2-channel radio that makes it possible to generate and share real-time information about the situation (location, image, voice, video, sensor data and UAV data) at all levels of organisation (command security). It has flexible configuration options and routing networks, capable of handling up to thousands of devices in one network. The use of several waveforms, even working simultaneously in this device, improves compatibility, which enables operation on different levels and missions.

Tough SDR Vehicular radio is presented in Figure 9.

Parameters of Tough SDR Vehicular personal radio are presented in Table 8.

Fig. 9. Tough SDR Vehicular personal radio
Source: [25].

The device operates based on the following waveforms:

1) Bittium TAC WIN Waveform,
2) Bittium Narrowband Waveform.

The device also works with the international European waveform: ESSOR High Data Rate Waveform (HDRWF).

The functionalities of the waveforms are briefly described in Table 9.

In addition to radios by Bittium, it is worth mentioning the development of a family of software-defined radio lines, which combined with the above-mentioned Tough SDR

Table 8. Basic parameters of Tough SDR Vehicular radio

PARAMETERS	
Frequency range	ANT1: 225 MHz to 2500 MHz ANT2: 30 MHz to 512 MHz
Radio channel frequency	ANT1: 25 kHz to 10 MHz ANT2: 25 kHz to 5 MHz
Wireless interface	GPS, WLAN 802.11 b/g/n, BT 4.1, LTE
Output power	ANT1: 40 W ANT2: 50 W
BASIC FUNCTIONAL CAPACITIES	
– implementation of ESSOR veveforms enables operation with most other SDR radios, – possibility of creating extensive, self-organising MANET networks, – possibility to upload and integrate C2 software (Command and Control), e.g.: BMS or Blue Force Tracking, – possibility of operating on a commercial LTE network, with the use of detachable LTE module	

Source: [26].

Table 9. Basic functionalities of waveforms: Bittium TAC WIN Waveform, Bittium Narrowband Waveform and ESSOR High Data Rate Waveform

WAVEFORMS AND THEIR BASIC FUNCTIONALITIES		
Bittium TAC WIN Waveform	**Bittium Narrowband Waveform**	**ESSOR High Data Rate**
– connects users within a tactical broadband network that enables real-time calls, messages and data transfer across the network, – high data transmission speed, – slow/fast frequency hopping, – time distribution in the network via radio interface, – optimised interference elimination algorithms, – supported bandwidths: 5/10/20 MHz, – QoS support, – supports up to 1000 nodes in one network	– reliable transmission and reception of voice and messages from the command network even with large communication distance and in overloaded networks, – allows to create a tactical network for soldiers and vehicles (typical network size up to 25 devices), – voice priority in CNR operation mode, – radio silence, – frequency hopping, – data encryption	– enables broadband data transfer, collaboration and direct communication between different national troops in coalition operations from the patrol team level, – enables the creation of/operation in an interoperable, safe, radio-based MANET transmission network, – enables operation in an expandable frequency range of 225-400 MHz, – 1.25 MHz bandwidth operation, – automatic establishment of parallel communication on different frequency channels

Source: [27-29].

radios form Bittium Tactical Wireless IP Network (TAC WIN), and can also be used to control UAVs. The radio line elements that make up the aforementioned system are presented and described in Table 10.

Table 10. Software-defined radio lines by Bittium

DESCRIPTION OF TECHNICAL CAPABILITIES OF SOFTWARE-DEFINED RADIO LINES BY BITTIUM		
Bittium TAC WIN Radio Head I	**Bittium TAC WIN Radio Head III**	**Bittium TAC WIN Radio Head IV**
Creation of a mobile ad hoc network (MANET), which is an optimal solution for soldiers located in a relatively small area who require a mobile and flexible network	Creation of a point-to-multipoint network, which is an ideal solution for access networks to provide services from the link network to Bittium TAC WIN MANET	Creation of a radio link network that ensures high capacity connections to a command centre or to a backbone network
– 225-400 MHz frequency band, – signal bandwidth of 5 MHz, – data throughput (Bittium TAC WIN Waveform): 12 Mb/s, – supports 2×2 MIMO, – 250 kHz inter-channel spacing, – transmitter power 2×4 W (TAC WIN Waveform), – passive cooling	– 1350-2400 MHz frequency band, – signal bandwidth of 5/10 MHz, – data throughput (Bittium TAC WIN Waveform): 26 Mb/s, – 250 kHz inter-channel spacing, – transmitter power 4 W (TAC WIN Waveform), – passive cooling	– 4400-5000 MHz frequency band, – signal bandwidth of 5/10/20 MHz, – data throughput (Bittium TAC WIN Waveform): 50 Mb/s, – 250 kHz inter-channel spacing, – transmitter power 4 W (TAC WIN Waveform), – passive cooling
		

Source: [30-32].

Due to the growing demand in contemporary areas of operation, UAVs are becoming the main reliable equipment used in dedicated military operations. When it comes to the use of SDR technology to secure reliable communication for UAVs the shrinking radio band resources are taken into account. This technology requires constant improvement of communication systems in the control of UAVs. The solution to those problems, and other ones, may be the application and development of cognitive radio technology, i.e. self-learning radio.

3. Evolution of SDR technology – cognitive radio

Cognitive Radio (CR) is a new solution and better use of the electromagnetic spectrum of radio signals. This, in turn, makes it possible to achieve the maximum evolution of traditional radio, as shown in Figure 10.

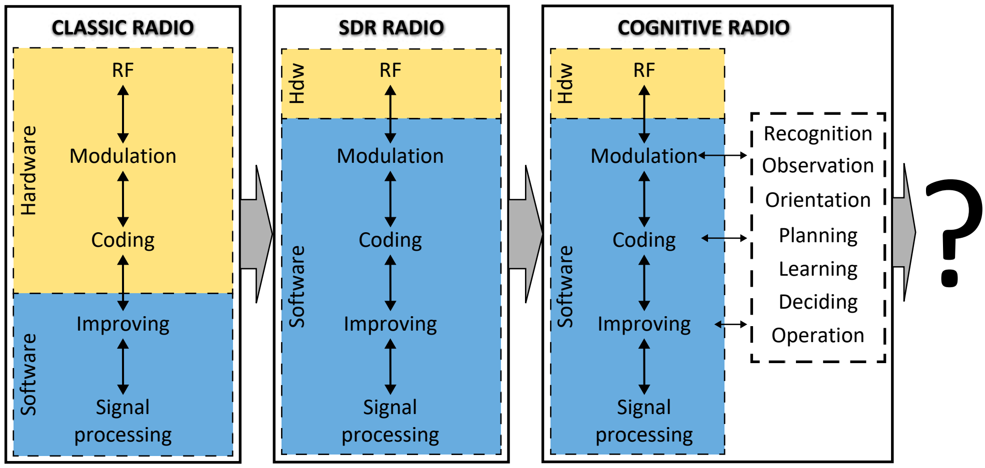

Fig. 10. Development of SDR technology
Source: Author's own elaboration.

It can be noticed that, technically, cognitive radio is an intelligent transmitter/receiver (transceiver) that can, in a programmed manner, recognise in real time the level of use of transmission (communication) channels of different frequencies and select those that can ensure the best quality of connection [33].

The concept of cognitive radio was introduced by Joseph Mitola III in his doctoral thesis, and earlier, in an article in IEEE Personal Communications published in 1999 [34, p. 246]. Cognitive radio can be defined as a self-organising radio system that collects information about the environment, "learns" and uses the collected information to change its operation to achieve predefined goals. This allows the use of the radio spectrum in a dynamic way, as opposed to the traditional, static use [35, p. 33]. This also enables more flexible and efficient use of the frequency spectrum. The technology is based on complex algorithms that analyse the bandwidth occupancy in the surroundings, and thus, it independently selects the frequency band and appropriate type of radio interface to enable communication. Cognitive radio enables automatic selection of frequency and modulation due to propagation properties [36, p. 195]. Thus, a device with this technology is able to analyse the environment (examine the entire frequency spectrum), in an intelligent and systematic way, with the use of a transceiver module. Moreover, it is able to adapt automatically. SDR, in turn, is another technology that radically changes the way radio connections work [37]. To perform the above-mentioned functions, cognitive radio uses three types of "parameters", presented in Figure 11.

The above-mentioned parameters have a significant impact during the implementation of cognitive communications in the so-called cognitive cycle. This cycle consists of the following stages:

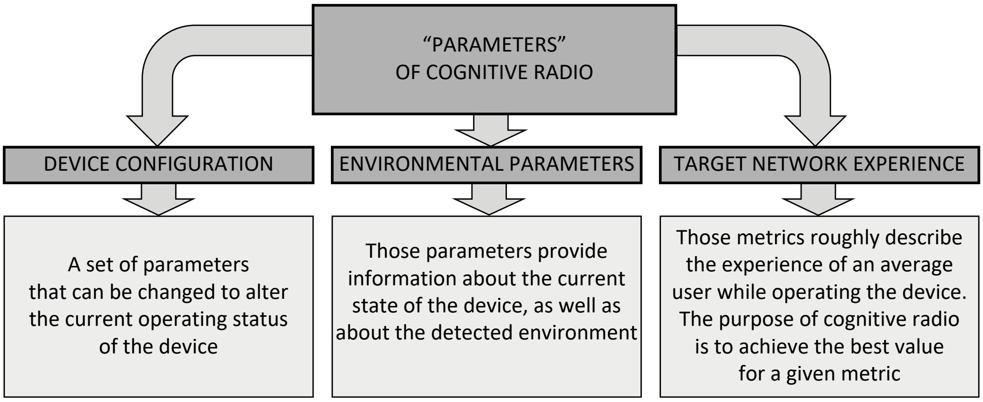

Fig. 11. "Parameters" of cognitive radio
Source: Own elaboration based on: [38, p. 291].

1) Observe – the beginning of the cycle is the analysis of external stimuli to extract the contextual cues contained in them that are necessary to perform the assigned tasks, which is included in the observation stage of the cognition cycle. This allows to determine the degree of importance of the call in the context of the need to establish communication and perform the necessary tasks;
2) Get oriented – determining how urgent it is to establish communication;
3) Plan – generating, developing and assessing alternative activities;
4) Decide – allocating computing and radio (spectrum) resources to subordinate software (conventional radio);
5) Act – initiating tasks using allocated resources for a specified period.

A graphical representation of the cognitive cycle is shown in Figure 12.

The basic practical element of the developed concept of cognitive radio is the recognition of the occupancy status of the radio spectrum and starting transmission in the section of the spectrum that is currently available without causing interference to other users. Recognition of the occupancy status of the radio spectrum is possible by means of:

1) physical detection of radio signals (sensing),
2) cognitive pilot channel (CPC),
3) geolocation databases.

The processes are described in Table 11.

To sum up, cognitive radio has all the advantages of programmable radio, i.e. flexibility of operation in various environments, standards or networks through the possibility of software reconfiguration. Other important advantages include: the ability to detect available resources of the spectrum and then use them opportunistically. This leads to better resource utilisation and greater spectral efficiency in the radio system or network. With advanced and intelligent decision-making and learning, cognitive radio adjusts its operation, in an optimal (or nearly optimal) way, to the conditions of the radio environment. This results in high-quality transmission by secondary users while protecting it [41, p. 84]. The presented features seem extremely desirable while creating reliable radio networks used on the modern battlefield and to control unmanned flying, riding or floating devices.

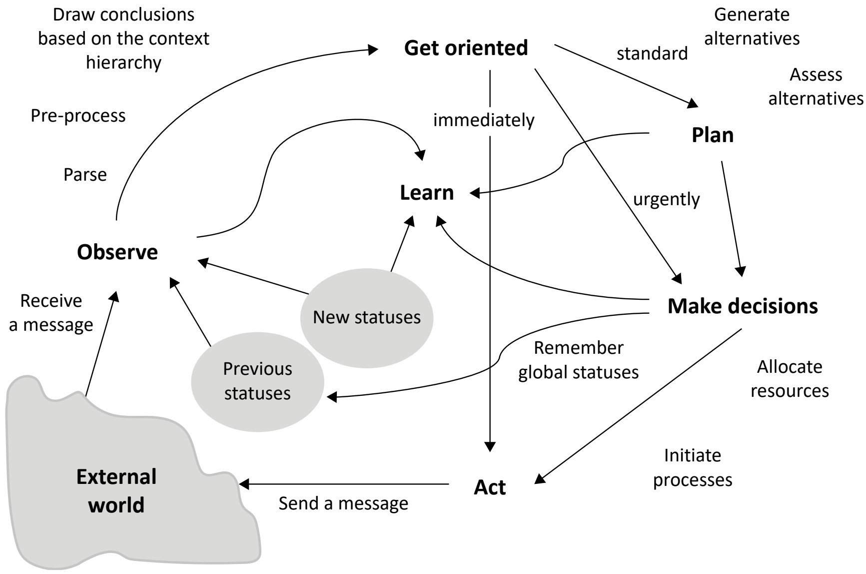

Fig. 12. Cognitive cycle
Source: Own elaboration based on the concept of Joseph Mitoly III.

Table 11. Methods of identifying occupancy status of radio spectrum

METHODS OF IDENTIFYING OCCUPANCY STATUS OF RADIO SPECTRUM
Physical detection of radio signals
It is the process of detecting radio signals emitted by other, closely located radio transceivers, determining own location and the location of other radio transceivers or radios. However, for the data collected by CRs to be complete, information on the rules and restrictions of a relevant band is also required. The collected data is then used by CR to prepare a "map". When it comes to the preparation of the "maps", there might be some problems, for example, physical obstacles which make it difficult for a cognitive radio to detect the transmission of another user in the same frequency range and, consequently, CR may "conclude" that a given spectrum is available but there may be harmful interference.
Cognitive pilot channel
In this case, the device obtains information on the state of the spectrum by receiving data transmitted by a radio beacon via a special channel that is used to transmit such information – the so-called CPC. This signal indicates the level of occupation of the channel(s) in a given frequency range and may also be the source of other types of information related to the possibility of using the band (e.g. signal levels, timing, etc.). It is also possible for other stations, which are able to identify the occupancy status of radio spectrum and which are not related to the priority user, to transmit the signal via the CPC channel (e.g. spectrum monitoring stations). However, when it comes to that method, a significant problem is the need to allocate (and protect) a radio band dedicated exclusively to the CPC channel and the need for simultaneous spectrum *sensing*. Also, due to the difficulty of coordinating and agreeing internationally on a single common frequency band dedicated to the CPC channel, the technique is not widely used.
Geolocation databases
They contain information on available frequency bands in relation to a specific location. This is the most reliable method among all methods of detecting the availability of resources but it can be used only with low dynamics of changes in that availability. Databases cannot be modified too often and too dynamically to be a reliable source of information.

Source: Own elaboration based on: [39, p. 46; 40, p. 35; 41, p. 51].

Conclusions

Cognitive radio is undoubtedly the technology of the future. In the future, it can solve problems that arise with constantly evolving networks, new diverse radio interfaces and increasing demands of the users of systems that involve UAVs. Those requirements can only be met by intelligently-managed radio networks, i.e. cognitive networks. The protection of the network against intentional interference with the use of cognitive radio will be based on the following distinctive characteristics:

1) flexibility – i.e. changes to the signal structure and network configuration,
2) efficiency – changes in used operating frequency bands,
3) recognition – ensuring monitoring of the status of the system,
4) reconfigurability – ensuring connectivity between multiple nodes with relatively high network capacity.

The above-mentioned properties ensure reliable communication with the use of many devices and in various radio networks, also when communicating with UAVs. Combining the features of SDR and CR radios allows increasing the communication range of UAVs. In addition, the level of reliability of data transmission in the operator – UAV system is increased. The SDR solutions presented in the article can definitely be applied in UAVs, as they are characterised by full configurability, reliability, resistance to interference and the possibility of adapting operating parameters to environmental conditions. The successor of SDR is cognitive radio. The technology is based on self-learning and is constantly evolving. Assessment of the functionality of cognitive radio is the subject of many studies and analyses. The Task Group IST-104/RTG-050 "Cognitive Radio" in NATO-II was established in NATO, which worked on evaluating the outcomes of the introduction of cognitive devices into service and on the effectiveness of increasing the operation of communication systems. The analysis of materials and publications of scientists who work on the development of cognitive technology allowed for the conclusion that the solution is reliable and resistant to radio-electronic interference. Application of that technology in UAVs, might be a good solution for communication. The technology enables automatic selection of frequency and modulation, taking into account the propagation conditions in which UAVs operate.

However, the current division of UAVs is determined by their structure, taking into account the parameters that define the assumed features, which depend on the type of design. The design affects the range, lifting capacity, handling capacity, type of take-off and landing. Therefore, UAVs are divided, taking into account their design, as follows: fixed-wing aircraft, tilt-rotor aircraft, propeller aircraft and multicopters. Depending on their design, the presented UAVs can be used for reconnaissance, special type and strike operations. Their various application depends on the type of task they are to perform.

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Conflict of interests

All authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Marek Błachut https://orcid.org/0000-0001-6974-7493
Piotr Pogorzelec https://orcid.org/0000-0001-9258-2535

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Biographical note

Marek Błachut – CPT, MA, graduate of the Officer Candidate School at the Military University of Land Forces in Wrocław. In 2015, he completed postgraduate studies at the Military University of Technology in Warsaw in the field of telecommunication systems and networks, as well as the organisation and operation of information systems. Between 1996 and 2015, he held a number of positions in the communications and information technology corps in the 2nd Communications Brigade and the 100th Communications Battalion. He has passed several specialist courses in the field of communications and IT, as well as obtained licences to operate equipment of types S, U, IP and R. Participant in the stabilisation mission of the Task Force White Eagle in Afghanistan. Currently, an assistant acting as the head of the Communication Systems Team at the Military University of Land Forces. Member of the Society of Admirers of 16th Elbląg Command Battalion. He is the author of publications on topics related to the development of ICT systems and devices affecting national security.

Piotr Pogorzelec – 2LT, MA, graduate of the Officer Candidate School at the Military University of Land Forces in Wrocław. He completed studies at the Bronisław Markiewicz State Higher School of Technology and Economics in Jarosław, majoring in security management. In 2019, he completed postgraduate studies at Rzeszow University of Technology in the field of management of human resources. From 2011 to 2020, he was involved in the Corps of Communications and Information Technology in the 21st Anti-aircraft Artillery Battalion in Jarosław as a WD-2001 command vehicle operator. He also completed several specialist courses in communications and IT. Currently, he performs the duties of a commander of the Command and Security Platoon in the 133rd Light Infantry Battalion in Cieszyn.

Zastosowanie radiostacji definiowanych programowo (software defined radios) w bezpilotowych środkach powietrznych

STRESZCZENIE

W artykule odniesiono się do wykorzystania na współczesnym polu walki radiostacji definiowanych programowo (SDR). Przede wszystkim skupiono się na wykorzystaniu technologii SDR do komunikowania się z bezpilotowymi środkami powietrznymi (BSP). Dokonano także przeglądu niektórych rozwiązań funkcjonujących w siłach zbrojnych

Finlandii, Stanów Zjednoczonych, Polski, Turcji oraz Izraela. Po prezentacji możliwości wcześniej wspomnianych rozwiązań przedstawiono rozważania nad podstawowym kierunkiem rozwoju technologii SDR – radiem kognitywnym.

SŁOWA KLUCZOWE radio definiowalne programowo, bezpilotowy środek latający, łączność troposferyczna, radio kognitywne, zajętość widma częstotliwości

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