Direct sequence spread spectrum: history, principles and modern applications

Nenad M. Stojanović[a], *Branislav* M. Todorović[b], *Vladimir* B. Ristić[c], *Ivana* V. Stojanović[d]

[a] Serbian Armed Forces, General Staff, Department for Telecommunication and Informatics, Center for Applied Mathematics and Electronics, Belgrade, Republic of Serbia,
e-mail: nivzvk@hotmail.com, **corresponding author**,
ORCID iD: https://orcid.org/0000-0001-9328-5348

[b] Institute for Artificial Intelligence of Serbia, Novi Sad, Republic of Serbia,
e-mail: branislav.todorovic@ivi.ac.rs,
ORCID iD: https://orcid.org/0000-0003-1932-8332

[c] University of Defence in Belgrade, Military Academy, Department of Telecommunications and Informatics, Belgrade, Republic of Serbia,
e-mail: vladarist@gmail.com,
ORCID iD: https://orcid.org/0000-0003-0422-9737

[d] „Telekom Srbija" a.d., Belgrade, Republic of Serbia,
e-mail: ivnvukanic@gmail.com,
ORCID iD: https://orcid.org/0009-0002-4216-935X

doi https://doi.org/10.5937/vojtehg72-49325

FIELD: telecommunications
ARTICLE TYPE: review paper

Abstract:

Introduction/purpose: Direct sequence spread spectrum modulation is widely used in many radiocommunications systems. At the first time, this modulation technique was used in military communications and navigation systems. Later, applications became diverse in civil communication systems as well. Today, there are many systems where direct sequence spread spectrum modulation is implemented as a part of the system. This article aims to sublimate knowledge about the direct sequence spread spectrum modulation technique and its applications.

Methods: The article presents a review of the historical development of the direct sequence spread spectrum modulation technique, its principles and the most important current applications.

Results: Based on a large number of references, this article summarizes the historical development, basic principles and modern applications of the direct sequence spread spectrum modulation in military and commercial communication systems.

Conclusion: Direct sequence spread spectrum modulation is widely used in modern wireless and satellite radiocommunications. It is expected to be part of future global communication systems.

Key words: radiocommunications, military communications, cellular mobile systems, spread spectrum, direct sequence, global positioning system, underwater acoustic communications, unmanned aerial vehicles, wireless fidelity, ZigBee.

Introduction

Spread Spectrum (SS) modulation has been developed in the middle of the 20th century. In the beginning, this modulation was developed for military purposes. Today, there are many reasons for commercial applications of SS modulation, such as: anti-jamming capability, interference rejection, low probability of intercept, multiple access capability, improved multipath and diversity reception, high resolution ranging, and accurate universal timing (Fazel & Kaiser, 2003). Also, these systems cause relatively minor interference with other systems operating in the same frequency band (Torrieri, 2015). There are also promising possibilities for its implementation in future global communication systems (Todorović et al, 2024).

In radiocommunication systems with SS modulation, the transmitted signal requires a much wider frequency bandwidth than the minimum bandwidth needed to transmit information in classical communication systems. The pseudonoise (PN) sequence is used for signal spreading at the transmitter and signal despreading at the receiver. The PN sequence, or code sequence as it is also called in SS, is independent of the data signal.

The two most commonly used SS modulations are: Direct Sequence Spread Spectrum (DS-SS) and Frequency Hopping Spread Spectrum (FH-SS) (Torrieri, 2015).

In the transmitter, a data signal arriving at the input of the transmitter is multiplied by the PN sequence generated locally. The PN sequence must have a much higher rate than the data signal. In this way, the data signal is spread. At the receiver, the incoming spread signal is multiplied by the same locally generated PN sequence which is synchronized with the PN sequence contained in the incoming signal. In that way, the spectrum of the transmitting signal is despread. In other words, the removal of the PN sequence at the receiver results in spectrum despreading and it is exploited by appropriate filtering to remove a large portion of the interference.

This paper presents: (1) the history of the DS-SS modulation technique and its application to radiocommunication systems, (2) the operating principles of the DS-SS modulation technique, and (3) an overview of modern systems, both military and commercial, using the DS-SS modulation technique. At the end of this paper, some conclusions are given.

History of DS-SS modulation technique

The first system which looks like today's DS-SS modulation appeared in 1935. Two Telefunken engineers, Paul Kotowski and Kurt Dannehl, made a device for masking voice signals. The voice was masked by combining it with a broadband noise signal produced by a rotating generator. The U.S. version of this patent (Kotowski & Dannehl, 1940), which was published in 1940, was considered as the forerunner of the DS-SS modulation technique. Kotowski and Dannehl had an idea to create a device that used key-stream generators for discrete data encryption. This patent did not mention the spreading spectrum, although there were some concepts of DS-SS modulation. These principles were implemented in radio devices in Very High Frequency (VHF) and Ultra High Frequency (UHF) bands during World War II (Scholtz, 1982).

The occurrence of DS-SS modulation is connected with the occurrence of Shannon's theory of information (Shannon, 1948). The idea was how to suppress interference and jamming signals (Scholtz, 1994).

In August 1954, a transcontinental system project called F9C (Green, 1954) commenced. The transmitter was located in Davis, California, and the receiver in Deal, New York, and based on DS-SS modulation. The system operated in a High Frequency (HF) band. A further test of the F9C system was performed in February 1955. The improvement of the system was tested in situations with and without jammers. In December 1956, the manuals for the new advanced F9C system named F9C-A were published. It was planned to make 16 pairs of transmitters and receivers and put them in final testing, but because of the limited funds of the project, only six were produced. The devices were installed in a couple of places around the world, and the testing lasted until 1959. The last version of this system was F9C-A/Rake. It had the additional implementation of a rake receiver, as a solution for ionospheric multipath propagations. The F9C-A/Rake was tested until 1962, between Hawaii and Tokyo. That system is no longer on-site, operational and supported by the United States Army (Scholtz, 1982).

The COded DOppler, RAnging, and Command (CODORAC) system was developed by Eberhardt Rechtin, Richard Jaffe, and Walt Victor

(Scholtz, 1982). In 1952, the Jet Propulsion Laboratory (JPL) of the California Institute of Technology was attempting to construct a radio command link for remote control of rocket systems. In 1953, DS-SS modulation began to be used in this project. In the period from 1954 to 1958, the radio guidance system for the Sergeant and Jupiter space programs (Mudgway, 2001) was developed from that project. In October 1958, the National Aeronautics and Space Administration (NASA) was officially established to consolidate the separately developing space-exploration programs of the United States Army, United States Navy, and United States Air Force into one civilian organization. That was the beginning of the deep space network (Scholtz, 1982).

In the NASA Apollo program, which lasted from 1969 to 1974, it was necessary to determine the precise position of the spacecraft during the journey to the Moon. Due to a great distance, frequently used pulse radars were not good enough due to excessive attenuation. To overcome that problem, a PN sequence was generated using a linear shift register with a length of up to 127 chips (the symbol of the data signal is called a bit, while a symbol of the PN sequence is called a chip). This method of signal transmission was chosen because it was easy to extract a significantly attenuated signal from the noise on the receiver, which is a very useful feature of the DS-SS modulation technique. The basic principles applied in this system are applied today in satellite communications, more precisely in the Global Positioning System (GPS) (Shirriff, 2022).

For the communication between fighter planes, the ARC-50 project was launched in 1953. The researchers who were on the CODORAC project proposed the use of DS-SS modulation for that communication. Before that time, the tactic of aero units was to keep planes in radio silence when they were in the range of radars or radio eavesdroppers. Then it was realized that upon entering the radar range, it was not necessary for aircraft to be in radio silence and therefore it was important to avoid possible radio signal interference, where the good characteristics of DS-SS modulation could be expressed. This system initially used PN sequences generated by linear shift registers with 31 registers. Later, Bob Gold proposed a way to generate PN sequences with very good cross-correlation characteristics, which was finally implemented (Scholtz, 1982).

The Joint Tactical Information Distribution System (JTIDS) was founded in 1973. It was created by the Department of Defence of the United States as a joint program office with the Air Force as an executive agent. In the beginning, their work on communication systems for military purposes was based on DS-SS modulation. Later, they also often used FH-SS in their radiocommunication solutions. The JTIDS solutions are also used by allies of the United States. Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) are used both in their network radio systems and in a combination with SS to reduce susceptibility to noise, jamming, and interception. Their equipment is highly survivable radio and meets the most stringent requirements of modern combat, providing reliable situational awareness for fast-moving forces. Great performances were shown during the Desert Storm operation. Even today, JTIDS solutions are implemented in the radio infrastructure of the North Atlantic Treaty Organization (NATO) (DTIC, 1988).

A project called SECRAL, which was realized during the 1950s, was based on DS-SS modulation and was intended for missile guidance. This project was terminated as a failure. This is only one of the known examples, and there were certainly others that were unsuccessful, but that information never reached the general public (Scholtz, 1982).

Major advances in the field of SS systems were made during the 1950s, 1960s and 1970s. Almost all researchers from that period were shrouded in secrecy because these systems were exclusively for military purposes. Some of these systemic solutions were later fully disclosed to the general public, while some never were (Malik, 2001).

Operating principles of the DS-SS modulation technique

The DS-SS modulation technique has great resistance to interference and multipath propagation. Also, it can operate in the environment of low Signal to Noise plus Interference Ratio (SNIR). Using the orthogonal code, sequences can create a system with multiple access, named Code Division Multiple Access (CDMA) in which all channels operate on the same frequency bandwidth simultaneously (Todorović, 2021).

Figure 1 shows a block diagram of the DS-SS transmitter. The spectrum is spread by the direct multiplication of the data signal, $u_m(t)$, and the PN sequence, $c(t)$, generated in the PN generator. The data signal in this case is assumed to be polar. The product of multiplication of the data signal and the PN sequence is labeled as $u_c(t)$, and that signal is further fed to the classic modulator. In the classic modulator, some of the classic digital modulation techniques are applied. PSK modulation techniques are most often used in applied systems. After the classic modulation, a DS-SS signal is obtained, and it is denoted with $u_{DS}(t)$ (Todorović, 2021).

Since the interval of the PN sequence chip is much shorter than the interval of the data bit, the chip rate defines the transmitting bandwidth.

Hence, the transmitted signal needs a much wider bandwidth than it would be necessary when only classical modulation is used.

Figure 2 shows the waveforms of the signals during the processing in the transmitter. In the example, Binary PSK (BPSK) modulation is applied.

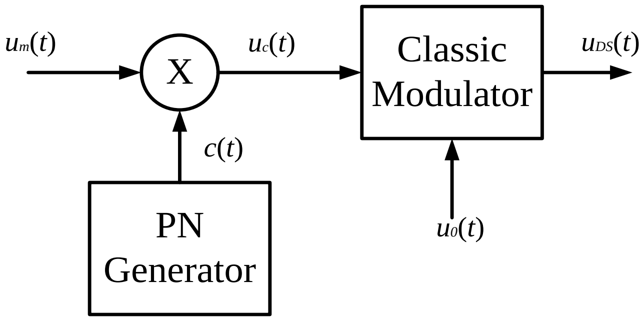

Figure 1 – Block diagram of the direct sequence spread spectrum transmitter

The processing gain or spreading ratio is an important system parameter in DS-SS systems. The processing gain is defined as:

$$PG = \frac{T_b}{T_c}, \tag{1}$$

where T_c is the PN sequence chip interval and the T_b is the data bit interval. It can be calculated also as:

$$PG = \frac{B_{DS-SS}}{B_{class}}, \tag{2}$$

where B_{class} is the frequency bandwidth necessary for signal transmission used only with the classic modulation technique and the B_{DS-SS} is the frequency bandwidth necessary for signal transmission in SS. The processing gain is more often expressed in dB as follows:

$$PG_{dB} = 10\log(PG). \tag{3}$$

The processing gain determines the level of interference protection. In modern devices, the processing gain value varies between 20 and 60 dB (Todorović, 2021).

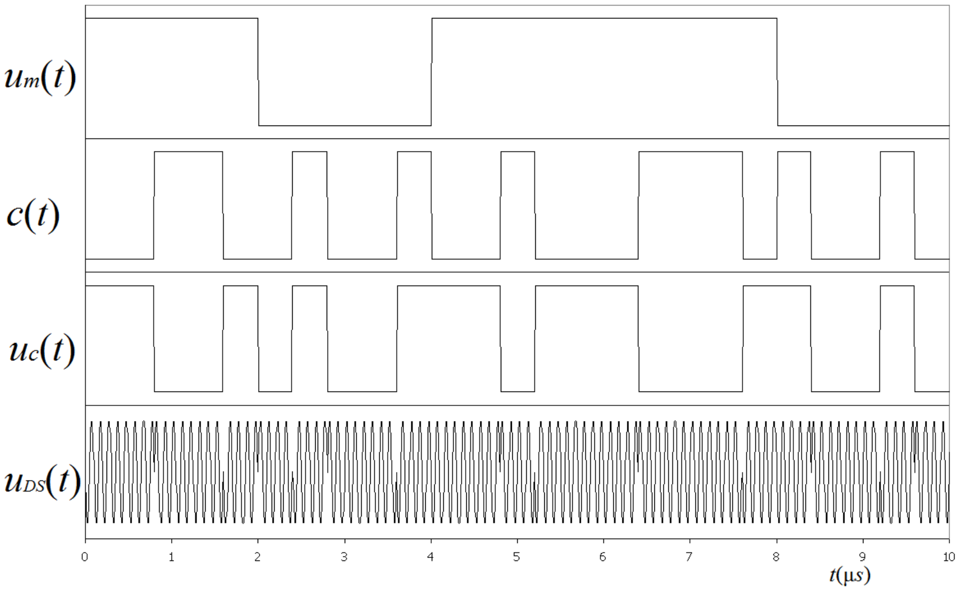

Figure 2 – Signals waveforms in the direct sequence spread spectrum transmitter

The block diagram of the DS-SS receiver is shown in Figure 3. At the receiver, the received spread spectrum signal is despread by the multiplication of signals $u_{DS}(t)$ and $c(t)$. The locally generated PN sequence has to be synchronized with the PN sequence contained in the received signal. If the two PN sequences are synchronized, the original data signal after correlation can be recovered. The aim of a bandpass (BP) filter is to remove the undesirable frequency components. Finally, classic demodulation is applied (Todorović, 2021).

Figure 4 presents the power spectral densities of the DS-SS data signal and interference before and after signal despreading at the receiver. In Figure 4 (a), the data signal is spread and its power spectral density is below the power spectral density of the narrowband interference. In the receiver, the data signal is despread by multiplying with the locally generated and synchronized PN sequence. In addition to the data signal, interference is also multiplied by the same PN sequence, thereby spreading the interference signal. The result is shown in Figure 4 (b). The data signal is despead to the bandwidth before spreading, while the interference is spread and its impact on the data signal is significantly reduced.

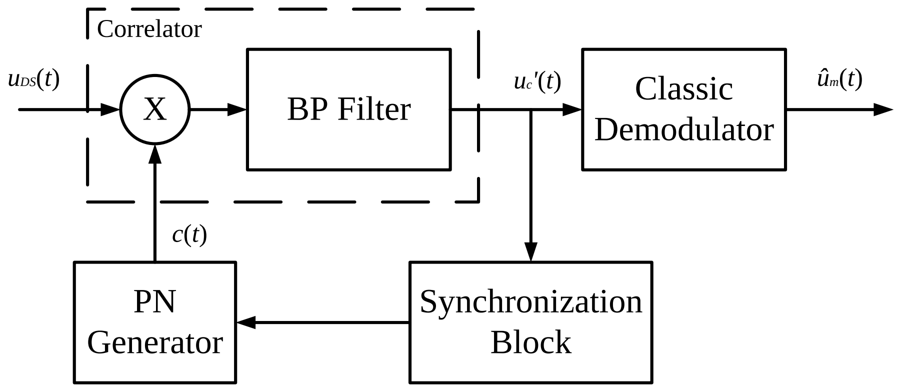

Figure 3 – Block diagram of the direct sequence spread spectrum receiver

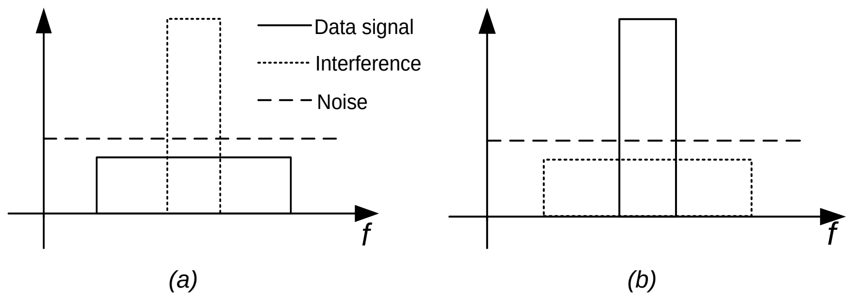

Figure 4 – Data signal and interference in the frequency domain at the receiver: (a) before and (b) after spectrum despreading

Modern applications

DS-SS modulation has been implemented in many modern radiocommunication systems. In the text which follows, eight applications of DS-SS modulation in commercial and military radiocommunication systems are described.

Interim standard 95

The Interim Standard 95 (IS-95) is the first commercial cellular radiocommunication system based on the DS-SS modulation technique and Frequency Division Duplex (FDD). This system was developed and implemented in the United States just after the introduction of the Global System for Mobile Telecommunications (GSM) in Europe (Fazel & Kaiser, 2003). It is also known as CDMAOne.

The IS-95 operates in two frequency bandwidths. The first frequency bandwidth is from 824-849 MHz for uplink and from 869-894 MHz for downlink. The second uses a frequency bandwidth from 1850-1910 MHz for uplink and from 1930-1990 MHz for downlink (Fazel & Kaiser, 2003).

The channel bandwidth is 1.25 MHz. Without guard bands, the channel bandwidth is 1.23 MHz. The processing gain of the system is 19.3 dB. The modulation scheme for the downlink is coherent Quadrature Phase Shift Keying (QPSK). The convolutional code is used for error protection with a code rate of 1/2 and nine memory elements. In the uplink, noncoherence Offset QPSK (OQPSK) is used. For error protection, the convolutional code with a code rate of 1/3 and nine memory elements is used after which the Walsh-Hadamard (6, 64) code is implemented. Spectrum is spreading using the short and long codes. For the short code, the Walsh-Hadamard orthogonal code is used and for the long code, the PN code is used. Timeshift offset of the same PN sequence is used. The maximal throughput is 14.4 kbit/s for data and 9.6 kbit/s for voice. The system chip rate is 1.2288 Mchip/s (Fazel & Kaiser, 2003), (Garg, 2007).

CDMA2000

The CDMA2000 was created as the evolution of the CDMAOne (IS-95) standard. It represents the family of third Generations (3G) of mobile communications. The common feature of these two technologies is that they are based on the same type of short (Walsh-Hadamard orthogonal code) and long (PN code) codes for spreading. The same channel width of 1.25 MHz and the same chip rate of 1.2288 Mchip/s are used to enable backward compatibility with CDMAOne systems. Some transmission modes in CDMA2000 use the same chip rate and carrier spacing as CDMAOne, but different spreading factors and channel coding schemes. In contrast to CDMAOne, the Walsh codes are not fixed but of variable length to offer a variety of data rates (Schullze & Lüders, 2005).

Some modifications have been introduced to offer more flexibility with the data rate and the chip rate. In the uplink, the CDMA2000 uses the DS-SS modulation technique. The chip rate is a multiple of 1.2288 Mchip/s. That multiple factor can be 3, 6, 9 or 12. Also, the channel width is a multiple of 1.25 MHz. The QPSK modulation scheme and fast closed loop power control are used here. For the downlink, a multicarrier concept has been defined. The number of carriers is also a multiple that can have values of 3, 6, 9 or 12. The width of each subchannel is 1.25 MHz and the chip rate is 1.2288 Mchip/s for each subcarrier (Schullze & Lüders, 2005; Garg, 2007).

Wideband CDMA

The wideband CDMA (WCDMA) is the heart of 3G Universal Mobile Telecommunication Systems (UMTS). This system is very similar to the CDMA2000 and it is implemented in Europe and Japan (Prasad & Ojanpera, 1998).

Compared to GSM, the improvement refers to higher data rates transmission as well as the ability to send better quality multimedia content and to enable video calls. Transmission rates reach up to 2 Mbit/s. Frequency bandwidths are defined for the uplink and downlink: for uplink from 1920 to 1980 MHz, and downlink from 2110 to 2170 MHz. The DS-SS modulation technique is used in both links. Possible channel bandwidths are 1.25 MHz, 5 MHz, 10 MHz and 20 MHz, depending on the transmission rate and the number of users at the moment (Garg, 2007).

Three-structured orthogonal variable spreading factor codes as short codes and PN codes as long codes are used for spectrum spreading. For user separation, contrary to CDMA2000, different PN sequences are used instead of time shifts of the same PN sequence. The chip rate of the system is 3.84 Mchip/s (Prasad & Ojanpera, 1998).

A coherent QPSK modulation scheme is used for both the downlink and uplink. Several types of correction codes are used to control errors. While transmitting voice, convolutional codes with a code ratio of 1/3 and nine memory elements are used. A combination of the concatenated Reed Solomon code and the convolutional code is used for data transmission. For a high rate of data transmissions and services that require high quality, convolutional turbo codes are used (Fazel & Kaiser, 2003).

Global positioning system

The Global Positioning System (GPS) is the first satellite navigation system. The GPS program started in the early 1970s and was put into operation status in 1995. This system nominally has 24 satellites in the Medium-altitude Earth Orbit (MEO), (Hegarty, 2017).

The GPS consists of three segments: (1) satellite constellation, (2) ground-control/monitoring network, and (3) user receiving equipment (Kaplan & Hegarty, 2006). The GPS was developed for military purposes by the Department of Defense of the United States. Later, it was opened to civil applications. The GPS offers two types of services: (1) Precise Positioning Service (PPS) and (2) Standard Positioning Service (SPS) which is less accurate than the PPS. The positioning is based on trilateration. A GPS device measures the propagation delay of the signal received from the three satellites. As the positions of the satellites are known, the position of the GPS terrestrial device is obtained as the intersection of the three spheres. If more than three satellites are used during the determining of the position, a more precise position is obtained (Schullze & Lüders, 2005).

The GPS uses two frequency bandwidths. The first frequency bandwidth is labeled as L1 and its carrier frequency is 1575.42 MHz. The other frequency bandwidth is labeled as L2 with a carrier frequency of 1227.6 MHz. The SPS uses only the first carrier, while the PPS requires both carriers. The modulation scheme that is used in the GPS is BPSK. The system processing gain is around 60 dB.

Two types of codes are used for the signal spreading. The first is Coarse/Acquisition or Clear/Access codes (C/A code) whose chip rate is 1.023 Mchip/s. The second is Precision or Protected code (P code) with a chip rate of 10.23 Mchip/s.

The C/A codes are Gold sequences generated in two 10-stage shift registers. These codes are used only with the first frequency carrier for SPS. These codes also divide the users who consume this service at the same time in nearby locations. The P code is used on both frequency bandwidths mainly for military applications. The determination of the user position with this code is more precise than with C/A codes (Schullze & Lüders, 2005).

The accuracy of the determined position became higher during the time and after the enhancements and modernizations of the system. The specified accuracy of the SPS is 13 m in 95% of cases for horizontal positioning and 22 m in 95% of cases for vertical positioning. These specification data are valid in an ideal environment. The performance of the system is typically better than the specification. Errors can be greater than specification due to atmosphere processes, multipath propagation and different user equipment. The PPS gives much better results than the SPS. In 95% of cases, the position precision is 1-2 m for both horizontal and vertical positioning. Advanced user equipment and modern positioning techniques can achieve accuracies better than 1 cm.

GPS transceivers are embedded in everyday devices such as smartphones. The performance of some smartphones' GPS and some sophisticated GPS devices were compared. Sophisticated GPS devices give better results than GPSs on smartphones, but the performance of smartphones is accurate enough for everyday life for fast positioning requirements (Zandbergen & Barbeau, 2011).

Wireless Fidelity

Wireless Local Area Network (WLAN) is a network type that is developed based on the IEEE 802.11 standard. This technology is also known as Wireless Fidelity (Wi-Fi). WLAN connects a small group of devices on short distances via the wireless access point. During the evolution of the IEEE 802.11 standard, several types of that standard were created (Schullze & Lüders, 2005). In the early beginning of Wi-Fi, DS-SS and FH-SS were planned to be used for transmission, but only products using DS-SS modulation have been established on the market. Today, there are several releases of IEEE 802.11 standards such as: IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, IEEE 802.11n, IEEE 802.11ac, etc. (IEEE802.11, 2024).

The DS-SS modulation technique is implemented in the IEEE 802.11b and IEEE 802.11g standards. IEEE 802.11b was released in 1999. The system operates on a frequency of 2.4 GHz with a channel bandwidth of 22 MHz. Transmission data rates are going from 1 to 11 Mbit/s. The maximum ranges from the access point are from 35 m in the indoor environment to 140 m in the outdoor environment (Abdelrahman et al, 2015).

The available frequency bandwidth of 2.4 GHz has actually 83.5 MHz and it is from 2.4 GHz to 2.4835 GHz. In the United States in this bandwidth, there are thirteen channels, and in Europe, there are fourteen channels. According to the bandwidth of one channel, in order to avoid inter-channel interference, it is recommended to use three non-overlapping channels at the same time: in the United States, the first, sixth and eleventh channel, and in Europe the first, seventh and thirteen channel (Al Agha et al, 2016). In Figure 5, channel allocations are illustrated with the markation of non-overlapped channels in the United States. IEEE 802.11b is the longest, well-supported, stable, and cost-effective technique, but security is the main disadvantage. It has a limited number of access points. Sometimes the IEEE 802.11b devices are affected by interference from other products that operate in the 2.4 GHz bandwidth (Garg, 2007). Devices operating in the 2.4 GHz frequency are microwave ovens, bluetooth devices, baby monitors and cordless telephones.

Four years later, in 2003, IEEE 802.11g was released. In this release, the transmission data rates are significantly higher relative to IEEE 802.11b and it can be from 6 Mbit/s to 54 Mbit/s. This system also operates on a 2.4 GHz frequency range and has a narrower bandwidth of 20 MHz. The maximum ranges from the access point are from 38 m in the indoor environment to 140 m in the outdoor environment (Abdelrahman et al, 2015). It is compatible with the IEEE 802.11b standard.

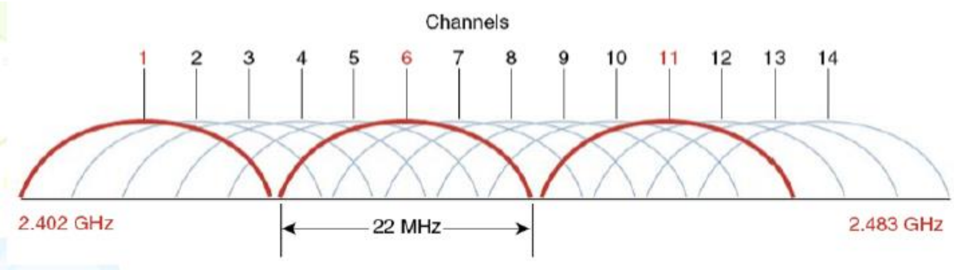

Figure 5 – Channel allocation of the IEEE 802.11b standard

Wi-Fi found a place in many applications like Internet distribution, Voice over Internet Protocol (VoIP) phone access, gaming and connecting consumer electronics devices. It is used as a radio interface for the sensor devices in the Internet of Things (IoT), especially in smart home solutions (Guo et al, 2012).

The latest IEEE 802.11 standards use Orthogonal Frequency Division Multiplexing (OFDM) instead of DS-SS modulation.

ZigBee

ZigBee is a set of specifications for Wireless Personal Area Networking (WPAN) or short-distance wireless networks. ZigBee is an often used standard in Wireless Sensor Networks (WSN). WSN request node devices with low power, low data rate, low cost and short time delay characteristics. The ZigBee standard got its name from the zigzagging patterns of honey bees between flowers which represent the communication between nodes in a mesh network (Ramya et al, 2011).

ZigBee is a standard based network protocol developed by the ZigBee Alliance that uses the transport services of the IEEE 802.15.4 network specification (ZigBee Alliance, 2024). The reasons why ZigBee is used are: low cost, easy to deploy, secure and reliable communication, open standards protocol, low power, low maintenance, very long battery life, supports a large number of nodes, etc (Ramya et al, 2011).

ZigBee found applications in areas like home automation, telecommunication services, healthcare, remote control, etc. (Challoo et al, 2012).

The physical layer of the communication process is based on the DS-SS modulation technique. It operates in three frequency bandwidths. The first frequency bandwidth is between 868-868.6 MHz. Only one channel labeled with 0 operates in this frequency bandwidth. This frequency bandwidth is used in Europe. The maximum throughput is 20 kbit/s. The modulation sheme is BPSK. The chip rate for spectrum spreading is 300 kchip/s.

The second frequency bandwidth is used in America. It encompasses a band from 902-928 MHz. Ten channels operate in this frequency bandwidth, labeled from 1 to 10. The maximum throughput is 40 kbit/s. The modulation scheme is BPSK and the chip rate is 600 kchip/s.

The third frequency bandwidth is used globally and that is the frequency bandwidth from 2400-2483.5 MHz. This frequency bandwidth is for industrial, scientific and medical (ISM) purposes. In this frequency bandwidth, there are 16 channels labeled from 11 to 26. The modulation type that is used is OQPSK. The maximum throughput in this frequency bandwidth is 250 kbit/s. The chip rate for spectrum spreading is 2000 kchip/s.

The transmission range can be between 10 meters and 75 meters, depending on power output and environmental characteristics, but in ideal conditions, it can achieve a distance of 150 meters in an outdoor environment (Ramya et al, 2011).

There are also some other standards similar to ZigBee which are used in WPAN and WSN based on DS-SS modulation such as IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) (Mulligan, 2007), (Ma & Luo, 2008). However, ZigBee is still the most popular choice.

Unmanned aerial vehicles

The Unmanned Aerial Vehicle (UAV) represents an aircraft without a crew. These aircraft are also called drones. UAVs come in two varieties: some are controlled from a remote location while others fly autonomously based on pre-programmed flight plans. If UAVs are controlled remotely, wireless communication can be direct, which can significantly affect the control range, or by using the infrastructure of some of wireless technologies, such as mobile cellular systems, satellite communications, etc. If a UAV flies autonomously based on the pre-programmed flight plan, it uses the GPS or computer vision, where the camera or appropriate sensors detect obstacles and, if necessary, bypass them (Zhao et al, 2018).

The very beginning of using UAVs was for military purposes. Later, UAVs began to be used in various civilian applications (Miličević & Bojković, 2021). UAVs are extremely important in modern military operations (Milic et al, 2019; Radovanović et al, 2022).

UAVs use two types of communication channels. One is used for the transmission of command and control data. Control data is sent in both directions, from the control station to the UAV (uplink) and from the UAV to the control station (downlink). The data sent through this channel is related to the control of the aircraft, whether it is generated by the operator by issuing commands or collected by the UAV during flight using the sensors it is equipped with. The data that the UAV sends to the control station is intended to provide a flight as reliable as possible. The second communication channel serves to collect the main data depending on the purpose of the UAV itself. It is mainly used for the transmission of video signals in the downlink (Miličević & Bojković, 2021).

Due to the need for high reliability and resistance to interference, the use of DS-SS modulation was suggested (Todorović & Orlić, 2010). Different vendors use DS-SS and FH-SS modulation techniques because of difficult interception and high resistance to interference. The most commonly used frequency bandwidth is the unlicensed band around 2.4 GHz. A brief overview of the vendors and the SS modulation techniques used is given in (Ristić et al, 2022).

Underwater acoustic communications

Underwater acoustic communications are used in military, scientific and civilian applications. Some of the applications are control of underwater vehicles and military facilities under the sea and on the seabed, instrument monitoring, pollution control, climate monitoring, prediction of natural changes, search and rescue missions, etc. (Song et al, 2019).

Underwater acoustic channels are time-frequency and spatially variable channels with limited bandwidth and interference that occurs due to multiple propagations (Du et al, 2019; Singer et al, 2009). These channels are bandwidth limited due to the increased attenuation at higher frequencies (Yang & Yang, 2008).

In this specific kind of communication, the DS-SS modulation technique is commonly used because of its excellent anti-interference ability, antichannel fading ability, and low Signal to Noise Ratio (SNR) performance. However, DS-SS modulation is limited by the narrow bandwidth of the underwater acoustic channel and has a low transmission rate (Chitre et al, 2008; Yang et al, 2021).

The biggest influence on the gain of an SS modulation is the fluctuation of the carrier phase. Fluctuation of the carrier phase directly affects the receiver to, for example, detect and decide which symbol was sent, which can lead to the inability to despread the signal. Carrier fluctuation is caused by the appearance of the Doppler effect. Multiple signal propagation in underwater communications can lead to the loss of orthogonality characteristics of the PN sequence, thus reducing decoding performance. The core of DS-SS underwater acoustic communication is to obtain the matched filter processing gain and the fast carrier phase fluctuation interference caused by the Doppler effect is the most important factor affecting the matched filter processing gain (Du et al, 2019).

Underwater acoustic communications are used to send control signals and commands to Autonomous Underwater Vehicles (AUVs) and underwater sensors. Due to their nature, controlling signals and short commands often require high reliability (Qu et al, 2009).

Since the very beginning of the use of underwater acoustic communications, DS-SS modulation has been used at low frequencies and small channel bandwidths. These communications were first tested for military purposes (Loubet et al, 1997).

In (Loubet et al, 1997), tests of DS-SS signal transmission at carrier frequencies from 1.5 kHz to 2 kHz are described. Channel bandwidths are very narrow, up to 500 Hz with the maximum transmission rates of 80 bit/s. For the purposes of spread spectrum, Gold and Kasami sequences are used with the system process gains of 9 dB and 18 dB, depending on the sequence duration.

In (Yang & Yang, 2008) the DS-SS modulated signals had a carrier frequency of 17 kHz with a channel bandwidth of 4 kHz. The transmitted symbols are spread with an m-sequence with 511 chips. The sequence of chips is then transmitted using BPSK modulation. The obtained processing gain is around 27 dB.

Other realizations using DS-SS modulation for underwater acoustic communications are presented in (Yang et al, 2021) and (Qu et al, 2009).

Conclusion

The DS-SS modulation technique is based on direct spectrum spreading by multiplying a data signal with the PN sequence defined in the PN sequence generator. The DS-SS modulation technique has been successfully implemented in many military and commercial applications, due to its high protection against interference, making communication difficult for reconnaissance and eavesdropping, and its ability to provide code division multiple access. The history, principles and modern applications of the DS-SS modulation technique are presented in this article.

Historically, the first developed DS-SS systems were used in military radiocommunications, since it requires a technique that has good resistance to various forms of electronic attacks. Later, DS-SS modulation found its applications in commercial radiocommunication systems.

Mobile phones, wireless sensor networks, wireless local area computer networks, radio-relay and satellite communications are just some of the applications. Communication links for UAVs control are very important, so they need to use technology that is difficult to interfere with. Applications to control signals of UAVs and underwater acoustic communications are promising in the near future.

References

Abdelrahman, R.B.M., Mustafa, A.B.A. & Osman, A.A. 2015. A Comparison between IEEE 802.11 a, b, g, n and ac Standards. *IOSR Journal of Computer Engineering (IOSR-JEC)*, 17(5), pp.26-29 [online]. Available at: https://www.iosrjournals.org/iosr-jce/papers/Vol17-issue5/Version-3/D017532629.pdf [Accessed: 15 February 2024].

Al Agha, K., Pujolle, G. & Yahiya, T.A. 2016. *Mobile and Wireless Networks*. Wiley-ISTE. ISBN: 978-1-84821-714-0.

Challoo, R., Oladeinde, A., Yilmazer, N., Ozcelik, S. & Challoo, L. 2012. An Overview and Assessment of Wireless Technologies and Co- existence of ZigBee, Bluetooth and Wi-Fi Devices. *Procedia Computer Science*, 12, pp.386-391. Available at: https://doi.org/10.1016/j.procs.2012.09.091.

Chitre, M., Shahabudeen, S., Freitag, L. & Stojanovic, M. 2008. Recent advances in underwater acoustic communications & networking. In: *OCEANS 2008*, Quebec City, QC, Canada, pp.1-10, September 15-18. Available at: https://doi.org/10.1109/OCEANS.2008.5152045.

-DTIC. 1988. Joint Tactical Information Distribution System (JTIDS) Cost and Training Effectiveness Analysis (CTEA). *DTIC Defense Technical Information Center*, 01 November [online]. Available at: https://apps.dtic.mil/sti/citations/ADA221656 [Accessed: 10 February 2024].

Du, P., Wang, L., Zhang, H. & Xie, Z. 2019. Performance analysis of direct-sequence spread-spectrum underwater acoustic communications based on at-sea data. In: *MATEC Web of Conerences - The 2nd Franco-Chinese Acoustic Conference (FCAC 2018)*, Le Mans, France, 283, art.number:07006, October 29-31. Available at: https://doi.org/10.1051/matecconf/201928307006.

Fazel, K. & Kaiser, S. 2003. *Multi-Carrier and Spread Spectrum Systems.* Chichester, West Sussex, England: John Wiley & Sons Ltd. ISBN: 0-470-84899-5.

Garg, V.K. 2007. *Wireless Communications and Networking.* Elsevier. ISBN: 978-0-12-373580-5.

Green, P.E.Jr. 1954. The Lincoln F9C radioteletype system. *Massachusetts Institute of Technology, Lincoln Laboratory, Technical Memorandum,* 61, May 14.

Guo, Y., Zhang, S. & Xiao, D. 2012. Overview of Wi-Fi technology. In: *Proceedings of the 2012 International Conference on Computer Application and System Modeling (ICCASM 2012)*, Taiyuan, Shanxi, China, pp.1293-1296, July 27-29. Available at: https://doi.org/10.2991/iccasm.2012.330.

Hegarty, C.J. 2017. The Global Positioning System (GPS). In: Teunissen, P.J. & Montenbruck, O. (Eds.) *Springer Handbook of Global Navigation Satellite Systems*, pp.197-218. Cham: Springer. Available at: https://doi.org/10.1007/978-3-319-42928-1_7.

-IEEE802.11. 2024. Wireless Local Area Networks: The Working Group for WLAN Standards. *IEEE802.org/11* [online]. Available at: https://www.ieee802.org/11/ [Accessed: 10 February 2024].

Kaplan, E.D. & Hegarty, C.J. 2006. *Understanding GPS: Principles and Applications, Second Edition.* Aptech House. ISBN: 1-58053-894-0.

Kotowski, P. & Dannehl, K. 1940. Patent US2211132A: Method of transmitting secret messages. *GooglePatents* [online]. Available at: https://patents.google.com/patent/US2211132A/en [Accessed: 15 February 2024].

Loubet, G., Capellano, V. & Filipiak, R. 1997. Underwater spread-spectrum communications. In: *Oceans' 97.MTS/IEEE Conference Proceedings*, Halifax, Canada, pp.574-579, October 6-9. Available at: https://doi.org/10.1109/OCEANS.1997.634429.

Ma, X. & Luo, W. 2008. The Analysis of 6LoWPAN Technology. In: *2008 IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application,* Wuhan, China, pp.963-966, December 19-20. Available at: https://doi.org/10.1109/PACIIA.2008.72.

Malik, R. 2001. Spread Spectrum - Secret Military Technology to 3G. In: *IEEE History of Telecommunications Contest*, St. John's, Newfoundland, Canada, pp.1-5, July 25-27 [online]. Available at: https://ethw.org/2001_IEEE_Conference_on_the_History_of_Telecommunications [Accessed: 15 February 2024].

Milic, A., Ranđelović, A. & Radovanović, M. 2019. Use of drones in operations in the urban environment. In: *Proceedings of 5th International Scientific-Professional Conference - Security and Crisis Management - Theory and Practice SeCMan,* Belgrade, Serbia, pp.124-130 [online]. Available at: https://bekmen.rs/zbornik/2019/2019-Zbornik-ENG.pdf [Accessed: 15 February 2024]. ISBN: 978-86-80692-04-3.

Miličević, Z. & Bojković, Z. 2021. From the early days of unmanned aerial vehicles (UAVs) to their integration into wireless networks. *Vojnotehnički glasnik/Military Technical Courier*, 69(4), pp.941-962. Available at: https://doi.org/10.5937/vojtehg69-33571.

Mudgway, D.J. 2001. *Uplink-Downlink: A History of the Deep Space Network, 1957-1997*. Washington DC: NASA SP-2001-4227, The NASA History Series [online]. Available at: https://www.nasa.gov/wp-content/uploads/2023/04/sp-4227.pdf [Accessed: 15 February 2024].

Mulligan, G. 2007. The 6LoWPAN architecture. In: *EmNets '07: Proceedings of the 4th workshop on Embedded networked sensors,* New York, USA, pp.78-82, June 25-26. Available at: https://doi.org/10.1145/1278972.1278992.

Prasad, R. & Ojanpera. T. 1998. A survey on CDMA: evolution towards wideband CDMA. In: *1998 IEEE 5th International Symposium on Spread Spectrum Techniques and Applications - Proceedings. Spread Technology to Africa (Cat. No.98TH8333),* Sun City, South Africa, pp.323-331, September 4. Available at: https://doi.org/10.1109/ISSSTA.1998.726251.

Qu, F., Yang, L. & Yang, T.C. 2009. High reliability direct-sequence spread spectrum for underwater acoustic communications. In: *OCEANS 2009*, Biloxi, MS, USA, pp.1-6, October 26-29. Available at: https://doi.org/10.23919/OCEANS.2009.5422362.

Radovanović, M., Petrovski, A., Jokić, Z. & Aleksić, A. 2022. Use of Unmanned Aerial Vehicles Integrated Into the C4IRS System in Modern Combat Operations. In: *8th International Forum "Safety for the Future" 2022: 8th Scientific-professional conference Security and Crisis Management - Theory and Practice (SeCMan)*, Sremska Kamenica, Serbia, pp.88-98, September 29-30. ISBN: 978-86-80692-09-8.

Ramya, C.M., Shanmugaraj, M. & Prabakaran, R. 2011. Study on ZigBee technology. In: *2011 3rd International Conference on Electronics Computer Technology*, Kanyakumari, India, pp.297-301, April 8-10. Available at: https://doi.org/10.1109/ICECTECH.2011.5942102.

Ristić, V., Todorović, B. & Stojanović, N. 2022. Frequency hopping spread spectrum: History, principles and applications. *Vojnotehnički glasnik/Military Technical Courier*, 70(4), pp.856-876. Available at: https://doi.org/10.5937/vojtehg70-38342.

Scholtz, R. 1982. The Origins of Spread-Spectrum Communications. *IEEE Transactions on Communications*, 30(5), pp.822-854. Available at: https://doi.org/10.1109/TCOM.1982.1095547.

Scholtz, R.A. 1994. The evolution of spread-spectrum multiple-access communications. In: *Proceedings of IEEE 3rd International Symposium on Spread Spectrum Techniques and Applications (ISSSTA'94)*, Oulu, Finland, pp.4-13, July 6-8. Available at: https://doi.org/10.1109/ISSSTA.1994.379623.

Schullze, H. & Lüders, C. 2005. *Theory and Applications of OFDM and CDMA: Wideband Wireless Communications.* John Wiley & Sons Inc. ISBN: 978-0-470-85069-5.

Shannon, C.E. 1948. A mathematical theory of communication. *The Bell System Technical Journal*, 27(3), pp.379-423. Available at: https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

Shirriff, K. 2022. The digital ranging system that measured the distance to the Apollo spacecraft. *Righto.com* [online]. Available at: https://www.righto.com/2022/04/the-digital-ranging-system-that.html [Accessed: 15 February 2024].

Singer, A.C., Nelson, J.K. & Kozat, S.S. 2009. Signal processing for underwater acoustic communications. *IEEE Communications Magazine*, 47(1), pp.90-96. Available at: https://doi.org/10.1109/MCOM.2009.4752683.

Song, A., Stojanovic, M. & Chitre, M. 2019. Editorial Underwater Acoustic Communications: Where We Stand and What Is Next? *IEEE Journal of Oceanic Engineering*, 44(1), pp.1-6. Available at: https://doi.org/10.1109/JOE.2018.2883872.

Todorović, B.M. 2021. *Osnove telekomunikacija*. Belgrade: Akademska misao (in Serbian). ISBN: 978-86-7466-864-1.

Todorović, B. & Orlić, V. 2010. Analysis and optimization of direct sequence spread spectrum scheme for an unmanned aerial vehicle PPM control signal. *Facta universitatis - series: Electronics and Energetics,* 23(3), pp.319-332. Available at: https://doi.org/10.2298/FUEE1003319T.

Todorović, B.M., Stojanović, N.M. & Velikić, G.S. 2024. Is Direct Sequence Spread Spectrum Modulation Promising for AI-Based Design of 6G Networks? *IEEE Consumer Electronics Magazine*. Early Access. Available at: https://doi.org/10.1109/MCE.2024.3349458.

Torrieri, D. 2015. *Principles of Spread-Spectrum Communication Systems*. Cham: Springer. Available at: https://doi.org/10.1007/978-3-319-70569-9.

Yang, G., Zhou, F., Lou, Y., Qiao, G., Ahmed, N. & He, Y. 2021. Double-differential coded M-ary direct sequence spread spectrum for mobile underwater acoustic communication system. *Applied Acoustics*, 183, art.number:108303. Available at: https://doi.org/10.1016/j.apacoust.2021.108303.

Yang, T.C. & Yang, W.-B. 2008. Performance analysis of direct-sequence spread-spectrum underwater acoustic communications with low signal-to-noise-ratio input signals. *The Journal of the Acoustical Society of America*, 123(2), pp.842-855. Available at: http://doi.org/10.1121/1.2828053.

Zandbergen, P.A. & Barbeau, S.J. 2011. Positional Accuracy of Assisted GPS Data from High-Sensitivity GPS-enabled Mobile Phones. *The Journal of Navigation*, 64(3), pp.381-399. Available at: https://doi.org/10.1017/S0373463311000051.

Zhao, J., Gao, F., Ding, G., Zhang, T., Jia, W. & Nallanathan, A. 2018. Integrating Communications and Control for UAV Systems: Opportunities and Challenges. *IEEE Access*, 6, pp.67519-67527. Available at: http://doi.org/10.1109/ACCESS.2018.2879637.

-ZigBee Alliance. 2024. ZigBee Specification FAQ. *Zigbee.org* [online]. Available at: https://web.archive.org/web/20130627172453/http://www.zigbee.org/Specifications/ZigBee/FAQ.aspx [Accessed: 15 February 2024].

Espectro ensanchado de secuencia directa: historia, principios y aplicaciones modernas

Nenad M. Stojanović[a], *Branislav* M. Todorović[b], *Vladimir* B. Ristić[c], *Ivana* V. Stojanović[d]

[a] Fuerzas Armadas de Serbia, Estado Mayor, Departamento de telecomunicaciones e Informática, Centro de Matemática Aplicada y Electrónica, Belgrado, República de Serbia, **autor de correspondencia**

[b] Instituto de Inteligencia Artificial de Serbia, Novi Sad, República de Serbia

[c] Universidad de Defensa de Belgrado, Academia Militar, Departamento de Telecomunicaciones e Informática, Belgrado, República de Serbia

[d] “Telekom Srbija", Belgrado, República de Serbia

CAMPO: telecomunicación
TIPO DE ARTÍCULO: artículo de revisión

Resumen:

Introducción/objetivo: La modulación de espectro ensanchado de secuencia directa se utiliza ampliamente en muchos sistemas de radiocomunicaciones. Al principio, esta técnica de modulación se utilizó en sistemas de navegación y comunicaciones militares. Posteriormente, las aplicaciones también se diversificaron en los sistemas de comunicación civiles. Hoy en día, existen muchos sistemas en los que se implementa modulación de espectro ensanchado de secuencia directa como parte del sistema. Este artículo tiene como objetivo sublimar el conocimiento sobre la técnica de modulación de espectro ensanchado de secuencia directa y sus aplicaciones.

Métodos: El artículo presenta una revisión del desarrollo histórico de la técnica de modulación de espectro ensanchado de secuencia directa, sus principios y las aplicaciones actuales más importantes.

Resultados: Basado en una gran cantidad de referencias, este artículo resume el desarrollo histórico, los principios básicos y las aplicaciones modernas de la modulación de espectro ensanchado de secuencia directa en sistemas de comunicaciones militares y comerciales.

Conclusión: La modulación de espectro ensanchado de secuencia directa se utiliza ampliamente en las radiocomunicaciones modernas inalámbricas y por satélite. Se espera que forme parte de futuros sistemas de comunicación globales.

Palabras claves: radiocomunicaciones, comunicaciones militares, sistemas móviles celulares, espectro ensanchado, secuencia directa, sistema de posicionamiento global, comunicaciones acústicas submarinas, vehículos aéreos no tripulados, fidelidad inalámbrica, ZigBee.

Спектр распространения прямой последовательности: история, принципы и современные применения

Ненад М. Стоянович[а], *Бранислав* М. Тодорович[б], *Владимир* Б. Ристич[в], *Ивана* В. Стоянович[г]

[а] Вооруженные силы Республики Сербия, Генеральный штаб, Управление информатики и телекоммуникаций (J-6), Центр прикладной математики и электроники, г. Белград, Республика Сербия, **корреспондент**

[б] Институт искусственного интеллекта Сербии, г. Нови-Сад, Республика Сербия

[в] Университет обороны в г. Белград, Военная академия, кафедра телекоммуникаций и информатики, г. Белград, Республика Сербия

[г] Телеком Сербия, а.д., г. Белград, Республика Сербия

РУБРИКАГРНТИ: 49.27.00 Система передачи,
49.43.00 Радиосвязь и радиовещание
ВИД СТАТЬИ: обзорная статья

Резюме:

Введение/цель: Модуляция расширение спектра методом прямой последовательности широко используется во многих системах радиосвязи. Впервые этот метод модуляции был использован в военных системах управления, связи и навигации. Затем применение распространилось и на системы гражданской связи. В современном мире существует множество систем, в которых модуляция расширенного спектра методом прямой последовательности стала частью системы. Целью данной статьи является обобщение знаний о методе модуляции с расширенным спектром методом прямой последовательности и его применении.

Методы: В статье представлен обзор исторического развития модуляции с расширенным спектром методом прямой последовательности, его принципов и наиболее важных в настоящее время приложений.

Результаты: В данной статье, основанной на большом количестве литературы, обобщаются историческое развитие, основные принципы и современное применение модуляции с расширенным спектром методом прямой последовательности в военных и коммерческих системах связи.

Вывод: Модуляция с расширенным спектром методом прямой последовательности широко используется в современной беспроводной и спутниковой радиосвязи. Можно предположить, что он станет частью будущих глобальных коммуникационных систем.

Ключевые слова: радиосвязь, военная связь, сотовые мобильные системы, расширенный спектр, прямая последовательность, глобальная система позиционирования, подводная акустическая связь, беспилотные летательные аппараты, Wi-Fi, ZigBee.

Пренос у проширеном спектру – директна секвенца: историја, принципи и савремене примене

Ненад М. Стојановић[а], *Бранислав* М. Тодоровић[б], *Владимир* Б. Ристић[в], *Ивана* В. Стојановић[г]

[а] Војска Србије, Генералштаб, Управа за телекомуникације и информатику (J-6), Центар за примењену математику и електронику, Београд, Република Србија, **аутор за преписку**

[б] Институт за вештачку интелигенцију Србије, Нови Сад, Република Србија

[в] Универзитет одбране у Београду, Војна академија, Катедра телекомуникација и информатике, Београд, Република Србија

[г] Телеком Србија, а. д., Београд, Република Србија

ОБЛАСТ: телекомуникације
КАТЕГОРИЈА (ТИП) ЧЛАНКА: прегледни рад

Сажетак:

Увод/циљ: Многи системи радио-комуникација користе систем преноса у проширеном спектру помоћу директне секвенце. На почетку, ова техника се користила у војним и навигационим системима, док се касније примењује за различите сврхе и у цивилним телекомуникационим системима. Данас постоје многи системи где је техника директне секвенце имплементирана у неком њиховом делу. Циљ овог рада јесте да сублимира знања о техници проширеног спектра са директном секвенцом и њеним применама.

Методе: Представљени су историјски развој технике проширеног спектра са директном секвенцом, принципи рада и најважније савремене примене.

Резултати: На основу доступне литературе, рад сумира историјски развој, основне принципе и савремене примене проширеног спектра са директном секвенцом у војним и комерцијалним телекомуникационим системима.

Закључак: Систем преноса проширеног спектра са директном секвенцом је у широкој примени у модерним бежичним и сателитским радио-комуникацијама. Очекује се да буде део будућих глобалних телекомуникационих система.

Кључне речи: радио-комуникације, војне телекомуникације, ћелијски мобилни системи, проширени спектар, директна секвенца, глобални систем позиционирања, подводне акустичне комуникације, беспилотне летелице, Wi-Fi, ZigBee.

Paper received on: 18.02.2024.
Manuscript corrections submitted on: 07.06.2024.
Paper accepted for publishing on: 08.06.2024.