Security of Infocommunication Systems and Internet of Things

2024 Vol 2, No 2

https://doi.org/10.31861/sisiot2024.2.02005

Received 18 September 2024; revised 24 October 2024; accepted 23 November 2024; published 30 December 2024

Analysis of Amateur Radio Frequency Code Modulation Protocols for Transmitting Short Messages

Ihor Klapashchuk* and Andrii Veryha

Radio Engineering and Information Security Department, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine

*Corresponding author (E-mail: igor.klapashchuk@gmail.com)

ABSTRACT The article is dedicated to analyzing common short message transmission protocols in digital code used by radio amateurs in amateur radio communication. The following protocols are considered: RTTY, AMTOR, PACTOR1, ISCAT, JT4, JT9, JT65, FT4, and FT8. All of them use frequency shift keying (FSK), which provides significantly better noise resistance since information is encoded in frequency changes rather than amplitude. Because of this, FM is widely used in broadcasting. The primary purpose of the listed protocols is to prevent signal fading due to radio wave reflection from the ionospheric layer (sporadic propagation), where reflection windows can be short. Therefore, modulation must be fast, and data transmission reliability must be high to ensure successful radio exchange. The article analyzes the main characteristics of these protocols, including the maximum signal-to-noise ratio (SNR) at which digital data reception and decoding are possible, transmission speed, and the bandwidth occupied by the signal. Additionally, related characteristics are examined, such as the bit transmission time and the use of error-correcting codes for noise immunity. The main FSK modulation modes are reviewed, comparing their advantages and disadvantages. It has been established that the JT4, JT9, JT65, QRA4, WSPR, FT4, and FT8 protocols provide a SNR greater than -20 dB compared to RTTY, AMTOR, PACTOR, and ISCAT. In such protocols, the signal occupies a narrower bandwidth. All the discussed protocols ensure a higher message transmission speed compared to other modulation modes. The conclusion is made that frequency modulation, combined with the use of error correction codes, significantly improves the SNR. The application of similar signal detection and decoding methods could enable the development of a decoder with substantially higher sensitivity. The development of a new type of signal for digital information transmission can be based on modifications of the JT4, JT9, JT65, QRA4, WSPR, FT4, and FT8 protocols.

KEYWORDS protocol, frequency modulation, coding, SNR.

I. INTRODUCTION

In order to create a stable signal that would work in conditions of high noise and interference levels, we will compare and analyze various methods and protocols for transmitting digital information. We will determine the most effective protocol for further work on a new type of signal with the possibility of its practical implementation.

Among radio amateurs in amateur radio communication, for transmitting short messages in a digital code, frequency modulation is used. The following protocols with such modulation are known: RTTY, AMTOR, PACTOR1, ISCAT, JT4, JT9, JT65, FT8 [1-12]. Their main purpose is to prevent signal attenuation when reflecting radio waves from the ionosphere layer (sporadic passage), where reflection windows can be short. Therefore, the modulation must be fast and there must be high reliability of data transmission to confirm radio exchange.

We are primarily interested in the minimum signal-to-noise ratio (SNR) at which decoding of the useful signal is possible. We are also interested in the frequency band occupied by the signal and some related characteristics, such as the transmission time of one bit, the use of noise-tolerant coding with error correction. For example, the use of signal detection and decoding methods can significantly increase the sensitivity of the decoder.

Frequency Shift Keying (FSK) or frequency modulation is a modulation in which information is transmitted in the frequency of the carrier wave by discrete changes. An example of the simplest FSK modulation is the binary transmission of information using a pair of discrete frequencies ("0" – spatial frequency and "1" – mark frequency) information).

Let's consider common FSK modulation protocols, compare their characteristics, advantages, and disadvantages.

II. SHORT MESSAGE TRANSFER PROTOCOLS

A. RTTY. Radio Tele Type (RTTY) protocol, it is not the best digital mode, but it is easy to set up and is one of the strongest in the HF bands as it is available in two forms: Baud and ASCII. Let's compare their characteristics, advantages and disadvantages [3].

It has the following characteristics:

– Lowest SNR: -5.5 dB;
– Interleaving: none;
– Data transfer rate: 45 baud; a character consists of a "start" bit (1 "space"), 5 information bits, and a "stop" bit (1.5 "mark");
– Receiving mode: USB;
– Demodulation: non-coherent;
– Speed: 60wpm;
– Convolution code: none;
– Modulation: FSK with two tones ("mark" and "space," "mark" high) with frequency shifts of 23 Hz, 170 Hz

(standard shift), 200 Hz, or 850 Hz;
- Pulse shape: rectangular;
- Patch code: none;
- Synchronization: at the "start";
- Bandwidth: For the standard 170 Hz shift – approximately 600 Hz (due to the rectangular signal shape);
- Pmean/Ppeak: 1.

RTTY mode 45 uses a non-standard 23 Hz frequency-shifted modulation known as minimum shift keying (MSK). Unlike FSK, RTTY demodulates through the measurement phase rather than using two 45 baud filters. The MSK mode operates at a 23 Hz shift and was developed by Makoto Mori (JE3HHT) in 2003.

This mode uses the ITA2 character set, which contains 32 letters and 32 numbers without error correction characters (all characters are fixed length). Lowercase letters are automatically converted to uppercase, and special characters are automatically converted to standard uppercase. The unpunched ribbon (ASCII CHR) character can be used to change the character set.

At a speed of 50 baud, a speed of 67 words per minute is achieved with a minimum SNR of -5 dB, and at a speed of 75 baud, a speed of 100 words per minute is achieved with an SNR of -3.5 dB.

One of the disadvantages of the Bodo code is the possibility of a recognition error, the special character LTRS or FIGS (LTRS switches to the letters of the table, FIGS to the number of the table) is decoded incorrectly. In this case, subsequent characters may be incorrect until the correct state of LTRS/FIGS is restored. This limitation is due to the fact that the Bodo code has only 5-bit codewords.

Unlike Bodo, the ASCII standard contains 128 code words that allow you to encode letters (upper and lower case), numbers and punctuation in a single table. ASCII also includes carriage return characters that allow you to correct errors entered with the Backspace key.

The RTTY protocol is widely used for digital operations, especially in the high frequency (HF) region. It's not the most efficient digital mode, but it's easy to set up. A large number of stations on the air can create interference, making decoding difficult. Although RTTY is fast enough to handle many stations, there is USB mode is required when using AFSK (Audio Frequency Shift Keying). All RTTY operations are provided as standard at 45 baud with a 170 Hz shift. For FSK the hardware filters of the radio station are more suitable, while in AFSK mode you can actually do without the SSB filter. RTTY supports a mode with high sensitivity to interference, after which its effective bandwidth greatly exceeds the shift itself. Selective fading due to polar transmission paths can cause part of the signal to disappear, resulting in a decoding error when transmitting "mark" bits.

B. AMTOR. The most similar protocol to RTTY is AMTOR (Amateur Teleprinting Over Radio) which has built-in ARQ (Automatic Request Query) and FEC (Forward Error Correction) and to ensure that receiving stations receive the text without errors.

AMTOR, like RTTY, uses audio frequency modulation (AFSK) with two frequencies, each corresponding to one of the binary values 0 or 1. These two frequencies, separated by a relative offset, modulate the signal that is transmitted to the radio frequency carrier and ensures the transmission of the radio frequency during broadcasting.

AMTOR can successfully transmit data even in conditions of high noise and signal attenuation.

Characteristics:
- Bandwidth: Approximately 800 Hz (due to the rectangular shape of the signal);
- Data transfer rate: 100 or 200 baud, depending on propagation conditions;
- Demodulation: Non-coherent;
- Modulation: FSK with two tones ("mark" and "space"), where "mark" is the higher tone, and the frequency shift between tones is 170 Hz;
- Pulse shape: Rectangular;
- Speed: From 0 to 67 s/min (67 s/min corresponds to 50 baud RTTY), depending on the number of repetitions;
- Receiving mode: USB;
- Synchronization: Automatic via signal;
- Correction code: Achieved through automatic repetitions and simple detection of erroneous characters, facilitated by the specific content of symbols (4 "space" bits and 3 "mark" bits);
- Pmean/Ppeak: 1;
- Interleaving: none;
- Convolution code: none.

AMTOR was developed in 1978 by Peter Martinez (G3PLX). AMTOR can operate in two modes: FEC (NAVText) and ARQ (SITOR-A): ARQ is for VMS (like Maritime Mobile Service System) or just TOR and FEC which helps the other station to receive what is being sent.

The AMTOR protocol uses a 7-bit code for each symbol. The received code must maintain a 4:3 ratio; if this ratio is violated, the receiver assumes an error has occurred. In error detection mode, the code word will be discarded, while in automatic request mode, the receiver will request a retransmission of the data.

A character consists of 4 "space" bits and 3 "sign" bits. A character block (eg "Block 1" or "Block 2") contains three characters with a total duration of 210 ms (70 ms per character). This is followed by a pause of 240 ms. During this pause, the receiving station transmits a 70 ms control signal, which can be an acknowledgment symbol ("ACK") to move to the next block, or a symbol indicating an error ("NACK") to request a retransmission of the last one block.

The AMTOR system uses the CCIR476-4 character set, which includes 32 letters, 32 digits, and 6 control, timing, or wait signal characters, excluding the (fixed-length) error reset character. In SITOR-A, this set can be extended to support the Cyrillic alphabet with a special "unpunched tape" character (third variation). Similarly, in AMTOR A, the same character allows the set to be extended to ASCII (from 32 to 128 characters). In AMTOR ARQ LISTEN mode, symbols are transmitted with maximum accuracy as retransmission requests are not possible. Because of this, the reception quality is often low.

C. PACTOR1. PACTOR 1 is an AFSK protocol that combines basic FSK modulation with an ARQ protocol to ensure reliable error detection and data transmission. It can also incorporate FEC for improved error correction.

It has the following characteristics:

- Lowest SNR: at 100 baud about -4 dB;
- Bandwidth: 600 Hz;
- Data transfer rate: 100 or 200 baud is selected automatically according to the distribution conditions;
- Modulation: two FSK tones (“space” and “mark”) with a 200 Hz shift between tones;
- Pulse shape: rectangular;
- Synchronization: automatic via signal;
- Speed: from 0 to approximately 260 mph;
- Receive mode: LSB or USB;
- Demodulation: non-coherent;
- Synchronization: automatic via signal;
- Patch code: none;
- Pmean/Ppeak: 1;
- Interleaving: none;
- Convolution code: none.

PACTOR was developed to improve digital data reception in cases where the signal is weak or noisy. It combines the bandwidth efficiency of packet radio with the error correction (CRC) and automatic repeat request (ARQ) features of AMTOR.

In the Pactor1 protocol, all communication is carried out using "frames" (a limited set of characters) and control signals (CS1 to CS4), similar to AMTOR ARQ. There are two types of frames: synchronization frames (used during connection establishment) and information frames (ensuring data transmission through an automatic transmission and acknowledgment procedure using CS1 to CS4 signals).

Each information frame includes:

- Header (a special character);
- Information field (contains 8 bytes of data at a speed of 100 baud and 20 bytes at a speed of 200 baud);
- FCS field (2 bytes containing the CRC – "Cyclic Redundancy Check", calculated for all frame data up to this field, excluding the header).

Each frame receives confirmation of the correctness of the transmission. The duration of each transmission cycle is fixed at 1.25 seconds. The protocol uses the ASCII character set + extended ANSI characters in "8-bit" format or only ASCII characters with Huffman compression.

D. PACKET. PACKET is a synchronous protocol in which data is transmitted in packets of ASCII characters. It is also known as FSK300, AX25 or X25, it is a packet protocol derived from the AX.25 computer network protocols [4] and HDLC [5].

There are several variants of this protocol. For the HF range, PACKET 300 is used, and for VHF, there are several variants, the most common of which are PACKET 1200 and PACKET 9600.

It has the following characteristics:

- Bandwidth: 12 kHz (for 1200 baud), 15 kHz (for 9600 baud);
- Data transfer rate: 300, 600, 2400, 4800, 9600 baud;
- Modulation: FSK with a shift between tones of 200 Hz (for 300, 600 baud) 1000 Hz (for 1200 baud); GFSK 4800 Hz (for 9600 baud).

E. ISCAT. This mode can be classified as a variant of FSK mode. It uses 42-tone frequency manipulation at a rate of 11025/512 = 21.533 baud (ISCAT-A) or 11025/256 = 43.066 baud (ISCAT-B). Tone frequencies are divided by the value in Hz, which is equal to the data transfer rate. The author describes this mode as 42FSK modulation.

It has the following characteristics:

- Bandwidth: ISCAT-A – 905 Hz; ISCAT-B –1809 Hz;
- Data transfer rate: ISCAT-A – 21.5 baud; ISCAT-B – 43.1 baud;
- Modulation: 42 FSK tones (“mark” and “space”);
- Transmission duration: ISCAT-A – 1.716 s; ISCAT-B – 0.588 s.

ISCAT messages are free-form, up to 28 characters long. The available character set includes numbers, uppercase Latin letters, and punctuation characters ("space", "/", ".", "?", "@", "-"). Transmissions consist of sequences of 24 characters represented in a special way.

F. JT4, JT9, JT65. All three protocols, JT4, JT9 and JT65, are designed specifically to improve the efficiency of amateur radio communications on the extremely weak VHF bands. All three protocols include error correction capabilities, making them robust and workable even with signals so "weak" that they cannot be heard.

All three protocols use error correction. JT4 and JT9 use FEC with strong convolutional coding [1, 6] with rate $r = 1/2$, limited length $K = 32$ and zero "tail". Synchronization sequences are also used (JT4 and JT9 within one minute of data transmission, JT65 on a separate reference frequency).

JT4 and JT9 use character sets: numbers, uppercase Latin letters, and punctuation characters ("space", "+", "-", ".", "/", "?"). JT4 [1, 7] uses 4-FSK modulation (4 tones to transmit a combination of two bits). JT4 has seven submodes (A…G) with intertone spacing:

$$(11025/2520) \times M = 4.375\text{ Hz} \times M,$$

where M is the pitch multiplier, equal to 1, 2, 4, 9, 18, 36, 72 for modes A, B, …, G respectively.

Occupies a frequency band of approximately:

$$(3 \times M + 1) \times 4.375\text{ Hz},$$

plus manipulation bandwidth.

The wider submodes are intended for operation in the higher microwave bands up to at least 24 GHz.

Traditionally (presumably for compatibility with other WSJT modes – a computer program for decoding the protocols described) the center frequency of the transmission is defined as:

$$11025\text{ Hz}/1024 \times 118 = 1270.46\text{ Hz},$$

which is in tone position 1.5 (midway between tones 1 and 2), and the frequency of the "zero" tone is:

$$11025/1024 \times 118 – 1.5 \times 4.375 \times M.$$

Given the convolutional code, the length of the encoded message is:

$$(72 + 31) \times 2 = 206\text{ information bits.}$$

The protocol uses 1-minute transmit/receive time intervals. One information bit and one synchronization bit are contained in each symbol JT9 protocol [1, 10] uses 9-FSK modulation, and has eight submodes (A…H) with intertone spacing:

$$(12000/6912) \times M = 1.73611 \text{ Hz} \times M,$$

where M is the multiplier of the distance between tones, equal to 1, 2, 4, 8, 16, 32, 64, 128 (2M-1) for modes A, B, …, H, respectively.

Occupies a frequency band of approximately:

$$(8 \times M + 1) \times 1.73611 \text{ Hz}.$$

Sixteen symbol intervals are allocated for synchronization, so the transmission requires a total of:

$$206/3 + 16 = 85,$$

(rounded up) channel symbols.

Synchronization symbols are the symbols numbered 1, 2, 5, 10, 16, 23, 33, 35, 51, 52, 55, 60, 66, 73, 83, and 85 in the transmitted sequence.

The protocol is also divided into nine submodes [10] JT9-1, JT9-2, JT9-5, JT9-10 and JT9-30, which differ in tone durations of 0.58 s, 1.28 s, 3.41 s, 6.91 s and 21 s respectively. The bandwidth is 15 Hz, 7 Hz, 2.6 Hz, 1.3 Hz and 0.4 Hz respectively, and the SNR is -27 dB, -30 dB, -34 dB, -37 dB and -42 dB respectively.

So, as you can see, JT9-30 provides the best SNR (-42 dB), but for radio communication the transmission time will be 180 min.

The JT65 [5] protocol uses 65-FSK modulation and also a convolutional code. These short messages are free of the "sync vector" and use intervals of 1.486 s (16384 samples) for alternating tones.

The protocol uses minute-long receive/transmit sequences and requires precise time and frequency synchronization between the transmitter and receiver. The transmission is divided into 126 consecutive time slots, each 0.372 s long (4096 samples at a rate of 11025 samples per second). The frequency change between slots is performed without changing the phase. The transmission starts 1 second after the beginning of the UTC minute and ends at 47.8 s.

JT65 has three submodes (A, B, C) with intertone spacing:

$$(11025/4096) \times M = 2.692 \text{ Hz} \times M,$$

where M is the multiplier of the distance between tones, equal to 1, 2, 4 for modes A, B, C, respectively.

The encoded information is transmitted during 63 intervals that are not used for transmitting the synchronization tone. Each channel symbol generates a tone at a frequency of:

$$1270.5 + 2.6917 \times (N + 2) \times M,$$

where N is the integer value of the symbol ($0 < N < 63$).

The lower frequency of the tone (also known as the synchronization reference tone) is always 1270.5 Hz. A pseudo-random "synchronization vector" is inserted into the signal between the information bits, which allows for precise determination of the relative errors in time and frequency, establishing the exact structure in which the signal decoder can operate. It also allows for averaging of successfully received sequences and decoding of weak sequences that cannot be decoded individually. The synchronization part of the signal is important and takes up half of the time of each transmission. The synchronization tone is transmitted in each interval that has a logical "1" value in a pseudo-random sequence. This sequence has the mathematical property that its normalized autocorrelation function equals unity for the zero-offset interval and is almost zero for all other intervals.

The interval between tones is:

$$26.917 \times n \times M, \qquad n = 2,3,4.$$

To allow for error correction, the entire message is converted into a 72-bit string and then encoded into a sequence of 63 6-bit symbols (the message is supplemented with 306 uniquely identifiable bits). Thus, the FEC coding coefficient is:

$$r = 72/378 = 0.19.$$

With a good error correction code, the efficiency and sensitivity obtained is much greater than simply repeating the message five times.

It has the following characteristics:

- Lowest SNR: in the 2500 Hz bandwidth – JT4 to -23 dB; JT9 to -27 dBv; JT65 to -25 dB;
- Bandwidth:
  JT4 from 17.5 Hz to 949.4 Hz;
  JT9 from 15.6 Hz to 1779.513 Hz;
  JT65 177.6 Hz;
- Data transfer rate:
  JT4 11025/2520 = 4.375 baud;
  JT9 12000/6912 = 1.736 baud;
  JT65 11025/4096 = 2.692 baud;
- Modulation:

JT4 4-FSK four-tone with an intertone interval of 4.375 Hz;

JT9 9-FSK nine-tone with intertone spacing for JT9A 1.736 Hz (1 reference tone for synchronization and 8 tones for data (1 tone encodes a combination of 3 bits);

JT65 65-FSK sixty-five-tone with intertone spacing for JT65A 2.692 Hz (1 reference tone for synchronization and 64 tones for data (1 tone encodes one of 63 symbols);

- Speed:

for JT4, a complete message of 207 symbols is sent in approximately 47 seconds, with the remaining 13 seconds reserved for timing and decoding inaccuracies. The duration of a symbol transmission is approximately 47 s/207 = 0.229 s;

for JT9 49 s and 11 s respectively. The duration of the symbol transmission is approximately 49 s/85 = 0.577 s;

for JT65 – 46.8 s;

- Synchronization: by time 1 s after the start of the UTC minute;
- Correction code: FEC.

G. QRA64. The QRA64 protocol, in its current implementation, shares similarities with JT65 and utilizes the 64-FSK modulation protocol. Designed as an experimental mode, QRA64 is intended for EME and other applications involving extremely weak signals.

The protocol uses a (63,12) Q-ary Repeat Accumulate code that outperforms the (63,12) Reed-Solomon code used in JT65, providing a 1.3 dB performance improvement. In addition, an updated synchronization method using three Costas 7×7 arrays provides an additional 1.9 dB of gain.

At present, QRA64 does not include message averaging, though this feature could be implemented in the future. During initial testing, numerous EME QSOs were successfully completed using QRA64A-E submodes across the 144 MHz to 24 GHz bands.
It has the following characteristics:
- Lowest SNR: -26 dB based on 2500 Hz bandwidth noise;
- Bandwidth: 111.1 Hz;
- Data transfer rate: 1.736 baud;
- Modulation: 64-FSK;
- Speed: message transmission takes 48.4 seconds.

H. WSPR. This protocol uses 4-FSK modulation. This mode is intended for use as a beacon network for real-time reporting of propagation conditions over the Internet, and also has the ability to switch the band.

A standard message consists of a callsign (28 bits) + a 4-digit locator (15 bits) + dBm (7 bits), a total of 50 bits after lossless compression.

Number of binary channel characters:

$$\text{nsym} = (50 + K - 1) \times 2 = 162.$$

Transmissions begin at the first second of the even minute UTC. Each channel symbol transmits one synchronization bit (LSB) and one data bit (MSB).

The protocol uses forward error correction (FEC): a non-recursive convolutional code with a length constraint $K = 32$, rate $r = 1/2$.

It has the following characteristics:
- Lowest SNR: about -28 dB on the WSJT scale (reference frequency band 2500 Hz);
- Bandwidth: about 6 Hz,
- Data transfer rate: 12000/8192 = 1.4648 baud;
- Modulation: continuous phase 4-FSK, tone separation 1.4648 Hz;
- Speed: 162 × (8192/12000) = 110.6 s;
- Synchronization: 162-bit pseudo-random synchronization vector.

I. FT4, FT8. Consider the FT8 digital protocol - which uses better techniques to quickly detect and decode a weak signal. FT8 is often performed for precision communication in amateur radio stations and beyond.

The size of messages in FT4 and FT8 is equal to 77 bits of information from the user, which provides maximum compactness. Of the 77 bits of the digital signal, 3 bits are allocated for one of 8 types of messages, and 74 bits carry user information.

Message integrity is checked by 14-bit (CRC), which is added to each 77-bit information stream and creates a 91-bit word "message + CRC" [11, 12], which uses polygon 0x6757 (hexadecimal). 83 bits are also added for direct error detection, creating a 174-bit codeword.

To correct errors in the FT4 and FT8 protocols, the so-called LDPC code was developed. This code is determined by two matrices: the generating matrix and the parity matrix. In the generating matrix, an additional CRC word is added to each 91-bit message (only 83 bits are used for parity calculation). Using the parity matrix, it is determined whether the 174-bit sequence is really a code word. That is, the generating matrix consists of 83 rows and 91 columns, the value of which is equal to 0 or 1.

CPFSK is an 8-channel continuous phase-frequency modulation that transmits the FT8 message. Each symbol contains a combination of 3 bits, which sequence of 174 bits is displayed as 174/3 = 58 symbols in the channel (an, n = 0...57). respectively, the value of each symbol in the tone is between 0 and 7. Using Gray code, a group of 3 symbols after the following bits are reported to be displayed on the channel symbols.

Unlike FT8, FT4 employs 4-tone CPFSK modulation, where each channel symbol encodes 2 message bits. This results in a sequence represented by 174/2 = 87 channel symbols (an, n = 0...86), each with an integral tone index ranging from 0 to 3. Similar to the FT8 protocol, the channel symbols are mapped using Gray code.

Tone conversions, known as Costas arrays, are integrated into the FT8 and FT4 signals to ensure that the receiving software is precisely synchronized with the received signals in both time and frequency. The FT8 uses a 7-tone sequence of 3,1,4,0,6,5,2, which is set at the beginning, middle and end of the signal. If we denote the synchronization sequence as S, aMA = {A0, A1,…A28} and **MB = {A29, A30,…A57}, then bn = {S, MA, S, MB, S}.

Has the following characteristics:
- Lowest SNR: in the 2500 Hz bandwidth to -21 dB;
- Bandwidth: about 50 Hz;
- Modulation: 8-CPFSK eight-tone (for FT8) and 4-CPFSK four-tone (for FT4) with an intertone interval of 6.25 Hz;
- Speed: a complete message of 174 symbols is sent in approximately 15 seconds. The duration of the symbol transmission is approximately 15 s/174 = 0.086 s;
- Correction code: LDPC.

III. CONCLUSION

The graphs of Figures 1,2,3 present the parameters that are of interest to us for comparison. Having considered the main protocols of FSK modulation, the following conclusions can be drawn.

The RTTY protocol is easy to configure and is one of the most reliable for use on the HF bands. However, it can be affected by selective signal fading due to polar trajectories. Sometimes, when transmitting "sign" or "space" bits, one side of the signal can completely disappear, causing errors during decoding.

AMTOR which has a built-in direct error correction function, as well as automatic request-to-request to ensure that receiving stations receive text without errors. It can successfully transmit data even in conditions of high noise and signal attenuation.

PACTOR1 works in difficult conditions, where the noise level and signal attenuation can be high. It also uses automatic request-to-request. Requires special equipment, such as a modem, for implementation.

RTTY, AMTOR, PACTOR1 have a low SNR with a wide frequency band, although they provide a high message speed. If errors occur, retransmission of the message leads to a decrease in the overall message transmission speed.

PACKET comes from computer network protocols and is a packet synchronous protocol. Allows you to work in the network as a radio extender, provides duplex communication. Compared to previous protocols, it provides a higher radio exchange rate with a smaller signal frequency band and greater noise immunity.

ISCAT is designed for data transmission over long distances using ionospheric scattering, due to which it has high resistance to interference and can work in any weather. One of the disadvantages of this network is the complexity of configuration and use, slower than previous protocols.

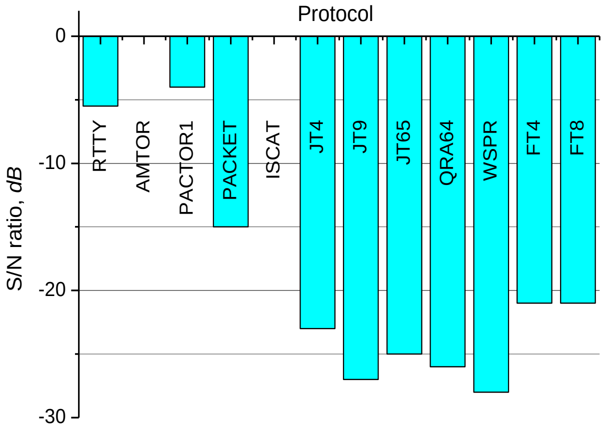

FIG. 1. SNR for reliable message reception in various protocols.

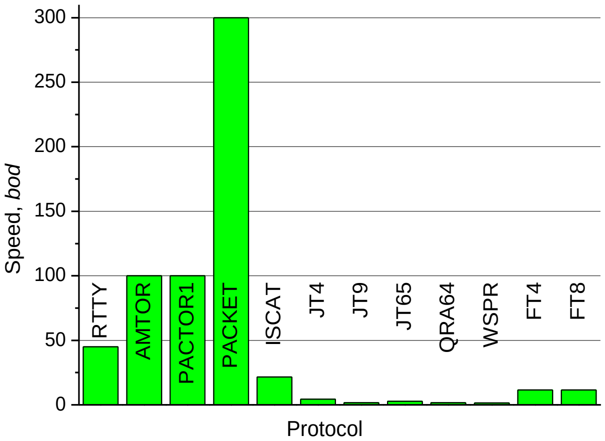

FIG. 2. Message transmission speed in different protocols.

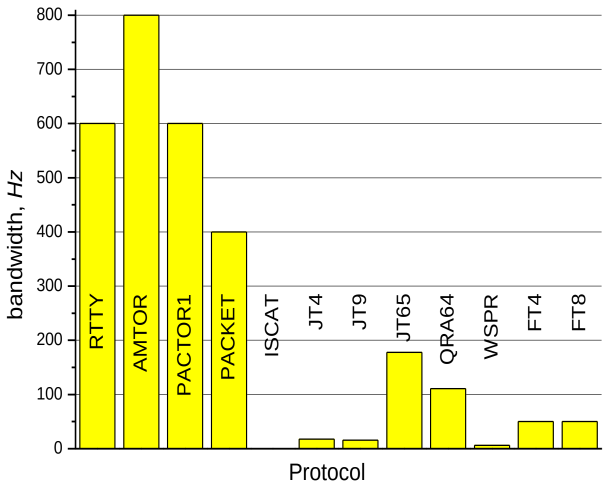

FIG. 3. Signal bandwidth in different protocols.

The JT4, JT9 and JT65 protocols are considered slow, but have a high SNR. They can successfully transmit data even in conditions of high noise and signal attenuation. JT65, despite its slightly lower SNR and lower message transmission speed, has a good error correction code. Therefore, it is more effective and sensitive because it does not repeat the message five times.

QRA64 is similar to JT65, but the use of Qary Repeat Accumulate coding, instead of the Reed Solomon code, provides an advantage of 1.3 dB. This protocol occupies almost half the bandwidth of JT65, providing a 3 dB higher SNR, although a 1 baud lower speed.

WSPR, given its purpose (use as a beacon network for real-time reporting of propagation conditions via the Internet), has a low exchange rate, the signal occupies a narrow bandwidth, has a high SNR.

FT4 and FT8, compared to other protocols (JT4, JT9, JT65, QRA4, WSPR), have the advantages of higher transmission speed and lower bandwidth.

As can be seen from the graphs, the JT4, JT9, JT65, QRA4, WSPR, FT4, FT8 protocols provide a SNR of more than -20 dB compared to the RTTY, AMTOR, PACTOR, ISCAT protocols and the signal occupies a smaller frequency band.

All of the above protocols provide a higher message transmission rate compared to other FSK modes.

In general, it can be concluded that the modulation method in conjunction with the use of error correction codes allows for a significant improvement in the SNR.

AUTHOR CONTRIBUTIONS

I.K. – conceptualization, investigation, writing-original draft preparation; A.V. – investigation, resources, writing-original draft preparation, supervision writing-review and editing.

COMPETING INTERESTS

The authors declare no competing interests.

ACKNOWLEDGMENT

The authors acknowledge the support from NFDU project №2023.04/0150 “Development of mobile radiowave source positioning and power measuring and visualising system”.

REFERENCES

[1] AC4M Digital Radio Site. [Online]. Available: http://ac4m.us/fsk_modes.html.

[2] "Frequency Shift Keying (FSK)," Wikipedia. [Online]. Available: https://uk.wikipedia.org/wiki.

[3] "American Standard Code for Information Interchange," Wikipedia. [Online]. Available: https://uk.wikipedia.org/wiki/ASCII.

[4] "Frequency-shift keying (FSK)," Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/AFSK.

[5] "High-Level Data Link Control (HDLC)," Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/HDLC.

[6] "Comparisons of QRA64 and JT4 for 10 GHz EME." [Online]. Available: https://www.ok2kkw.com/more/comparisons_of_qra64_and_jt4_for_3cm_eme.htm.

[7] J. Taylor, K1JT, S. Franke, K9AN, and B. Somerville, G4WJS, “Work the World with WSJT-X: Part 1,

Operating Capabilities," *QST*, vol. 101, no. 10, pp. 30–36, Oct. 2017.
[8] J. Taylor, K1JT, "WSJT: New Software for VHF Meteor-Scatter Communication," *QST*, vol. 85, no. 12, pp. 36–41, Dec. 2001.
[9] "The FT4 and FT8 Communication Protocols." [Online]. Available: https://wsjt.sourceforge.io/FT4_FT8_QEX.pdf.
[10] "QRA de SM7VRZ." [Online]. Available: https://sm7vrz.wordpress.com/.
[11] "A Painless Guide to CRC Error Detection Algorithms." [Online]. Available: https://www.zlib.net/crc_v3.txt.
[12] "Princeton Physics." [Online]. Available: http://physics.princeton.edu/pulsar/k1jt/ft4_ft8_protocols.tgz.

Ihor Klapashchuk

Received a bachelor's and master's degree in radio engineering and cybersecurity from Yuriy Fedkovych Chernivtsi National University, Ukraine. Currently receiving a PhD. Radio engineer from Yuriy Fedkovych Chernivtsi National University.

Andrii Veryha

Received BS and MS degrees in Radio Engineering from Yuriy Fedkovych Chernivtsi National University, Ukraine. He received a Ph.D. in Radio Engineering from Yuriy Fedkovych Chernivtsi National University. He is currently an assistant of the Radio Engineering Department of Yuriy Fedkovych Chernivtsi National University. His research interests include signal processing, development of electronic circuits.

ORCID ID: 0000-0002-2616-3057

Аналіз радіолюбительських протоколів частотної кодової модуляції для передавання коротких повідомлень

Ігор Клапащук*, Андрій Верига

Кафедра радіотехніки та інформаційної безпеки, Чернівецький національний університету імені Юрія Федьковича, Чернівці, Україна

*Автор-кореспондент (Електронна адреса: Igor.klapashchuk@gmail.com)

АНОТАЦІЯ Стаття присвячена аналізу поширених серед радіолюбителів в радіоаматорському зв'язку протоколів передавання коротких повідомлень в цифровому коді. Розглянуто наступні протоколи: RTTY, AMTOR, PACTOR1, ISCAT, JT4, JT9, JT65, FT4, FT8. Всі вони застосовують частотну модуляцію (FSK), має значно кращу стійкість до шумів, оскільки інформація кодується у зміні частоти, а не амплітуди. Завдяки цьому FM широко застосовується у радіомовленні. Основне призначення вище перелічених протоколів запобігти затуханню сигналу при відбиванні радіохвиль від шару іоносфери (спорадичне проходження), де вікна відбивання можуть бути короткими. Тому модуляція повинна бути швидкою і має бути висока надійність передачі даних для підтвердження радіообміну. Проаналізовано основні характеристики цих протоколів, а саме максимальне відношення сигнал/шум при якому можливе приймання та декодування цифрових даних, швидкість передавання та смуга частот, яку займає сигнал. Також розглянуто супутні характеристики, такі як час передавання одного біта, використання завадостійкого кодування із виправленням помилок. Розглянули основні режими FSK модуляції, порівняли їхні переваги та недоліки. Встановлено, що протоколи JT4, JT9, JT65, QRA4, WSPR, FT4, FT8 забезпечують відношення сигнал/шум більше -20 дБ в порівнянні з протоколами RTTY, AMTOR, PACTOR, ISCAT. В таких протоколах сигнал займає меншу смугу частот. Всі вищерозглянуті протоколи забезпечують вищу швидкість передавання повідомлень порівняно з іншими режимами модуляції. Зроблено висновок, що частотний спосіб модуляції в парі із застосуванням кодів виправлення помилок дозволяє значно покращити сигнал/шум, а застосування подібних методів виявлення і декодування сигналів може дозволити розробити декодер із суттєво вищою чутливістю. Розроблення нового типу сигналу для передавання цифрової інформації можна базувати на модифікації протоколів JT4, JT9, JT65, QRA4, WSPR, FT4, FT8.

КЛЮЧОВІ СЛОВА протокол, частотна модуляція, кодування, сигнал/шум.