Protection of Information Networks Based on LoRa Technology

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Abstract. The paper deals with modern technology for transmitting short messages over long distances named LoRa, where the transmitted signal uses linear frequency modulation (chirp). The object of the study to define lack of transmitters that it has a design on LoRa technology for assessment their applicable in condition urban city where there are a lot of radiation sources. The goal of the work is the creation of a method of assessing the act the interference conditions that based on measurement bit error rate and signal-noise ratio and via on which to get individual host vulnerability levels. The processing of these signals is carried out by means of a time-frequency transformation. The chirp signal is characterized by 4 parameters: frequencies, time, modulation rate and amplitude. By analogy with the wavelet transform, the processing of chirp signals involves a chirplet decomposition. Since the chirp signals are strongly influenced by mutual interference due to multipath, the article studies the effectiveness of LoRa technology in conditions of mutual interference of radiation sources. The developed method utilized chirplet decomposition and retrieve symbols of a message in the dictionary. The conducted experiments have confirmed the proposed software operability and allow recommending it for use in practice for solving the problems receiving signal. The prospects for further research may include the creation of parallel methods for calculation of the set of proposed indicators, the improvement of software, as well as an experimental study of proposed indicators in real conditions.

Keywords: Chirp, Time-Frequency Transform, Chirplet Decomposition, LoRa Technology, Interference.

1 Introduction

Currently, LoRa technology is widely used to create a number of devices for the Internet of things, data collection and transmission systems, and also portable devices, through which short messages can be transmitted over long distances (according to some data up to 20 km). An additional advantage of the technology is the conservation of energy resources of the user devices (galvanic cells). This technology uses chirp pulses, the message symbols in which are coded by 4 parameters such as amplitude, center frequency, deviation range and the center of the pulse. Each symbol is assigned a chirp, characterized by these 4 parameters. A complete set of symbols forms a dictionary of chirplets, named by analogy with wavelets. The analysis of the message consists of selecting symbols from the dictionary and finding the best matching of the chirplets to the symbols of the received message. This analysis, called a chirplet decomposition, is carried out in the time-frequency domain. In spite of the fact that chirp signals use the spreading of the spectrum the jamming in the receiving channel cause some difficulties. Processing of chirp signals is complicated by mutual interference from similar sources, as a result of which the received signal has distortions. The main goal of the paper is to research the effectiveness of the chirplet decomposition under interference conditions.

2 Review of the Literature

Previous work [1] addressed general issues of network congestion assessment, without reference to vulnerability. However, solution providers, operators, and researchers show a natural interest in the latest network technology LoRa. The most detailed analysis of this technology is presented in [2]. This paper deals with some open questions related to LoRa research and development. The innovative mathematical model of the network LoRaWAN is presented in [3]. This model provides a determination of the network capacity and reliability of information transmission. Mathematical simulation of the radio channel for the LoRaWAN transceiver in various operating states for different environments covering the urban, suburban and rural areas is given in [4]. The study in [4] has shown that the best suitable model for all registered levels of the received measurement signal is described by the Nakagami distribution and, in general, LoRa is a reliable portable wireless technology. Asynchronous protocol LoRaWAN by type ALOHA for access to the channel without the limitation of the working cycle is presented in [6].

However, the processing of LoRa signals is currently not fully researched. The quality of signal processing is based on the research of their types and the methods of protection against interference that are used. It should be noted that the use of frequency analysis alone, in conjunction with classical digital processing, as it was used in [6], is not suitable since LoRa uses spread spectrum technology. Measurement of only the center frequency of the signal is not sufficient to decipher the complete message. General information on the modulation used in LoRa technology is given in [7]. The main technology is the use of signals with linear frequency modulation. Processing chirp signal based on decomposition by Gaussian chirplets was an active area of research in signal processing in the 90s of the last century [8, 9].

The approach to chirplet-decomposition of the received signal is presented in [10]. However, the expansion of the adopted chirp on the basis of Gaussian functions turned out to be unsuitable, since Gaussian chirplets do not form an orthogonal basis. A promising solution was the scheme of decomposition of signals based on matching. An algorithm for searching of optimal Gaussian chirplets using a crude dictionary is presented in [11]. A similar algorithm for estimating the characteristics of visually evoked potentials (VEP) based on the Chirplet representation is applied in [12]. In [13, 14] the structure of the Chirp-Binary Orthogonal Keying (BOK) system is studied on a background of white Gaussian noise and a frequency filter for eliminating slit-like interference in direct-spectrum communications (DSC).

The main result of [13] is the estimation of the number of erroneous bits (BER) in the Chirp-BOK system. The protection of the receiving channel based on the decomposition of chirplet is presented in [14]. This paper also shows some chirplet-decomposition possibilities under interference conditions. The obtained results can be used in many areas including systems of communications of unmanned aerial vehicles for monitoring objects of different type [15].

3 Problem Statement

Chirp is a signal that has the form

$$s(t) = \begin{cases} a(t)\cos(2\pi ft + ct^2) \text{ if } |t| \le \tau_0 / 2; \\ 0, \text{otherwise}, \end{cases} \tag{1}$$

where $a\ (t)$ is the law of amplitude variation (envelope); f is the central frequency; t is time, and c is the phase modulation coefficient. If $c > 0$, the frequency increases, if $c<0$, the frequency decreases, $c = 0$ corresponds to a harmonic signal that is not modulated in frequency; τ_0 is the pulse duration.

The received signal can be presented as an additive mixture of a useful signal $s(t)$, a white noise with zero mean $n(t)$ and a signal of re-reflections $w(t)$

$$y(t) = s(t) + n(t) + w(t) \tag{2}$$

The main indicators of information network security are topological characteristics, one of which is a host's vulnerability. Host vulnerability is determined based on known vulnerabilities and the main type of vulnerability for LoRa system is the interference for receiving set. To assess the quality of reception, we use the signal-to-noise ratio and bit error rate and estimate the effectiveness of the LoRa system under consideration by measuring the signal-to-noise ratio in a densely populated urban area.

4 Elements of Protection

LoRa technology has a few elements of protection. First of them is a signal spectrum that it is completely determined by the phase modulation component and represents the Fourier transform of the signal $s\ (t)$, i.e.

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft} dt \tag{3}$$

For the signal $s(t)$, representing a rectangular pulse of unit amplitude, i.e. $a(t) = 1$ and duration τ_0, expression (2) can be written in the form

$$S(f) = \int_{-\tau_0/2}^{\tau_0/2} e^{jct^2} e^{-j2\pi ft} dt \tag{4}$$

The spectrum of the signal τ_0 =10 μs and bandwidth 200 MHz of the form (1) is shown in Fig. 1.

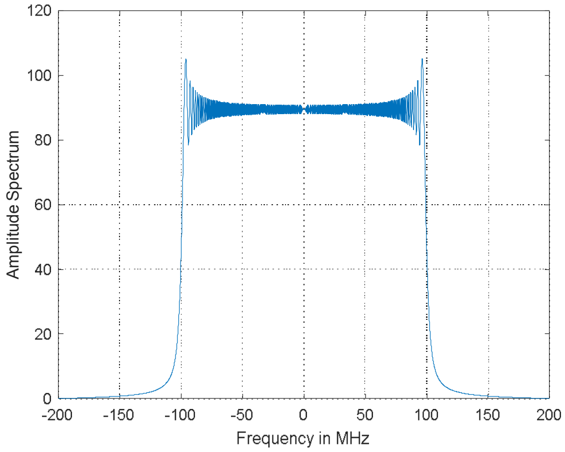

Fig. 1. Typical spectrum for chirp signal.

It should be noted that the width of the spectrum is an indirect indicator of security since high-density interference is difficult to create in a wide frequency range.

The next element of protection is encoding a chirp signal. In decoding used to use chirplet decomposition. Chirplet is a Gaussian function of the form

$$g_c(t) = \frac{1}{\sqrt{\sqrt{\pi}\sigma}} \exp\left(-\frac{(t-t_c)^2}{2\sigma} \right) \exp(j2\pi f_c(t-t_c) + \mu_c(t-t_c)^2), \tag{5}$$

where t_c, f_c are parameters of the time and frequency of the function; σ is the variance, which determines the duration of the chirp function; and μc is the modulation rate. The Gaussian chirplet is a fundamental function. Therefore, it is desirable to represent the receiving signal during its processing as a weighted sum of Gaussian chirplet. The form of the chirplet signal is shown in Fig. 2.

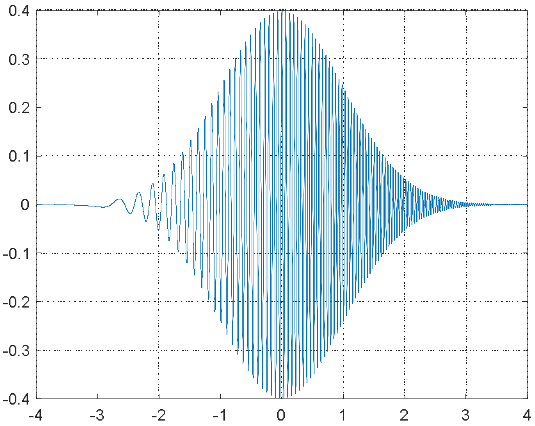

Fig. 2. The form of a chirplet

For the parameters $t_c = 0$, $\sigma = 1$, $\mu_c = 0$, $f_c = 0$, the function $g_c(t)$ takes the form

$$g_c(t) = \frac{1}{\sqrt[4]{\pi}} \exp\left(-\frac{t^2}{2}\right) \tag{6}$$

Expression (6) is called the base function of transformations. Modification (6) can be used for the identification of parameters of the Gaussian function for its representation by a harmonic oscillation with frequency modulation of a given kind.

A set of chirplets can be used for the representation of chirp particles. For this purpose, in [8] it was suggested to use time convolution, frequency multiplication together with time and frequency shifts. Unfortunately, this approach to chirplet transformation does not give a positive result, because these transformations are interdependent, therefore such a chirplet cannot be chosen as a basis for orthogonal functions [10].

Recently, a direction has been developed, related to the development of the Fourier transform, in particular, a fractional Fourier transform, which measures the angular distribution of the signal energy in the time-frequency plane. This operator, given by the Wigner distribution for the signal $s(t)$

$$W(t,\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s\left(t - \frac{\tau}{2}\right) s^*\left(t + \frac{\tau}{2}\right) e^{-j\omega\tau} d\tau \tag{7}$$

rotates the signal in the time-frequency plane. In formula (7) asterisk for signal $s^*(t)$ means the complex conjugate signal $s(t)$, ω is the angular frequency equal to $2\pi f$. Rotation represents a special combination of chirp convolution and of multiplication chirp as a result of an orthogonal transformation of time-frequency coordinates. This property is achieved by multiplying on the scale factor, using rotation, and by the time and frequency shifts that form the four time-frequency atom parameters. However, it is possible to use the chirplet decomposition to represent the complex signal in a compact form. The appropriate time-frequency transform is presented in Fig. 3.

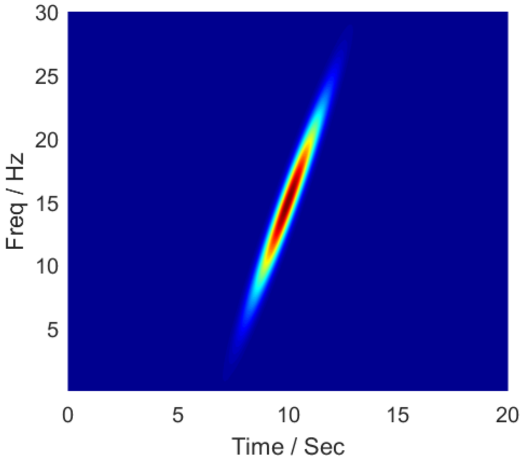

Fig. 3. Time-frequency transform of a chirplet for signal $a = 1$ V, $f = 15$ Hz, $c = 15$, $\tau_0 = 20$ sec.

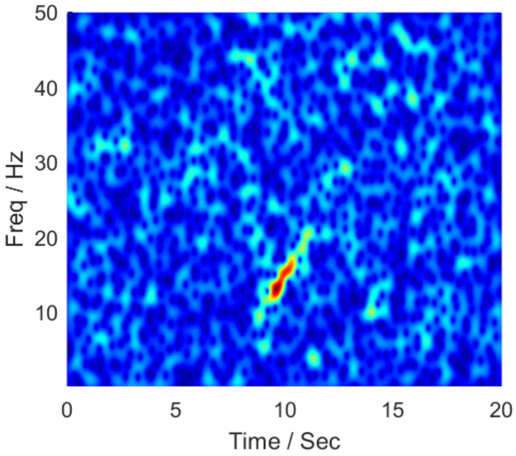

Fig. 4. Time-frequency representation for chirp signal in noise, SNR=2.

An effective measure of the quality of the received data packet in an interfering noise environment is the probability of a transmission error of the data packet p_p, which can be expressed by the relation

$$p_p = 1 - (1 - p_e)^N, \tag{8}$$

where p_e is the bit error probability of the information bit or bit error rate (BER), N is the number of bits in the packet. Assuming p_e small, we get

$$p_p \approx p_e N. \tag{9}$$

To reduce the errors in the transmission of the information packets if they have equal length of the packet N, we need to decrease the value of the bit error p_e as follows from expression (7).

There are known [15] relations for estimating BER when representing the transmission channel by the additive Gaussian white noise model. Therefore, the BER of binary phase-shift keying (BPSK) modulation is

$$p_e = 0.5 erfc\left(\sqrt{\frac{E_b}{N_0}}\right), \tag{20}$$

In the chirplet expansion, the signal parameters $g(\gamma)= g\ [(l,\ \alpha,\ t,\ \omega)]$ are determined. The received signal is digitized, resulting in a set of $g(\gamma_n)= g[(l_n,\ \alpha_n,\ t_n,\ \omega_n)]$, $n \le N$. And γ_n is the set of possible sampled parameter values form a dictionary D, i.e. $\gamma_n \in D$. Any function $s(t)$ can be represented by a set of atoms $g(\gamma)$. An algorithm that allows searching a suitable combination of data from a dictionary should provide a maximum of the search function

$$s(t) = \sum_{n=1}^{N} s(\gamma_n) g_{c_n} \tag{31}$$

The parameters $s(t)$ specifying a maximum (10), will determine the maximum approximation to the original signal. In this case, the parameter l_n determines the time domain dilatation, and its reciprocal value is the signal compression in the frequency domain, the ellipse rotation angle α_n corresponds to the linear modulation of the signal center frequency, and the variables t_n, ω_n are the time and frequency of the central part of the signal. It becomes necessary to develop an algorithm for searching $s(\gamma_n)$.

The peculiarity of the algorithm is that a set of parameters is selected from the parameter block dictionary. The algorithm is iterative to provide the best internal signal structure by computing the scalar product of the functions $s(\gamma_n), g_{cn}$. The received value must satisfy the condition

$$|sg_0| = \sup_{\bar{\gamma}} |sg_\gamma| \tag{42}$$

Further, we compute the remainder term, which at the beginning of the algorithm is equal to the signal itself

$$R_0 = s(t) \tag{53}$$

and carry out the next steps

$$R_1 = R_0 - |sg_0| g_0 \tag{64}$$

$$R_2 = R_1 - |sg_1|g_1 = R_0 - |sg_0|g_0 - |sg_1|g_1 \tag{75}$$

$$R_i = R_{i-1} - |sg_{i-1}|g_{i-1} = R_0 - \sum_{k=1}^{i-1}|sg_k|g_k \tag{16}$$

$$\ldots$$

$$R_i = R_{i-1} - |sg_{i-1}|g_{i-1} = R_0 - \sum_{k=1}^{i-1}|sg_k|g_k \tag{87}$$

The stopping criterion is the ratio

$$\rho = \frac{\left\| \sum_{k=1}^{n} |sg_k| g_k \right\|}{\|R_n\|} \tag{98}$$

The higher this ratio value, the worse the chosen decomposition parameters.

5 Experiments

Consider a typical signal LoRa system that is a linear frequency modulated pulse signal. This signal can be obtained, for example, with a voltage-controlled oscillator in the form (1). A useful signal is a packet of pulses with binary modulation. In this case, the logical signal "1" corresponds to the condition $c > 0$ and the opposite signal, a logical "0", is obtained if $c < 0$.

In the experiment, a LoRa system transceiver is based on the SX1276 chip to transmit a short message at a frequency of 868 MHz. The receiver is installed on the top floor of the building. The transmitter gradually moves through the building from the top floor to the basement room, which creates interference. In addition, interference is created by mobile communication transmitters, whose antennas are located on the roof of the building. In addition to the signal-to-noise ratio, the reception quality was also determined by determining the number of erroneous bits in a message and measuring the bit error rate (BER). The measurement scheme is shown in Fig. 5.

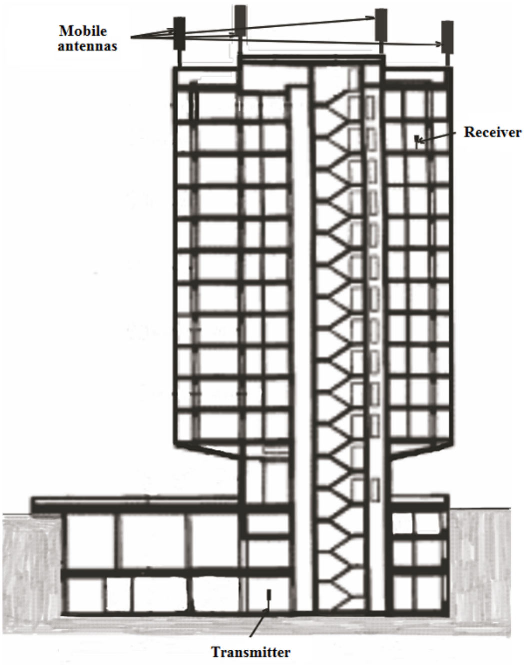

Fig. 5. The scheme of measurement.

The transmitting antennas of mobile operators and Wi-Fi routers that located near the building create jamming with reception. The signals of these devices create an interfering background, which is taken for "white" noise $n(t)$. Crosstalk $w(t)$ is created by multiple re-reflection raying from the interior of the building from the reinforced concrete structures. On each floor of the building, the level of signal and noise is fixed and the quality of the message is controlled. The panoramic receiver selected as the benchmark additionally documents the measurement results. A preliminary analysis of the interference situation presented in Fig. 6.

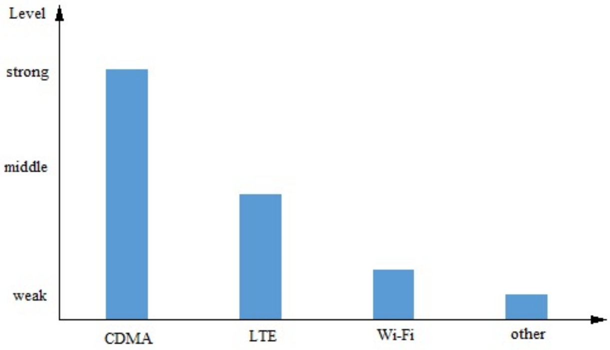

Fig. 6. The radiation intensity.

The results of the measured BER and signal error ratio are presented in Fig. 7.

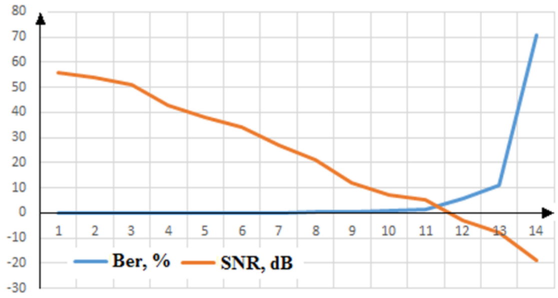

Fig. 7. The measurement of BER and SNR.

The obtained results allow us to represent the vulnerability of the host numerical scale, when the high level of vulnerability corresponds to BER = 10%, SNR = -10 dB, the average level of vulnerability BER = 5%, SNR = -5 dB, weak level BER = 2%, SNR = 2 дБ.

6 Conclusions

Although LoRa technology is relatively new for telecommunication systems, linear frequency modulation signals are used for data transmission, which are considered standard in wireless communication systems over short distances (IEEE 802.15.4a). The complexity of processing this type of signals is associated with the need for simultaneous time-frequency analysis of the received signal.

Moreover, an improvement in the accuracy of time measurement leads to deterioration in the accuracy of frequency measurement and vice versa, which is explained by the time-frequency uncertainty principle known in radar. The output in this situation is the time-frequency decomposition of the received signal using the matching pursuit algorithm to the message dictionary. The peculiarity of the study is the most suitable use environment-a densely populated district in the city. The result of the study shows that the placement of devices on the surface gives quite good results. Acceptable results are achieved on the 1st and 2nd floor, where BER is about 1% and the signal-to-noise ratio is not worse than 1-2 dB. Future research is planned to focus on the creation of parallel methods for calculation of the set of proposed indicators, the improvement of software, as well as an experimental study of proposed indicators in real conditions.

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