Vodopianov, Serhii; Martynova, Oksana; Krainosvit, Arkadii

Article

Development of a method of analysis of energy and information characteristics of wireless networks of critical application under conditions of limitations on the signal/(interference plus noise) ratio

Reference: Vodopianov, Serhii/Martynova, Oksana et. al. (2023). Development of a method of analysis of energy and information characteristics of wireless networks of critical application under conditions of limitations on the signal/(interference plus noise) ratio. In: Technology audit and production reserves 2 (1/70), S. 30 - 34.
https://journals.uran.ua/tarp/article/download/278280/273242/642278.
doi:10.15587/2706-5448.2023.278280.

ISSN 2664-9969

UDC 621.39:629.73](045)
DOI: 10.15587/2706-5448.2023.278280

Serhii Vodopianov,
Oksana Martynova,
Arkadii Krainosvit

DEVELOPMENT OF A METHOD OF ANALYSIS OF ENERGY AND INFORMATION CHARACTERISTICS OF WIRELESS NETWORKS OF CRITICAL APPLICATION UNDER CONDITIONS OF LIMITATIONS ON THE SIGNAL/(INTERFERENCE PLUS NOISE) RATIO

The object of the research, the results of which are presented in the article, is the process of analyzing the energy and information characteristics of wireless networks of critical application. The presented article examines the problems of information and telecommunication systems of air transport as hard real-time systems. Thanks to the development of methods for analyzing the bandwidth of heterogeneous networks that function under the conditions of external interference, caused, among other things, by the random nature of multiple access, the asymptotic characteristics of networks and their dependence on the number of network and terminal nodes, the size of the network as a whole, were obtained. The specificity of wireless networks is the propagation of signals through a free environment, that is, fundamentally open access to signals as carriers of information that is transmitted from one subscriber to another. Based on the results of the analysis of promising information and communication and computer networks of critical application, it was found that the main problems for networks are their vulnerability to external interference of various origins, which worsens QoS indicators, in particular, performance. Therefore, in addition to the general problems of managing information and telecommunication networks, the problems of protection against unauthorized interference and external interference of various origins are quite acute in wireless networks. In order to constantly monitor network characteristics at the proper level, a method of calculating the current signal/(interference plus noise) ratio has been developed. According to the results of the analysis of the energy and information characteristics of the network, their relationship is established, which is not always obvious, but very indicative and useful, for example, for solving the tasks of multi-criteria optimization of parameters and management of the network state.

Keywords: *air transport, wireless information and telecommunication system, energy characteristics of the network, network performance.*

Received date: 14.03.2023
Accepted date: 28.04.2023
Published date: 30.04.2023

How to cite
Vodopianov, S., Martynova, O., Krainosvit, A. (2023). Development of a method of analysis of energy and information characteristics of wireless networks of critical application under conditions of limitations on the signal/(interference plus noise) ratio. Technology Audit and Production Reserves, 2 (1 (70)), 30–34. doi: https://doi.org/10.15587/2706-5448.2023.278280

1. Introduction

The intensive progress of information and telecommunication technologies, their implementation in all areas of human activity is associated with the development and construction of complex and advanced information and computing systems. Such systems include, for example, aviation, rocket-space, railway, transport, energy and other special purpose systems [1–5]. As a rule, they work in conditions of continuous round-the-clock application in real time [6–10].

According to the results of the analysis of the methods of organization and ensuring the quality of service in promising information and communication and computer networks of air transport, it was found that the heterogeneity of network traffic and congestion, which worsen QoS indicators (quality of service), create certain technical and organizational problems.

Air transport information and telecommunications systems contain autonomous network segments that are wireless by definition. Receiving any information at the access point is already carried out through wireless channels – from *Wi-Fi*, *WiMAX* networks to satellite networks.

The specificity of wireless networks is the propagation of signals through a free environment, that is, fundamentally open access to signals as carriers of information that is transmitted from one subscriber to another. Therefore, in addition to the general problems of managing information and telecommunication networks, the problems of protection against unauthorized interference and external interference of various origins are quite acute in wireless networks.

The purpose of the paper is to develop a method for analyzing the bandwidth of heterogeneous wireless networks with restrictions on the signal/(interference plus noise) ratio. Since bandwidth is an integral component of overall network performance, the topic we are dealing with is very relevant.

2. Materials and Methods

The object of research is the process of data exchange in wireless networks of critical applications with heterogeneous traffic.

The research used a systematic approach, analysis and synthesis, mathematical analysis, and computer modeling.

3. Results and Discussion

Let's give a brief description of the network. The network volume is not fixed:

$$L_{netw} \le L_{netw\max}\big|_{q \ge q_{\min}},$$

where $L_{netw\max}$ – the maximum distance between network nodes determined by the minimum signal/(interference + noise) ratio. The volume of the network is constantly changing randomly. Changes depend on various (internal and external) factors. If the network capacity is exceeded, the network management system immediately tries to restore the network to its initial state. The control mechanism is a triplet of *QoS* service quality. To ensure *QoS* standards in accordance with Y.1564-201602-III recommendations – traffic flow certification – the following parameters (key *QoS* triplet) are usually used: bandwidth C_{th}; transmission delay τ_{lt} and its probability distribution $w(\tau_{lt})$; the average number of bit errors in the stream f_{err}.

A very important characteristic of the performance of communication systems is the signal-to-noise ratio (SNR). SNR is the ratio of the signal energy per 1 bit to the noise power density per 1 hertz (Hz). Consider a signal containing binary digital data transmitted at a certain rate – R bit/s. Let's recall that 1 W = 1 J/s and calculate the specific energy of one signal bit:

$$Eb = S \cdot Tb,$$

where S – the signal strength; Tb – the transmission time of one bit. The transmission speed can be expressed in terms of the difference between the entropy of the useful signal $H(u)$ and the conditional entropy $H(u|\nu)$, which is equal to the entropy of the thermal noise [8]. Given that the thermal noise present in a 1 Hz bandwidth for any device or conductor is:

$$N_0 = kT(\mathrm{W/Hz}), \quad (1)$$

where N_0 – the noise power density in watts per 1 Hz band; k – Boltzmann's constant; T – the temperature in degrees Kelvin (absolute temperature), then:

$$\frac{E_b}{N_0} = \frac{S/\nu}{N_0} = \frac{S}{kT\nu}. \quad (2)$$

The ratio E_b/N_0 is of great practical importance, since the rate of appearance of false bits is (decreases) a function of this ratio. With the known value required to obtain the desired level of errors, it is possible to choose other parameters in the given equation. It should be noted that in order to maintain the required value when the data transfer rate R is increased, the power of the signal transmitted in relation to the noise will have to be increased.

Quite often, the noise power level is sufficient to change the value of one of the data bits. If to double the transmission speed, the bits will be «packed» twice as tightly, and the same extraneous signal will lead to the loss of two bits of information. Therefore, with a constant signal power and noise, an increase in the transmission speed entails an increase in the level of errors.

To calculate the range, let's use the classic formula for calculating losses in free space [4]:

$$F_{SL} = 33 + 20(\lg F + \lg r),$$

where F_{SL} – free space loss (dB); F – the central frequency of the channel on which the communication system operates (MHz); r – the distance between two points (km).

F_{SL} is determined by the total gain of the system. It is calculated as follows:

$$Y = P_\Sigma + G_t + G_r - P_{min} - L_t - L_r\ [\mathrm{dB}], \quad (3)$$

where P_Σ [dBmW] – the power of the transmitter; G_t [dB] – the gain of the transmission antenna; G_r [dB] – the gain of the receiving antenna; P_{min} [dBmW] – sensitivity of the receiver at this speed; L_t [dB] – signal losses in the coaxial cable and connectors of the transmission path; L_r [dB] – signal losses in the coaxial cable and connectors of the receiving path.

F_{SL} is calculated by the formula:

$$F_{SL} = Y - S_{OM}, \quad (4)$$

where S_{OM} (System Operating Margin) is the reserve in radio communication energy (dB). Takes into account possible factors that negatively affect the range of communication, such as:

– temperature drift of receiver sensitivity and transmitter output power;
– various atmospheric phenomena: fog, snow, rain;
– inconsistency of the antenna, receiver, transmitter with the antenna-feeder path.

The parameter is usually taken equal to 10 dB [3]. It is believed that a 10-decibel amplification margin is sufficient for engineering calculation [4].

As a result, let's obtain the communication range formula:

$$r = 10^{\left(\frac{F_{SL}}{20} - \frac{33}{20} - \lg f_0\right)}. \quad (5)$$

Let's consider a specialized information and communication network and transmission delays. Network nodes can be both mobile and stationary (Fig. 1).

The network contains N switching nodes (SwN), one source s_n and one information gathering node (receiver) d_n. The diagram of the location of nodes is shown in Fig. 2.

The task is to transmit information from the source to the receiver with minimal delay and limiting the energy consumption of the source and network switching nodes.

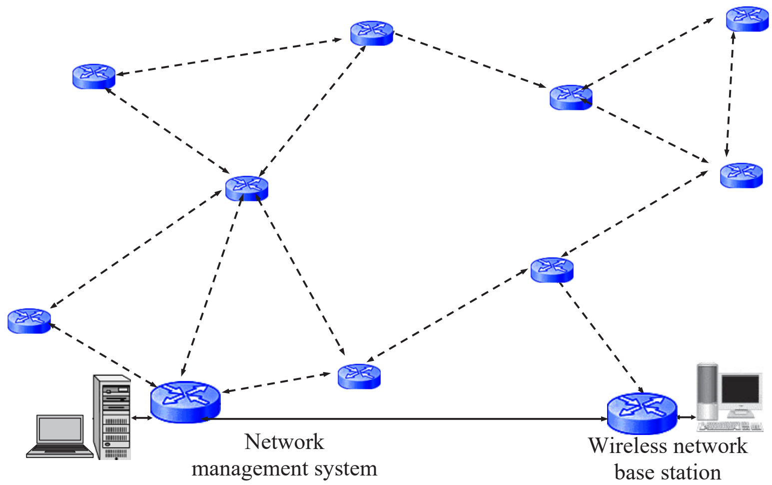

Fig. 1. Diagram of a network with mobile nodes

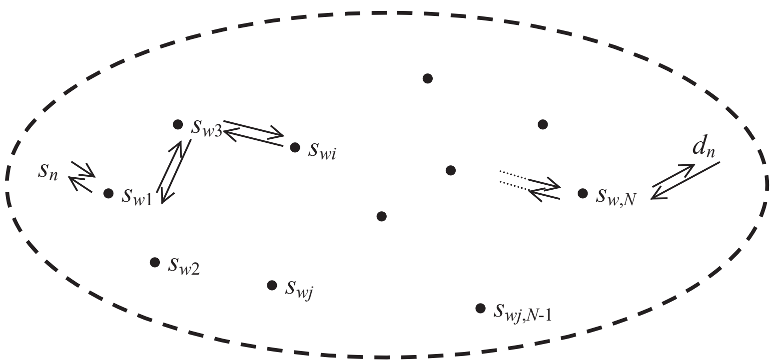

Fig. 2. Scheme of successive transmissions of messages with intermediate confirmations

Let's consider the transmission in the network successful if the following rules [4] are met:

– the source, after transmitting the next message, receives confirmation of receiving the message from at least one SwN;

– the SwN that received the message stores it until a connection is established with any switching node (except the one from which this message was received) or until a certain time elapses before the expected moment of contact with any switching node SwN – the custodian of the message transmits it and receives confirmation of receipt;

– the recipient, who received a message from one of the SwNs closest to it, in turn sends a confirmation of receipt;

– if at any of the intermediate stages of the message passing through the network, confirmation by the i-th node $(i=1,2,\dots j,\dots,M \quad M<N)$ is not received within the specified time, the transmission of the message by the i-th node is repeated.

Considering the distribution laws of the signal and noise to be mutually independent, the formula of the composition of the distribution laws was used to find the distribution law of the sum of the signal and noise [7].

Let the input signal be an additive mixture of the useful signal and noise:

$$y(t)=s(t)+n(t).$$

Dispersion of the signal y_{out}:

$$\sigma_{out}^2=\frac{N_0}{2}\int_{-\infty}^{\infty}\left[s(t-t_c)\right]^2 \mathrm{d}t=N_0E_0/2.$$

Detection probability:

$$P_d=\int_{y_n}^{\infty}w(y|s\neq 0)\mathrm{d}y=\frac{1}{\sqrt{2\pi(N_0E_0/2)}}\times$$
$$\times\int_{y_n}^{\infty}exp\left[-\frac{(y_{out}-aE_0)^2}{2(N_0E_0/2)}\right]\mathrm{d}y_{out}. \quad (6)$$

The integral in the right-hand side of (6) is a tabulated function – the integral of probability $\Phi(x)$ [3]. Accordingly, the detection probabilities P_d and false alarms P_f can be written as:

$$P_d=1-\Phi\left[y_n\sqrt{2(N_0E_0/2)}-\sqrt{R}\right];$$
$$R=2E/N_0, \quad (7)$$

$$P_f=1-\Phi\left[y_n\sqrt{2(N_0E_0/2)}\right], \quad (8)$$

where $E_0=\int_{-\infty}^{\infty}\left[s(t-t_0)^2\right]\mathrm{d}t$ – the energy of the «reference» signal, which is determined by the type of signal being transmitted.

Taking into account the expressions (1)–(8), a methodology for calculating the communication range in free space has been developed.

Let there be a transmitter with power P_Σ with an isotropic emitter. The electromagnetic field is radiated by a sphere of radius r. Then the power flux density per unit surface of the sphere is determined by the following expression:

$$\Pi_{\Sigma 0}=\frac{P_\Sigma}{4\pi r^2}. \quad (9)$$

If the signal energy generated by the transmitter is radiated into space through an antenna with gain G_Σ, then:

$$\Pi_{\Sigma G}=\frac{P_\Sigma G_\Sigma}{4\pi r^2}. \quad (10)$$

The signal power at the input of the receiver located at a distance r is equal to:

$$P_{PRM}=\Pi_{\Sigma G}A_{ef}=\frac{P_\Sigma G_\Sigma A_{ef}}{4\pi r^2}. \quad (11)$$

Taking into account the ratio:

$$A_{ef}=\frac{G\lambda^2}{4\pi},$$

where λ – the wavelength of the emitted signal, (11) can be written in the following form:

$$P_{prm}=\frac{P_\Sigma G_\Sigma G_{prm}\lambda^2}{(4\pi r)^2}. \quad (12)$$

To take into account the influence of internal noise and external interference, let's introduce the concept of «equivalent noise level at the receiver input». Let's express it in terms of the noise coefficient k_n:

$$k_n=\frac{P_{prm}/k_BT\Delta f}{(P_{prm}/N_n)_0}, \quad (13)$$

where $k_B = k = 1.38 \cdot 10^{-23}$ (W/Hz)·°K – Boltzmann's constant; T – the absolute temperature of the radiation source, K; Δf – equivalent noise bandwidth of the receiver; P_{prm}/N_n – the ratio of the signal power calculated by formula (12) to the noise power delivered to the receiver input.

Let's take $T_0 = 290$ K, then:

$$\left(P_{prm}/N_n\right)_0 k_n = \frac{P_{prm}}{k_B T \Delta f \cdot k_n}. \quad (14)$$

From equation (14) obtain:

$$N_n = k_B T \Delta f \cdot k_n \,. \quad (15)$$

Combining equation (12) with equation (15) and introducing the loss factor L_s for the communication system as a whole, let's obtain the communication range equation in a simple and convenient form:

$$\frac{P_{prm}}{N_n} = \frac{P_\Sigma G_\Sigma G_{prm} \lambda^2}{(4\pi r)^2 k_B T_0 \Delta f \cdot k_n L_s}. \quad (16)$$

It can be seen that the signal-to-noise ratio at the receiver input is inversely proportional to the square of the distance between the transmitter and the receiver. Fig. 3 shows graphs of the dependence of the probability of detection on the square of the range for a signal with a Gaussian distribution and a signal with a Pareto distribution. For clarity, the graphs themselves are shown in Fig. 4 in a logarithmic scale.

Initial data for calculations [5]:

1. The probability of message delivery is at least 0.9.
2. The standard range is from 1 to 2.5.
3. The signal-to-noise ratio is from 10 to 20 dBW.
4. The gain coefficients of the transmitting and receiving antennas are from 10 to 20 dB.

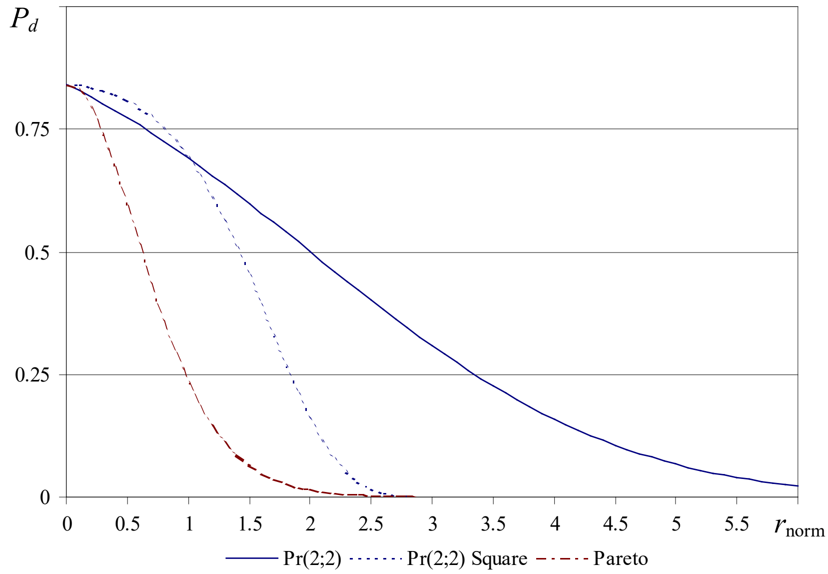

Fig. 3. Dependence of detection probability on the square of the normalized range. The signal-to-noise ratio by power is 4

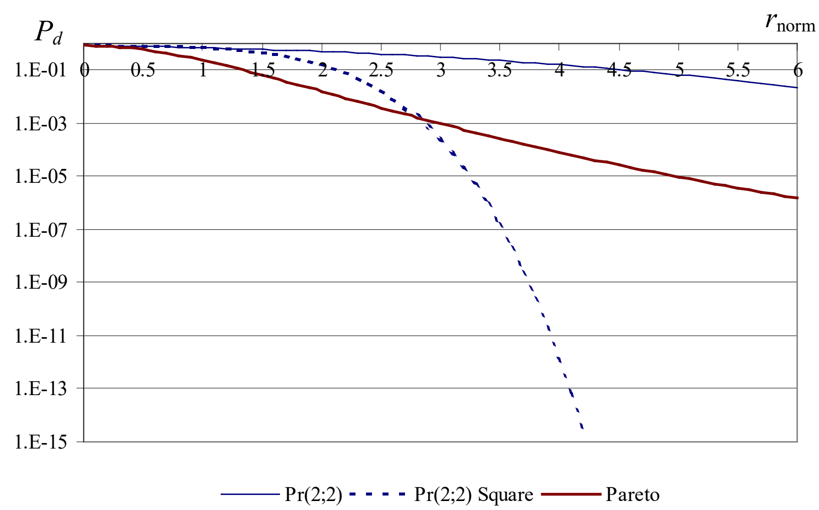

Fig. 4. Dependence of the probability of detection on the square of the normalized range (logarithmic scale). The signal-to-noise ratio by power is 4

Let's enter the normalized range $r_{norm} = r/r_{max} = m^{-0.5}$. The value r_{norm} can be considered as a coefficient that takes into account the reduction of the communication range compared to the maximum due to the probabilistic nature of the communication.

It can be seen that with increasing range, the probability of detecting a signal with a Pareto distribution decreases more slowly than a signal with a normal (Gaussian) distribution. Because of this specific feature of probability distributions of self-similar traffic, they are often called heavy-tale distributions. Using the above formulas, equations and graphs, it is necessary to calculate the required power of transmitting devices, the number and sensitivity of receiving devices, which provide the necessary probability of message delivery.

The obtained results can be used to study the dependence of the probability of message delivery on the number of switching nodes that receive the message and forward it further.

Let's note an important circumstance regarding the field of application of the obtained results.

When conducting research on the dependence of the communication range on the signal/(interference plus noise) ratio, the following must be taken into account:

1. In some cases, interference should include not only noise and interference from extraneous sources of radiation (unintentional and intentional interference), but also signals – requests from subscribers of a given network, which can create collisions with multiple accesses of a random nature. This problem was not considered in the article, as it is of an independent nature and lies a little aside from the main direction of research. It seems to us that the simplest solution is computer modeling with a clear outline of the network operating conditions and careful consideration of the statistical characteristics of multiple accesses. In the future, it is planned to return to the mentioned problem in subsequent studies.

2. When considering a network in the class of opportunistic networks (Opportunistic Networks), the statistical problems of multiple access can be overcome to a certain

extent. The approach to a wireless network with random multiple access as an opportunistic network promises very broad prospects for improving existing wireless networks and creating networks of a new level.

4. Conclusions

The presented work proposes a formal model of combined (statistical and signature) analysis of messages arriving at the entrance of network segments with closed access. This allows to switch to a qualitatively new method of detecting and processing data not only at the network and transport levels, but also directly at the physical level. Due to the use of such an approach, it is possible to overcome the limitations inherent in deterministic methods of network-independent levels of the reference model. The statistical approach is also the guarantee of protection against wrong decisions caused by new, previously unknown attacks and intrusions – so-called «zero-day exploits».

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The manuscript has no associated data.

References

1. Drovovozov, V. I., Vodop'ianov, S. V., Zhuravel, S. V. (2022). Protection of vehicle networks against unauthorized access through isolation of exchange protocols. *Problems of Informatization and Management, 4 (72),* 26–34. doi: https://doi.org/0.18372/2073-4751.72.17458
2. Ciuonzo, D., Rossi, P. S. (Eds.) (2019). *Data Fusion in Wireless Sensor Networks.* Michael Faraday House, 323.
3. *Radio Resource Management White Paper* (2018). Cisco Systems, Inc., 52.
4. Frenzel, L. (2022). *Principles of Electronic Communication Systems.* McGraw Hill, 946.
5. Shen, X., Zhang, X. L. K. (Eds.) (2020). *Encyclopedia of Wireless Networks.* Springer Nature, 1566.
6. Dordal, P. L. (2019). *An Introduction to Computer Networks.* Loyola University of Chicago, 872.
7. Gentle, J. E., Mori, Y., Härdle, W. K. (Eds.) (2012). *Handbook of Computational Statistics Concepts and Methods.* Springer, 1204. doi: https://doi.org/10.1007/978-3-642-21551-3
8. Tanenbaum, A. S. (2011). *Computer Networks.* Prentice Hall, 960.
9. Kurose, J. F., Ross, K. W. (2017). *Computer Networking: A Top-Down Approach.* Pearson Education, Inc., 864.
10. Vodopianov, S. V. (2018). *Metody pobudovy avtonomnykh komp'iuternykh sehmentiv aerovuzlovoi merezhi.* Kyiv: NAU, 164.

Serhii Vodopianov, *PhD, Department of Computer Information Technologies, National Aviation University, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0006-0424-6173*

✉***Oksana Martynova,*** *PhD, Associate Professor, Department of System Programming and Specialized Computer Systems, National Technical University of Ukraine «Ihor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, e-mail: ksmartyn2015@gmail.com, ORCID: https://orcid.org/0000-0003-1250-134X*

Arkadii Krainosvit, *Assistant, Department of System Programming and Specialized Computer Systems, National Technical University of Ukraine «Ihor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: https://orcid.org/0009-0005-2246-6121*

✉*Corresponding author*