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Method of Increasing the Relative Throughput of Requesting Radar Systems

***Abstract**. In the presented work, a method is proposed for increasing the relative throughput of requesting radar systems for monitoring airspace in which a successive transition is made from servicing a separate requester of radar systems to servicing a network of requesters. They observe this air object by forming an analysis time interval on the aircraft's responder, detecting request signals at this time interval. If at least one request signal is detected in the time analysis interval, at the end of the analysis time interval, a response signal is emitted, which includes the spatial coordinates of the given air object. This makes it possible to exclude the possibility of paralyzing an aircraft transponder by a deliberate correlated interference of the required intensity by the interested party and, as a result, to increase the relative throughput of requesting radar systems for airspace monitoring.*

***Streszczenie.** W prezentowanej pracy zaproponowano metodę zwiększenia względnej przepustowości żądających systemów radarowych do monitorowania przestrzeni powietrznej, w której następuje sukcesywne przejście od obsługi odrębnego zleceniodawcy systemów radarowych do obsługi sieci zleceniodawców. Obserwują ten obiekt powietrzny, tworząc przedział czasu analizy w urządzeniu odpowiadającym samolotu, wykrywając sygnały żądania w tym przedziale czasowym. Jeżeli co najmniej jeden sygnał żądania zostanie wykryty w przedziale czasu analizy, na końcu przedziału czasu analizy emitowany jest sygnał odpowiedzi, który zawiera współrzędne przestrzenne danego obiektu lotniczego. Pozwala to wykluczyć możliwość sparaliżowania transpondera statku powietrznego przez celową skorelowaną ingerencję o wymaganym natężeniu przez zainteresowaną stronę i w efekcie zwiększyć względną przepustowość żądania systemów radarowych do monitorowania przestrzeni powietrznej. . (**Metoda zwiększania względnej przepustowości żądających systemów radarowych**).*

Keywords: bandwidth; information network; mobile communication network; space division multiple access; adaptive antenna system; multiple input multiple output; antenna pattern.
Słowa kluczowe: pasmo; sieć informacyjna; sieć komunikacji mobilnej; podział przestrzeni wielodostęp; adaptacyjny system antenowy; wielokrotne wejście wielokrotne wyjście; wzór anteny.

Introduction

Requesting airspace surveillance radar systems, which include SSR [1-4] and IFF [5-8], which are based on the principle of two-channel information transmission, play a significant role in the information support of both the airspace control system and air traffic control. The main function of interrogating radar systems is to receive flight information at control points from on board an air object, as well as to identify an air object on the basis of "friend or foe". However, the construction of this information system on the principles of surveillance systems involves measuring the coordinates of air objects on the requester, as shown in [9], on the one hand, and implementing this surveillance system on the principles of an open single-channel queuing system, servicing the first received request signal [10, 11] significantly reduces the possibility of obtaining flight data from an air object. The presence of a significant intensity of intra-system interference, as shown in [12-14], showed that the effectiveness of the systems under consideration can be assessed using interference measures, such as the density of received pulses, and the presented results of the analysis of the signal environment at a frequency of 1090 MHz, recorded during flight experiments, which showed a significant interference density in the specified frequency range. Indeed, the frequency band 1030/1090 MHz is allocated for air traffic surveillance, including SSR (IFF), collision avoidance system and automatic dependent surveillance-broadcast (ADS-B) systems. Concerns have been raised that the 1030/1090 MHz band will experience significant congestion to the point where media in this frequency band will not be able to meet even the minimum requirements. Already today, in some areas with high air traffic density, intermittent availability of the SSR transponder is observed.

The presence of intra-system interference of significant intensity in the considered frequency range led to the difficulties in the operation of SSR (IFF) requesting radar systems, which led to the development and implementation of a new mode of operation of IFF MODE 5 systems [15-20]. These sources show that the IFF Mark XII system, as the combat equipment of the United States and other NATO countries, has the following disadvantages: a simple signal form; single modulation method and low interference immunity. Based on this, mode 5 is added and the Mark XIIA IFF system is proposed. The Mark XIIA system improves the anti-jamming capability, security and privacy of the system [16]. In addition, the Mode 5 system improves security and privacy during the request and response process [17]. In recent years, researchers have carried out preliminary studies on Mode 5 signals, and most studies of their anti-jamming performance have been analyzed in terms of message formats, request and response process, and spread spectrum coding technologies. Currently, most of the anti-jamming methods in the Mark XIIA Mode 5 system are based on the transmitting mechanism of the system. Since the ability of interference protection is limited, it is necessary to decide how to improve the throughput of the considering information system.

It should be noted that Mark XIIA is a new type of IFF system developed by NATO armies, and IFF mode 5 is the core of the system. It is shown that Mode 5 has not only the ability to identify airborne objects, but also the ability to inform about the situation on the battlefield and data transmission [17].

In [18,19], a method for detecting a mode 5 signal is proposed by detecting the signal preamble.

However, it should be noted that the constant transmission of air object coordinates when using Mark XIIA mode 5 via the IFF system response channels, although coded, unmasks the air object and, as a result, allows estimating its coordinates based on multi-position radio systems.

The work [20] presents a digital processing system in transponders in a new type of IFF, in particular, including the MOD5 receive and transmit processing method and the minimum keying base modulation theory, most probability Viterbi demodulation, propagation and Walsh compression. An algorithm for weighted demodulation and signal compression with minimal manipulation and a joint demodulation and compression algorithm based on the improved Viterbi demodulation algorithm with maximum probability [21] are proposed.

However, as shown in [22-25], without changing the principles of constructing the request channel of IFF systems, as well as the principles of servicing request signals, it is impossible to achieve acceptable probabilities for users of the quality of information support. To reduce the negative impact of interference on the quality of information functioning of an aircraft responder, it is proposed to carry out a successive transition to requesting systems for transmitting flight data, which eliminates the need to calculate the coordinates of air objects on requesters of the IFF system and, as a result, increase the relative throughput of aircraft responders [26, 27].

The purpose of the proposed work is to develop and study a method for increasing the relative throughput of requesting radar systems.

The impact of interference and construction principles on the throughput of requesting radar systems

As follows from the above, the most vulnerable point in requesting radar systems, which significantly affects the relative throughput of the considered information systems, is the aircraft responder [28-30]. Indeed, based on the principle of constructing an aircraft responder and the principle of serving request signals, the main interference for aircraft responders of requesting airspace surveillance systems are: intrasystem interference; intentional correlated and uncorrelated interference.

This circumstance is due to the fact that the modern network of ground-based requesters and aircraft responders is built on the principle of a non-synchronous network. At the same time, the aircraft responder is built on the principle of a single-channel queuing system with refusing. Thus, the arrival of a stream of request signals leads to a temporary paralysis of the aircraft responder for the duration of the service of the received request signal. It should be noted that when receiving request signals on the main lobe of the requester's antenna pattern, the aircraft responder is completely paralyzed for the time the request signal is served, and when receiving request signals on the side lobes of the antenna pattern, the aircraft responder is paralyzed for the time between the pulse of the request signal, the amplitude of which is also remembered by the side lobe suppression pulse.

Unlike correlated impulse noise, uncorrelated impulse noise suppresses individual impulses of the request signal, which makes it impossible to service this request signal, and also paralyzes the aircraft responder due to the formation of false request signals (false alarms of the first and second kind).

The negative impact of these types of interference on the flight information transmission channel (aircraft responders response channel) is the same. Indeed, the action of both intra-system and deliberate correlated interference leads to a significant decrease in the throughput of the aircraft responder (P_0), which subsequently leads to a significant decrease in the probability of transmitting flight information and the rate of transmission of flight information from an airborne object. Indeed, the rate of transmission of flight information in the general case is determined by the relative bandwidth of the aircraft responder $R=F(P_0)$. Methods of protection against these difficulties can be implemented only by changing the configuration of the principle of system construction of requesting surveillance systems or by changing the principle of servicing request signals. However, it should be noted that deliberate correlated interference, as a rule, can appear only at some special moment. This allows us to consider this case separately.

This procedure is due to the fact that when modernizing the considered interrogation radar systems of airspace surveillance, a successive transition from existing systems to new ones should be observed, which is caused by the impossibility of replacing all considering systems at the same time. In addition, changing the principle of construction or the principle of maintenance is a very expensive technology.

Let's consider a method for increasing the relative throughput of requesting radar systems for airspace monitoring. The essence of the proposed method lies in the fact that the address method is implemented when transmitting the coordinates of the aircraft responder only in the response channel. Requesting systems survey the space in a circular method. Therefore, in the proposed case, the functioning of the request channel of the considering information systems does not change in comparison with existing secondary radar systems. However, in aircraft responders of the requesting surveillance system, implemented according to the indicated principle, the algorithm for servicing request signals is somewhat changed. To do this, some analysis time interval T_a, is formed in the aircraft responders, during which the input request signals are received and decoded. The analysis time interval can be determined according to the relation

$$T_a = T_0 \beta_a / (k \cdot 360), \quad (1)$$

where T_0 is the requester antenna survey period, β_a is the requester antenna beam width, k is a constant factor that takes into account the factor of the required number of response signal emissions to detect and determine the coordinates of air objects.

At the end of the time interval T_a and upon receipt during this time interval of at least one request signal, a response signal is generated and emitted. The composition of the response signal includes both flight information and the spatial coordinates of the aircraft responder. In this case, spatial coordinates can be both absolute and relative. In the second case, the volume of the information package is reduced.

Therefore, the implementation of the proposed method (address type by response signal) leads to a significant decrease in the intensity of the flow of response signals. In addition, this implementation of request signaling makes this intensity of response signals independent of the intensity of the request signal flow. The maximum intensity of response signals flow from the aircraft responder when implementing the proposed method can be estimated from the following expression $\lambda_{\max}=1/T_a$. Indeed, the intensity of the flow of response signals does not depend on the intensity of the input flow of request signals. Since, when implementing this method, not individual request signals are serviced, but only if there is at least one request signal in the observation time interval, then setting deliberate interference with aircraft responders in order to paralyze the latter becomes inappropriate, since it is necessary to create a situation in which it is impossible accept no request signal on the analysis interval T_a. The above shows that in order to suppress the request signals, it is necessary to produce fluctuation interference [31–33] with significant intensity. However, this leads to significant energy costs and becomes nonsensical. It should be noted that the request signal of any requester of the considered network (even an unauthorized request of the interested party) received in the analysis interval undoubtedly leads to the formation of a response signal. Since the response signal of the considering system contains the coordinates of the aircraft responder, this leads to a transition from servicing a separate aircraft responder to servicing the network. Indeed, the request of any requester allows the reception of response signals by all secondary radar systems observed for this aircraft.

Changing the principle of servicing individual requesters to servicing the entire information network of radar surveillance systems undoubtedly leads to an increase in the relative capacity of the coordinate data transmission system. Indeed, in this case, the relative throughput of the aircraft responder increases due to a significant decrease in the intensity of the response signal flow, and, consequently, a significant reduction in the paralysis time of the aircraft responder. In addition, the probability of suppression of request signals of the considering requester by simulated interference is reduced. This is predetermined by the fact that the aircraft responder generates a response signal not for each request signal, but only in the case when at least one received request signal is detected during the analysis of the time interval. This predetermined that in order to eliminate the response signal, it is necessary to suppress all request signals in the request channel during the analysis time interval T_a which is practically impossible. Indeed, in order to suppress the request signal, it is necessary to create a powerful interference of such intensity that it does not allow receiving any request signal. However, this requires fluctuation interference during the entire observation time, which requires significant energy costs and is nonsensical.

Estimation of the relative throughput of requesting radar airspace surveillance systems

Let's analyze the availability factor of the aircraft responder and estimate the relative throughput of SSR (IFF) for response signals under the combined influence of request signal flows and chaotic impulse noise.

With the simultaneous receipt of chaotic impulse noise and a stream of request signals at the input of the analyzer of the response signals of the aircraft responder, the following situations unfavorable for the correct reception of request signals can be observed:

- suppression of the request signal of the considered requester through the superposition of advanced request signals of neighboring requesting surveillance radar systems. This leads to distortion of the received request signal;
- suppression of request signals of the considered requester through the superposition of advanced request signals of adjacent requesting surveillance radar systems radiated through the side lobes of the requester's antenna pattern;
- suppression of individual pulses of the request signals of the considered requester at a high frequency due to the coincidence in time of the pulses of chaotic impulse noise and the flow of request signals at unfavorable phase relationships;
- suppression of the request signals due to the inertia of the circuits of the input decoder shapers.

The presented situations exclude the possibility of correct reception of request signals on the time interval T_a. In addition, the presence of chaotic impulse noise leads to the false creation of request signals and the emission of response signals by the responder in the absence of valid request signals.

Let's estimate the probabilities of the above unfavorable situations that lead to the exclusion of the response signal, under the following assumption: chaotic impulse noise and the total flow of request signals affect the request signals received by the aircraft responder of the considered requester, independently of each other.

We will assume that the following is received at the input of the aircraft responder:

- flow of chaotic impulse noise with intensity λ_0;
- a stream of request signals that are radiated over the main lobes of the requester's antenna and cause the emission of response signals, with intensity λ_1;
- the flow of request signals radiated along the side lobes of the requester's antenna pattern, intensity λ_2.

Let's assume that the duration of the pulses in the request signals and the pulses of the total flow of chaotic impulse noise is the same, does not change in the observation time, and also coincides with the pulse duration of the used request signal pulse τ_0.

For the considered situation, the general effect of intentional uncorrelated impulse noise undoubtedly leads to the suppression, at high frequency, of individual pulses of the request signal by chaotic impulse noise and the total flow of request signals with unfavorable phase relationships. Consequently, the intensity of the total flow of chaotic impulse noise, as well as the request signals, decreases.

The probability of an event in which at least one pulse from the total flow of chaotic impulse noise in the request channel coincides in time with a separate pulse of the request signal flow and suppresses it can be estimated based on the following relation

$$P_p = \gamma\left(1 - e^{-\lambda_0 \tau_0}\right). \tag{2}$$

This will reduce the intensity λ_1 and λ_2 of the request signal streams and which will be:

$$\lambda_1^1 = \lambda_1 (1 - P_\mathrm{p})^\mathrm{n}, \quad \lambda_2^1 = \lambda_2 (1 - P_\mathrm{p})^\mathrm{n}. \tag{3}$$

The probability that at least one request signal will fall into the leading time interval and will suppress the request signals of the surveillance radar system. This is considered, due to the superposition of individual pulses of the request signal stream, can be estimated from the following relation

$$P_1 = 1 - \exp\left(-\lambda_1^1 t_1\right). \tag{4}$$

It should be noted that the intensity of the flow of false n-pulse request signals, formed from uncorrelated chaotic impulse noise, can be determined based on the following expression

$$\lambda_0^1 = n \lambda_0^n \left(\tau_0 - \tau_c\right)^{n-1}, \tag{5}$$

where: τ_c is the threshold for pulse selection by duration.

The probabilities that at least one request signal will fall into the leading interval and suppress the decoding of the request signals of the considered surveillance system due to the reception time of the request signal stream pulses radiated along the side lobes of the requester's antenna pattern, as well as created from chaotic impulse noise, respectively, are

$$P_2^1 = 1 - \exp\left(-\lambda_2^1 t_2\right), \quad P_2^2 = 1 - \exp\left(-\lambda_0^1 t_1\right). \tag{6}$$

In the considering situation, the total probability of suppressing the request signals of the requesting radar surveillance system, which is considered, due to the reception time of the request signals emitted both along the side lobes of the request antenna pattern, as well as false request signals created from chaotic impulse noise, will be

(7) $$P_2 = 1-\left(1-P_2^1\right)\left(1-P_2^2\right).$$

The probability that at least one pulse from the flow or chaotic impulse noise, or request signals will coincide in time with the request signal pulse of the considered requesting airspace surveillance system and suppress it, can be estimated from the following expression

(8) $$P_{10} = \gamma\left[1-\exp\left(-\lambda_c \tau_0\right)\right],$$

where: $\lambda_c = \lambda_0 + \lambda_1^1 + \lambda_2^1$.

Taking into account the fact that the request signal consists of n-pulses, then the total probability of suppressing request signals will be

(9) $$P_3 = 1-\left(1-P_{10}\right)^n.$$

The probability of suppression of request signals of a requesting radar surveillance system due to the appearance of a false suppression pulse formed from chaotic noise at the position of the considered signal is:

(10) $$P_4 = \left(1-P_{п}\right)P_{10}.$$

The probability of suppression of the considered request signal due to the inertia of the input shapers of the aircraft responder can be determined based on the following relation

(11) $$P_5 = 1-\exp\left(-\lambda_c \tau_f\right).$$

Based on the foregoing, the probability of a single decoding of the request signal during the analysis time interval can be estimated based on the following relationship

(12) $$P_a = \prod_{i=1}^{5}(1-P_i).$$

The dependence of the probability of a single decoding of the request signal on the analysis time interval P_a on the intensity λ_1 of the request signals flow emitted along the main lobe of the request's antenna pattern for n=2, λ_2=5λ_1, at different intensities of chaotic impulse noise λ_0 is shown in Fig.1. From Fig.1 it follows that the probability of undistorted reception of request signals weakly depends on the intensity of the flow of chaotic impulse noise and rapidly decreases with an increase in the intensity of the flow of request signals. With the intensity of the request signals flow λ_1=500 the probability of receiving an undistorted request signal is 0.58…0.65.

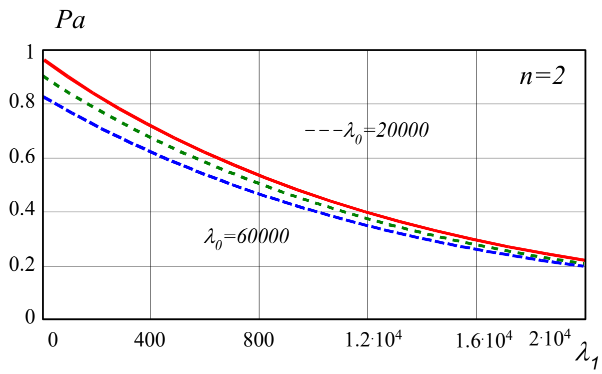

Fig.1. Dependence Pa=f(λ_1).

The probability of emitting the response signal of the aircraft responder (the relative throughput of the aircraft responder) of the considered requesting radar surveillance system, taking into account the time interval of the analysis, can be determined from the following relation

(13) $$P_0 = 1-(1-P_a)^M.$$

In this case, the conditional probability of false emission due to the formation of a false request signal from chaotic impulse noise, provided that there is no real request signal in the analysis time interval, can be estimated by the following expression

(14) $$F = P_{01}(1-P_0),$$

where $P_{01} = 1-(1-P_2^2)^M$ is the conditional probability of a false alarm of the first kind when receiving and detecting request signals.

The results of calculating the probability of transmitted information package radiation of the coordinate code of the air object after the end of the analysis time strobe for n=2, and M=3, is shown in Fig. 2.

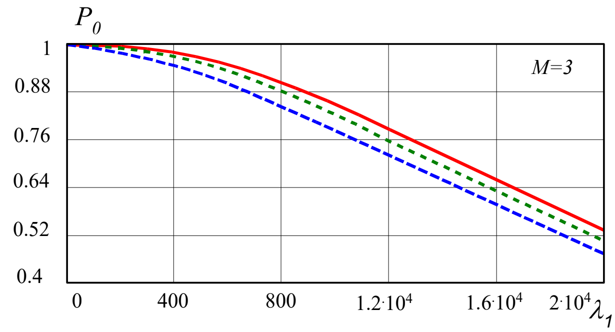

Fig.2. Dependence P_0=f(λ_1).

The results of calculating the probability of an information package radiation from an aircraft responder confirm the complexity of paralyzing an aircraft responder to exclude radiation of an information package. So, if there are intentional interference in the request channel with an intensity of 20000, 40000 and 60000 (Fig. 2) and the formation of 800 requests per second, the radiation probability will change from only 0.9 to 0.8.

Thus, the use of an addressable response signal in requesting observing airspace radar systems with the inclusion of an information message of the coordinates of an air object in its structure makes it possible to practically exclude the possibility of the influence of deliberate uncorrelated interference on the relative capacity of both the aircraft responder and the entire requesting radar system. This makes it possible to increase both the noise immunity and the relative throughput of the considered requesting radar systems.

Conclusion

The above leads to the following conclusion: the implementation of an information transmission system with the inclusion of the spatial coordinates of an air object in the transmitted information can significantly increase the relative throughput of the considered requesting radar systems for monitoring airspace due to the successive transition from servicing a single requester to servicing a network of requesting radar systems for monitoring airspace and, as a result, to increase the information capabilities of the considered requesting airspace monitoring radar systems.

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