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Articles

Comparative characteristics of anti-collision processing of radio signal from identification tags on surface acoustic waves

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Introduction: *Collision of information signals is a common problem in the measurement of physical magnitudes, such as temperature, pressure, stress, etc., with acoustic-electronic sensors. This problem is caused by overlapping response signals in the time domain, which makes it difficult to interpret correctly the device identification codes or the sensor data received.* **Purpose:** *Analysis of anti-collision algorithms for radio-frequency tag code detection and identification by response information signals from acoustic-electronic devices which use the methods of time, frequency and frequency-time division of the response radio signals.* **Methods:** *Probabilistic methods for calculating the parameters of digital detectors of radio pulse bursts with given false alarm values and gaussian white noise background; individual code group identification methods when studying the attenuation of acoustic-electric signal during their propagation in the tag substrate, taking into account the dependence of the attenuation on the tag topology.* **Results:** *We have derived analytical expressions to calculate the probability of the correct identification of each tag, taking into account the dependence on tag topology, attenuation characteristics, the anti-collision signal processing methods and the signal-to-noise ratios. Curves which allow you to compare the advantages and disadvantages of the considered anti-collision signal processing methods are calculated and shown in the article. The analysis of the graphic charts demonstrating the correct identification probability has shown that identification tags with frequency-time coding have better ratios as compared to frequency or time methods of collision prevention.* **Practical relevance:** *The obtained result allows you to effectively evaluate the condition of technical objects, improving the predictability and prevention of possible environmental and man-made disasters.*

Keywords — *RFID tag, surface acoustic wave, anti-collision, radar, onboard radars, multistatic radars, control, correct detection probability, false alarm, correct identification probability, digital detector, attenuation, environmental assessment, multistrip coupler, reflector gratings.*

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Introduction

In meeting the challenges of environmental monitoring and assessing the state of technology-induced objects, acoustoelectronic tags which are polled by onboard aircraft transceivers can be used as sensors for measuring physical quantities — temperature, humidity, pressure, stress and strain of materials, etc. [1].

It allows for the automation of data gathering and processing of information regarding objects placed in large areas. Using airborne synthetic-aperture radar system [2–9], or multistatic radar systems [10–13] provides us with the possibility of tag location with sufficient precision. It also makes possible the binding of their coordinates to a map or other specific map points of the objects.

It should be noted that to increase the information content and reliability of the evaluation of the physical state of monitoring objects, it is necessary to increase the number of tags in the interrogated area that is being examined. Therefore, response tag signals could overlap, causing an RFID (Radio Frequency Identification) tag code collision, which reduces reliable data collection and processing ability.

We devote attention to a consideration of the question of tag's radio signals anti-collision processing. In this context, the paper focuses on the signal's energy ratio while the unique identification code determination in the collision case for three main encoding approaches: time position encoding, frequency and time-frequency encoding [14–16]. Such a review has been implemented for common RFID tag design, interrogation signal with the same energy characteristics as the signals and the same receiving conditions. It makes possible comparing different anti-collision methods with each other and outlining their advantages and disadvantages. Such methodology of the study could be adapted to the specific tag topology, specific interrogation signal and specific undesirable factors.

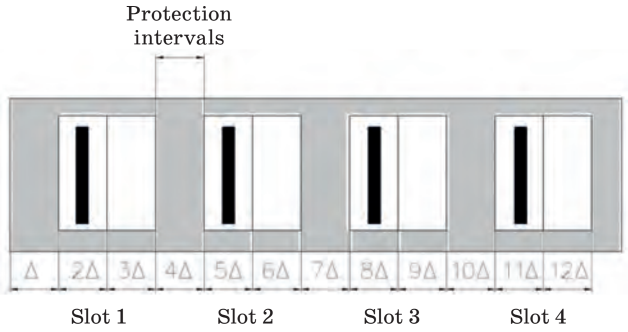
A simple design of the typical surface acoustic wave device

A typical surface acoustic wave (SAW) RFID tag design is shown in Fig. 1 [17–19]. For this case, we are limiting it to the image of only that part of the device that forms an individual RFID tag code. This shown design contains the reflectors placed on the piezoelectric substrate in the notional time slots, which are separated by guard intervals.

Each slot has one reflector — the location of the reflector on the left side of the slot corresponds to "1", and on the right side to "0". In the figure, the location of the reflectors corresponds to the identification code "1111".

The interrogation signal coming from the reader to the tags' reflectors is transduced to an acoustic wave that is propagated along the substrate.

The acoustic wave time delay corresponds to the distance Δ, each of which is the same here. This fact is not really important for the issues considered in this paper. The acoustic waves propagate across the surface and impinge upon the reflector gratings. These reflectors produce delayed reflections of the pulse that are used to interrogate the tag. Part of the wave passes to the following structures, and part is reflected in the opposite direction. Here, we are implying that the reflection occurs in such a way that a part of the wave reflected from each reflector propagates to its interdigital transducer (IDT) emitter through its own acoustic channel, which is achieved with the use of a multistrip coupler, conventionally shown in Fig. 2 [20–29].



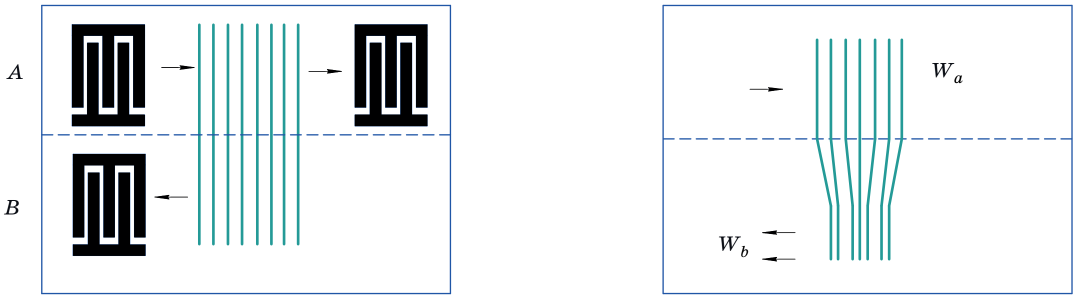
■ *Fig. 1.* An example of a notional SAW tag design

The unique identification code of the tag is coded in its delayed response, i. e., the reflector placement.

Receiving an electromagnetic signal emitted by the tag, the reader processes the tag code getting the information about the measured physical quantity. In this paper, we confine ourselves to anti-collision researching, which in effect means that we are interested in the possibility of determining only the tag codes. Therefore, we consider the problem of determining unique tag codes in the case of using anti-collision algorithm processing of the received signal.

Currently, two approaches to the signals' separation are most widely used — time division and frequency division [16–18]. In practice, time division [17, 18] is frequently used. The authors did not find comparative anti-collision algorithm characteristics for the time and frequency encoding of tag signals in the literature. For narrowing the research area, further consideration refers to passive SAW RFID tags.

Time division. Two cases are possible here. First, when only one tag is interrogated, and this does not cause a collision. Second, when several tags are interrogated, and their signals are overlapping, which is the collision case [16]. In this case, the anti-collision algorithm for processing response signals is as follows: the interrogation signal and the topology of the tags provide for the possibility of blocking the response signal for all interrogated tags [14]. One tag "responds" to the request, and the rest are blocked. When you re poll a group of tags — "answer" another tag — the first and the rest are blocked. This algorithm repeats until all tags are interrogated. Thus, due to the specific interrogation signal and the specific tag topology design, a temporary orthogonalization of the response signals occurs. If there are N tags in the polling zone (for example, tags used to assess the state of a man-made object), the number of response signals from each tag decreases N times. This an-



■ *Fig. 2.* Example of a multistrip coupler ti-collision signal processing algorithm solves the problem of collisions but reduces the energy of response information signals. This applies to reduce the signal energy used to measure physical quantities (temperature, pressure, strain and stress of materials, etc.).

Frequency division. In this case, each tag is tuned to its own specific frequency [16, 29]. The interrogation signal contains interrogation pulses at all frequencies of all tags that fall within the field of view of a transceiver. Tag signals are orthogonal in frequency and can be received simultaneously, ideally, without "interfering" with each other. The collision problem in this case is also solved, but at the expense of the energy of the response signal because if there are N tags in the polling zone, each receives energy N times less. Thus, here, just as with anti-collision algorithm based on time encoding, the problem of overcoming collisions is solved at the expense of the energy of signals [20–23]. In contrast to the previous case, the number of response signals from each label is (ideally) the number of interrogation signals, but the energy of each response signal is N times less.

Time-frequency division. This way of overcoming collisions is described in detail in [16]. Because of the complication of the topology of the label and the rather substantial complication of processing the response radio signals of the tags in the transceiver polling device, the authors managed to avoid the energy losses inherent in the above-described anti-collision processing methods. This statement applies only to passive tags and for the "ideal" implementation of such a topology. According to the authors, the presence of multistrip couplers (a passive six-terminal network) allows you to create various versions of such structures and implement the proposed anti-collision algorithm in practice. In this algorithm, the number of response signals is equal to the number of interrogations and, unlike the frequency method, the energy of the response signal is the same as with the time method [18].

False alarm probabilities while the tag code identification by a transceiver

As was mentioned previously we confine ourselves to identifying correctly the tag code for the three considered anti-collision algorithms. Because of this, we consider only that part of the receiving-transmitting device that is intended to determine the identification codes of the tags. To compare correctly the characteristics of anti-collision algorithms, these parts of the receiving-transmitting devices should be the same for all three algorithms being analyzed. The problem statement considers identifying the tag codes with simultaneous determination of their coordinates to "link" the sensors with identification code (ID) or tags to the map points or certain points of man-made objects, as well as the fact that the reader quickly moves relative to the sensor tags while monitoring. In this way, it is reasonable to set the identification task as the task of detecting packets of response radio pulses that determine the tag's identification code because it is very difficult to implement optimal identification algorithms in such dynamic conditions. As for the Neyman — Pearson quasi-optimal digital detection algorithms of the type "k of n" [2–4], they have certain robust properties, and their "loss" in relation to the optimal ones, with the requirements for the algorithms presented in this research, does not exceed 1–1.5 dB [30]. In addition, these detection algorithms allow a simple way for the determination of the sensors' or tags' coordinates with sufficiently high accuracy [10]. These algorithms are used in this work to solve the problem of identifying the tag code.

The "k of n" detector composes of an envelope detector with output as the envelope of the a signal at the output of the receiving device in the corresponding time interval; an analog comparator with an analog threshold U_0, which converts the input signal into a sequence of single "1" and zero "0" signals; a digital adder which accumulates the n of "1" bits; a digital comparator with digital threshold k; an output device, which gives "1", in the case when total adder's bits quantity, exceeds of the threshold k.

For each tag time slot which is shown in the Fig. 1, the two detectors are required while m-digit code identification. For the whole tag's slots a $2m$ detectors are required. In this paper for the proposed tag design we are considering 8 detectors.

The probabilities of the appearance of single "1" bits at the output of analogue comparators with only the noise P_n and the presence of an additive mixture of the information signal and the noise P_s are determined by the expressions:

$$P_n = \int_{U_0}^{\infty} f_n(U)\mathrm{d}U = \int_{U_0}^{\infty} \frac{U}{\sigma_n^2} e^{-\frac{U^2}{2\sigma_n^2}}\mathrm{d}U = e^{-\frac{U_0^2}{2\sigma_n^2}}; \quad (1)$$

$$P_s = \int_{U_0}^{\infty} f_{s+n}(U)\mathrm{d}U =$$

$$= \int_{U_0}^{\infty} \frac{U}{\sigma_n^2+\sigma_s^2} e^{-\frac{U^2}{2(\sigma_n^2+\sigma_s^2)}}\mathrm{d}U = e^{-\frac{U_0^2}{2(\sigma_n^2+\sigma_s^2)}}, \quad (2)$$

where $f_n(U)$ and $f_{s+n}(U)$ — the corresponding probability density envelope of the signals at the detector output; σ_n and σ_s — of the noise power and signal. Formulas (1) and (2) are true for arbitrary distributions of noise envelopes $f_n(U)$ and signal convolutions with noise $f_{s+n}(U)$. But the final expressions of these formulas correspond to the normal distributed noise and rapid-fluctuating signal model [30].

When using such detectors to identify the tag code, it is necessary to clarify some concepts that we will use below, namely the concepts of false alarm detector, false alarm for each slot and false alarm for each tag. The first concept is commonly used [2–4], but the last two require clarification.

False alarm detector. False alarm detector P_{fa} is defined as the probability of detecting a signal in its absence. For the detector "k of n" P_{fa} is calculated by the well-known expression:

$$P_{fa} = \sum_{l=k+1}^{n} C_n^l P_n^l (1-P_n)^{n-l}, \qquad (3)$$

where $C_n^l = \dfrac{n!}{l!(n-l)!}$; n — packet size of received pulses; k — digital comparator threshold [4, 30, 31].

False alarm for each slot. False alarm on slot concept here means as P_{fa} — probability of appearance "1" or "0" in the corresponding digit of the identification tag code in the absence of the real information signal at the inputs of the detectors of this slot. This event occurs only when one of the detectors generates a detection digit "1", and the second detector — a digit "0". The combination of "1" and "0" digits for one slot corresponds to the decision — this digit of the identification tag is equal "1", and the combination of "0-1" — the digit of the identification tag is equal to "0". Events "1-1" — detection of a signal by both detectors and "0-0" — non-detection of a signal by both detectors are ignored since in these cases the tag code is undefined.

Since all events "1-0", "0-1", "1-1", "0-0" are independent, $P_{fa\ s}$ is equal to the sum of the probabilities of events "1-0" and "0-1":

$$P_{fa\ s} = P_n(1-P_n) + (1-P_n)P_n = 2P_n(1-P_n). \qquad (4)$$

Expression (4) is written for the most common case of determining the tag code in the binary system, as shown in Fig. 1.

False alarm for each tag. False alarm for each tag $P_{fa\ t}$ — the probability of determining the tag code in the absence of information signals at the input of the receiving and transmitting device. This event occurs only when the presence of an information signal detected in each slot:

$$P_{fa\,t} = P_{fa\ s}^m = \left(2P_n(1-P_n)\right)^m, \qquad (5)$$

where m — the number of binary digits of the tag code, in the example in Fig. 1, $m = 4$. Expression (5) is valid for writing the tag code in the binary system.

In order to allow a proper comparison the characteristics of time, frequency, and time-frequency anti-collision signal processing algorithms, it is necessary to make the false alarm of each tag $P_{fa\ t}$ the same in all algorithms. At the same time, the requirements for the detectors parameters of the type "k of n" — a false alarm for each detector P_{fa}, the threshold of the analog comparator U_0, the probabilities P_n, the threshold of the digital comparator k are different.

Let us determine the above parameters of the detectors "k of n" for the three considered algorithms of anti-collision processing.

Suppose that M of tags placed in the notional area are interrogated by moving transceiver. During the time it takes to cross this area, the transceiver transmits n interrogation signals. In this case, for a time type anti-collision algorithm, each tag is polled $n\ time = E(n/M)$ times, where $E(.)$ — floor function, and for frequency and time-frequency algorithms, tags are polled n times. In order to allow a proper comparison, it is necessary that n be divided by M without a remainder, which can always be achieved by an appropriate choice of M. From expression (5) it follows that with equal $P_{fa\ t}$ for these algorithms $P_{time\ s}$ will be the equal too. Therefore, P_{fa} will be equal for all types of the algorithms.

The "k of n" detection dataset packet for the frequency and time-frequency algorithms is defined as $n = n\ time\ M$, for the time algorithm — $n\ time$. Therefore as it follows from expression (1) and (3), it is possible to achieve the equality of P_{fa} for detectors only by changing the U_0 and k — thresholds of the analog and digital comparators. The radar handbook by Skolnik [31] recommends choosing a digital threshold defined as $k = E(\sqrt{1.5n} + 0.5)$. Following this recommendation, in our case, it is necessary for a given P_{fa} of (3) to determine P_n, and then, from expression (1), find the threshold U_0 equal to:

$$U_0 = \sigma_n \sqrt{-2 \cdot \ln P_n}. \qquad (6)$$

After all calculations we get following results.

False alarms for each tag are the same for all three algorithms $P_{fa\ t} = P_{fa\ t\ time} = P_{fa\ t\ freq} = P_{fa\ t\ time\text{-}freq}$, hereinafter an additional subscript is introduced, mnemonically associated with the name of the algorithm. False alarms on the slot are also the same $P_{fa\ s} = P_{fa\ s\ time} = P_{fa\ s\ freq} = P_{fa\ s\ time\text{-}freq}$. And, finally, false alarms on the detector are also the same $P_{fa} = P_{fa\ d} = P_{fa\ d\ time} = P_{fa\ d\ freq} = P_{fa\ d\ time\text{-}freq}$.

The parameters of the detectors for the time algorithm are determined by the expressions: $n = n\ time$, $k = k\ time = E(\sqrt{1.5n\ time} + 0.5)$, $P_n = P_{n\ time}$ by numerical solution of the equation:

$$P_{fa} = P_{fa\,time} =$$

$$= \sum_{l=k\ time+1}^{n\ time} C^{l}_{n\ time} P^{l}_{n\ time} (1 - P_{n\ time})^{n\ time - l}, \quad (7)$$

$U_0 = U_{0\ time}$ — the threshold of the analog comparator with an arbitrary distribution of interference is determined from the expression (1), for our case $U_{0\,time} = \sigma_n \sqrt{-2 \cdot \ln P_{n\ time}}$.

Detector parameters for the frequency and time-frequency algorithm are determined by the expressions

$$n = n\ freq = n\ time\text{-}freq = n\ time\,M,$$

$$k = k\ freq = k\ time\text{-}freq = E(\sqrt{1.5n\ freq} + 0.5) =$$
$$= E(\sqrt{1.5n\ time\text{-}freq} + 0.5),$$

$$P_n = P_{n\ freq} = P_{n\ time\text{-}freq}$$

by numerical solution of the equation:

$$P_{fa\ freq} = \sum_{l=k\ freq+1}^{n\ freq} C^{l}_{n\ freq} P^{l}_{n\ freq} (1 - P_{n\ freq})^{n\ freq - l} =$$
$$= P_{fa\ time\text{-}freq} = \sum_{l=k\ time\text{-}freq+1}^{n\ time-freq} C^{l}_{n\ time\text{-}freq} \times$$
$$\times P^{l}_{n\ time\text{-}freq} (1 - P_{n\ time\text{-}freq})^{n\ time\text{-}freq - l}, \quad (8)$$

$U_0 = U_{0\,time}$ — the threshold of the analog comparator with an arbitrary distribution of interference, as well as for the time algorithm, is determined from the expression (1) for our case

$$U_{0\,freq} = \sigma_n \sqrt{-2 \cdot \ln P_{n\ freq}} =$$
$$= U_{0\ time\text{-}freq} = \sigma_n \sqrt{-2 \cdot \ln P_{n\ time\text{-}freq}}.$$

Probabilities of correct tag code identification by transceiver

Similar to the previous section, we introduce concepts that will be used in the further considering.

Detection probabilities. Detection probability P_d it is a commonly used concept, defined as probability that the search object will be detected under given conditions if it is in the area searched. For considered detectors "k of n" P_d calculated by the expression:

$$P_d = \sum_{l=k+1}^{n} C^l_n P^l_s (1 - P_s)^{n-l}, \quad (9)$$

where, as well as in expression (3) $C^l_n = \dfrac{n!}{l!(n-l)!}$, n — the size of the packet, the received pulses; k is the threshold of the digital comparator [30, 31], and P_s is defined by formula (2).

When substituting into the expression (2) the threshold U_0, defined by the expression (1), we get:

$$P_s = \exp\left(\frac{\sigma_n \cdot \ln P_n}{\sigma_n^2 + \sigma_s^2}\right) = P_n^{\frac{1}{1+(\sigma_s/\sigma_n)^2}} = P_n^{\frac{1}{1+\rho^2}}, \quad (10)$$

where $\rho^2 = (\sigma_s/\sigma_n)^2$ — signal-to-noise power ratio. While calculating for each anti-collision algorithm, it noteworthy feature is using specific parameters k, n, and U_0 and also parameters with appropriate subscripts.

Probability of correct code bit identification. The correct identification of the i-th slot when using "k of n" detectors type occurs when the following conditions fulfilled: the detection of a signal at time corresponding the place in slot in which the reflector is present and the non-detection of a signal at time moment which is corresponding the place in the other slot part. This probability, denoted as $P_{ci\ s}$, is calculated by the expression:

$$P_{ci\,s} = P_d\,(1 - P_{fa}), \quad (11)$$

here it is necessary to use P_{fa} and P_d which are correspond with the respective algorithm with its subscripts. Unlike the definition of $P_{fa\ s}$, only one of the four possible events determines the probability of correct identification: if there is a "1" signal in the slot, the event "1-0" should be correctly defined, and the events "1-1" and "0-0" lead to ignoring the tag code, however, the event "0-1" could be defined as a false definition of the tag code, since it does not ignore the identification of the code, but we do not use this concept further.

Similarly, if there is a "0" signal in this slot, the "0-1" event must be correctly detected. In the example shown in Fig. 1, signal "1" corresponds to the presence of a reflector in the right half of the slot, and signal "0" in the left half.

Probability of correct tag identification. The tag code is determined correctly if in all m slots defining the binary m bit tag code, the correct identification of digits occurs. The probability of correct tag identification $P_{ci\ t}$ is determined by following expression:

$$P_{ci\,t} = \prod_{i=1}^{m} P_{ci\ s} = (1 - P_{fa})^m \prod_{i=1}^{m} P_{d\ i}, \quad (12)$$

where $P_{ci\ s}$ — correct identification probability of a binary digit of i-th tag ID; $P_{d\,i}$ — probability of correct detection of an information pulse from the i-th digit of the tag code. Here it is necessary to substitute into the probability expression corresponding to the three anti-collision processing algorithms. From expressions (9), (10) and (12) it follows that with an unlimited (hypothetical) increase in the power of the interrogation signal, which leads to an unlimited increase in the signal-to-noise ratio, the limit value will be $P_{ci\ t} = (1 - P_{fa})^m < 1$. This means that with a given n tag code cannot be identified correctly with probability one, physically this situation corresponds to the rapid movement of the interrogator relative to the tag (or tag relative to the interrogator). However, the consideration of this issue is beyond the scope of this work.

Relative proportions of energy tag signals for time, frequency and time-frequency anti-collision algorithms

A calculation of probability correct tag ID codes identification demands taking into account SAW propagation attenuation, reflection k_r and transmission coefficients $k_{tr} = 1 - k_r$ for reflectors.

The SAW propagation attenuation is described as an exponential function described as: $\exp(-\alpha L)$, where α — attenuation coefficient; L — SAW wave path to reflector and back. The signal power P_i, which depends on the distance to i-th tag's reflector and back is equal:

$$P_i = P_0 e^{-\alpha L_i} k_{r\ i} \prod_{j=1}^{i-1} k_{tr\ j}, \qquad (13)$$

where P_0 — input signal power. Here we are not considering the reflection and transmission losses what could be expected in the real tags. We take into account the propagation losses only which are approximately constant on the way, with some attenuation coefficient α. The signal-to-noise ratio ρ^2, shown in (10), it is proportional to P_i.

Anti-collision time and frequency algorithms allow the optimization of the reflection and transmission coefficients, objective to pulse-amplitude equalization reflected from tag slots, which leads to increasing the probability of correct identification of tag code. For time-frequency algorithm, such alignment and optimization are impossible [32].

For a time anti-collision algorithm, with optimized reflection coefficients, the power $P_{time\ i}$ of the information signal at the input of the radiating IDT is equal to

$$P_{time\ i} = P_{time} = P_0 e^{-3\alpha\Delta} \frac{e^{6\alpha\Delta} - 1}{e^{6\alpha m\Delta} - 1},$$
$$i = 1,\ 2,\ \ldots,\ m. \qquad (14)$$

In expression (14), it is assumed that the guard intervals and half slots have the same size Δ, as it's shown in Fig. 1. The reflection coefficient from the last slot is 1. In all slots are given the "1". Tag code identification is carried out at the receiving a data packet with size $n\ time = n/M$, where M is the number of simultaneously polled tags in the interrogated area.

For frequency anti-collision algorithm with optimized reflection coefficients, the power $P_{freq\ i}$ of the information signal at the input of the radiating IDT is equal to

$$P_{freq\ i} = P_{freq} = \frac{P_0 e^{-3\alpha\Delta}}{M} \frac{e^{6\alpha\Delta} - 1}{e^{6\alpha m\Delta} - 1}.$$
$$i = 1,\ 2,\ \ldots,\ m. \qquad (15)$$

The tag replies on the corresponding interrogation signal only. But identifications occurs when data packet $n\ freq = n$.

For time-frequency anti-collision algorithm the power expressed as

$$P_{time\text{-}freq\ i} = \frac{P_0 e^{-3\alpha\Delta}}{M} e^{-6\alpha(i-1)\Delta},\ i = 1, 2, \ldots, m, \qquad (16)$$

here all $P_{time\text{-}freq\ i}$ is different, the reflected signal with the lowest power comes from the last slot. The identifications occurs when data packet has a size $n\ time\text{-}freq = n\ freq = n$.

At the inputs of the transceiver detectors, the signal-to-noise ratio ρ^2 is respectively equal:

— for the time algorithm

$$\rho^2_{time} = \sigma^2_{s\ time}/\sigma^2_n = P_{time\ i} R/\sigma^2_n = P_{time} R/\sigma^2_n;$$

— for the frequency algorithm

$$\rho^2_{freq} = \sigma^2_{s\ freq}/\sigma^2_n = P_{freq\ i} R/\sigma^2_n = P_{freq} R/\sigma^2_n;$$

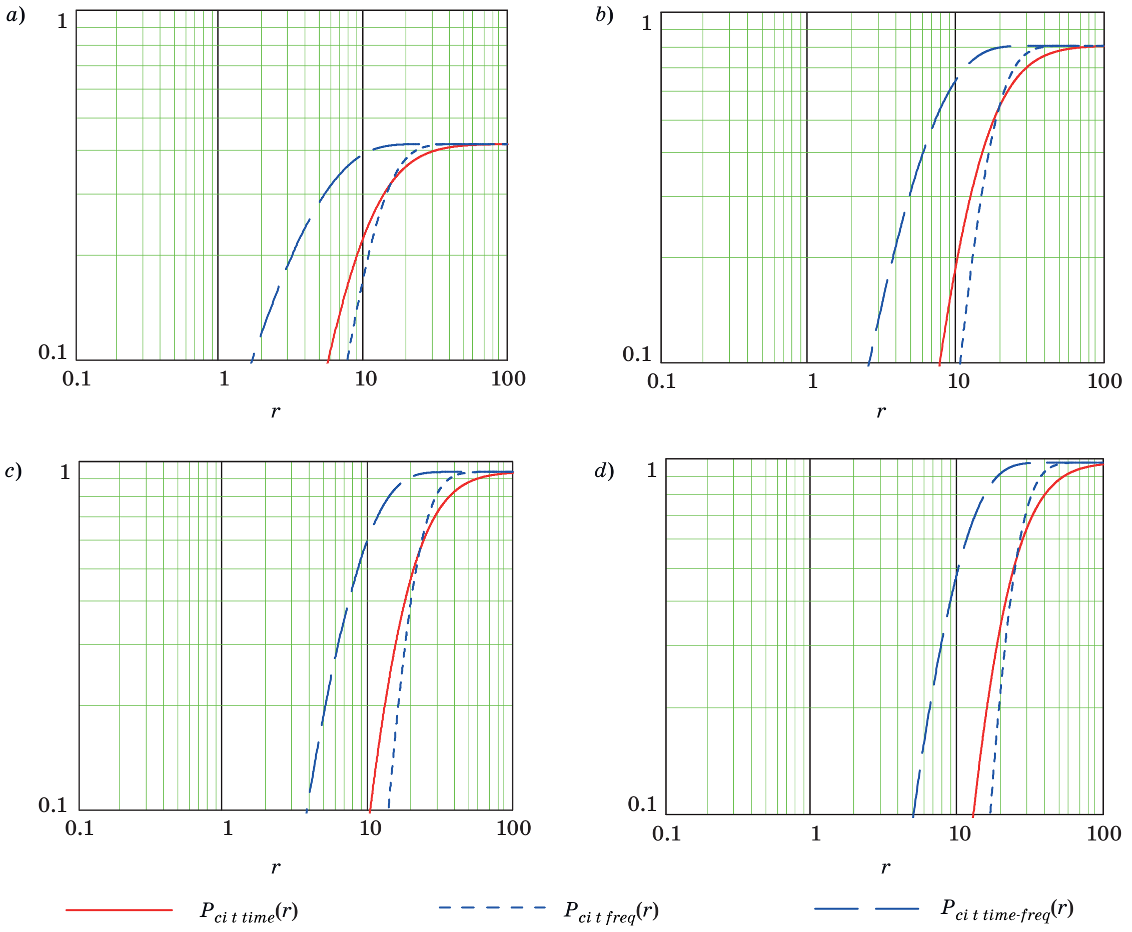
— for time-frequency anti-collision algorithm

$$\rho^2_{time\text{-}freq\ i} = (\sigma_{s\ time\text{-}freq\ i}/\sigma_n)^2 = P_{time\text{-}freq\ i} R/\sigma^2_n,$$

where R — path loss (or path attenuation) coefficient [31]. The functions $P_{ci\ t\ time}(r)$, $P_{ci\ t\ freq}(r)$, $P_{ci\ t\ time\text{-}freq}(r)$, where $r = P_0/\sigma^2_n$ — probabilities of correct tag identification, calculated in (11), are shown in the Fig. 3, *a–d*.

The calculations were performed for the following values of the parameters of anti-collision algorithms: slots number $m = 4$; tags number placed in the interrogation area $M = 4$; false alarms for tag $P_{fa\ t} = 10^{-2}$, 10^{-4}, 10^{-6}, 10^{-8}; number of tag polls $n\ time = 8$, $n = n\ freq = n\ time\text{-}freq = 32$; digital comparators thresholds $k\ time = 4$, $k = k\ freq = k\ time\text{-}freq = 7$; path attenuation between two neighboring reflectors taken as 20 dB.

These functions show that $P_{ci\ t}$ remaining low in the case of using specific values of the algorithms and detectors coefficients and also, increasing response signal power. To increase the probability of



■ ***Fig. 3.*** Probabilities of correct tag identification $P_{ci\ t\ time}(r)$, $P_{ci\ t\ freq}$ (r), $P_{ci\ t\ time\text{-}freq}(r)$ for $P_{fa\ t} = 10^{-2}$ (*a*); 10^{-4} (*b*); 10^{-6} (*c*); 10^{-8} (*d*)

correct identification of tags, in such cases, it is necessary to accumulate packets of response signals. With the accumulation of N pulse packets, the probability of correct identification is equal to $P_{ci\ t\ pack} = 1 - (1 - P_{ci\ t})^N$, tends to the “1” value for all three algorithms with any false alarm $P_{fa\ t} < 1$.

Conclusion

Analysis of the three algorithms for anti-collision processing of response signals from RFID tags shows, that time-frequency algorithm has the highest probability of correctly identifying tag codes for all mathematical models of tags, their polling conditions, identification algorithms, interference characteristics, and response information signals. The time and frequency algorithms are approximately equivalent in the probability of correct identification, but both are given a way to the time-frequency algorithm. These conclusions correspond with the physical concepts. Despite the rather significant differences in the parameters of the time and frequency processing algorithms and the differences in the observation conditions for the radio signals of the tags, the total energy of the received signals for these algorithms is approximately the same. For the time-frequency algorithm, the signal energy is higher, but the total increase of the correct tag identification probability is not proportional to the increase in energy due to the fact that, due to the specificity of this algorithm, there is no possibility to optimize the topology of the tags and, consequently, optimize its parameters. The above analysis of algorithms is easily summarized with other types of interference and information signals, which differ from normal noise and rapidly fluctuating packets of the radio signal pulses. However, with more complex models of interference and signals, the characteristics of the algorithms in the form of simple analytical expressions cannot be obtained. For this reason, only numerical analysis is possible, which makes research much more difficult. Despite the above fact the qualitative conclusions regarding the algorithms given above remain valid.

All of the three considered anti-collision algorithms suggest some modification of the tag topology for the getting an individual object ID. It goes beyond the scope of the present research but we included some references to the patents and papers showing the possibility of implementing such tasks. In addition, the complexity of the polling devices for the time and frequency algorithms is about the same, and for the time-frequency — the polling device It's a big task, but not as unattainable as it would seem. The advantages of the time-frequency anti-collision algorithm are due to the complexity of its structure in processing the received RFID tags information response signals.

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Сравнительные характеристики методов антиколлизионной обработки ответных радиосигналов идентификационных меток на поверхностных акустических волнах

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Постановка проблемы: при использовании акустоэлектронных устройств для измерения физических величин, таких как давление, температура, сила сжатия, напряжение и т. д., возникает проблема коллизий информационных сигналов, которые получены при опросе акустоэлектронных устройств. Проблема вызвана перекрытием ответных радиосигналов устройств во времени, что делает невозможным ни определение индивидуального кода устройства, ни считывание информации с него об измеряемой физической величине. **Цель:** анализ антиколлизиционных алгоритмов обнаружения и идентификации кодов радиочастотных меток по ответным информационным сигналам акустоэлектронных устройств, использующих методы временного, частотного и частотно-временного разделения ответных радиосигналов. **Методы:** вероятностные методы расчета характеристик цифровых обнаружителей пачек радиоимпульсов при заданных значениях ложных тревог на фоне нормального белого шума; методы идентификации индивидуальных кодовых групп при учете затухания акустоэлектрических сигналов при распространении в подложке метки с учетом зависимости затухания от топологии используемых меток. **Результаты:** получены аналитические выражения для расчета вероятности правильной идентификации кодов меток в зависимости от топологии меток, характеристик затухания, способа антиколлизиционной обработки информационных радиосигналов и отношения сигнал/шум; рассчитаны и приведены соответствующие кривые, позволяющие сравнить достоинства и недостатки рассмотренных антиколлизиционных методов обработки ответных радиосигналов акустоэлектронных устройств. Анализ графиков, демонстрирующих вероятность правильной идентификации, показал, что идентификационные метки с частотно-временным кодированием имеют лучшие соотношения по сравнению с частотными и временными методами предотвращения коллизий. **Практическая значимость:** полученный результат позволит эффективно оценивать состояние технических объектов, что в свою очередь поможет благодаря своевременной информации предупредить и избегнуть экологических и техногенных катастроф.

Ключевые слова — радиочастотная идентификационная метка, поверхностная акустическая волна, антиколлизия, радиолокация, бортовые радиолокационные станции, многопозиционные радиолокационные станции, контроль, вероятность правильного обнаружения, ложная тревога, вероятность правильной идентификации, цифровой обнаружитель, затухание, экологический мониторинг, многополосковый ответвитель, отражательные решетки.

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