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The Estimation of Accumulating Detection Probability of Objects with the Help of Short Range Wireless Devices

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Abstract

The article introduces the concept and finds the detection probability of objects with the help of short range wireless devices for different detection conditions. The article also considers the intensity of target detection at distance for a quantitative estimation of detection device effectiveness. Expressions that connect momentary probabilities and intensity of detection through the speed of an object movement or through the scan period of a detection device are presented. An estimation of the expectable probability of a moving object detection both in constant and changing detection conditions has been obtained.

Keywords: Short Range Wireless Device, Object Detection, Momentary Detection Probability, Intensity of Detection, Expectable Detection Probability

1. Introduction

The solving of the problem of creation and theoretical analysis of a problem connected with any short range wireless device (SRWD) used for detection [20] and measuring of extended objects movement parameters [5] leads to the solving of several local tasks among which one of the most important is the development and assessment of effectiveness indices of SRWD taking into account the extended character of the objects under detection with constantly changing distance and different momentary detection probability laws. Earlier it was studied [20] the question of finding the valid law of distance distribution of detection devices and systems referring to the moving extended object depending on its speed of movement, character of a reflective surface, working conditions of SRWD, taking into account static characteristics of reflected signals [13], [17], [12], as well as forms of direction response pattern of detection device in which radio-location modes of operation are used.

We refer to [20] for estimations of detection faithfulness of extended objects on the basis of static distribution of SRWD distance as well as analytical correlations for the function of distance action distribution of detection devices which allow estimating the probability of extended object detection penetrating into the zone of SRWD action.

Moreover in most cases is could arise a necessity of acquiring analytical expressions for estimation of detection probability of an object at statistical distribution of action distance of SRWD [14].

In order to solve this task it is necessary to state mathematical laws with the help of which it is possible to characterize real distribution of action distance of detection devices which in its turn suppose the study of questions connected with the definition and estimation of accumulating detection probability of objects with the help of SRWD.

The solving of theoretical aspects of extended objects detection allows implementing significant questions of both integrated realization of Doppler radar [18], [15], [16], widely used in detection devices, and solving more general questions of object detection system building [7], [2].

2. Theoretical foundations of the method

2.1 The uncertainty of the object detection of short range wireless device

If we consider the object detection as a random process [3] (which characteristic for the most of practical cases) that is being performed in quite homogeneous “typical” conditions, the distance distribution of detection complies with a certain distribution law.

According to the type of conditions the influence of some dominating factors on the process of detection is restricted, i.e. it is supposed that during some period of time some factors influencing the detection process remain unchanged (e.g. meteorological factors, object character, type of detection device etc.) [6] or are changed insignificantly within the stated limits.

Thus, every separate category of “typical” conditions has opportunities for implementation of this or that distribution law if the acquiring of this or that value of action distance of SRWD (as well as random value) is conditioned by the cooperation of a great number of factors of insignificant power.

It was established empirically and analytically, that the object which got into the control zone of short range wireless device, hardly ever gets detected at its limit range [4].

It is also established, that in a number of cases event with a relatively small range (much smaller than the average range of SRWD) the object may not be detected [8]. The reason is that detection depends not only on the distance to the object, but also on a number of factors, which can be divided into three groups:

- factors characterizing SRWD;
- factors characterizing the distribution conditions of physical fields (signals) in the environment;
- factors characterizing a detected object.

In each of these groups there are such factors that have the crucial influence on patterns of variation in the range of SRWD. These factors are commonly referred to as main factors. For example, it is the transmitter power for a radar station, the effective area of the antenna, image intensifier of target (in the case of SRWD of detectable object), and wavelength. Studying the main factors one can predict a numerical value of the range, without resorting to a special experience.

Along with this, it should be noted that any natural phenomenon, including the detection of objects is inevitably accompanied by random deviations. Therefore, in practice, no matter how accurately conditions of the experiment for the determination of the range of different SRWD are fulfilled, it is not possible to achieve exactly the same results when repeating the experience. These random deviations are caused by the presence of such secondary factors as changing the course angle of the object relative to SRWD, the isotropy of the environment, the instability of the supply voltage, the presence of “shiny” spots [8] and other.

In addition, the effectiveness of any technical device depends on the quality of work of the operator (if we do not consider automated and intelligent systems that operate without human intervention) as the target recording element in the overall scheme of indication, that makes the decision about the fact of detection (intrusion into a zone of control of SRWD).

Different values of the recorded range can be obtained under the same conditions using different detection criteria depending on different time periods spent for their implementation.

2.2 Random nature of the detection range

Methods of probabilistic estimates of expected range of object detection [19] using a statistical distribution range of SRWD make it possible to determine such characteristics that allow us to mathematically describe the processes and acts of establishing the instrument contacts in all situations of object search and object detection. In particular it is instant and accumulating probability of objects detecting.

The difficulties of direct and precise definition of the expectable value of detection distance *R* are conditioned by the fact that the influence of these or those factors can be not only of stable but in most cases of unstable character and therefore cannot be previously reported and controlled.

Nevertheless, while estimating the accumulating (momentary and expectable) probabilities of object detection by SRWD it is possible to significantly improve the faithfulness of object detection including the acquiring of necessary indices of distance distribution of SRWD.

Let us consider firstly the detection probability of objects by SRWD. Depending on the design peculiarities of detection devices and ways of their usage the investigation of the space during the process of detection can be continuous or consisting of separate momentary actions.

The observation should be referred to the continuous process if the observer constantly fixes his eyes on some part of space or if the observation is being carried out with the help of direct focus means.

If the direct focus means are used for investigation of space within some angle exceeding the width of the diagram of direction of these means, it should be considered as the observation consisting of a range of separate momentary actions. The periods of time during which momentary actions of observation are carried out depend on the degree of the angle and angular speed of observation. Sometimes these periods can be so little that the observation can be considered as continuous.

In general case the decision on the question of observation type depends on the fact which of these types provides greater precision of description of the process of device contact establishment.

In the case when the observation consists of separate actions the important criterion for estimation of observation means effectiveness during the searching is the momentary (elementary) probability g of object detection on the given distance by means of a single momentary observation.

If in the process of searching a constant observation is being carried out, the important criterion for estimation of observation means is the momentary (elementary) probability γdt of detection within a very short time period *dt*. The value γ is the intensity (momentary density of probability) of detection number.

The above mentioned characteristics are statistical ones, i.e. the can be found in [1]. For this purpose the following formulas are used

$$g = 1/\bar{n}; \qquad \gamma = 1/\bar{t}\,, \tag{1}$$

where $\bar{n}$ is a mathematical expectation of observation number during which the object detection by SRWD is provided; $\bar{t}$ is the mathematical expectation of time during which the object detection number from the moment of switching on of the detection system (device) is provided.

Use of values g and γ for quantitative characteristic of detection devices effectiveness is provided by the possibility of detection of statistical distributions of distance of object detection and definition o their basis the relationships of $\gamma(R)$ for the typical detection conditions under observation. The mentioned graphics for different (good, normal, bad) detection conditions are presented in [1]. The graphics have a decreasing character at increasing of the distance from SRWD to the detected object; the lines of the graphic come closer to the increase of the mentioned distance under different conditions of detection (i.e. the detection conditions are levelled out on the significant distances; it should be noted that under such conditions the probability of object detection is minimum).

2.3 Intensity of object detection

Besides the two mentioned characteristics one can use the third one which is called intensity (momentary density of probability) of object detection at distance.

$$f = -d\varphi / dR = -P(R)/[1 - P(R)], \tag{2}$$

where $\varphi = \varphi(R)$ is a detection potential, $P(R)$ is an integral law of distance distribution of object detection.

Review of analytical dependences shows that for SRWD with low efficiency even when the object is in the immediate vicinity of SRWD, the probability of finding a given object will be less than unity. For the most effective SRWD reliable detection occurs at some distance.

Among the considered characteristics there are definite expressions [1] which connect them with the speed of movement of a detected object:

$$\gamma = fV_{ob}, \tag{3}$$

$$g = 1 - \exp(-\gamma T), \tag{4}$$

where V_{ob} – speed of movement of the object; T – period of view;

$$f = \gamma / V_{ob} = \ln(1/(1-g))/V_{ob}T. \tag{5}$$

If we know the law of distribution $P(R)$ we can find an analytical expression for f. Comparable function graphs $P(R)$, $\varphi(R)$ and $f(R)$ are represented on the Figure 1.

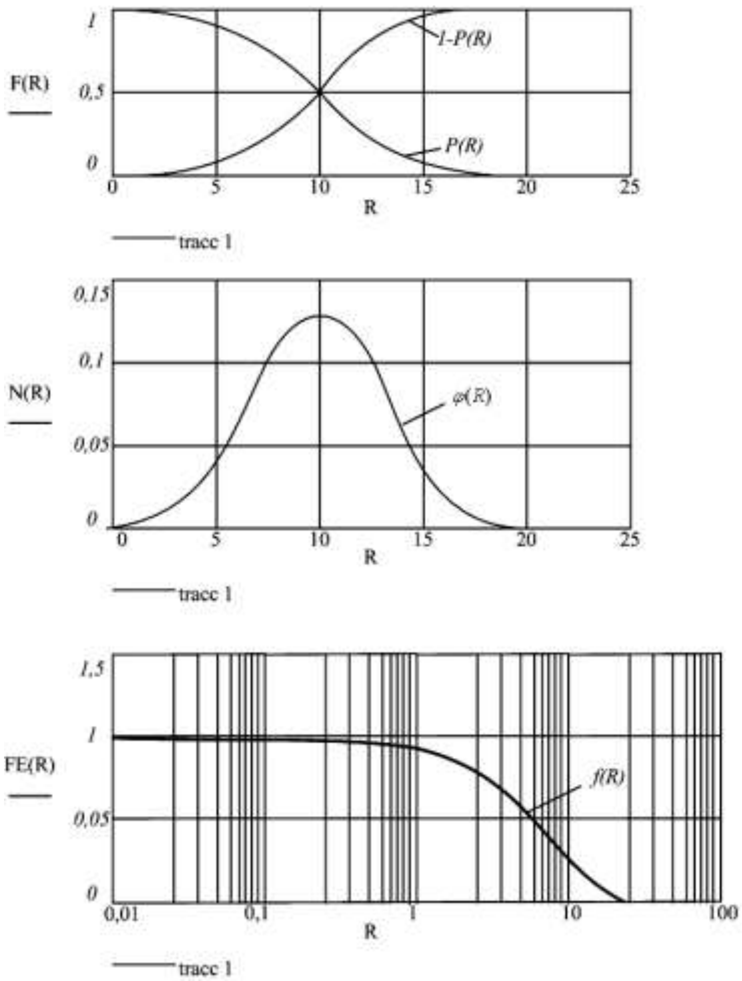

Figure 1. Function graph $P(R)$, $\varphi(R)$ and $f(R)$

The relation of $f(R)$ for detection devices of low effectiveness (*a*), with a silent zone (*b*), relatively high effectiveness (*c*) and the most effective (*d*) are represented on Figure 2. From these graphs we see that the detection probability for SRWD with low effectiveness will be less than 1. For more effective detection devices the faithful detection occurs at some distance R_r.

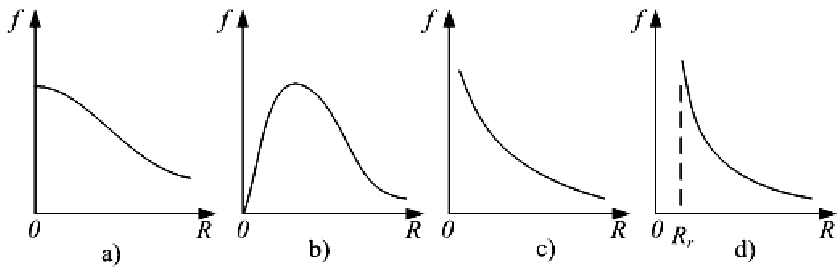

Figure 2. Relation $f(R)$ for different detection systems

The effectiveness of the process of contact establishment with the object within this or that time period can be assessed with the help of accumulating (increasing) detection probabilities of an object [1], [9]. Let us study this question stage by stage for different detection conditions and character of object behaviour.

3. Expectable detection probability of objects by security systems

3.1 Unchangeable observation conditions (g *= const,* γ *= const)*

If the sampling action detection system is used and the detection of an object during every detection cycle is a dependent event, the detection probability $P(n)$ of an object ca be found at least once under the conditions of n momentary observations in accordance with the theory of repetition of independent experiments according to the formula [11]:

$$P(n) = 1 - (1-g)^n . \tag{6}$$

Basing on this formula we can draw an important practical conclusion: when the physical conditions, in which the detection is taking place, provide certain detection probability g within a single momentary observation, the probability $P(n)$ (be it never so small) can be very close to the value 1 having n big enough, i.e. the event of detecting an object will ten to one occur.

If the observation is being carried out continuously within the time *t* under the unchangeable physical conditions, the detection probability of an object P within the time t is being determined by the formula

$$P(t) = 1 - \exp(-\gamma t) . \tag{7}$$

Formula (4) shows that having the value of a quantity γ and describing the observation time t, it is possible to calculate the detection probability of an object upon non-measurable observation conditions (upon the unchangeable distance to an object R = const in particular).

Considering the above said it was accepted that an object is at a certain distance from the detection device, which is not changed in the course of time. It was also supposed that γ is not changed in the course of time t.

One can see that the value γt in the degree of expression (7), (be the value γ so small) theoretically can be infinitely big as it is always possible to choose such observation time t, that the detection probability $P(t)$ will be close to the value 1.

3.2 Changeable observation conditions (g *= var,* γ *= var)*

Let us mark the changing values of momentary probabilities with g_i and γdt, where g_i is a momentary detection probability of object for the momentary observation i, and γdt is a density of detection probability of an object that changes in the course of time. The formula for calculation of detection probability in this case will be as follows:

- for discrete observation

$$P(n) = 1 - (1 - g_1)(1 - g_2)\ldots(1 - g_n) = 1 - \prod_{i=1}^{n}(1 - g_i)\,; \quad (8)$$

- for continuous observation

$$P(t) = 1 - \exp\left[-\int_0^t \gamma_t dt\right]. \quad (9)$$

4. Estimation of the expectable detection probability of a moving object

4.1 Unchangeable observation conditions (g = const, γ = const)

Concerning quickly moving objects one can state that during the time of their movement in the area of detection devices control which is restricted by the outer detection limit R_{lr}, the sufficient change of physical observation conditions as well as changes of the values g and γ connected to this observation are not taking place. This supposition is admissible and even regular in some cases [20].
That's why one can consider (Figure 3) that the change of the values g and γ in the area restricted by the radius R_{lr} will be conditioned only by the movement of an object in the area of detection device control (change of its relative location). Point H on the Figure 3 denotes the place of an observer location (detection device).

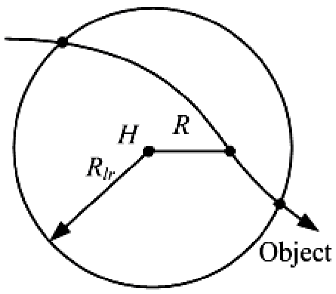

Figure 3. Object trajectory in the area of SRWD action

Thus, g and γ are the functions of the current distance to the object r, which is denoted inside the area of detection device activity R, i.e. $g_i = g_i(r) = g_i(R)$ and $\gamma_i = \gamma_i(r) = \gamma_i(R)$. Values $P(n)$ and $P(t)$ can be defined according to the formula:

$$P(n) = 1 - \prod_{i=1}^{n}\left[1 - g_i(R)\right]. \quad (10)$$

$$P(t) = 1 - \exp\left[-\int_0^t \gamma_i(R)dt \right]. \tag{11}$$

Values $g_i(R)$ and $\gamma_i(R)$ can be chosen by the SRWD operator.

4.2 Changeable observation conditions (g = var, γ = var)

The situation at which g and γ are the functions of not only the current distance to the object R, but also of the current time t (as in the course of time the detection conditions, leading to the change of g and γ change) is the most common one. In this case $g_t = g_t(R,t)$ and $\gamma_t = \gamma_t(R,t)$ and formulas for defining detection probabilities $P(n)$ и $P(t)$ are as follows:

$$P(n) = 1 - \prod_{i=1}^{n} \left[1 - g_t(R,t)\right]. \tag{12}$$

$$P(t) = 1 - \exp\left[-\int_0^t \gamma_t(R,t)dt \right]. \tag{13}$$

Values $g_t(R,t)$ and $\gamma_t(R,t)$ a chosen as applied to the corresponding conditions characteristic for every detection i. However in order to directly calculate value $P(t)$ using the formulas (11) and (13) it is necessary to find analytical expressions for laws of change $\gamma_t(R)$ and $\gamma_t(R,t)$.

5. The efficiency of the detection devices

The ability of SRWD to detect objects can be characterized by the field of the instantaneous density of probability and field of cumulative probability of detection [2].

Each point in the plane corresponds to a definite value of the instantaneous density of probability and cumulative probability of detection. For detection of fixed devices, one can build a statistical field [10] that will be figured with lines equal to the instantaneous densities of detection probability or lines equal to cumulative probability of detection.

Consider the situation when the range distribution of SRWD forming the boundary complies with normal or truncated normal distribution, for which:

- in the case of Gaussian distribution

$$W_n(R) = \left(\delta\sqrt{2\pi}\right)^{-1} \exp\left\{-(R-m)^2/2\delta^2\right\}; \tag{14}$$

$$P_n(R) = \left(\delta\sqrt{2\pi}\right)^{-1} \int_R^{\infty} \exp\left\{-(R-m)^2/2\delta^2\right\} dR = 0{,}5\left[1 - \Phi\left\{(R-m)/\delta\sqrt{2}\right\}\right]; \tag{15}$$

- in the case of truncated Gaussian distribution

$$W_{tn}(R) = \left(\delta\sqrt{2\pi}\right)^{-1} \times \exp\left\{-(R-m)^2/2\delta^2\right\} \times \left\{0{,}5\left[1 - \Phi\left\{(R-m)/\delta\sqrt{2}\right\}\right]\right\}^{-1}; \tag{16}$$

$$P_{tn}(R) = \frac{1 + \Phi\left(\frac{R - m}{\delta\sqrt{2}}\right)}{1 + \Phi\left(\frac{m}{\delta\sqrt{2}}\right)}. \quad (17)$$

To simplify the notation in expressions (14)-(17) we denote: mathematical expectation $m = m_R$; variance $\delta = \delta_R$; Φ – the function of the Laplacian.

For certain laws of range distribution for detection devices the estimation of expected probability of establishing the instrument contact is reduced to the determination of the cumulative detection probability $P(t)$ on the basis of function $\gamma = \gamma(t)$, calculated having taken into account the characteristics of these laws and the nature of motion of the object:

$$P(t) = 1 - \exp\left[-\int_0^t \gamma(t)dt\right]. \quad (18)$$

Under other equal conditions, the ability of SRWD to detect an object is different for different points of its range. It usually grows with decrease of the distance to the target and decreases with its increase, i.e., there is dependence

$$\gamma = \gamma(R). \quad (19)$$

Based on that we can determine the law of establishing the instrument contact in a function of t for a certain character of the motion of an object, i.e.

$$\gamma = \gamma(t). \quad (20)$$

Using the function $\gamma(t)$ to quantify the effectiveness of SRWD is conditioned by the ability to determine in practice the statistical distributions of range of the object detection and based on them we get dependence $\gamma(R)$ for all kinds of typical conditions for detection

$$\gamma(R) = W(R)\bar{V} / (1 - P(R)). \quad (21)$$

where $W(R)$ – is the function of probability density, in this case describing the differential law of range distribution; $(1 - P(R)) = F(R)$ – is the distribution function characterizing the integral law of non-detection range distribution; P(R) – is the distribution function characterizing the integral law of detection range distribution; $\bar{V}$ – the average speed of the object for which we got statistics, that determines the law of range distribution.

6. Conclusion

The present paper introduces the concept and finds the detection probability of objects with the help of detection systems for different detection conditions. The concept of intensity of object detection at distance is defined. The analytical expression for detection intensity f for normal distribution law was found.

Estimations of the expectable probability of a moving object detection both in constant and changing detection conditions have been obtained. In particular, if the physical conditions provide certain detection probability g within a single

momentary observation, the event of object detection, in spite of its smallness, will ten to one occur if n is big enough.
It is shown that with the certain laws of range distribution of SRWD the estimation of the expected probability of establishing the instrument contact is reduced to the determination of the cumulative detection probability $P(t)$ based on the function of the instantaneous detection probability $\gamma = \gamma(t)$, that we calculate taking into account the characteristics of these laws and the nature of the motion of the object.

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