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Duration of data collection when measuring occupancy of stationary radio channels[1]

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Purpose. *Effective management of any resource is based on high-precision control of the use of this resource. In relation to radio spectrum management, this implies, in particular, the ability to accurately and reliably measure the occupancy of radio channels and frequency bands. The standardization of relevant measurements is regulated at the international level by documentation of the Radiocommunication Sector of the International Telecommunication Union (ITU-R). However, the analysis of this documentation shows that both in the current version of Recommendation ITU-R SM.1880-2 "Spectrum occupancy measurement and evaluation" and in the ITU Handbook on Spectrum Monitoring, the proposed solutions do not provide answers to some questions that arise when organizing occupancy measurements. The purpose of the present paper is to clarify the differences between occupancy measurement modes, which in regulatory documents are traditionally called measurements based on "independent samples" and "dependent samples", as well as to search for calculation relationships that allow, under different conditions, to reasonably determine the duration of data collection sufficient to ensure accurate and reliable measurement of occupancy.* ***Methods.*** *The development of recommendations for determining a sufficient duration of data collection is based on classical methods of statistical analysis, and in relation to occupancy measurements based on "dependent samples" on the representation of a sequence of sample values by a first-order Markov chain.* ***Novelty.*** *The novelty elements of the presented solution are the study of the dependence of the required number of samples accumulated for a reliable assessment of occupancy on the relationship between the mean value of transmission duration in the analyzed radio channel and the interval for testing the state of this channel by radio monitoring equipment.* ***Results.*** *The developed calculation relationships make it possible to determine the required duration of data collection for almost any combination of transmission durations in the analyzed channel and channel state testing intervals. The correctness of the calculation relationships is confirmed by the coincidence of the values obtained by them with the required number of data samples in the classic work of Spaulding, A.D. & Hagn, G.H. "On the definition and estimation of Spectrum Occupancy" (1977). The revealed derivations are supposed to be used as an addition to the current versions of Recommendation ITU-R SM.1880-2 and the ITU Handbook on Spectrum Monitoring.* ***Practical relevance.*** *Obtained derivations eliminate a number of contradictions that arise when measuring occupancy based on existing ITU regulatory and methodological documents and the proposed calculation relationships allow controlling the procedure for measuring the occupancy of radio channels, taking into account the speed obtained by radio monitoring equipment.*

Key words: *spectrum occupancy, occupancy evaluation, data collection, dependent samples, integration time.*

Introduction

Activities to manage the use of the radio frequency spectrum should be based on up-to-date information about the utilization of this resource. One of the indicators traditionally used to manage the radio frequency spectrum utilization is its occupancy, which characterizes the probability that at a randomly selected time

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a radio frequency channel (frequency band) will be used to transmit information. As a rule, the channel occupancy analysis is performed from an energy point of view; a channel is considered "occupied" if the emission level registered in it exceeds a certain pre-selected threshold. Recommendations on the choice of this threshold can be found, for example, in subsection 3.4 of the Report ITU-R SM.2256-1 "Measurements and assessment of spectrum occupancy" [2].

In the documents of the Radiocommunication Sector of the International Telecommunication Union (ITU-R), the time interval of data accumulation to determine the occupancy of a radio channel (frequency band) is called the integration interval T_I. Figure 1 shows an example of a possible change of the signal level in a radio channel at such interval in relation to the case of continuous monitoring of the channel state. The durations and distribution on the time axis of the Δt_k intervals occupied by radio transmissions are random. In accordance with the statistical definition of probability, occupancy is a value at an infinite interval T_I:

$$m = P\{\text{ the channel is occupied }\} = \frac{1}{T_I} \cdot \sum_{k=1}^{K} \Delta t_k \, \big|_{T_I \to \infty}, \tag{1}$$

where K is the number of cases of the channel being in the "occupied" state;

$\Delta t_1, \Delta t_2 \ldots \Delta t_K$ is the duration of the intervals for registration the "occupied" state.

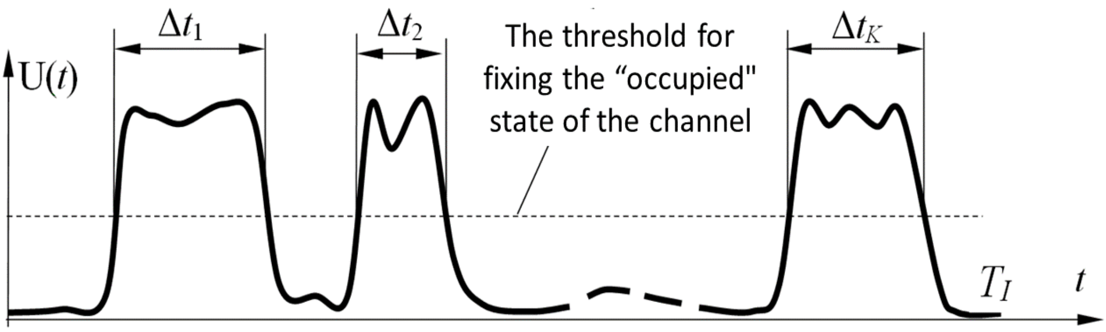

Fig. 1. An example of a possible time change in the signal level $U(t)$

Real occupancy measurements are based on the integration interval T_I of a finite duration. Due to the need to simultaneously inspect a large number of radio channels, instead of continuously tracking $U(t)$, the monitoring equipment checks the status of channels only from time to time, taking only "snapshots" (samples) of the frequency channel state through more or less equal time intervals T_R. In this case, the occupancy estimate $\hat{m}$ is formed as the ratio of the number of samples (checking moments) N_O at which the "occupied" state of the channel is registered to the total number of samples N:

$$\hat{m} = \frac{N_O}{N},$$

where N is the total number of samples placed in the integration interval T_I; N_O is the number of "occupied" samples.

The episodicity of checking the state of radio channels is one of the reasons for the appearance of an error in the measurement of occupancy. Let us consider the case of study a channel presented in Fig. 2, the occupancy of which is close to 50%. When the checking moments are placed on the time axis in accordance with the central diagram in Fig. 2, where the "occupied" samples are displayed as solid lines and the "unoccupied" ones are dotted, the proportion of samples which demonstrate the "occupied" state of the radio channel will be 7/16 = 43.75%, i.e. the resulting estimate will be understated. If the location of the checking points turns out to correspond to the last diagram, then the proportion of "occupied" samples will increase up to 9/16 ≈ 56.25% and the resulting occupancy estimate will be overstated.

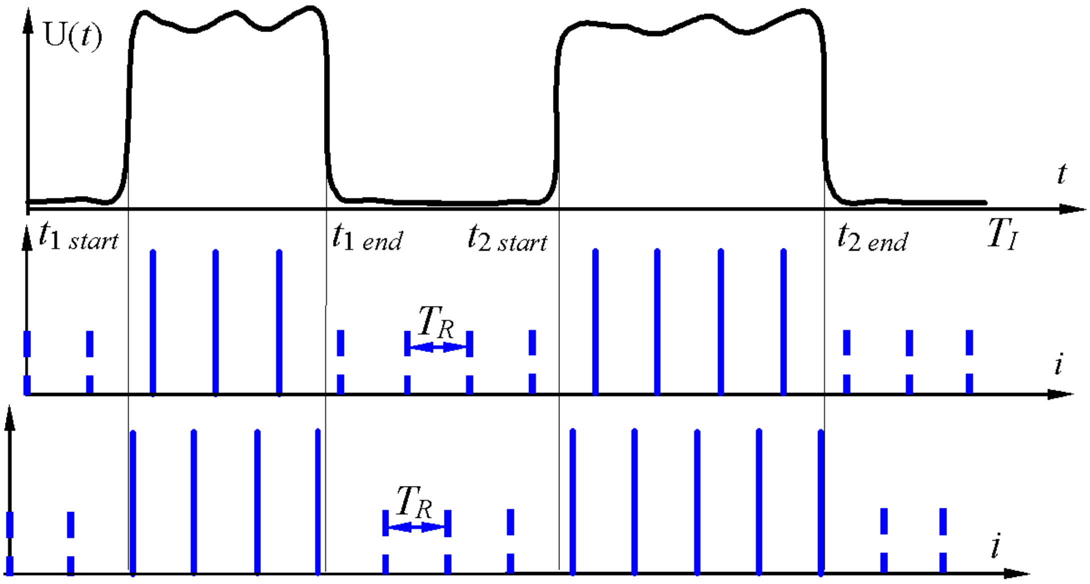

Fig. 2. Error in occupancy measurements generated by selective checking of the radio channel state

It should be noted that the active introduction into practice of information transmission systems using noise-like and/or frequency-hopping spread spectrum signals, as well as the joint use of frequency bands by various sources of radio emissions in the time-sharing mode, generates a number of problems when measuring occupancy. Some ways to overcome these problems and recommendations on the organization of measurements can be found in section 8 of the ITU-R Report SM.2256-1 [2]. For actively used radio channels, with a long integration time T_I and a small interval between samples T_R, it is usually possible to estimate occupancy with sufficient accuracy and reliability. On the contrary, the analysis of the recommendations given in the ITU-R normative documents in relation to the occupancy measurement of radio channels, where signals of significant duration appear only occasionally, shows the presence of contradictions and ambiguities. It should be noted that the methodological basis for measuring occupancy for many years has been an article by authors Spaulding A.D. and Hagn G.H. «On the definition and estimation of Spectrum Occupancy» [1]. However, some provisions of this work are still not fully reflected in the ITU-R documents. The purpose of this article is to present some important results of the work [1] in a form focused on the practical needs of spectrum monitoring.

Differences in the concepts of occupancy related to the stationarity or non-stationarity of the studied radio channels

The work [1] contains a detailed and mathematically rigorous study of the radio channels occupancy under the assumption that the statistical properties of the channel do not change over time, i.e. the channel is considered stationary, and occupancy characterizes the degree of use of the channel for transmitting information over an infinitely long time interval.

At the same time, if the properties of the channel along the time axis change, and their stability can be counted only in short time intervals, then the task of estimating occupancy at individual intervals with predetermined boundaries on the time axis is also of interest.

The material on the formation of "local" occupancy estimates at limited time intervals is presented in articles by employees of the IRCOS company [3-5] and in Appendix 1 of the ITU-R SM.2256-1 Report "Measurements and assessment of spectrum occupancy" [2]. Estimating the occupancy of stationary channels does not presuppose any predetermined time limits for data collection and can take many hours. At the same time, the question of the minimum required duration of data collection $T_{I\,min}$ is one of the key issues in the planning of research activities and in the measurement process. It is precisely the problems of estimating the occupancy of stationary channels over long time intervals that the article [1] and the present study are devoted to.

Developing a boundary condition that determines whether data samples are dependent or independent

In the article by Spaulding & Hagn [1], the Δt_k intervals included in (1) are interpreted as the values of the random transmission duration in radio channel V, expressed in seconds. At the same time, for further analysis, in addition to the physical duration of V, it is useful to introduce a normalized indicator of the random duration of transmission

$$\alpha = V / T_R, \qquad (2)$$

where T_R is the interval between samples characterizing the current state of the radio channel.

In fact, T_R is the time interval between adjacent moments of checking the state of the radio channel. Figure 3 shows a fragment of the time axis containing one active transmission in the channel, having a normalized duration $\alpha \approx 3.5$. In this case, the origin of the coordinates of the local time scale is set to the moment of the start of the current transmission in the radio channel, and the process of forming samples separated by T_R is illustrated for the case, when the moment of formation of the first sample falls on the point $t \approx T_R$. Consequently, the integer number of "occupied" samples N_{1O}, which turned out to represent one separate current transmission, is $N_{1O} = 3$.

Since transmissions appear asynchronously in relation to the sampling process, with a different location of checking points relative to the moment the transmission starts, the number of "occupied" samples may increase to $N_{1O} = 4$. The shift of the first of the "occupied" samples in relation to the time of the transmission appearance is distributed evenly on the interval 0...T_R. And for the case shown in Fig. 3, the fourth (relative to the beginning of the transmission) sample will be registered as "occupied" if the first sample falls on a section of the time axis from 0 to $T_R \times \{\alpha\}$ (here $\{x\}$ is the operation of taking the fractional part of the number x). The situation in Fig. 3 corresponds to the hit of the first sample on a later section of the time axis, and in the result, the fourth sample is registered as "unoccupied".

So, the integer number of "occupied" samples N_{1O}, which represent one separate transmission, even for its particular duration V, turns out to be a random variable:

$$P[\, N_{1O} = \lfloor\alpha\rfloor \,] = 1 - \{\alpha\},$$
$$P[\, N_{1O} = \lceil\alpha\rceil \,] = \{\alpha\},$$

where $\lfloor\alpha\rfloor$ - operation of rounding down; $\lceil\alpha\rceil$ – operation of rounding up; $\{\alpha\}$ is the fractional part of the number α.

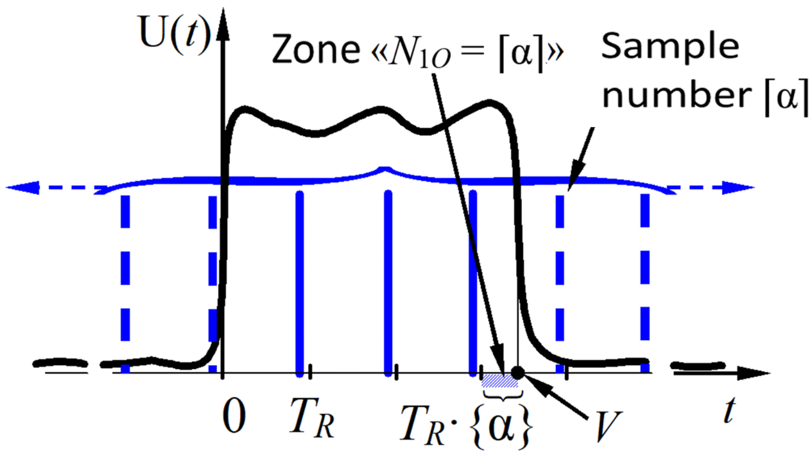

Fig. 3. On the issue of determining the probabilistic characteristics of the number of "occupied" samples N_{1O} registered for one particular transmission

In particular, for $V < T_R$, i.e. at $\alpha < 1$, with probability $(1 - \alpha)$, the transmission is skipped and with probability α is represented by a single "occupied" sample; for $T_R \leq V < 2T_R$, i.e. at $1 \leq \alpha < 2$, with probability $(1 - \{\alpha\})$ it will be represented by one sample and with probability $\{\alpha\}$ by two samples.

With an increasing probability of the appearance of several consecutive "occupied" samples, measurements in the ITU documents under consideration are proposed to be considered as dependent. The concept of dependence of samples in [1] is explained as grouping of states; however, it would be useful to quantify the boundary condition that would allow us to consider the generated samples as dependent or independent, with reference to the duration of transmission V and to the rate of checking the state of radio channels. To this end, taking by analogy with [1] the exponential distribution law of magnitude V, we obtain a formula for calculating the probability that a separate next transmission will be represented when estimating the occupancy by no more than one sample $N_{1O} \leq 1$.

Let us further denote the average duration of an individual transmission in the analyzed radio channel, measured in seconds, by $E[V]$. Then the duration of the random transmission α, expressed in T_R intervals, determined by (2), will obey the distribution law

$$W_{\alpha}(x) = q^{-1} \cdot \exp(-x / q),$$

where

$$q = E[V] / T_R \tag{3}$$

– the average transmission duration, expressed in T_R intervals, and the conditional probabilities of the occurrence of values $N_{1O} \leq 1$ are

$$P[\, N_{1O} \leq 1 \mid (\alpha = x) < 1 \,] = 1,$$

$$P[\, N_{1O} = 1 \mid 1 \leq (\alpha = x) < 2 \,] = 2 - x.$$

The unconditional probability $P[\, N_{1O} \leq 1 \,]$ will be defined as

$$P[\, N_{1O} \leq 1 \,] = \int_0^1 W_{\alpha}(x)dx + \int_1^2 (2-x)W_{\alpha}(x)dx = 1 - q \cdot (e^{-1/q} - e^{-2/q}).$$

The graph of the corresponding dependence is shown in Fig. 4.

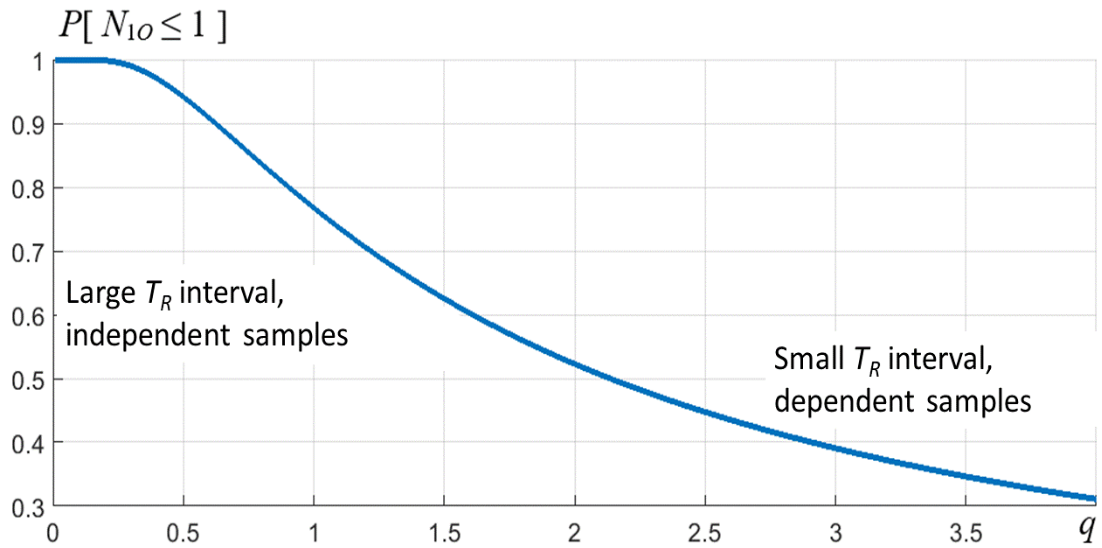

Fig. 4. Probability of registering transmissions by single "occupied" samples

A convenient starting point for further considerations can be the case when the interval between samples is twice the average transmission duration in the channel $T_{R\text{ind}} = 2 \cdot E[V]$. From physical considerations it is clear that when taking samples at such large time intervals (relative to the values of other parameters considered in each specific case), one can hardly expect the occurrence of mutual dependence of the states of adjacent samples (accordingly, the index "*ind*" will be used hereinafter to indicate that the discussed indicators were obtained in relation to independently ("independent") changing samples of the radio channel state). The probabilistic analysis just carried out confirms this: with $q_{\text{ind}} = E[V] / T_{R\text{ind}} = 0.5$, the probability that a single transmission will be registered by no more than one sample is 94%, which makes it possible to classify cases with $q \leq q_{\text{ind}} = 0.5$ as measurements with independent samples.

Let us separately consider the cases $q > 1$. The larger q, the more often the channel is tested, that will gradually transform the measurements to the dependent sampling mode. In accordance with the materials of article [1], the use of dependent samples when estimating occupancy requires an increase in N_O - the total number of registered "occupied" samples, which in article [1] is referred to as the "number of successes", and therefore the use of a larger number of samples in general. At the same time, the probability of maintaining the "occupied" state of the samples

$$\lambda = P[\, x_i = 1 \mid x_{i-1} = 1 \,]$$

it is proposed to calculate (see [1, example on p. 274]) based on the exponential distribution as

$$\lambda_{\max} \approx \lambda = e^{-T_R/E[V]}, \qquad (4)$$

that determines the required increase in the number of "occupied" dependent samples N_O, as [1, formula (33)]

$$N_{O\ dep} = N_{O\ ind} \cdot \left(\frac{1+\lambda_{\max}}{1-\lambda_{\max}} \right). \qquad (5)$$

From (3), (4) and (5) it follows that for different relationships between $E[V]$ and T_R, the coefficient χ, which determines the necessary increase in the number of samples in the case of "dependent" measurements, will depend on the above introduced indicator q according to the ratio:

$$\chi = N_{O\,\text{dep}} / N_{O\,\text{ind}} = (\, 1 + e^{-1/q} \,) / (\, 1 - e^{-1/q} \,). \qquad (6)$$

The corresponding dependence graph is shown as a solid line in Fig. 5.

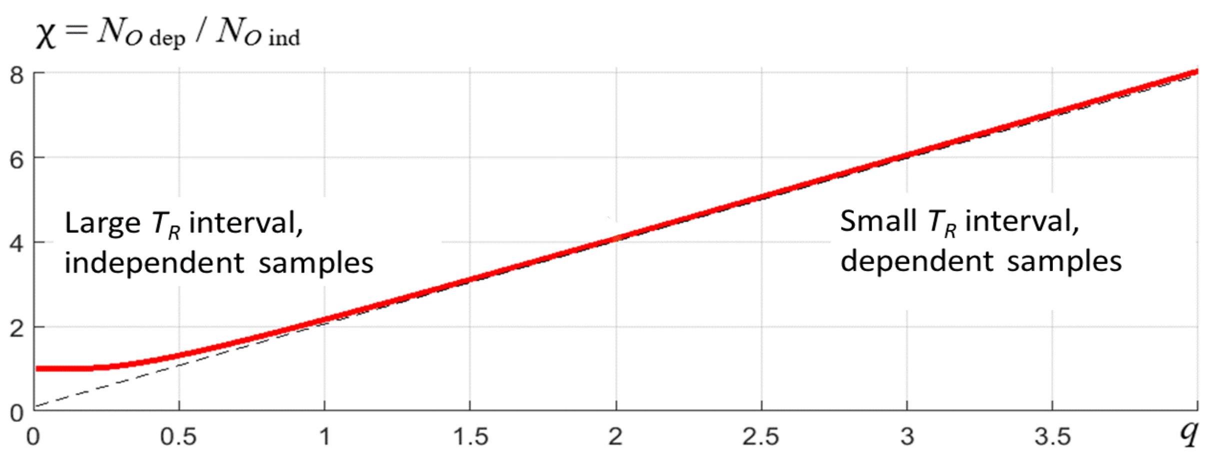

Fig. 5. Dependence of the coefficient χ of increasing the required sample volume on the ratio between the average transmission duration $E[V]$ in the channel and the T_R interval

So, for occupancy (1), defined as the probability of a stationary radio channel being in a "occupancy" state, the coefficient of increase in the required number of dependent samples χ turns out to be related to the indicator q (for values $q > 0.5$) in fact by direct proportionality. This allows us to draw the following conclusions, understandable from the point of view of practice:

a) if a certain interval between samples T_R generates a stream of dependent samples and provides a reliable assessment of occupancy at a certain integration interval T_I, then one should not expect to improve the quality of occupancy assessment by reducing the interval T_R, say, to $T_{R2} = T_R / 2$. This happens because the concomitant increase in the degree of the sample dependence will require the same 2 times increase the "number of successes" of $N_{O\,\mathrm{dep}}$. At the same time, the total time of data collection and the reliability of the assessment will remain unchanged, but the hardware cost of data collection will double, since the q index and the required number of samples in the integration interval T_I will increase by 2 times;

b) on the contrary, under increasing the interval between samples T_R by a factor of γ the index

$$q_\gamma = E[V] / (\gamma T_R)$$

will still satisfy the condition $q_\gamma > 0.5$, then such an increase in the T_R interval is acceptable and does not reduce the reliability of the occupancy assessment. If the condition $q_\gamma > 0.5$ is violated, then it is not recommended to use a γ-fold increase of the interval T_R. It is because this action will lead to a transition from the case of dependent samples to the use of independent samples, and the required number of independent samples is noticeably greater than the value obtained on the basis of direct proportionality;

c) the attempt presented in the text of Recommendation ITU-R SM.1880-2 [6] to distinguish samples simply into "independent" and "dependent" is rather simplified, since with a decrease in the interval between samples T_R, the degree of their mutual dependence increases (along with an increase in the indicator q). Therefore, for example, with $T_R \approx E[V] \cdot 2/3$, the coefficient of increase in the required number of samples is equal to $\chi = N_{O\,\mathrm{dep}} / N_{O\,\mathrm{ind}} \approx 3$ (this is exactly the value used in Table 1 of Recommendation [6]), and when using, for example, $T_R \approx E[V]/4$ a significantly different correction factor is needed, namely, $\chi = 8$.

The minimum number of transmissions in the data collection interval to ensure the reliability of measurements when they are dependent

Earlier, when analyzing the dependence of the coefficient χ on the indicator q, it was found that for $q > 1$ this dependence is close to linear, and for the required number of "occupied" dependent samples, an following approximate ratio can be proposed:

$$N_{O\,\mathrm{dep}} \approx 2q \cdot N_{O\,\mathrm{ind}}, \tag{7}$$

where $N_{O\,\mathrm{ind}}$ is the required number of independent samples registered as "occupied" in the integration interval T_I;
q is the average duration of the transmission, expressed in the intervals T_R.

Taking into account the physical meaning of q, relation (7) suggests that the number of transmissions

$$L = N_{O\,\mathrm{dep}} / q, \tag{8}$$

which should fit over the entire integration interval T_I to ensure the reliability of measurements, should not be chosen less than a constant

$$L_{\min} \approx 2 \cdot N_{O\,\text{ind}},$$

where $N_{O\,\text{ind}}$ is the required number of independent "occupied" samples, determined in accordance with [1, Fig. 2].

Let's test this assumption based on several examples from [1], presented there on pages 274-275. The main indicators related to this test from the examples are presented in Table 1.

Table 1 – Benchmarks from [1] to verify the need for $L \geq L_{\min}$

Example	Occupancy m, %	$E[V]$, seconds	T_R, seconds	$q = E[V]/T_R$	$N_{O\,\text{dep}}$ [1]	Number of transmissions L from (8)
"Option 2" on page 275	5	6	12	0.5	512	1024
"Starting" on page 274	6.67	6	4	1.5	1212	808
«Option 1» on page 275	0.1	30	12	2.5	1977	791

It follows from the analyzed examples that when estimating occupancy based on dependent samples characterized by an indicator $q > 1$, the required number of transmissions L in the integration interval T_I really does not change significantly. Taking into account the ratio (6), the dependence of the minimum required number of transmissions $L_{\min}$ on q will be determined by the expression

$$L_{\min} = N_{O\,\text{ind}} \cdot (1 + e^{-1/q}) / (1 - e^{-1/q}) / q. \qquad (9)$$

The dependence of $L_{\min}(q)$, presented in Fig. 6, shows that to ensure a relative error of 10% at a confidence level of 95%:

a) with a small T_R values (i.e., with a high rate of testing the state of the radio channel and really dependent samples) for a diverse combination of parameters at which $q \geq 1.75$, the information on the occupancy should be collected on the T_I interval that accommodates at least 800 transmissions;

b) at average T_R values, when the dependence of states in adjacent samples decreases, and the average transmission duration expressed in T_R intervals is in the range $1 \leq q < 1.75$, for occupancy measurements it is necessary to collect information within the T_I interval containing 850 transmissions;

c) for q values in the range $0.5 \leq q < 1$, to determine the number of transmissions $L_{\min}$ within the integration interval T_I, one should be guided directly by (9). For example, for q = 0.5, calculations give $L_{\min} = 1024$ transmissions;

d) at $q < 0.5$, the samples should be considered independent and the required number of "occupied" $N_{O\,\text{ind}}$ samples should be determined according to the rules corresponding to independent measurements.

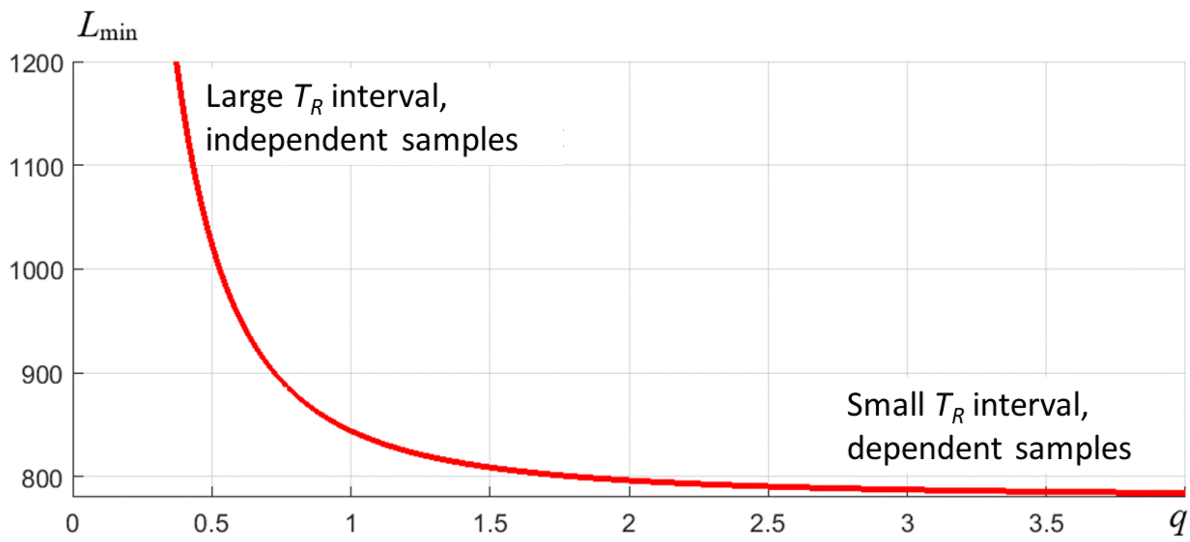

Fig. 6. Dependence of the required number of transmissions $L_{\min}$ within the integration interval T_I on the average transmission duration expressed in T_R intervals (with a relative accuracy of 10% and a confidence level of 95%)

So, if the examined radio channel is assumed to be stationary over the entire unlimited measurement interval, a high rate of testing the channel state is used (i.e., the samples are dependent), and occupancy means the probability of the channel being in a "occupancy" state at an arbitrarily selected time, then:

a) it turns out to be problematic to unambiguously determine the number of samples required for accurate and reliable measurements of occupancy. This is because according to (6) and/or Fig. 5 a sufficient number of dependent samples is directly proportional to the indicator q. The indicator is determined by the ratio (3) of the average duration of transmissions in channel $E[V]$ and the interval between samples T_R. Accordingly, the range of suitable values formally turns out to be very wide and the number of samples used in practice is selected taking into account both the speed of the monitoring equipment and the entire configuration of the task for the study of the availability of spectral resources or the measurement process;

b) if information is available on the average duration of transmissions in the channel $E[V]$ and on the a priori expected occupancy of channel m_0, it is possible to calculate the minimum required duration of the data collection interval in seconds:

$$T_{I\,\min} = E[V] \cdot L_{\min} / m_0. \qquad (10)$$

Let us check the correctness of the above statements based on the comparison of the results obtained with the recommended data collection durations from [1]. The relevant information is presented in Table 2.

The data obtained shows:

1) In the first case (m = 5%, q = 0.5), where the exact $L_{\min}$ value calculated on the basis of (9) was used, the recommended data collection interval $T_{I\,\min}$ coincided with the value specified in [1] with high accuracy.

Table 2 – Comparison of the new rules for determining the duration of data collection for occupancy measurements with examples from [1]

An example	Occupancy m, %	$E[V]$, seconds	$q = E[V]/T_R$	Value $L_{\min}$ from (9)[1]	Value $T_{I\min}$ from (10), hours	Measuring interval from [1][2], hours
"Option 2" on page 275	5	6	0.5	1024	34.1	34
"Starting" on page 274	6.67	6	1.5	850	21.2	20.2
«Option 1» on page 275	0.1	30	2,5	800	6666	6590

Note 1: see paragraphs (a) – (c) after formula (9).
Note 2: In the article by Spaulding & Hagn [1], this value is referred to as "total measurement time".

2) In the other two cases where the coarsened $L_{\min}$ value was used, the recommended duration demonstrates a "margin" of 5% of samples at $q = 1.5$ and 1% of samples at $q = 2.5$. Thus, the use of coarsened values to calculate the minimum required duration of data collection $T_{I\min}$ turns out to be quite acceptable.

Recommendations for ensuring the reliability of occupancy measurements

Let us write down a slightly different expression for calculating the value $T_{I\min}$, which determines the duration (in seconds) of the data collection time sufficient to ensure the accuracy and reliability of occupancy measurements. Taking into account (9), the expression (10) can be converted to the form:

$$T_{I\min} = E[V] \cdot (N_{O\,\text{ind}} / m_0) \cdot T_{\text{coef}}(q) \quad (11)$$

where $E[V]$ is the average duration of transmissions in the radio channel in seconds; $N_{O\,\text{ind}}$ is the required number of independent samples registered as "occupancy" at the minimal required data collection interval $T_{I\min}$; m_0 is the expected (according to a priori information) occupancy of the radio channel and a used correction coefficient equals:

$$T_{\text{coef}}(q) = (1 + e^{-1/q}) / (1 - e^{-1/q}) / q,$$

where q is the average transmission duration expressed in T_R intervals.

Note that the degree of mutual dependence of the samples is determined precisely by the indicator q. In relation (11), the $N_{O\,\text{ind}}$ multiplier is determined by the requirements for accuracy and reliability of the estimation, the elements $E[V]$ and m_0 are constants characterizing the channel, and only the coefficient $T_{\text{coef}}(q)$ reflects the influence of sample dependence on the procedure of the occupancy measurements. The graph of the function $T_{\text{coef}}(q)$ is shown in Fig. 7. It can be seen that as q increases, the values of the coefficient gradually decrease, approaching the constant "2". This means that:

a) The wording of the last paragraph of the text of item 2.2 "Dependent samples" from Annex 2 to the ITU Recommendation ITU-R SM.1880-2 [6] seems rather simplified, since the statement "*... It can be seen that the number of required dependent samples is about three times higher than with independent sampling.*" for an unprepared reader is equivalent to the statement, that collecting data for reliable occupancy estimates based on dependent samples will take 3 times longer. However, when monitoring a particular radio channel, it is possible to transit from independent samples to dependent ones only by reducing T_R interval. Figure 7 shows that an increase of $N_{O\,\mathrm{dep}}$ and the required number of dependent samples has less effect on $T_{I\,\min}$ than a decrease of T_R. Accordingly, it would be useful to clarify the quoted wording from [6]. For example: "*... In radio channels where there are extended transmissions with a duration comparable to or exceeding the interval between samples, the required number of dependent samples may be three or more times higher than the required number of independent samples for channels with short-duration transmissions. If the dependence of the samples is produced by a decrease in the time interval between samples, then the number of samples required for reliable occupancy estimation also increases, but the required duration of data collection is whereas reduced*".

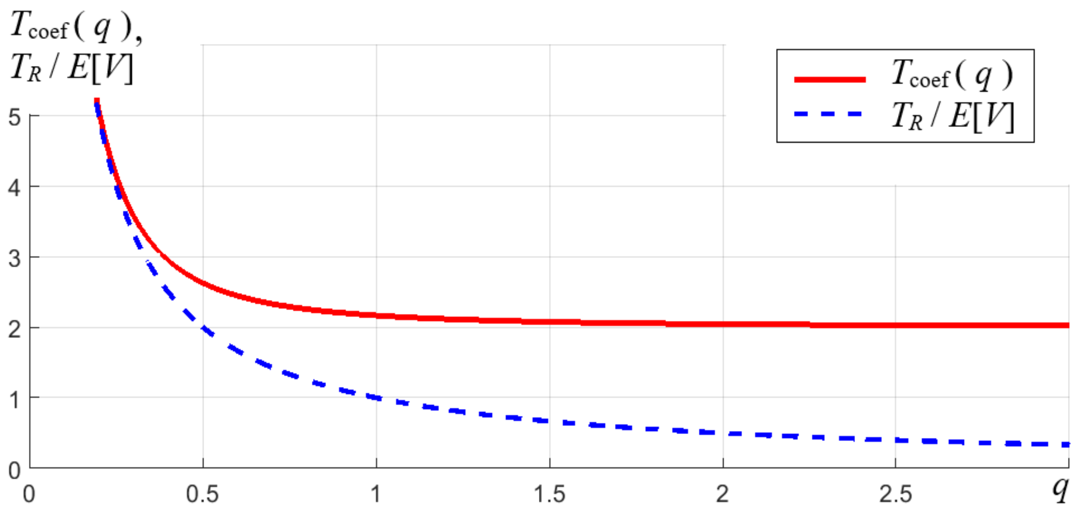

Fig. 7. Dependence of the correction coefficient $T_{\mathrm{coef}}(q)$ on the ratio q between the average transmission duration and the interval between samples T_R

b) The minimal data collection time for accurate and reliable occupancy assessment is formally:

$$T_{I\,\min\,\mathrm{cont}} = 2 \cdot (N_{O\,\mathrm{ind}} / m_0) \cdot E[V],$$

however, such an interval is sufficient for data collection only if $q \to \infty$, i.e., in fact, under changeover to continuous monitoring of the radio channel state, which is obviously wasteful from the point of view of resources expenditure. Therefore, the value of $T_{I\,\min\,\mathrm{cont}}$ can be considered as a starting point when planning measurements, and when they are actually carried out, nevertheless, be guided by a more precise requirement (11).

Note also that a priori information about channel occupancy may be inaccurate; in such a case, after collecting data at the time interval $T_{I\,\min\,0}$ corresponding to the expected occupancy value m_0, there is a risk of getting an estimate $m \ll m_0$. In such a situation, it makes sense to calculate a new $T_{I\,\min}$ value corresponding to the occupancy m and continue measuring occupancy in order to refinement the resulting estimate. A similar iterative measurement process (starting with the assumption that $m_0 \approx 30..50\%$) can also be used in the absence of a priori information about the occupancy of the radio channel from the operator of the radio monitoring equipment.

Conclusion

The methodology of measuring occupancy in radio channels (frequency bands) significantly depends on whether the statistical properties of the channel remain unchanged along the time axis (the channel is stationary) or the properties of the channel change dynamically. It also depends on how long the interval for testing the channel state is relative to the average duration of transmissions in the channel.

If the channel is non-stationary, then a "local" assessment of occupancy is carried out, as a rule, at 15-minute intervals in accordance with the instructions provided in the Report ITU-R SM.2256-1 [2].

If the channel is stationary, then the determination of occupancy is aimed at assessing the probability that at any given time the channel will be in an "occupied" state; under this, the recommended duration of information collection may be significantly longer than 15 minutes and depends on many factors.

If the spectrum monitoring equipment provides frequent testing of the channel state (i.e., the interval between samples is less than the average duration of transmissions in the channel), then adjacent samples of channel states turn out to be dependent. In this case, in order to determine the required duration of data collection, Recommendation ITU-R SM.1880-2 [6] suggests using the values from its Table 1. However, the number of dependent samples determined by this Table ensures the required accuracy and reliability of estimation only if the average duration of transmissions in the channel exceeds the interval between samples (the period of monitoring the state of the radio channel) by exactly 1.5 times. With a different rate of data collection (or a different average transmission duration), the relative accuracy of 10% when estimating occupancy at a reliability level of 95% is not really guaranteed by the provisions of [6].

The calculating relationships proposed in this paper make it possible to determine the minimum required duration of data collection for arbitrary combinations of the average duration of transmissions in the channel and the interval between samples. It is shown that if the dependence of samples in occupancy measurements is provided by a decrease in this interval, then the number of samples required for reliable occupancy estimation increases, but the minimum required duration of data collection is reduced. The data collection durations obtained on the basis of calculating relationships coincide with the results of classical work [1].

The results of this study may form the subject of proposals from the Russian Federation for further improvement of the Recommendation ITU-R SM.1880.

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