Radiocommunication Study Groups

Received: 2012

Subject: Contribution for the draft new Report on spectrum occupancy measurement, being developed by the Correspondence Group

Document 1C/2-E
5 April 2012
Original: Russian

Russian Federation

CONTRIBUTION FOR THE DRAFT NEW REPORT

SPECTRUM OCCUPANCY

Introduction

It is clear from the texts of new Recommendation ITU-R SM.1880 and § 4.10 of the new version of the ITU Handbook on spectrum monitoring (2011 edition) that the reliability (statistical confidence) of spectrum occupancy measurements, which is such an important factor for practical applications, depends on a whole series of parameters of the measurement process. These include: degree of spectrum occupancy, revisit time and overall number of samples (measurement points), stipulated confidence interval, etc. However, the above-mentioned texts do not contain any calculation functions that could be incorporated in software for managing data collection and for processing spectrum occupancy measurement results. The information is limited to nothing more than a small table with specific values without any accompanying equations and which is incomplete in terms of providing the requisite information.

In line with the working document entitled “Working document towards a preliminary draft new Report” (see Annex 5 to Document 1C/159 dated 14 June 2011), hereinafter referred to as the “draft Report”, the Correspondence Group is currently developing a new Report on spectrum occupancy measurement. In the present contribution, it is proposed to include in the Report being developed a number of subsections and annexes (see Attachments 1 to 5 to this contribution), analysing how the statistical confidence of the spectrum occupancy calculation depends on the features of the measurement process. Subsequently, when Recommendation ITU-R SM.1880 is next revised, some of the proposed material may be transferred into the new version of the Recommendation and/or into the next new version of the ITU Handbook on spectrum monitoring.

Contact: A.B. Tokarev, TokarevAB@ircoc.vrn.ru

General recommendations

1 The text of the draft Report proposes that the “Definitions” section include definitions of frequency channel occupancy (FCO) and frequency band occupancy (FBO). However, the section will contain only short textual descriptions of these concepts. Users of the Report should also be provided with a detailed and clear description of the concept of “occupancy”, and also be familiarized with the reasons why error can occur in occupancy measurement. Accordingly, a subsection should be inserted before the section on “Measuring procedure” (or at the very beginning of that section), on “Concept of spectrum occupancy and verifying the accuracy and statistical confidence level of spectrum occupancy measurement”. A proposed text for such a subsection is set out in Attachment 1 below.

2 The text of the draft Report proposes sections for inclusion in the Report entitled “Measuring procedure” and “Calculation of occupancy”. However, having two separate sections does not help, but rather hinders the presentation of the material they contain, since the calculated occupancy is the natural culmination of a measuring procedure, and different measuring procedures entail the use of different calculation equations. Consequently, the features of the measuring procedures, the calculation equations[1] and also issues of confidence in the results obtained have to be considered as a single whole within the section on “Measuring procedure”. In this case, the separate section on “Calculation of occupancy” can be deleted from the Report. The text we propose for inclusion in the section “Measuring procedure” is set out below in Attachment 2.

3 Studies on the statistical properties of spectrum occupancy calculations have shown that confidence is affected not only by occupancy itself, but also by several other characteristics of the channel and the measurement procedures. Such information is not absolutely essential for carrying out the measurements, but will nevertheless be useful for any users of the Report who are called upon to explain the influence of calculation parameters on the statistical confidence of the values obtained. It is suggested that examples illustrating the impact of signal flow rate in the radio channel on reliability of the measurements be provided as Annex A to the Report on spectrum occupancy measurement. A proposed text for that Annex A is set out in Attachment 3 to this contribution. It is proposed that the calculation relationships determining the change in confidence level of the occupancy measurements be formulated as Annex B to the Report on spectrum occupancy measurement. A text for that Annex B is set out in Attachment 4 to this contribution.

4 The material in Attachments 1 to 4 hereto is founded on a number of parameters which hitherto have not been given much attention in measuring spectrum occupancy, but which exert an influence on the confidence level of the measurement results obtained. These parameters should be reflected in the “Definitions” section of the Report. Recommended texts for the corresponding definitions in question are set out in Attachment 5 to this contribution.

---

[1] In the ITU Recommendations and Handbook on spectrum monitoring, with regard to occupancy measurement no reliable indications as to values could be found. Furthermore, it is hardly possible to define calculation relationships in textual form alone (without using illustrative values). Therefore, it is necessary to put forward some kind of range of values. The authors of this contribution have used their own system of values which, naturally, will be subject to future alignment with the proposals of other collaborators.

ATTACHMENT 1

Proposed content for a subsection entitled “Concept of spectrum occupancy and verifying the accuracy and statistical confidence level of spectrum occupancy measurement”

Spectrum occupancy means the probability that, at a randomly selected moment in time, a frequency channel, frequency band or other frequency resource being analysed will be in use for the transmission of information.

For the analysis of spectrum occupancy[2] it is considered that only two channel states are possible: active (“occupied”), whereby the signal level in the channel exceeds a selected detection threshold, and passive (“free”), whereby the signal level in the channel is small. Spectrum occupancy Z is determined by the probability of its being in the active state.

FIGURE 1

Definition of the concept of frequency channel occupancy

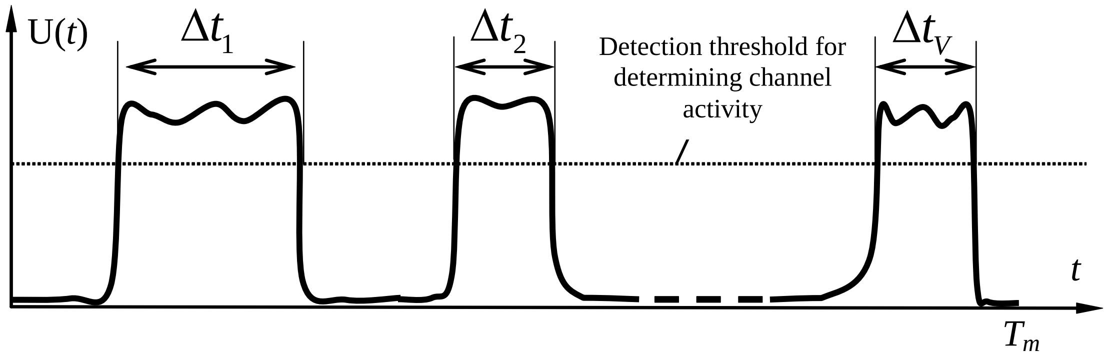


Figure 1 shows an example of the possible change over time in the level $U(t)$ of a signal in a channel over a measurement period T_m. The probability that an active signal state will be detected at a randomly selected sample point on the time axis will be equal to the ratio of the aggregate duration of active state intervals Δt_1, Δt_2 … Δt_v to the total measurement period T_m. Thus, channel occupancy over this measurement period is expressed by:

$$Z = \sum_{v=1}^{V} \Delta t_v \Big/ T_m \tag{1}$$

where:

Z : true value of occupancy over the current measurement period

T_m : duration of the measurement period

---

[2] In the following paragraph or paragraphs, specific recognition could have been given to the occupancy of other frequency resources, but this contribution relates primarily to issues of measurement confidence and, for the sake of clarity, we concentrate on the measurement of frequency channel occupancy. Any extension of the definition to other resources should be proposed by members of the Correspondence Group and other collaborators.

V : number of active state intervals during the period T_m

$\Delta t_1, \Delta t_2 \ldots \Delta t_v$: duration of active state intervals in the frequency channel.

1.1[3] Occupancy measurement error

When monitoring frequency ranges containing a large number of frequency channels, continuous observation of each channel is problematical. Instead, monitoring instruments collecting data for occupancy calculations generally check the status of channels only intermittently. The number of channel state samples J_m during the occupancy measurement period is determined by the length of the measurement period T_m and the channel state sampling revisit time T_{rv} (which, in turn, is determined by the operating speed of the monitoring equipment and the number of frequency channels in which occupancy is being measured).

With intermittent sampling, we cannot accurately pinpoint the instants when a channel switches from active to passive state and vice versa; thus, for measuring occupancy, instead of the exact equation (1), it is necessary to use approximations. For example, for a uniform distribution of channel state sampling points on the time axis, the following estimation can be used to measure occupancy:

$$\tilde{Z} = S_{act} \big/ \left(S_{act} + S_{pass} \right)$$

where:

$\tilde{Z}$: estimated spectrum occupancy

S_{act} : number of active channel states detected during the measurement period

S_{pass} : number of passive channel states detected during the measurement period.

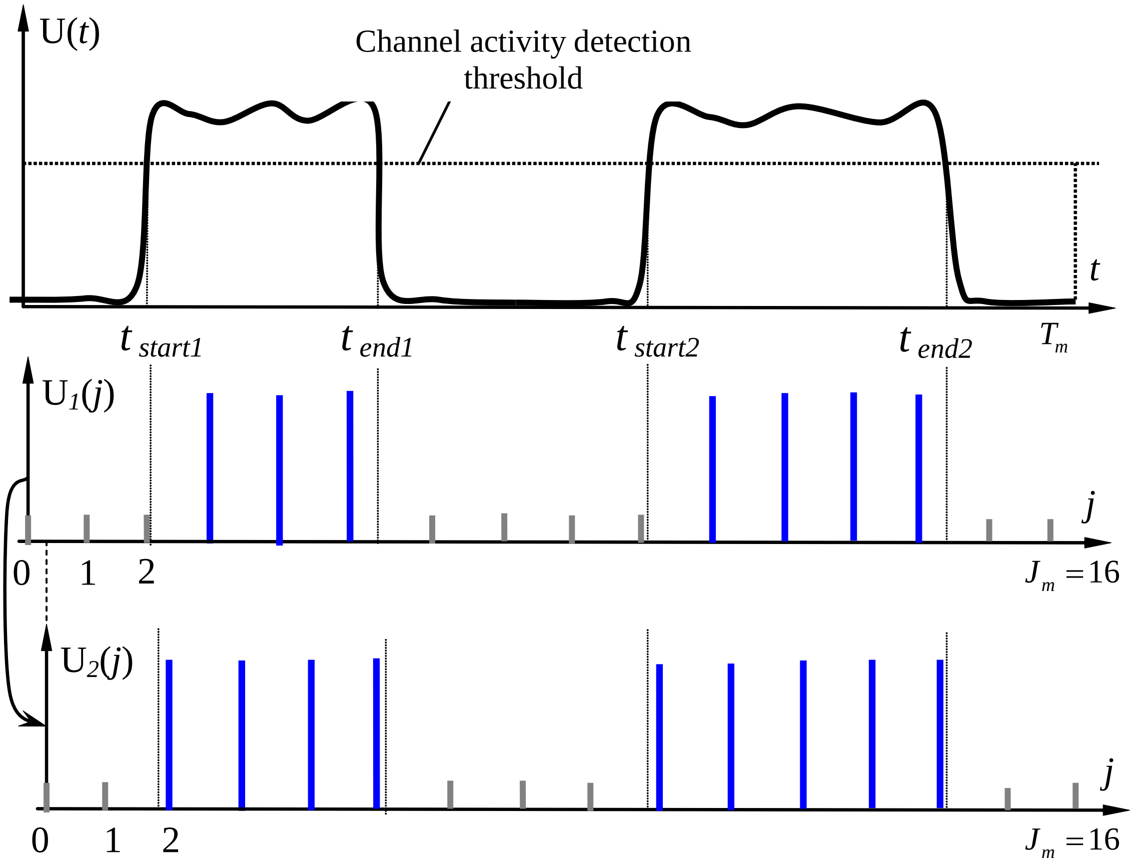
We shall demonstrate the potential spectrum occupancy measurement error for a signal behaving as depicted in Fig. 2. The top diagram $U(t)$, which shows the continuous change in the signal level in the channel over time, corresponds to a true value $Z \approx 50\%$. The two following diagrams illustrate occupancy measurement with the same number of samples J_m, but with a slight “mismatch” in terms of the points as from which the time is counted. Comparing diagrams $U_1(j)$ and $U_2(j)$, it can be seen that the measured occupancy value in the first case will be $\tilde{Z}_1 = 7/16 \approx 43.75\%$ and in the second case $\tilde{Z}_2 = 9/16 \approx 56.25\%$.

---

[3] Unfortunately, the section numbering in this contribution cannot follow the same numbering as the sections of the original Report on spectrum occupancy measurement, since for the purposes of making cross-references in the text of the contribution, it is necessary to introduce artificial references “linked” to the numbers used in the attachments constituting this contribution.

FIGURE 2

Occupancy measurement error



It is obvious that:

1) In addition to the first and second diagrams presented, other variants are also possible with different distributions of calculation start points, in which there will be exactly eight instances of channel activity over the measurement period, giving a precise occupancy estimate of $\tilde{Z}_r = 8/16 = 50\%$.

2) Increasing the number of samples J_m reduces the potential spread of measurement results and makes it possible to guarantee negligible error in the occupancy calculation irrespective of the calculation start time selected.

Thus, the occupancy estimates $\tilde{Z}$ are random values, and the quality of the occupancy measurements has to be analysed from a statistical standpoint.

1.2 Accuracy and confidence level of occupancy measurement

For the reasons considered under § 1.1, frequency channel occupancy measurement is in practice subject to error. It may be shown (see, for example, [3]) that the occupancy measurement error in a specific r-th sample $\delta Z_r = (\tilde{Z}_r - Z)$ is a random value with, as a rule, a close-to-normal distribution. Error magnitudes may vary very significantly in each sample. This means that conditions have to be imposed on the quality of occupancy evaluation from the standpoints of accuracy and confidence.

Confidence P_Z is the probability that the calculated occupancy $\tilde{Z}$ will differ from the true value Z by no more than the permissible absolute error Δ_Z.

$$P_Z = P\left\{ \left| \tilde{Z} - Z \right| \leq \Delta_Z \right\} \tag{2}$$

where:

P_Z : confidence level of the occupancy measurement

Z : true value of occupancy over the measurement period

$\tilde{Z}$: calculated occupancy value obtained for the current measurement period

Δ_Z : permissible absolute measurement error threshold corresponding to half of the confidence interval.

Accuracy requirements are also often expressed in terms of the permissible relative measurement error threshold δ_Z, which is linked to the permissible absolute error by the equation:

$$\delta_Z = \Delta_Z / Z \tag{3}$$

Whether accuracy requirements should be expressed in terms of absolute or relative error depends on what kind of magnitudes of occupancy values (small or large) it is more important to measure in practice.

Limiting the permissible relative measurement error places higher demands (small confidence interval) on measurement accuracy in frequency channels with a low occupancy and relaxes the demands on measurement accuracy for channels with high occupancy. For example, taking a typical value $\delta_Z = 10\%$, for a channel with an occupancy $Z = 2\%$ values in the range $1.8\% \leq \tilde{Z} \leq 2.2\%$ will be considered as falling within the confidence interval (confidence interval of 0.4%), whereas for an occupancy $Z = 20\%$ the confidence interval will increase to 4%, and for a channel with an occupancy $Z = 92\%$ any values will be considered acceptable within the range $82.8\% \leq \tilde{Z} \leq 100\%$.

When it is the permissible absolute measurement error which is limited, the size of the confidence interval is independent of the actual channel occupancy. In particular, with the value of $\Delta_Z = 0.5\%$ that is recommended for use in practice, the size of the confidence interval remains at 1% for both low-occupancy and high-occupancy channels. This corresponds to a very rough estimate for channels with low occupancy, and a very accurate assessment for channels with high occupancy. For instance, for an occupancy $Z = 92\%$, values lying in the range $91.5\% \leq \tilde{Z} \leq 92.5\%$ are considered acceptable.

As regards the required confidence levels, values in the range 90-99% are generally recommended for use in practice. In this Report, a value of $P_Z = 95\%$ will henceforth be used as a basis.

1.3 Possible variants in assumptions for calculating occupancy

To select the right method for measuring occupancy, it is necessary to distinguish between the following two variants.

The first variant assumes that channel occupancy may change through time. Here:

– to monitor the changes, the time axis has to be divided into a set of measurement intervals $T_{m\,r}$. These measurement intervals shall be of fixed duration, usually of between 5 and 15 minutes;

– for each r-th measurement interval, the occupancy value $\tilde{Z}_r$ has to be calculated, which determines channel activity for the specific interval $T_{m\,r}$ in question;

- to obtain valid occupancy figures for each interval, fast, state-of-the-art monitoring systems need to be used;
- the overall monitoring duration is determined by the time interval at which the occupancy changes need to be analysed, and will as a rule be the aggregate of the measurement intervals $T_{m\,r}$.

The occupancy corresponding to the variant described above may be termed "instant occupancy". Issues relating to the statistical confidence of instant occupancy measurement are considered in more detail in the section entitled "Measuring procedure" and in Attachments A and B to this Report.

The second variant assumes that channel occupancy does not change through time. Here:

- any differences in channel properties in different measurement intervals $T_{m\,r}$ observed during practical measurement are to be considered as random fluctuations;
- the purpose of the measurements is to determine a single indicator for channel occupancy, namely "average occupancy", characterizing the channel's properties over the whole time axis;
- there is a time interval which is sufficient for evaluating average channel occupancy with a specified level of statistical confidence, and which determines the necessary monitoring duration;
- there are no stringent requirements in terms of the measuring equipment – low operating speed can be offset by increasing the monitoring duration.

The features of average channel occupancy measurement are studied in detail in [4], while recommendations regarding statistical confidence for average channel occupancy measurement may be found, for example, in Table 1 in [2]. The data in that table were obtained with a limit on the maximum permissible relative measurement error δ_Z. In accordance with § 1.2 of this Report, this places higher demands on measurement accuracy for low occupancy values and relaxes the measurement accuracy in high-occupancy channels. The natural consequence of limiting the permissible relative error is the ability to complete measurements quickly in high-occupancy channels and the need to take a huge number of measurements in low-occupancy channels.

1.4 Parameters affecting the statistical confidence of occupancy measurement

1.4.1 Signal flow rate in the frequency channel

It is shown in [3] that the accuracy and confidence level of occupancy measurements is strongly dependent on the number of transmissions (or the number of changes in state of the channel) within the measurement period. Attachment A to this Report also contains examples showing that for different numbers of signals detected during the measurement period, the required number of samples for a confident occupancy measurement may vary by around an order of magnitude.

Signal flow rate λ is the average number of signals present in the channel over a given time period. For example, if, in a particular channel, 140 transmission sessions are observed within every one-hour time period, then the signal flow rate for that channel will be $\lambda = 140$ signals/hour. Recommendations regarding the consideration of signal flow rate in occupancy measurement will be provided in § 2.1.3.3.

It should be borne in mind that the signal flow rate in a frequency channel λ for different time periods may vary significantly. This means that the variation in signal flow rate has to be tracked during the course of the measurements and the measurement parameters adjusted accordingly [3].

1.4.2 Relative instability of revisit time

There are a number of reasons that might lead to an uneven distribution of channel state samples on the time axis:

- When measuring occupancy in channels with significantly different signal flow rates, the required number of samples may vary five or tenfold. Strictly cyclical sampling of the state of such channels is ineffectual, and switching to a flexible channel sampling procedure will lead to an uneven distribution of samples on the time axis.
- State-of-the-art monitoring systems are extremely fast and, when the number of channels to be monitored is small, are capable of undertaking occupancy measurement data collection and other monitoring tasks in parallel, but when equipment resources are divided up in this way the distribution of samples on the time axis also becomes uneven.

There may also be other reasons causing instability of the revisit time between samples.

Let the times t_j ($1 \leq j \leq J_m$) correspond to the real distribution of samples on the time axis. The intervals $T_{rv\,j}$ between samples:

$$T_{rv\,j} = t_{j+1} - t_j, \quad 1 \leq j < J_m \tag{4}$$

in practice experience random fluctuations in relation to the mean value:

$$T_{rv} = T_m / J_m \tag{5}$$

where:

T_m : duration of the measurement period

J_m : number of samples within the measurement period.

The relative instability of the sampling interval is called δT, and is determined by the maximum deviation of the interval between samples from its mean value. It is expressed by:

$$\delta T = \max_j \left\{ \left| t_{j+1} - t_j \right| / T_{rv} \right\}, \quad 1 \leq j < J_m \tag{6}$$

where:

δT : relative instability of the sampling interval

t_j : real sampling times

T_{rv} : average value of the revisit time, derived from (5)

J_m : number of samples within the measurement period.

1.4.3 Use of lock-in and lock-out measurement systems to analyse frequency channels with pulse signals and continuous signals

The confidence level of occupancy measurements depends on the typical duration of the signals in the frequency channel analysed, and, in the case of unstable revisit times, also on whether the measuring system used is a lock-in or a lock-out system. When measuring instant occupancy, continuous signals are considered to be those whose duration Δt_v is at least one thousandth of the measurement period, i.e. meeting the condition $\Delta t_v \geq 10^{-3} \cdot T_m$; pulse signals are those with a duration $\Delta t_v < 10^{-4} \cdot T_m$.

Lock-in systems feature the use of a high-precision frequency generator, which determines a kind of ideal grid of sampling points on the time axis. The real sampling points may be displaced in relation to the nodes of this ideal grid, but for points located in the different sections of the measurement period these displacements are independent.

Lock-out systems are understood to be ones in which there is no time grid, measurement is carried out on the basis of approximately equal revisit intervals, and the displacement of any point affects the distribution on the time axis of all subsequent sampling points.

For short time intervals, the difference in the systems' behaviour is not too noticeable, but for a typical measurement period duration T_m of hundreds of seconds, the differences in the distribution of sampling points on the time axis become significant and have a noticeable impact on the statistical characteristics of occupancy measurement in frequency channels with continuous signals. Recommendations for achieving measurement confidence for lock-in and lock-out systems will be given in the section “Measuring procedure”. Statistically confident measurement of occupancy in channels with pulse signals requires a much larger number of samples in the measurement period, although for such signals the difference between lock-in and lock-out systems becomes negligible.

ATTACHMENT 2

Proposed content for a subsection "Measuring procedure/ /frequency channel occupancy (FCO)"

2.1 Recommendations for measuring occupancy with lock-in measuring systems

2.1.1 Data collection

To measure occupancy, one must at the very least determine for each measurement period the number S_{act} of observations of active channel states and the number S_{pass} of occurrences of the channel in passive state.

Where there are predominantly continuous signals in the channel, in order to verify measurement confidence information is also required on the signal flow rate λ. When such information is lacking, it is worthwhile checking the grouping of active and passive states so as to set a quantity V_r of signals detected in the channel in the r-th measurement period. The number of signals detected V_r is considered to be equal to the number of switches from passive to active state and vice versa.

2.1.2 Occupancy measurement rule

The rule for the measurement of occupancy was already discussed earlier in § 1.2, and takes the form:

$$\tilde{Z} = S_{act} \Big/ \left(S_{act} + S_{pass}\right) \tag{7}$$

where:

$\tilde{Z}$: estimated spectrum occupancy

S_{act} : number of active channel states detected during the measurement period

S_{pass} : number of passive channel states detected during the measurement period.

2.1.3 Selecting the number of samples

2.1.3.1 Recommendations for selecting the number of samples for measuring average channel occupancy and for limiting the permissible relative measurement error threshold δ_Z may be found in [1,2].

2.1.3.2 A description of the statistical properties of instant occupancy calculations with limitation of the permissible absolute measurement error threshold Δ_Z may be found in Annex B. Measurement confidence will behave differently for channels with continuous signals and pulse signals. For channels with continuous signals, it is determined first of all by the quantity of signals within the measurement period. For channels occupied by pulse signals, confidence depends on the value of frequency channel occupancy itself.

2.1.3.3 For frequency channels with continuous signals, the number of samples required to achieve a confidence P_Z = 95% with a maximum permissible absolute measurement error Δ_Z = 0.5% may be obtained by substituting these constants in the general equations (26-30) in Annex B. The rule for achieving statistical confidence of occupancy measurements then takes the form:

$$J_{m\,\min} = 194.2 \cdot \sqrt{V_{avr} \cdot \left(1.06 + \delta T^2\right)} \tag{8}$$

where:

$J_{m\,\min}$: recommended (minimum necessary) number of samples

δT : relative instability of revisit time

V_{avr} : average number of signals expected within the occupancy measurement period, equal to:

$$V_{avr} = \lambda \cdot T_m \tag{9}$$

Here:

λ : signal flow rate in the channel (see § 1.4.1)

T_m : duration of the occupancy measurement period.

Examples of the application of equation (8) to frequency channels with different signal flow rates are shown in Table 1. We note that, in accordance with Annex B, with most modern monitoring systems there is no need to make any corrections to the relationship between adjacent sampling results when measuring occupancy.

According to the data in Table 1, for channels with continuous signals and a low occupancy (hence, also a low signal flow rate λ), statistically reliable measurement results are obtained with a number of samples $J_m < 10^3$, which diverges from the information given in [1,2]. The discrepancies are explained by the fact that, in Table 1 shown here, the data were obtained with a limitation not on the relative but on the absolute measurement error, which does not assume any narrowing of the confidence interval for cases of low frequency-channel occupancy (see § 1.2). In § 1.1 it was established that occupancy measurement error arises from the lack of accurate data on the instants when the frequency channel switches over from active to passive state and vice versa. Thus, the more such switchovers there are during the measuring period, the greater the potential measurement error. It is precisely for this reason that, in order to achieve statistical confidence in the results, it is necessary in equation (8) to increase the number of samples not as the occupancy rate increases but as the average number of signals expected in the channel over the measurement period increases. In this way, by setting the permissible absolute error rate Δ_Z for both channels with low occupancy and channels with high occupancy but not many changes in state (such as those occupied by broadcasting stations), it is sufficient to carry out only between 632 and 703 revisits. Only for channels displaying a large number of changes in state over the measurement period does the required number of samples become significant.

TABLE 1

Recommended number of samples for a channel with continuous signals required to achieve an absolute occupancy measurement error Δ_Z of no more than ±0.5% with a confidence of P_Z = 95%

Signal flow rate in the channel λ (*average* number of signals observed in the occupancy measurement period), not exceeding:	**Recommended number of samples**	
	For even distribution of samples on the time axis	**For uneven distribution of samples $0.25 \le \delta T \le 0.5$**
10	632	703
30	1 095	1 217
50	1 414	1 572
100	2 000	2 223
300	3 463	3 850
500	4 471	4 970

NOTE – The data in the right-hand column of the table are given under the assumption of application of equation (7) for lock-in measuring systems, or equation (15) for lock-out measurements.

If the signal flow rate λ over the occupancy measurement period is not previously known, then it is recommended to stipulate a value selected with a margin. To specify the signal flow rate for the measurement process, it is recommended to use the equation in [3]:

$$\lambda_{(r+1)} = \left(w\lambda_r + V_r\right)/(w+1) \tag{10}$$

where:

$\lambda_{(r+1)}$: flow rate expected in the next measurement period

λ_r : flow rate for the current (elapsed) measurement period

V_r : number of signals recorded in the current measurement period

w : weighting coefficient determining the response time of the adaptation procedure, usually selected within the range $5 \leq w < 20$.

2.1.3.4 For frequency channels with pulse signals, the number of samples required to achieve a confidence level P_Z = 95% for a maximum permissible absolute measurement error of Δ_Z = 0.5% may be obtained by substituting these constants in the general equation (38) from Annex B. The rule for achieving statistical confidence in occupancy measurements then takes the form:

$$J_{m\,\min} = 153\,664 \cdot Z \cdot (1 - Z) \tag{11}$$

where:

$J_{m\,\min}$: recommended (minimum necessary) number of samples

Z : frequency channel occupancy.

With pulse-type signals, the confidence of the calculation (7) is determined by the occupancy value itself and is practically independent of instability in the distribution of samples along the time axis and also of whether the measurements involved are of the lock-in or lock-out variety. The application of equation (11) to frequency channels with different occupancies is illustrated in Table 2.

2.1.4 Effect of incorrect choice of number of samples on the confidence level of the occupancy measurement

Reducing the number of samples J_m by a factor of K in relation to what is recommended in Tables 1 and 2 will reduce reliability, or widen the confidence interval proportionally with K.

Let us assume, for example, that we need to measure the occupancy of a frequency channel under the following conditions: using a lock-in measuring system obtaining a sample distribution with a relative instability $0.25 \leq \delta T \leq 0.5$, with a signal flow rate in the channel of no more than 50 signals within the measuring period. From the last column in Table 1, we see that the recommendation in this case is to sample the channel state 1 572 times. Complying with this recommendation, the occupancy calculation (7) will deviate by no more than Δ_Z = 0.5% from the real value, with a confidence level of P_Z = 95%. If we now assume, on the other hand, that the system is actually capable of taking only 393 channel state measurement samples over the measurement period, i.e. four times less than the recommended number, then on average the occupancy will as before be measured faithfully, but the range within which the real occupancy value will occur with a confidence level of 95% is increased fourfold to ±2% either side of the measurement result.

An inadequate number of samples J_m may also be observed when data collection for the occupancy calculation is curtailed prematurely. In such cases, the occupancy calculation (7) remains unbiased but the confidence level of the results is diminished similarly to the example discussed above.

TABLE 2

Recommended number of samples for a channel with pulse signals, required to achieve an absolute occupancy measurement error Δ_Z of no greater than ±0.5% with a confidence of $P_Z = 95\%$

Frequency channel occupancy *Z*, %	Recommended number of samples J_m	Recommended revisit time T_{rv}, ms	
		For T_m = 5 minutes	For T_m = 15 minutes
5	7 300	41.1	123.2
10	13 830	21.7	65.0
20	24 586	12.2	36.6
35	34 960	8.6	25.7
50	38 416	7.8	23.4

NOTE – The required number of samples for channels with an occupancy $Z^* > 50\%$ coincides with the number of samples for an occupancy $Z = 1 - Z^*$. In other words, for instance, to achieve statistically confident measurements in a channel with an occupancy of 80% it is necessary to select J_m = 24 586, as in the case of occupancy $Z = 1 - 0.80 = 20\%$.

2.2 Recommendations for measuring occupancy with lock-out measuring systems

Rule (7) may be used to calculate occupancy in lock-out systems too, but the statistical confidence of the occupancy calculation in such systems deteriorates noticeably as the relative instability δT increases. Calculation quality can be improved by accurately setting the moments in time at which the frequency channel state is evaluated. Broadly speaking, the measurements should not verify the number of occurrences of active and passive states in the channel, but rather the length of time the channel spends in active or passive state.

2.2.1 Data collection

To calculate occupancy, it is necessary as a minimum, in each measurement period, to record the aggregate length of time spent by the channel in active $T_{\Sigma\,act}$ and passive $T_{\Sigma\,pass}$ states.

At the start of the measurements, one should set $T_{\Sigma\,act} = 0$ and $T_{\Sigma\,pass} = 0$ and determine the channel state corresponding to time t_0. Subsequently, if the channel is observed to be in passive state at sampling points t_j and t_{j+1}, then the value $T_{\Sigma\,pass}$ is increased to the duration of the revisit time $t_{rv\,j}$ between sampling points determined in (4):

$$T_{\Sigma\,pass}(j) = T_{\Sigma\,pass}(j-1) + T_{rv\,j} \tag{12}$$

If the channel state was active at both points, then $T_{\Sigma\,act}$ is increased:

$$T_{\Sigma\,act}(j) = T_{\Sigma\,act}(j-1) + T_{rv\,j} \tag{13}$$

And if within the interval $T_{rv\,j}$ a change in channel state is observed, then both values are corrected:

$$T_{\Sigma\,pass}(j) = T_{\Sigma\,pass}(j-1) + T_{rv\,j}/2, \qquad T_{\Sigma\,act}(j) = T_{\Sigma\,act}(j-1) + T_{rv\,j}/2 \tag{14}$$

In order to verify the confidence level of the measurements, as was done with lock-in systems, one should record the quantity of signals observed over the occupancy measurement period (see §§ 2.1.1 and 2.1.3.3).

2.2.2 Occupancy calculation rule

The rule for calculating occupancy takes the form:

$$\tilde{Z} = T_{\Sigma\, act} \Big/ \left(T_{\Sigma\, act} + T_{\Sigma\, pass} \right) \tag{15}$$

where:

$\tilde{Z}$: estimated spectrum occupancy over the measurement period

$T_{\Sigma\, act}$: aggregate length of time spent by the channel in active state

$T_{\Sigma\, pass}$: length of time spent by the channel in passive state.

2.2.3 Selecting the number of samples

A description of the statistical properties of equation (15) may be found in Annex B. Setting the length of time during which active and passive states are observed in the channel prevents the accumulation of error which is characteristic of lock-out measurements. As a result, the statistical characteristics of equation (15) for lock-out measuring systems coincide with the quality obtained in equation (7) for lock-in systems. This means that the number of samples required to achieve a confidence level P_Z = 95% may be calculated using rules (8) and (11) above or read off from Tables 1 and 2.

Using equation (7) for lock-out measurements is in principle acceptable, but the quantity of samples required to achieve measurement confidence rises sharply as the relative instability of the revisit time increases. The relevant calculation relationships may be found in Annex B.

ATTACHMENT 3

Proposed content for Annex A to the draft report on occupancy measurement

ANNEX A

Typical examples of the impact of signal flow rate in the radio channel on the confidence level of spectrum occupancy calculations

This annex gives examples testifying to the importance of tracking signal flow rate in frequency channels where the aim is to obtain occupancy measurements with a high degree of accuracy and statistical confidence. Occupancy calculations are analysed for cases of frequency channels with a significantly different number of periods of activity (communication sessions) over the measurement period. In all the cases compared, the real occupancy value remains the same, namely $Z = 5\%$. The accuracy requirements imposed entail a maximum permissible absolute measurement error of $\Delta_Z = 0.5\%$, which for $Z = 5\%$ corresponds to a relative error $\delta_Z = 10\%$.

Case A: One single signal present in the measurement period

Let us assume that, during the occupancy measurement period T_m, only one single signal may be observed in the channel with a duration $T_s = 0.05 \cdot T_m$, which corresponds to an occupancy $Z = 5\%$. We will satisfy ourselves that, to achieve a confidence level $P_Z = 100\%$ with an even distribution of samples on the time axis, it is sufficient to carry out $J_m \geq 200$ measurements.

In reality, with a revisit period T_{rv} determined from (5), during the period of signal activity T_s there will be either:

$$S_{act\,\min} = \text{int}\left[T_s \cdot J_m / T_m\right] = \text{int}\left[0.05 \cdot J_m\right] \tag{16}$$

where int[·] is the operation of returning the integer portion of the number, or ($S_{act\,\min} + 1$) samples. Taking into account rule (7) and the fact that $(S_{act} + S_{pass}) = J_m$, we obtain an occupancy calculation error at the r-th measurement of:

$$\delta Z_r \leq \delta Z_{\max} = \max\left(0.05 - \frac{S_{act\min}}{J_m}; \frac{S_{act\min} + 1}{J_m} - 0.05\right) \tag{17}$$

For $J_m \geq 200$, the maximum absolute error actually achievable in accordance with (17) is $\left|\delta Z_{\max}\right| = 0.005$, which corresponds to a relative error of 10%. We also note that, for $J_m \geq 600$, from equation (17) we obtain $\left|\delta Z_{\max}\right| = 0.00167$, which, (for $Z = 5\%$) corresponds to a relative error less than 3.5% (for a 100% confidence level).

Case B: Twelve signals during the measurement period

Let us now assume that in the measurement period T_m there are 12 pulses of equal duration $T_s = 0.00417 \cdot T_m$, which again corresponds to an occupancy of $Z = 5\%$. With the number of samples within the range $485 \leq J_m < 715$, the pulse length remains higher than the revisit time $T_{rv\,avr}$, and so each pulse will, depending on its position in relation to the "grid" of samples, be represented by either two $S_{act\,\min} = T_s/T_{rv\,\max} = \text{int}[0.00417 \cdot J_{m\,\min}] = 2$ or three $S_{act\,\max} = \text{int}[0.00417 \cdot J_{m\,\max}] + 1 = 3$ active states. For $J_m \approx 500$, it will be pairs of points with active channel status that will occur more often, whereas with $J_m \approx 700$ active states will more often be grouped in threes.

Let us look in more detail at the case $J_m = 600$, in which both scenarios of sample groupings will be equally probable. The total number of occurrences of activity registered S_{act} may in this situation be modified from $S_{act\,\mathrm{min}} = 12 \cdot 2 = 24$ to $S_{act\,\mathrm{max}} = 12 \cdot 3 = 36$. In measurement instances where the value S_{act} falls in the range from 27 to 33, the occupancy obtained from equation (7) will diminish within the limits of ±10% of the relative error. The probability of $24 \leq S_{act} \leq 26$ or $34 \leq S_{act} \leq 26$ may be calculated from the rule:

$$P_{error} = 0.5^{12} \cdot \left(C_{12}^{0} + C_{12}^{1} + C_{12}^{2} + C_{12}^{10} + C_{12}^{11} + C_{12}^{12} \right) = \frac{2 \cdot (1 + 12 + 66)}{4096} \approx 3.86\% \qquad (18)$$

Here, C_{12}^{k} corresponds to k determinations of pairs of active states when observing the next of 12 pulses.

Thus, for the same occupancy $Z = 5\%$ as in case A, and with the same number of samples $J_m = 600$, although the occupancy calculation $\tilde{Z}$ satisfies the requirements in [1,2], there is an almost 4% probability that it may deviate from the real value Z with a relative error exceeding ±10%.

Case C: Several dozen signals within the measurement period

Finally, let us assume that within the period T_m there are 80 pulses of equal length $T_s = 6.25 \cdot 10^{-4} \cdot T_m$, which again gives $Z = 5\%$. For $J_m = 600$, the revisit rate will be $T_{rv} \approx 1.67 \cdot 10^{-3} \cdot T_m$. Here, any of the pulses will be represented as being not greater than the single active state, and with a probability $P_{miss} = 1 - T_s/T_{rv} \approx 62.5\%$ will simply be missed! Does this mean that it is now impossible to perform an occupancy calculation?

Disregarding the probability of pulse overlapping and treating cases of pulse "detection" as independent, for the expected value of the number of active states S_{act} we obtain:

$$m_1 \{S_{act}\} = 80 \cdot (1 - P_{miss}) = 80 \cdot 0.375 = 30 \qquad (19)$$

And, hence:

$$m_1 \{\tilde{Z}\} = 30/60 = 0.05 \qquad (20)$$

In this way, the average occupancy value remains unbiased. This is explained by the fact that, even though some of the pulses may actually be missed, the remainder will in essence be accounted for not as being of length T_s but as lasting for a duration T_{rv}, which compensates for the previous effect.

For analysing the quality of occupancy calculations under new conditions, we shall take it that the results corresponding to a relative error within ±10% will be obtained only for a number of detected signals lying within the range from 27 to 33. The real number of detected signals will be a random value following a binomial distribution.

Taking into account, however, that with a sufficiently large overall number of detected pulses $n = 80$ this distribution may be approximated to normal, we obtain the following expression for the confidence level of the measurement:

$$P_{\tilde{Z}} = F_{st}\left(\frac{33-30}{4.33}\right) - F_{st}\left(\frac{27-30}{4.33}\right) \approx F_{st}(0.7) - F_{st}(-0.7) \approx 52\% \qquad (21)$$

where $F_{st}(z)$ is a function of the probability distribution of the standard normal random value:

$$F_{st}(z) = \frac{1}{\sqrt{2\pi}} \cdot \int_{-\infty}^{z} \exp\left(-\frac{t^2}{2}\right) dt \qquad (22)$$

and $\sigma = \sqrt{80 \cdot 0.375 \cdot 0.625} \approx 4.33$ is the standard deviation of the measurement $\tilde{Z}$.

Thus, with a large number of short pulses within the measurement period, the occupancy values obtained will on average be close to the real values, but the confidence level of the measurement will be low (in this case $P_{\tilde{Z}} = 52\%$).

The above examples show that for frequency channels containing continuous signals, the confidence level of the occupancy measurement depends primarily not on the occupancy value itself, but on the number of changes of state taking place in the channel in question during the measurement period. Where there are infrequent changes of state in the frequency channel, even a small number of samples will ensure a relatively accurate and reliable occupancy measurement. Where there are frequent changes of state in the frequency channel, accurate and reliable occupancy measurement can be ensured only by significantly increasing the number of samples within the measurement period.

ATTACHMENT 4

Proposed content for Annex B of the draft report on occupancy measurement

ANNEX B

Statistical characteristics of frequency channel occupancy measurement

This annex contains a summary of the statistical characteristics of spectrum occupancy measurement.

B.1 General provisions

The main reason why error can occur in occupancy measurement is the lack of precise data on the instants when a channel switches from active to passive state and vice versa, due to the limited number of samples taken during the measurement period. Each switch adds a random correction to the occupancy measurement value. The comparability in terms of magnitude and the normally occurring statistical independence of such events create a normalizing effect. The numerical characteristics of error distribution in occupancy measurement depend on the distribution of samples on the time axis and on the length of the signals in the frequency channel.

B.2 Features of occupancy measurement for channels with continuous signals when samples are distributed evenly on the time axis

In occupancy measurement, signals are considered continuous where they have a length of $\Delta t_v \geq 10^{-3} \cdot T_m$. When such signals are present in the frequency channel, the state-switch points tend to fall at different, independent intervals relative to the samples, and the occupancy measurement is random with a close-to-normal distribution. For a uniform distribution J_m of samples on the time axis, one would expect the occupancy measurement to equal $m_1 \{\tilde{Z}\} = Z$, but the effective value is determined first by the quantity I of channel state switches within the measurement period [3]:

$$\sigma_{\tilde{Z}} \approx \sqrt{\frac{I}{3}} \cdot \frac{1}{2 \cdot J_m} \tag{23}$$

This being the case, the confidence level of the calculation (7), at a first approximation, is determined by the formula:

$$P_{\tilde{Z}} \approx \Phi\left(\Delta_Z / \sigma_{\tilde{Z}}\right) \tag{24}$$

where $\Phi(z)$ is the probability integral:

$$\Phi(z) = \frac{2}{\sqrt{2\pi}} \cdot \int_0^z \exp\left(-\frac{t^2}{2}\right) dt \tag{25}$$

When measuring occupancy with values lying within the range $0.2 \leq Z \leq 0.8$, the above approximations (23)-(24) are sufficiently accurate. Where large and small occupancy values are measured, the behaviour of $\tilde{Z}$ deviates from the norm, which leads to a negligible reduction in the confidence level compared to the results obtained by applying (24). The number of samples necessary to ensure the required measurement accuracy and confidence level can be calculated as:

$$J_m = k_Z\left(\tilde{Z}\right)\cdot\frac{x_P}{\Delta_Z}\cdot\sqrt{\frac{V_{avr}}{6}} \tag{26}$$

where:

J_m: recommended (necessary) number of samples within the measurement period

V_{avr}: average number of signals expected in the channel during the measurement period (see § 2.1.3.3)

k_Z: correction factor, reflecting the degree to which the distribution of the confidence measurement deviates from the norm [3]

Δ_Z: maximum permissible deviation of the occupancy measurement from the true value, corresponding to half of the confidence interval

x_P: percentage point of the probability integral $\Phi(x)$, corresponding to the required confidence value P_Z, for the calculation of which the following approximation can be recommended on the basis of (26.2.22) in [5, p. 729]:

$$x_P = y - \frac{2.30753 + y\cdot 0.27061}{1 + y\cdot(0.99229 + y\cdot 0.04481)} \tag{27}$$

where:

$$y = \sqrt{2\cdot\ln\left(\frac{2}{1-P_Z}\right)} \tag{28}$$

The value of the correction factor $k_Z\left(\tilde{Z}\right)$ in equation (26) does not exceed $k_Z = 1.2$. This means that if this factor is consistently applied (irrespective of the actual occupancy of the frequency channel in question), the loss of output incurred will not exceed 20%, which is permissible in practice. Consequently, where the samples are arranged evenly on the time axis, the following rule can be recommended to calculate their number:

$$J_m = \frac{x_P}{\Delta_Z}\cdot\frac{\sqrt{V_{avr}}}{2} \tag{29}$$

B.3 Factoring in the instability of the time interval between samples

The instability of the interval between samples leads to an increase in the standard deviation of measurement $\tilde{Z}$.

Let us assume that, in a lock-in measurement system, the random displacement of samples in relation to the nodes of the ideal time grid are evenly distributed. The permissible threshold deviations of the samples, equal to $\pm 0.5 \cdot \delta T \cdot T_m/J_m$, and the quadratic growth of occupancy measurement dispersion in relation to the sampling interval δT, correspond to the relative instability of δT. For lock-in systems using occupancy measurement (7) the following rule can thus be recommended for calculating the necessary number of samples[4]:

$$J_m = \frac{x_P}{\Delta_Z} \cdot \frac{\sqrt{V_{avr} \cdot \left(1.06 + \delta T^2\right)}}{2} \tag{30}$$

Owing to an accumulation of displacements, the variation in the distribution of samples on extensive parts of the time axis can be noticeably higher in lock-out systems than in lock-in systems, and the standard deviation $\sigma_{\tilde{Z}}$ of the occupancy measurement (7) depends both on the average number of continuous signals V_{avr} observed in the frequency channel within the measurement period, and on the occupancy Z of the frequency channel. If the duration of the sampling interval is evenly distributed within the range from $(1 - \delta T) \cdot T_m/J_m$ to $(1 + \delta T) \cdot T_m/J_m$, then $\sigma_{\tilde{Z}}$ is approximated by the equation:

$$\sigma_{\tilde{Z}} \approx \frac{1}{J_m} \cdot \sqrt{\frac{V_{avr}}{6} + \left\{0.54 - \left|0.5 - Z\right|\right\} \cdot \frac{2 \cdot J_m \cdot \delta T^2}{9}} \tag{31}$$

where:

J_m: number of samples within the measurement period
V_{avr}: average number of signals within the measurement period
δT: relative instability of the sampling interval (6)
$\sigma_{\tilde{Z}}$: standard deviation of the occupancy measurement (7).

As a rule, the standard deviation determined in (31) significantly exceeds the corresponding value for lock-in systems.

If, however, in a lock-out measurement system we apply measurement (15) to determine occupancy, then registering the duration of active and passive states in the channel would prevent errors from accumulating. The standard deviation $\sigma_{\tilde{Z}}$ for measurement (15) for channels with continuous signals is determined by the equation:

$$\sigma_{\tilde{Z}} \approx \frac{1}{J_m} \cdot \sqrt{\frac{V_{avr}}{6} \cdot \left(1.06 + \alpha \cdot \delta T^2\right)} \tag{32}$$

where for lock-out measurement systems the factor $\alpha = 1.0$, and for lock-in systems $\alpha = 0.4$.

Thus, the instability of the time interval between samples has the smallest effect on the statistical confidence of occupancy measurement (15) in lock-in measurement systems, and has an equal effect on the quality of measurement when measurement (15) is used in lock-out systems and occupancy measurement (7) is used in lock-in systems. The use of measurement (7) in lock-out systems is not recommended; as in (31), a significantly higher number of samples would be required in this case to ensure the statistical confidence of the measurements.

---

[4] The authors have previously suggested using the correction factor $1/\sqrt[3]{1-\delta T}$, determined through experimentation, to calculate the effect of sample distribution instability. However, this factor was arrived at in respect of possible sample displacements $\pm\delta T \cdot T_m/J_m$, which does not correspond to definition (6) of δT. If we compare the new correction factor in (30) with the dependence $1/\sqrt[3]{1-0.5\cdot\delta T}$ it quickly becomes clear that their relative error is no greater than 5%.

B.4 Simplified method for calculating the number of samples within the measurement period

Equation (30) can be used if the typical relative instability of the sampling interval δT for the monitoring instruments used is known. In the absence of data regarding the instability δT, it can either be determined during the measurement process, or a value selected within a margin can be used. For example, for $\delta T \approx 0.5$ in (30) we obtain:

$$J_m = \frac{x_P}{\Delta_Z} \cdot \frac{\sqrt{V_{avr}}}{1.75} \tag{33}$$

Lastly, let us consider that the percentage point value of the probability integral $\Phi(x)$ $x_P \approx 2.0$ corresponds to the confidence value $P_Z = 95\%$. Applying the maximum permissible error $\Delta_Z = 0.5\%$ recommended in this report (in respect of $\delta T \leq 0.5$) enables us to obtain a practical formula for calculating the number of samples needed:

$$J_{\min} \approx 222 \cdot \sqrt{V_{avr}} \tag{34}$$

B.5 Statistical confidence of occupancy measurement in channels containing pulse signals

Let A_j be a random event to be recorded in an active state channel at sampling point t_j. If the durations of the signals in a channel $\Delta t_v < 10^{-4} \cdot T_m$ are shorter than the interval T_{rv} between channel state samples, then all of the active states detected in an arbitrary subset of samples constitute independent events, the statistical confidence levels of which coincide and are equal to:

$$P\{A_j\} = Z \tag{35}$$

Given the known quantity J_m of samples within a time period T_m, the number S_{act} of active states detected will constitute a binomially distributed random value with the numerical characteristics:

$$m_1\{S_{act}\} = J_m \cdot Z, \quad D\{S_{act}\} = J_m \cdot Z \cdot (1 - Z) \tag{36}$$

With this being the case, measurement (7) can, as a rule, be considered as having close-to-normal distribution with the numerical characteristics:

$$m_1\{\tilde{Z}\} = Z, \quad D\{\tilde{Z}\} = \sigma_Z^2 = Z \cdot (1 - Z) / J_m \tag{37}$$

Thus, measurement (7) is, for channels with pulse signals as well, an undisplaced occupancy measurement, the confidence level of which is determined by equation (24). If we express from (37) the necessary number of samples J_m as a function of Δ_Z and P_Z, we obtain:

$$J_m = Z \cdot (1 - Z) \cdot \left(\frac{x_P}{\Delta_Z} \right)^2 \tag{38}$$

where x_P is the percentage point of the probability integral $\Phi(x)$, determined by (27)-(28).

B.6 Dependency of states in occupancy measurement samples

When measuring the occupancy of frequency channels there are a number of alignments (factors) that affect the entire range of measurements taken. In particular, the results of an occupancy measurement will be affected by the geographical location of the monitoring device, sensitivity of the receiver and threshold chosen for dividing the channel’s states between active and passive. However, all these factors will have no effect on the confidence value of an occupancy measurement for a set threshold at a determined geographical point.

Calculation of sample interdependency is necessary in cases where monitoring of the channel’s state is accompanied by a change in the internal state of the monitoring equipment which, in turn, affects the results of one or several subsequent measurements. Let us consider two adjacent channel state samples, j and ($j = 1$), and assume that at moment t_j the channel is occupied (in an active state), whereas at moment t_{j+1} it is free (in a passive state). If the features of the measuring equipment are such that, after detecting an active state in the channel at point j, the probability of detecting an active state at point ($j + 1$) as well increases, despite the fact that its true state is passive, then to compensate for this dependency the number of measurements carried out over the sampling period must be increased, as discussed in [1, 2]. If, however, the monitoring equipment detects an active state in the channel several times in a row only because the channel is really in that state, then there is no need to make corrections to the interdependency of the measurements.

ATTACHMENT 5

Proposed additions to the "Definitions" section of the Report on spectrum occupancy

- **Frequency channel occupancy (FCO)**

The probability that, at a randomly selected moment in time, a frequency channel is being used for the transmission of information, an indicator of which is deemed to be the observation within the channel of a signal whose level exceeds the threshold.

- **Instant occupancy**

Occupancy value corresponding to a specific time period of limited duration and hence to be measured in each such period.

- **Average occupancy**

Average occupancy value over an unlimited time period, in relation to which deviations of the instant occupancy are considered to be random fluctuations.

- **Confidence level of measurement**

Probability that the calculated occupancy will differ from the true value by no more than the permissible absolute (or relative) measurement error threshold.

- **Lock-in measurement system**

A system in which the distribution of samples on the time axis is determined by a frequency generator, while their actual observed deviations from an ideally uniform time grid are independent.

- **Lock-out measurement system**

A system in which there is no time grid, state monitoring is carried out on the basis of approximately equal revisit intervals, and the displacement of any point affects the distribution on the time axis of all subsequent sampling points.

- **Continuous signals (transmissions)**

Signals whose duration exceeds the average interval between repeat measurements (i.e. between frequency channel state samples).

- **Pulses (transmissions)**

Signals whose duration is markedly shorter than the average interval between repeat measurements.

- **Signal flow rate**

Number of signals (transmissions) observed in the frequency channel on average per unit time.

- **Relative instability of revisit time**

Relationship of the maximum deviation from the mean value of the revisit time between samples to that same mean value.

BIBLIOGRAPHY

[1] Handbook on Spectrum Monitoring, ITU, 2011

[2] Recommendation ITU-R SM.1880 – Spectrum occupancy measurement

[3] Kozmin, V.A., Tokarev, A.B. – A method of estimating the occupancy of the frequency spectrum of an automated radio-control server in the following paginated issue of Measurement Techniques: Volume 52, Issue 12 (2009), Page 1336. http://www.springerlink.com/openurl.asp?genre=article&id=doi:10.1007/s11018-010-9442-9

[4] Spaulding, A.D., Hagn, G.H. [August 1977] – On the definition and estimation of spectrum occupancy. IEEE Trans. In EMC, Vol. EMC-19, No. 3, p. 269-280

[5] Handbook on Special Functions [in Russian] – Abramovits, M., Stigan, I., Moscow: Nauka, 1979 – 830 pages.