Radiocommunication Study Groups

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DRAFT REVISION OF REPORT ITU-R SM.2256-1

Spectrum occupancy measurements and evaluation

Introduction

The most recent version of Report ITU-R SM.2256 was adopted in 2016. Studies conducted since then have shown that Annex 1 to the report requires certain corrections, in particular, in order to more precisely and concretely distinguish between the statistical properties of a spectrum occupancy evaluation of a stationary radio channel over an infinitely long period of time and a set of current radio channel occupancy evaluations derived from discrete, short-duration integration times of 5 or 15 minutes.

A draft revision of Annex 1 to Report ITU-R SM.2256-1 is given in Annex below.

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Attachment: 1

ATTACHMENT

REPORT -ITU-R SM.2256-2~~1*~~

Spectrum occupancy measurements and evaluation

(2012-2016-....)

Main body of report unchanged.

Annex 1

Influence of measurement parameters on accuracy and confidence level

A Preface

This Annex covers in detail the dependencies of measurement parameters such as revisit time, required number of samples, and their influence on measurement accuracy and confidence level. The mathematical calculations described here are especially relevant in circumstances such as:

- Unevenly timed measurement samples.
- Measurement delays when detecting used channels.
- Equipment being used for different measurement tasks simultaneously, thereby not being able to dedicate all time to the occupancy measurement task.

The relevance and application of the principles of this annex may be decided on a case-by-case basis, depending on the aim of the measurement, required accuracy and/or confidence level, and capabilities of the measurement equipment.

A1 Statistical approach to define spectrum occupancy

The Annex describes the requirements for measuring equipment and for relevant data handling process that allows determination of spectrum occupancy for a large set of radio channels on the stipulated time interval with the desired accuracy and statistical confidence. The findings described in this Annex have already found their practical implementation showing good results [A.1].

The statistical approach described below is based on the definition of spectrum occupancy as the probability that, at a randomly selected moment in time, a radio channel, frequency band or other frequency resource being analysed will be in use for the transmission of information [A.2]. Its description is presented in [A.3].

~~Channel occupancy may change over time. To monitor the changes, the time axis has to be divided into a set of integration time periods. These integration time periods shall be of fixed duration, usually between 5 and 15 minutes. The occupancy value has to be calculated for each integration time, and the overall duration of monitoring T_T will, as a rule, be the aggregate of the integration time periods.~~

~~* Radiocommunication Study Group 1 made editorial amendments to this Report in the year 2018 in accordance with Resolution ITU-R 1.~~

From a statistical point of view, on the basis of limited observations, occupancy can only be estimated. Due to the influence of random factors, this estimation may differ from the true value of occupancy, which could be determined only in the case of continuous monitoring of the channel. Therefore, in this Annex, a distinction is made between true values of occupancy and its estimation obtained by calculation. For the sake of simplification, this Annex focuses on measurements of distinct radio channels, although the principles are valid for other spectrum resources like frequency band occupancy. The general term “spectrum occupancy (SO)” is used to denote the true value of occupancy and the term “spectrum occupancy calculation result(s) (SOCR)” is the result of relevant processing of the ~~measured~~ measurement data.

For the analysis of SO, it is considered that only two channel states are possible: “occupied”, whereby the signal level in the channel exceeds a selected detection threshold, and “free”, whereby the signal level in the channel is small. SO is determined by the probability of it being in the occupied state.

FIGURE A1

Definition of the concept of radio channel occupancy

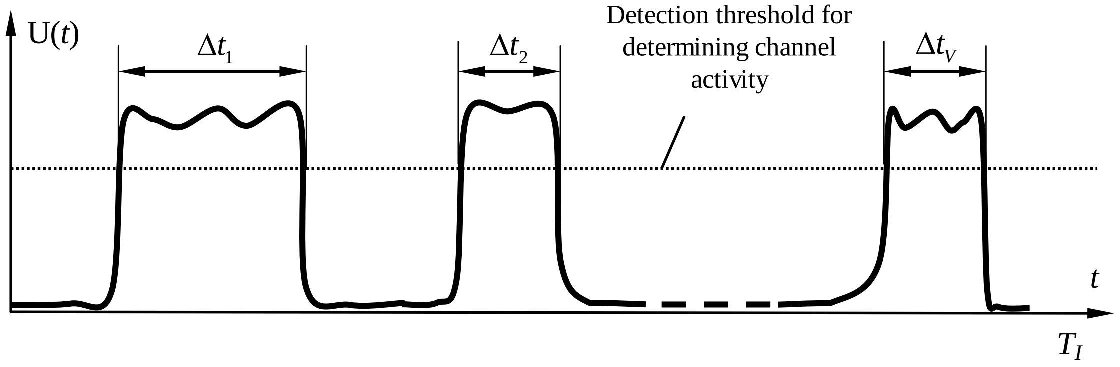


Figure A1 shows an example of the possible change over time in the level $U(t)$ of a signal in a channel over an integration time T_I. The probability that an occupied signal state will be detected at a randomly selected sample point on the time axis will be equal to the ratio of the aggregate duration of occupied state intervals Δt_1, Δt_2 …Δt_v to the total integration time T_I. Thus, spectrum occupancy over this integration time is expressed by:

$$SO = \sum_{v=1}^{V} \Delta t_v \Big/ T_I \qquad \text{(A1)}$$

where:

SO : true value of occupancy over the current integration time
T_I : duration of the integration time
V : number of occupied state intervals during the integration time T_I
Δt_1, Δt_2 …Δt_v : duration of occupied state intervals in the radio channel in case of its continuous monitoring

Channel occupancy may change over time. To monitor the changes, the time axis has to be divided into a set of integration times. These integration times shall be of fixed duration T_I, usually between 5 and 15 minutes. The current occupancy has to be calculated for each integration time, and, when the overall duration of monitoring T_T is significant, i.e. after collecting occupancy data for a large set of integration times T_I, it becomes possible to evaluate overall occupancy, a constant which describes the properties of stationary radio channels over an infinite period of time.

It should be noted that, because of the short duration of the individual integration times, the spectrum occupancy calculation results (*SOCR*) for consecutive integration times T_I may vary significantly, even for stationary radio channels. In order to obtain an overall estimation of stationary radio channel occupancy, as described in [A.2], it is necessary to take an arithmetical average of all current SOCR gathered for the total duration of monitoring T_T.

Formally, both current occupancy values observed at times T_I and the final occupancy evaluation formed over a prolonged duration of monitoring T_T are determined using a single rule (A1) or similar rules, as described in §§ 2.16-2.18 of this Report. However, because of the difference in the time periods to which the current and final occupancy evaluations correspond, the statistical properties of the evaluations differ. This Annex provides requirements to ensure a confident evaluation of current occupancy values at intervals T_I, and [A.2] and [A.7] are dedicated to issues involved in choosing the total duration of monitoring T_T for a confident evaluation of the constant (stationary radio channel occupancy). See § A5.1.4 for more detail on the difference between the statistical properties of current and overall occupancy evaluations.

A2 Impact of the measurement timing

When monitoring frequency ranges containing a large number of radio channels, continuous monitoring of each channel is problematic. Instead, monitoring equipment collecting data for occupancy measurements generally check the state of channels only intermittently. The number of channel state samples J_I during the current occupancy integration time depends on the length of this time T_I and the channel state sampling revisit time T_R (which, in turn, depends on the operating speed of the monitoring equipment and the number of frequency channels in which occupancy is being measured).

With intermittent sampling, it is not possible to accurately pinpoint the instant in time when a channel changes from an occupied to free state and vice versa; thus, for measuring current occupancy, instead of the exact equation (A1), it is necessary to use approximations. For example, for an even placement of channel state samples on the time axis, the following estimation can be used to calculate current occupancy:

$$SOCR = J_o / J_I$$

where:

$SOCR$: spectrum occupancy calculation result

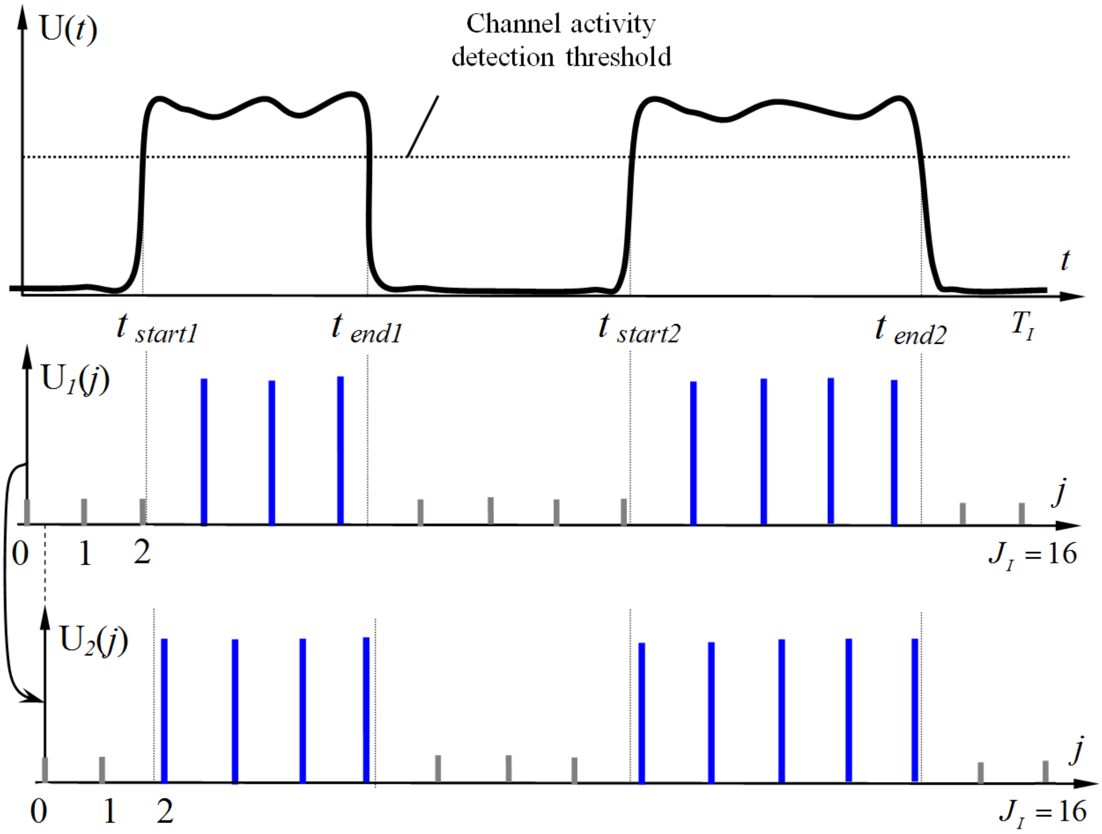
J_O : number of samples in which occupied channel states detected during the integration time

J_I : total number of channel state samples throughout of the integration time

It is possible to demonstrate the potential current spectrum occupancy measurement error for a signal behaving as depicted in Fig. A2.

FIGURE A2

Occupancy measurement error



The top diagram $U(t)$, which shows the continuous change in the signal level in the channel over time, corresponds to a true value $SO \approx 50\%$. The two following diagrams illustrate occupancy measurement with the same number of samples J_I, but with a slight “mismatch” of the points 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 $SOCR_1 = 7/16 \approx 43.75\%$ and in the second case $SOCR_2 = 9/16 \approx 56.25\%$.

It is obvious that:

1) In addition to the first and second diagram presented, other options are possible with different measurement start points, in which there would be exactly eight instances of channel activity over the integration time, giving a precise occupancy estimate of $SOCR = 8/16 = 50\%$.

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

Thus, *SOCR* are random values, and the quality of these measurements has to be analysed from a statistical standpoint.

A5 Measurement considerations

A5.1 Radio channels with lengthy signals

A5.1.1 Data collection and occupancy measurement rule for the case of small instability of the revisit time

With the relative instability δT of an interval between repeated measurements, not exceeding units of a percent, during data collection for each time period of integration T_I, it is sufficient to fix quantity of samples related to the occupied state of a channel J_O among total number of samples of the channel state J_I.

The rule for the measurement of occupancy was already discussed earlier in § A2, and takes the form:

$$SOCR = J_o / J_I \tag{A7}$$

where:

$SOCR$: spectrum occupancy calculation result

J_O : number of samples in which occupied channel states detected during the integration time

J_I : total number of channel state samples throughout of the integration time

Where there are predominantly lengthy signals in the channel, in order to ensure measurement confidence, information is also required on the signal flow rate λ. When such information is lacking, it is worthwhile to track the grouping of occupied and free states so as to determine a quantity V_r of signals detected in the channel in the r-th integration time. The number of signals detected V_r is considered to be equal to the number of changeovers from free to occupied state and vice versa.

A5.1.2 Data collection and occupancy measurement rule for the case of meaningful instability of the revisit time

At an instability δT exceeding 10%, instead of the number of samples it is necessary to record the actual integration time T_{AI} and the aggregate length of time spent by the channel in occupied state T_O.

At the start of the measurements, one should set $T_{AI} = 0$ and $T_O = 0$ and determine the channel state corresponding to time t_0. After each subsequent observation, the value T_{AI} should be increased up to the duration of the revisit time $t_{R\,j}$ determined by equation (A4):

$$T_{AI}(j) = T_{AI}(j-1) + T_{R\,j} \tag{A8}$$

If the channel state was occupied at both sampling points $t_{j\text{-}1}$ and t_j, then T_O should be also increased up to the same increment:

$$T_o(j) = T_o(j-1) + T_{R\,j} \tag{A9}$$

If within the interval $T_{R\,j}$ a change in channel state is observed then only a half of the revisit time should be included as an occupied state duration:

$$T_o(j) = T_o(j-1) + T_{Rj}/2 \tag{A10}$$

And if the channel is observed to be in passive state at both sampling points the occupied state length T_O should be left unchanged.

The rule for calculating occupancy takes the form:

$$SOCR = T_o / T_{AI} \tag{A11}$$

where:

$SOCR$: spectrum occupancy calculation result

T_O : aggregate length of time spent by the channel in occupied state

T_{AI} : length of the actual integration time

In order to determine the confidence level of the measurements, one should record the quantity of signals observed over the occupancy integration time (see § A3.1.1).

A5.1.3 Selecting the number of samples on the base of the expected signal flow rate

Requirements for measuring equipment and for relevant data handling processes of occupancy calculations for channels with lengthy signals will be different from channels with pulsed signals. For channels with lengthy signals, it is determined first by the quantity of signals within the integration time. For channels occupied by pulsed signals, confidence depends on the value of radio channel occupancy itself (see § A5.2.2 below).

For radio channels with lengthy signals, the number of samples required to achieve a confidence P_{SOC} with a permissible absolute measurement error tolerance Δ_{SO} may be calculated as follows:

$$J_{I\,\min} = \frac{x_p}{\Delta_{SO}} \cdot \frac{\sqrt{V_{avr} \cdot \left(1.06 + \delta T^2\right)}}{2} \tag{A12}$$

where:

$J_{I\,\min}$: required (minimum necessary) number of samples

Δ_{SO} : maximum permissible absolute measurement error, corresponding to half of the confidence interval

δT : relative instability of revisit time

V_{avr} : average number of signals expected within the occupancy integration time

x_P : percentage point of the probability integral, corresponding to the required confidence value P_{SOC}, for the calculation of which the following approximation can be recommended.

$$x_p = y - \frac{2.30753 + y \cdot 0.27061}{1 + y \cdot (0.99229 + y \cdot 0.04481)} \tag{A13}$$

where:

$$y = \sqrt{2 \cdot ln\left(\frac{2}{1 - P_{SOC}}\right)} \tag{A14}$$

The average number V_{avr} of signals expected within the integration time used in equation (A12) can be predicted as:

$$V_{avr} = \lambda \cdot T_I \tag{A15}$$

where:

λ : signal flow rate in the channel (see § A4.1)

T_I : duration of the occupancy integration time

For a confidence level P_{SOC} = 95% with a permissible absolute measurement error tolerance Δ_{SO} = 0.5% equation (A12) can be represented as:

$$J_{I\,\min} = 194.2 \cdot \sqrt{V_{avr} \cdot \left(1.06 + \delta T^2\right)} \tag{A16}$$

Examples of the application of equation (A16) to radio channels with different signal flow rates are shown in Table A1.

TABLE A1

Number of samples for a channel with lengthy signals required to achieve an absolute occupancy measurement error tolerance Δ_{SO} of no more than ±0.5% with a confidence of P_{SOC} = 95% for measurements with a relative instability of revisit time $\delta T \leq 0.5$

Signal flow rate in the channel λ (*average* number of signals observed in the current occupancy integration time), not exceeding:	**Required number of samples**
10	703
30	1 217
50	1 572
100	2 223
300	3 850
500	4 970

According to the data in Table A1, for channels with lengthy signals and a low occupancy (hence, also a low signal flow rate λ), statistically reliable measurement results are obtained with a number of samples $J_I < 10^3$, which diverges from the information given in Table 4.10-1 of the ITU Handbook on Spectrum Monitoring [A.4] and Table 1 of Recommendation ITU-R SM.1880-~~1~~2 [A.5]. The discrepancies are explained by the fact that, in Table A1 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 radio channel occupancy (see § A3). When measuring occupancy on channels with lengthy signals, the source of error arises from the lack of accurate information on the instants in time when the radio channel changes from an occupied to free state and vice versa [A.3]. Thus, the more changeovers during the integration time, the greater the potential measurement error. For this reason, to achieve statistic confidence in the results, it is necessary in equation (A7) to increase the number of samples as the average number of signals expected in the channel over the integration time increases (not as the occupancy value increases). By setting the permissible absolute error tolerance Δ_{SO} for both channels with low occupancy and channels with high occupancy but with only few changes in state (such as those occupied by broadcasting stations), it is sufficient to carry out only between 632 and 703 revisits. The required number of samples becomes significant only for channels with a large number of state changes over the integration time.

If the signal flow rate λ over the occupancy integration time is not previously known, then it is recommended to stipulate a value selected with some margin. To adjust the signal flow rate in the course of the measurements, it is recommended to use the equation:

$$\lambda_{(r+1)} = \left(w\lambda_r + V_r\right)/\left(w+1\right) \tag{A17}$$

where:

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

λ_r: flow rate for the current (elapsed) integration time

V_r: number of signals that has been determined in the current integration time

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

To start the evolution according to equation (A17) an initial value λ_0 is needed which is usually unknown *a priori*. It is advisable to choose a maximum among all values expected within the given frequency range, which corresponds to the worse case.

A5.1.4 Impact of signal flow rate in the radio channel and sample dependence on the confidence level of spectrum occupancy evaluations

It should be noted that, when radio channels differ in signal flow rate and duration of transmissions in the channel, that difference can have varying effects on the statistical properties of current occupancy evaluations for individual integration times T_I and on properties of the overall radio channel occupancy evaluation for the whole duration of monitoring T_T. In particular, in radio channels with lengthy signals, where consecutive samples reflecting channel state are dependent, an increased degree of such dependence, arising, for example, from longer transmissions, can have different effects on the confidence level of estimations obtained when evaluating current occupancy and final occupancy of a stationary channel.

[A.7] shows that when evaluating the constant (stationary radio channel occupancy), the duration of monitoring must last at least as long as the time required to cover on average 800 transmissions in the channel. This period can, however, be very long for radio channels with a high level of sample dependence, i.e. those typically with lengthy transmissions. Accordingly, the lower the channel occupancy and the slower the change of channel state (i.e. the higher the level of sample dependence), the longer the total duration of monitoring T_T required to evaluate overall occupancy of a stationary radio channel with a suitable level of confidence. This kind of estimation is discussed in [A.2] and [A.7]; specifically, an extended period (many hours) of sampling is required to obtain the constant (stationary radio channel occupancy).

When generating current occupancy evaluations that characterize radio channel properties for only short (5-15 minute) integration times, any dependence of samples (fixed in number), on the contrary, helps to increase the confidence level of the measurements. A series of simple examples is given below to illustrate this fact.

We shall analyse occupancy calculations for cases of radio channels with a significantly different number of signals (communication sessions) over the integration time. In all the cases compared, the real occupancy value remains the same, namely $SO = 5\%$. The accuracy requirements imposed entail a permissible absolute measurement error of $\Delta_{SO} = 0.5\%$, which for $SO = 5\%$ corresponds to a relative error $\delta_{SO} = 10\%$.

A5.1.4.1 Case A: One single signal present in the integration time

Let us assume that, throughout the integration time T_I, only one signal may be observed in the channel with a duration $T_s = 0.05 \cdot T_I$, which corresponds to an occupancy $SO = 5\%$. We will satisfy ourselves that, to achieve a confidence level $P_{SOC} = 100\%$ with an even placement of channel state samples on the time axis, it is sufficient to carry out $J_I \geq 200$ samples.

In reality, with a revisit time T_R determined from (A5), the number of samples recorded for the period of signal activity will be either:

$$J_{o\min} = \text{int}\left[T_s \cdot J_I / T_I\right] = \text{int}\left[0.05 \cdot J_I\right] \tag{A18}$$

where int [·] is the operation of returning the integer portion of the argument, or $(J_{O\min} + 1)$ samples. Taking into account rule (A7), we obtain an occupancy measurement error of:

$$(SOCR - SO)_r \leq \max\left(\left|SOCR - SO\right|\right) \leq \max\left(0.05 - \frac{J_{o\min}}{J_I}; \frac{J_{o\min} + 1}{J_I} - 0.05\right) \tag{A19}$$

For $J_I \geq 200$, the maximum absolute error actually achievable in accordance with (A19) is $\max\left(\left|SOCR - SO\right|\right) = 0.005$, which corresponds to a relative error of 10%. We also note that, for $J_I \geq 600$, from equation (A19) we obtain $\max\left(\left|SOCR - SO\right|\right) = 0.00167$, which, (for $SO = 5\%$) corresponds to a relative error less than 3.5% (for a 100% confidence level).

A5.1.4.2 Case B: Twelve signals throughout the integration time

Let us now assume that in the integration time T_I there are 12 pulses of equal duration $T_s = 0.00417 \cdot T_I$, which again corresponds to an occupancy of $SO = 5\%$. With the number of samples within the range $485 \leq J_I < 715$, the pulse length remains higher than the revisit time T_R, and so each pulse will, depending on its position in relation to the “grid” of samples, be represented by either two $J_{O\min} = T_s/T_{R\max} = \text{int}\,[0.00417 \cdot J_{I\min}] = 2$ or three $J_{O\max} = \text{int}\,[0.00417 \cdot J_{I\max}] + 1 = 3$ occupied samples. For $J_I \approx 500$, an active channel state will more often occur in pairs of points, whereas with $J_I \approx 700$ occupied samples will more often be grouped in threes.

Let us look in more detail at the case $J_I = 600$, in which both scenarios of sample groupings will be equally probable. The total number of occupied samples J_O may in this situation be lying from $J_{O\min} = 12 \cdot 2 = 24$ to $J_{O\max} = 12 \cdot 3 = 36$. In measurement instances where the value J_O falls in the range from 27 to 33, the occupancy estimation obtained from equation (A7) will fall within the limits of ±10% of the relative error. The probability of $24 \leq J_O \leq 26$ or $34 \leq J_O \leq 36$ may be calculated from the rule:

$$P_{error} = 0.5^{12} \cdot \left(C_{12}^{0} + C_{12}^{1} + C_{12}^{2} + C_{12}^{10} + C_{12}^{11} + C_{12}^{12}\right) = \frac{2 \cdot (1 + 12 + 66)}{4096} \approx 3.86\% \tag{A20}$$

Here, C_{12}^{k} corresponds to k cases of fixation of pairs of occupied samples with respect to 12 radio signals falling within the integration time.

Thus, for the same occupancy $SO = 5\%$ as in case A, and with the same number of samples $J_I = 600$, although the occupancy calculation $SOCR$ satisfies the requirements in [A.4, A.5], there is an almost 4% probability that it the occupancy calculation will deviate from the real value *SO* with a relative error exceeding ±10%.

A5.1.4.3 Case C: Several dozen signals throughout the integration time

Finally, let us assume that throughout the integration time T_I there are 80 pulses of equal length $T_s = 6.25 \cdot 10^{-4} \cdot T_I$, which again gives $SO = 5\%$. For $J_I = 600$, the revisit time will be $T_R \approx 1.67 \cdot 10^{-3} \cdot T_I$. Here, each of the radio pulses will be represented as being not greater than a single occupied sample, and with a probability $P_{miss} = 1 - T_s/T_R \approx 62.5\%$ that the pulse 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 mathematical expectation of the number of occupied samples J_O we obtain:

$$m_1\{J_o\} = 80 \cdot (1 - P_{miss}) = 80 \cdot 0.375 = 30 \qquad \text{(A21)}$$

And, hence:

$$m_1\{SOCR\} = 30/600 = 0.05 \qquad \text{(A22)}$$

In this way, the average occupancy value remains unbiased. This is explained by the fact that, even though some of the radio pulses may be missed, the remainder will in essence be accounted for not as being of length T_s but as having a duration T_R, 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 recorded occupied samples lying within the range from 27 to 33. The real number of recorded occupied samples will be a random value following a binomial distribution.

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

$$P_{SOC} = F_{st}\left(\frac{33-30}{4.33}\right) - F_{st}\left(\frac{27-30}{4.33}\right) \approx F_{st}(0.7) - F_{st}(-0.7) \approx 52\% \qquad \text{(A23)}$$

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

$$F_{st}(z) = \frac{1}{\sqrt{2\pi}} \cdot \int_{-\infty}^{z} \exp\left(-\frac{t^2}{2}\right) dt \qquad \text{(A24)}$$

and $\sigma = \sqrt{n \cdot (1 - P_{miss}) \cdot P_{miss}} = \sqrt{80 \cdot 0.375 \cdot 0.625} \approx 4.33$ is the standard deviation of the measurement *SOCR*.

Thus, with a large number of short pulses falling within the integration time T_I, 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 $P_{SOC} = 52\%$).

The above examples show that for radio channels containing lengthy signals, the confidence level of the current 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 integration time. Where there are infrequent changes of state in the radio channel, even a small number of samples will ensure a relatively accurate and reliable current occupancy measurement. Where there are frequent changes of state in the radio channel, accurate and reliable current occupancy measurement can be ensured only by significantly increasing the number of samples falling within the integration time.

A5.2 Radio channels with pulsed signals

A5.2.1 Data collection and occupancy measurement rule

To measure occupancy, one must, at the very least, determine the number J_O of occupied channel state samples for each integration time.

For channels with pulsed signals, calculation (A7) gives an unbiased occupancy measurement but requires significantly more samples to achieve a confidence P_{SOC} with a permissible absolute measurement error tolerance Δ_{SO}.

A5.2.2 Selecting the number of samples on the base of the expected occupancy level

When measuring occupancy on channels with pulsed signals, the necessary number of samples $J_{I\min}$ can be calculated as:

$$J_{I\min} = SO \cdot (1 - SO) \cdot \left(\frac{x_p}{\Delta_{SO}} \right)^2$$

(~~A18~~A25)

where:

$J_{I\min}$: required (minimum necessary) number of samples

SO : expected radio channel occupancy for the channel with pulse signals

x_p : percentage point of the probability integral (see equation (A13))

Δ_{SO} : maximum permissible absolute measurement error, corresponding to half of the confidence interval.

For a confidence level P_{SOC} = 95% and a maximum permissible absolute measurement error Δ_{SO} = 0.5% equation (~~A18~~A25) can be expressed as follows:

$$J_{I\min} = 153664 \cdot SO \cdot (1 - SO)$$

(~~A19~~A26)

With pulsed signals, the confidence of the calculation (A7) is determined by the occupancy value itself and is practically independent of instability of sample placement along the time axis. The application of equation (A~~19~~26) to radio channels with different occupancies is illustrated in Table A2.

TABLE A2

Number of samples for a channel with pulse signals required to achieve an absolute occupancy measurement error tolerance Δ_{SO} of no more than ±0.5% with a confidence of P_{SO} = 95%

Radio channel occupancy *SO* (%)	**Required number of samples, J_I**	**Maximum acceptable revisit time, T_R (ms)**	
		for T_I = 5 minutes	**for T_I = 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

Radio channel occupancy SO (%)	**Required number of samples, J_I**	**Maximum acceptable revisit time, T_R (ms)**	
		for T_I = 5 minutes	**for T_I = 15 minutes**

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

To obtain practical recommendations for selecting the numbers of samples, it is useful to analyse the differences in relationships $J_{I\,\min}(SO)$ brought about by limiting the permissible absolute (Δ_{SO}) and relative (δ_{SO}) evaluation errors.

Table 2 in Recommendation ITU-R SM.1880-1 [A5] (which, for convenience, is reproduced below as Table A3) sets out the results of calculations of the number of samples required to achieve a maximum 10% relative error or a 1% absolute error depending on channel occupancy.

As can be seen from the table a fixed (10%) limitation of the relative error for small occupancy values (lower than 5%) will lead to a significant increase in the required number of samples because the resulting absolute error is small. At the same time, ensuring a comparable degree of accuracy for large (over 30%) occupancy values requires only a small number of samples. In contrast, a fixed (1%) limitation of the absolute error will lead to an increase in the required number of samples for large (greater than 20%) occupancy values, because the resulting relative error is small. At the same time, ensuring such a degree of accuracy for an occupancy of less than 3% requires only a small number of samples.

In order to minimize the required number of samples over the entire range of occupancy variations, a possible solution is to make an estimate while, for large occupancy values, customarily limiting the permissible relative error, and, for small values, limiting the permissible absolute error [A.6]. If the transition from one type of limitation to the other is at the 10% occupancy level, the required number of samples will be determined by the values shown in bold type in Table A3, which is acceptable from the practical standpoint.

TABLE A3

Number of samples required to achieve a maximum 10% relative error δ_{SO} or a 1% absolute error Δ_{SO} with a 95% confidence level

Channel occupancy (%)	**Required relative error δ_{SO} = 10%**		**Required absolute error Δ_{SO} = 1%**	
	Resulting magnitude of absolute error (%)	**Required number of independent samples**	**Resulting magnitude of relative error (%)**	**Required number of independent samples**
1	0.1	38 047	100.0	**380**
2	0.2	18 832	50.0	**753**
3	0.3	12 426	33.3	**1 118**
4	0.4	9 224	25.0	**1 476**
5	0.5	7 302	20.0	**1 826**
10	1.0	**3 461**	10.0	**3 461**
15	1.5	**2 117**	6.7	4 900
20	2.0	**1 535**	5.0	6 149

30	3.0	**849**	3.3	8 071
40	4.0	**573**	2.5	9 224
50	5.0	**381**	2.0	9 608
60	6.0	**253**	1.7	9 224
70	7.0	**162**	1.4	8 071
80	8.0	**96**	1.3	6 149
90	9.0	**43**	1.1	3 459

With this approach, the relative evaluation error increases for small occupancy values; however, from the practical standpoint, this can be acceptable since the absolute evaluation error will be small. Thus, for a 2% occupancy, the boundaries of the confidence interval are 1% and 3% corresponding to a 50% relative evaluation error and characterize an extremely low channel occupancy. In this case, it may not be worth the effort to spend the additional computing resources to confirm this obvious fact with the additional accuracy amounting to no more than a few tenths of a percent.

The meaning of the required number of samples shown in bold type in Table A3 can be explained as follows. Where a channel for which there is no prior occupancy information is evaluated on the basis of 1 000 samples, the measurement accuracy for occupancy values in the order of 27% and 3% will be approximately as shown in Table A3, i.e. an approximate 10% relative error for 27% occupancy and an approximate 1% absolute error for 3% occupancy. Occupancy values greater than 27% will be measured with a relative error of less than 10%, while occupancy values lower than 3% will be measured with an absolute error of less than 1%. For radio channels with an occupancy from 3% to 27%, measurements will be characterized by a relative error exceeding 10% and an absolute error exceeding 1%.

Thus, adopting an approach to evaluating spectrum occupancy measurement quality for small occupancy values based on permissible absolute error simply implies accepting the possibility of increased relative measurement error for small occupancy values, recognizing that the absolute error values remain small.

A5.3 Selecting the number of samples in the absence of *a priori* information on an occupancy level

By analysing the dependencies shown in Table A3 between the required number of samples and channel occupancy, it is easy to observe that among the values shown in bold type, the most significant (3 461) corresponds to an occupancy of 10%. This means that by selecting a higher value, for example 3 600 samples (corresponding to a sampling rate of four times per second over a period of 15 minutes), this can be used as the single universal number of samples for the entire range of occupancy variation from 1% (and below) to 100%.

The measurement error will then be lower than 10% of the relative error for channels with an occupancy exceeding 10%, and lower than 1% of the absolute error for channels with an occupancy of less than 10%. A decrease in occupancy (from 10%) will be accompanied by a consequential decrease in the absolute estimation error, while an increase in occupancy (relative to 10%) will be accompanied by a consequential decrease in the relative error. Specific calculated values for the resulting errors are shown in bold type on the left-hand side of Table A4.

TABLE A4

Occupancy measurement errors corresponding to a 95% confidence level, achievable when estimating occupancy with exactly 3 600 and 1 800 data samples

Occupancy (%)	**Number of samples: 3 600**		**Number of samples: 1 800**	
	Resulted absolute error (%)	**Resulted relative error (%)**	**Resulted absolute error (%)**	**Resulted relative error (%)**
1	**0.33**	32.5	**0.46**	46.0
2	**0.46**	22.9	**0.65**	32.3
3	**0.56**	18.6	**0.79**	26.3
4	**0.64**	16.0	**0.91**	22.6
5	**0.71**	14.2	**1.01**	20.1
10	**0.98**	**9.8**	**1.39**	**13.9**
15	1.17	**7.8**	1.65	**11.0**
20	1.31	**6.5**	1.85	**9.2**
30	1.50	**5.0**	2.12	**7.1**
40	1.60	**4.0**	2.26	**5.7**
50	1.63	**3.3**	2.31	**4.6**
60	1.60	**2.7**	2.26	**3.8**
70	1.50	**2.1**	2.12	**3.0**
80	1.31	**1.6**	1.85	**2.3**
90	0.98	**1.1**	1.39	**1.5**

In most cases, it is possible to use half the number of samples, i.e. 1 800 samples, as a single universal number, corresponding to a sampling rate of twice per second over a period of 15 minutes, thereby allowing for the use of slower equipment. The calculated values of the resulting errors for 1 800 samples are shown on the right-hand side of Table A4.

Where 1 800 samples are used instead of 3 600, both absolute and relative estimation errors increase by a factor of $\sqrt{2} \approx 1.41$. In the case of 10% occupancy, the relative error is increased from 10% to 14%. Nevertheless, with 1 800 samples, the corresponding absolute error values remain relatively small, differing from the 3 600 case only by tenths of a per cent, which is acceptable for practical purposes. Additionally, Fig. 1 in Recommendation ITU-R SM.1880-1 [A.5] shows the resulting relative error values for 1 800 samples do not fall within the no-go area, confirming acceptability.

Therefore, in the absence of *a priori* data on an occupancy level in an analyzed radio channel, it is recommended to make a primary occupancy estimation on the basis of a universal sample number, e.g. 3 600 (or 1 800 samples in the case of the low-speed radio monitoring equipment). If more accurate measurements are needed, modify the number of samples on the basis of the obtained SO value and the recommendations of § A5.2.2, and repeat the calculation.

As already mentioned above, the values shown in Table A4 correspond to the occupancy measurement of channels with pulsed signals. For channels with lengthy signals, the absolute estimation errors are inversely proportional to the number of processed samples and, as can be seen in Fig. A3, can be significantly smaller. When it is known that such signals are occurring in the channel, the number of samples can be reduced to 600, as can be seen from the data in Table A5. This shows the calculated values of the relative and absolute errors according to channel occupancy and the ratio τ_s / T_I, where τ_s is the duration of each lengthy signal, and T_I is the integration time. In the model used to build the table, lengthy signals are considered to be of equal length in time. From

Table A5 it can be seen that the measurement errors diminish considerably as the relative duration of lengthy signals increases.

TABLE A5

Error corresponding to the confidence level of 95% observed when estimating occupancy in a channel with lengthy signals of a duration not less than the specified value of the ratio τ_s / T_I for 600 data samples

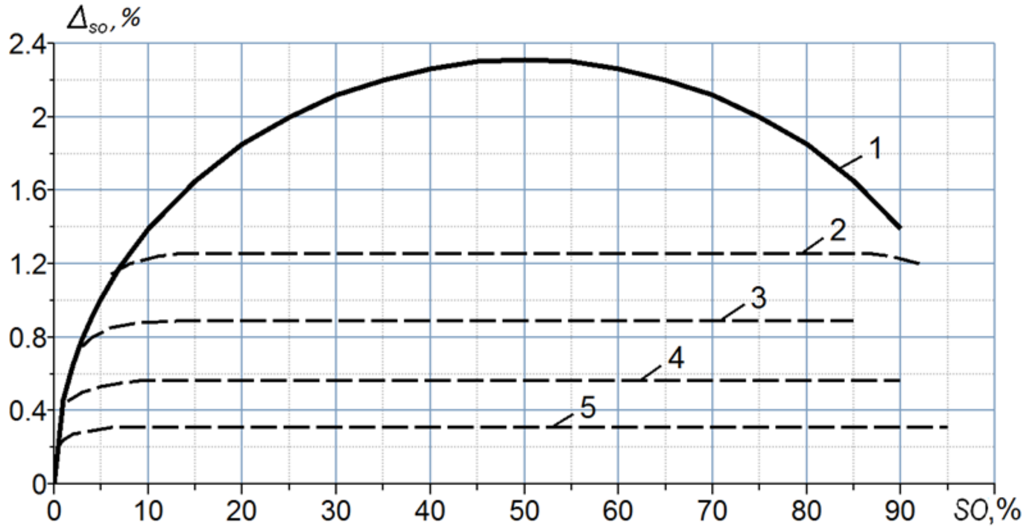
Channel occupancy (%)	**$\tau_s / T_I = 0.0025$**		**$\tau_s / T_I = 0.01$**	
	Resulted absolute error (%)	**Resulted relative error (%)**	**Resulted absolute error (%)**	**Resulted relative error (%)**
1	**0.34**	33.64	**0.17**	16.82
2	**0.48**	23.79	**0.24**	11.89
3	**0.58**	19.42	**0.29**	9.71
4	**0.67**	16.82	**0.34**	8.41
5	**0.75**	15.04	**0.38**	7.52
10	**1.06**	**10.64**	**0.53**	**5.32**
15	1.30	**8.69**	0.65	**4.34**
20	1.50	**7.52**	0.75	**3.76**
30	1.84	**6.14**	0.92	**3.07**
40	2.13	**5.32**	1.06	**2.66**

TABLE A5 (*END*)

Channel occupancy (%)	**$\tau_s / T_I = 0.0025$**		**$\tau_s / T_I = 0.01$**	
	Resulted absolute error (%)	**Resulted relative error (%)**	**Resulted absolute error (%)**	**Resulted relative error (%)**
50	2.38	**4.76**	1.19	**2.38**
60	2.61	**4.34**	1.30	**2.17**
70	2.81	**4.02**	1.41	**2.01**
80	3.01	**3.76**	1.50	**1.88**
90	3.19	**3.55**	1.60	**1.77**

FIGURE A3

Absolute error Δ_{SO} of a spectrum occupancy estimate with a 95% confidence level, in the case of 1 800 samples for pulsed signals in channel (1), or 500 (2), 250 (3), 100 (4) or 30 (5) lengthy signals in the channel over the integration time



A5.4 Effect of reduced number of samples on the confidence level and the occupancy measurement error

Reducing the number of samples J_I by a factor of K in relation to what is recommended in Tables A1 to A3 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 radio channel with a signal flow rate of no more than 50 signals within the integration time. From the last column in Table A1, we see that the recommendation in this case is to sample the channel state 1 572 times. Complying with this recommendation, the occupancy calculation (A7) will deviate by no more than $\Delta_{SO} = 0.5\%$ from the real value, with a confidence level of $P_{SOC} = 95\%$. If we now assume, on the other hand, that the system is actually capable of taking only 393 channel state samples over the integration time, i.e. four times less than the recommended number, then on average, the occupancy will as before be measured accurately, but the range within which the real occupancy value will occur with a confidence level of 95% is increased fourfold to ±2% of the measurement result.

A reduced number of samples J_I may also be observed when data collection for the occupancy calculation is curtailed prematurely. In such cases, the occupancy calculation (A7) remains unbiased but the confidence level of the results is diminished similarly to the example discussed above.

Reference to Annex 1

[A.1] Measurement procedure qualification certificate No. 206/000265/2011 on “Measurement of radio-electronic equipment emission properties with ARGAMAK-I, ARGAMAK-IM and ARGAMAK-IS Digital Measuring Radio Receivers”, including those with ARC-KNV4 Remote Controlled Frequency Down-Converter. http://www.ircos.ru/en/news.html.

[A.2] 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.

[A.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

[A.4] Handbook on Spectrum Monitoring, ITU, 2011.

[A.5] Recommendation ITU-R SM.1880-1 – Spectrum occupancy measurement and evaluation.

[A.6] KOZMIN, V.A, PAVLYUK, A.P., TOKAREV, A.B. – Optimization of requirements to the accuracy of radio-frequency spectrum occupancy evaluation. Electrosvyaz, 2014 – No. 6 (in Russian – the article translated into English is available at the website: http://www.ircos.ru/en/articles.html).

[A.7] TOKAREV A. B., KOZMIN V. A., PAVLYUK A. P., POLEV V. Y. *Duration of data collection when measuring occupancy of stationary radio channels // Systems of Control, Communication and Security*, No 1, 2024. https://sccs.intelgr.com/arch.html (in Russian – the article translated into English is available at: http://www.ircos.ru/en/articles.html).
