International Telecommunication Union

ITU-R
Radiocommunication Sector of ITU

Recommendation ITU-R SM.1880-2
(09/2017)

Spectrum occupancy measurements and evaluation

SM Series
Spectrum management

International Telecommunication Union

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RECOMMENDATION ITU-R SM.1880-2*

Spectrum occupancy measurement and evaluation

(2011-2015-2017)

Scope

Although automatic occupancy measurement will not completely replace manual observations, it is still well suited for most cases. Frequency channel occupancy, as well as frequency band occupancy, should have a certain level of accuracy in order to be compared or merged if necessary. By using the technique and proper method a more efficient use of existing equipment is possible.

Keywords

Spectrum occupancy measurements, frequency channel occupancy, revisit time, busy hour

The ITU Radiocommunication Assembly,

considering

a) that the increasing demand of radiocommunication services requires the most efficient use of the radio-frequency spectrum;

b) that good spectrum management can only satisfactorily proceed if the spectrum managers are adequately informed on the current usage of the spectrum and the trends in its demand;

c) that results of spectrum occupancy measurements would provide important inputs into:

– frequency allotments and assignments;

– verification of complaints concerning channel blocking;

– establishment of the degree of efficiency of spectrum usage;

d) that information obtained from frequency assignment databases does not reveal the degree of loading on each frequency channel;

e) that some administrations assign the same frequency to more than one user for shared use;

f) that it is desirable to compare measurement results from different countries in border areas or for instance in the aeronautical or maritime mobile services bands;

g) that automatic monitoring equipment is now in use by administrations, including methods for the analysis of records, and a number of parameters can be evaluated, which are of considerable value in enabling more efficient utilization of the spectrum;

h) that in designing an automated system to gather occupancy data for use in spectrum management, one must determine what parameters are to be measured, the relationship among these parameters and how often measurements have to be taken to ensure the data are statistically significant;

i) that measurement procedures and techniques should be harmonized to facilitate the exchange of measurement results between various countries;

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* Radiocommunication Study Group 1 made editorial amendments to this Recommendation in the year 2023 in accordance with Resolution ITU-R 1.

j)   that successful merging or combining monitoring data not only depends on the data format in which the data is stored but also on the environmental and technical conditions under which the data is gathered,

recognizing

a)   that various principles and methods of spectrum occupancy measurements are in use in the different countries;

b)   that one particular method exists to get the high-accuracy frequency channel occupancy data and that such data usually is the basic to form the frequency band occupancy,

recommends

1   that the measurement procedures and techniques specified in Annexes 1 and 2 should be used for spectrum occupancy measurements;

2   that both Report ITU-R SM.2256 and the ITU Handbook on Spectrum Monitoring in force should be used as guidance for spectrum occupancy measurements and the equipment should satisfy the requirement mentioned in that Handbook;

3   that a common data format, that is a line-based ASCII file derived from the radio monitoring data format (RMDF), should be used following Recommendation ITU-R SM.1809.

Annex 1

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1 Introduction

Annex 1 describes frequency channel occupancy measurements performed with a receiver or spectrum analyser. The signal strength of each frequency step is stored. By means of post-processing the percentage of time that the signal is above a certain threshold level is determined. An example of the procedure for such post-processing is presented in Report ITU-R SM.2256 (Annex 1). Different users of a channel often produce different field-strength values at the receiver. This makes it possible to calculate and present the occupancy caused by different users.

2 Definitions

Frequency channel occupancy measurements: Measurements of channels, not necessarily separated by the same channel distance, and possibly spread over several different frequency bands to determine whether the channel is occupied or not. The goal is to measure as many channels as possible in a time as short as possible.

Revisit time: The time taken to visit all the channels to be measured (whether or not occupied) and return to the first channel.

Observation time: The time needed by the system to perform the necessary measurements on one channel. This includes any processing overheads such as storing the results to memory/disk.

Maximum number of channels: The maximum number of channels which can be visited in the revisit time.

Transmission length: The average length of individual radio transmission duration.

Integration time: Time interval for which an individual occupancy estimate is made. Normally 5 or 15 minutes.

Duration of monitoring: The total time during which the occupancy measurements are carried out.

Preset threshold level for measurement: If a signal is received above the threshold level, the channel is considered to be occupied.

Busy hour: The highest level of occupancy of a channel in a 60-min period.

3   Requirements

3.1   Equipment

A suitable system capable of making frequency channel occupancy measurements by using frequency band registrations will consist of a radio receiver or spectrum analyser, appropriate antenna, cable, a PC/controller, with interface adaptor, suitable acquisition and post-processing software.

Other features may include GPS, for mobile/nomadic operation of the station, communications modem, for remote control and data exchange, system calibration for traceable field strength measurements, antenna switches, filters and attenuators, for multiple band and/or strong EMF exposure environments.

3.2   Site considerations

Site should be chosen such as that the expected signal strength for the emissions of interest is above the expected threshold level. The relation between these two parameters will define an area within which the measurement performed is of relevance to any station operating above a certain effective radiated power (e.r.p.) level or effective isotropic radiated power (e.i.r.p.) level.

The expected signal strength can be evaluated considering the licensed stations at the region, their emission profile and using simulation software. The threshold can be estimated considering the system sensitivity (noise floor) or previous measurements performed under similar conditions with the same equipment and configuration.

If no preliminary information is available, a site survey using portable equipment could be performed. This is especially important if the equipment placement is of definitive nature and future relocations may not be easily performed.

Measurement results should ideally be accompanied by a report of analysis performed to select the site, indicating the area and the emitters that are expected to be considered.

3.3   Time related parameters

There is a relationship between observation time, number of channels, average transmission length and the duration of monitoring.

The revisit time is directly dependent on the observation time and the number of channels. Also the processing time (data transfer between receiver and controller) influences the revisit time and should be kept as short as possible.

Revisit time = (Observation time × Number of channels of identical bandwidth) + Processing time

The observation time per channel is limited by the scanning speed of the monitoring equipment. In order to maintain a reasonably short revisit time with relatively slow equipment, the number of channels to be measured must be reduced.

Whenever applying the above equation to spectrum analysers, when the RBW is set equal to the channel bandwidth, the Number of channels can be considered as the number of bins[1] per sweep and the observation time as the dwell time per bin.

On FFT analysers the principle still applies, especially if the number of channels to be scanned is greater than the FFT size and some sweep still being performed. On this case however, the number of scanned channels should be divided by the number of channels evaluated on each single FFT.

The monitoring system needs to scan at an acceptable speed in order to detect individual short transmissions.

There are principally two different approaches to obtain channel occupancy figures:

a)   Capturing every transmission in the band under observation. This approach requires a maximum revisit time that is half the minimum on or off time of any transmission in the band, whichever is shorter. This method delivers an accuracy that is independent of the occupancy result and may allow shorter monitoring duration.

b)   Statistical approach: Especially when considering bursts of digital systems, the minimum transmission time might be too small for the practical application of the above principle. However, if the monitoring time is long enough to provide enough samples, the occupancy result will be correct even with far longer revisit times, because the statistical probability of catching a transmission vs. the probability of missing it is the same as the duty cycle of the transmission. The accuracy of the statistical approach, however, depends on the value of occupancy as described below.

The duration of monitoring is a combination of the revisit time, typical transmission lengths expected, number of channels to be scanned and the wanted accuracy of the results.

The duration of monitoring should be long enough to allow the monitoring of all relevant emissions. If no time distribution pattern is known, initial evaluations should consider at least 24 h or multiples of 24 h. One week of monitoring gives the difference in occupancy over the various days of the week and occupancy during the week end. Seven periods of 24 h spread of a longer period of time (e.g. one year) gives more reliable occupancy information.

3.4   Accuracy, statistical confidence level and required number of samples

From a statistics point of view, the result of spectrum occupancy measurement is an estimate or statistical value, thus it has accuracy and reliability attributes. Accuracy reflects the control of error, usually measuring with relative accuracy or relative error as well as absolute error, and reliability indicates the confidence of the result marking with confidence level. Measurement itself can be deemed as a sampling process from a given population, and result analysis is essentially as a process of estimating the population using the limited samples.

In practice, the result of the collection and processing of data is abbreviated as *SO*, but it is not a true value as just mentioned. Even in cases where, during the integration time, the monitoring equipment provides only a small number of data samples, calculation of the occupancy estimate will give a number of values characterizing the radio-channel occupancy to a greater or lesser degree. However, such values will correspond to the true value of occupancy (*SO*) only when averaged over a large number of integration times, while the individual evaluations may deviate considerably from *SO*.

On the other hand, under computer control it is possible to collect a large number of samples, more than is necessary for determining occupancy with the required accuracy. There is an optimum number

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[1]   Bins in statistics refer to groups (or categories or classes) of data that fall within a certain range of values.

of samples, beyond which additional data may not significantly improve results. The optimum number of samples needed is discussed in the current Report ITU-R SM.2256.

There is no linear relationship between accuracy and revisit time. In the case of measuring 100 channels with a revisit time of 1 s, which is a practical value, the number of channels can be increased to 1 000 with a revisit time of 10 s without affecting the confidence level/accuracy too much.

There is a linear relationship between the occupancy and the number of samples required to achieve a desired confidence level. The lower the occupancy, the more samples will be needed.

Table 1 compares independent sampling that is the simplest case using central limit theorem and dependent sampling using a first order Markov-chain differ little from many more complicated mathematical models.

TABLE 1

**Number of dependent and independent samples required to achieve 10%
relative accuracy and a 95% confidence level at various occupancy
percentages (assumes a −1 s sampling period)**

Occupancy (%)	Number of required independent samples	Number of required dependent samples	Required hours of dependent sampling
6.67	5 368	16 641	4.6
10	3 461	10 730	3.0
15	2 117	6 563	1.8
20	1 535	4 759	1.3
30	849	2 632	0.72
40	573	1 777	0.5
50	381	1 182	0.32
60	253	785	0.22
70	162	502	0.15

The quality of the measurements can also be characterized by the absolute accuracy Δ_{SO}, which determines the extent to which large deviations in the estimates from the true value SO are considered permissible, and by the confidence (confidence level) which indicates the minimum probability with which occupancy estimates must fall within the interval from $(SO - \Delta_{SO})$ to $(SO + \Delta_{SO})$, referred to as the confidence interval. It is sometimes more convenient to state the confidence interval limits in the form $SO \cdot (1 \pm \delta_{SO})$, where $\delta_{SO} = \Delta_{SO} / SO$ is the maximum permissible relative evaluation error.

To ensure sufficiently accurate and confident measurements with economical use of computing resources, the following issues need to be taken into account.

The accuracy and confidence of occupancy estimates are determined not only by the number of samples obtained over the integration time, but also by the nature of the signals observed in the radio channel. The most exacting requirements in regard to the number of accumulated samples and operating speed of the monitoring equipment come into play in the case of radio channels with predominantly pulsed signals having duration of less than one thousandth of the integration time. This type of analysed signal is also characteristic when it comes to the measurement of frequency-band occupancy. In the case of channels with pulsed signals, the number of samples required to produce accurate and confident measurements is determined, all other things being equal, by the actual level of channel occupancy, as can be seen from Table 2.

TABLE 2

**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

Measurement errors for different occupancy values and differing numbers of processed data samples can be estimated using the graph shown in Fig. 1. Green dots at curves indicate values of absolute errors for some particular numbers of samples, particularly for 1 600 and 3 600. The upper left-hand part of the graph is a shaded inadvisable area, signifying that to estimate occupancy with such a small number of samples is not recommended owing to an unacceptable increase in error. More detailed information may be found in Annex 1 to Report ITU-R SM.2256.

If, however, lengthy signals are observed in the radio channel, the required number of samples will depend primarily on the average number of signals observed during the integration time, and will generally be markedly lower than in the case of pulsed signals. Suggestions on occupancy evaluation for channels with lengthy signals may be found in Annex 1 to Report ITU-R SM.2256.

FIGURE 1

**Dependency of the relative error of occupancy estimates (δ_{SO}, %) on the number
of accumulated samples (J_m) with a 95% confidence
level for channels with pulsed signals**
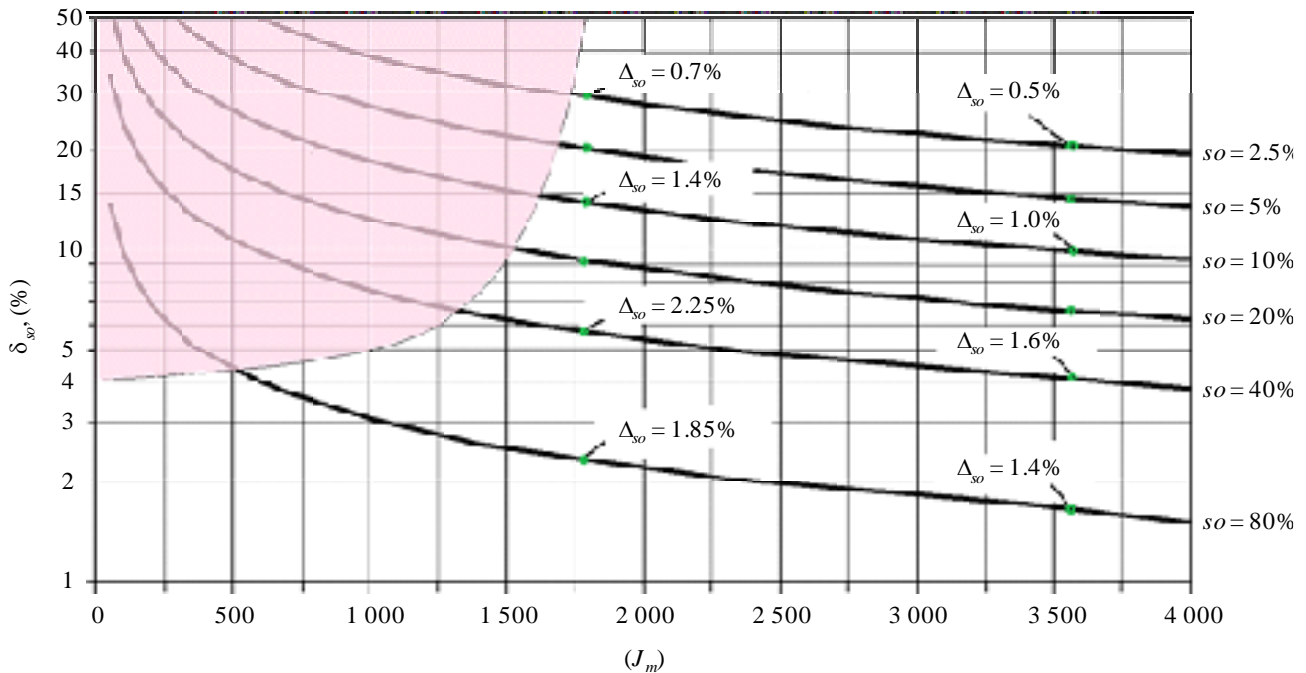
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3.5   Considerations on occupancy measurements

3.5.1   Emission identification

Simply recording the level does not allow discrimination between wanted and unwanted emissions or more than one user operating on a single frequency within the coverage area of the monitoring system. All emissions, if they are above the chosen threshold value, are usually treated as occupied channels.

Using modern real time and post-processing software may enable discrimination between different users taking into consideration information such as field-strength or direction of arrival at the receiver, selective code information, modulation characteristics.

3.5.2   Monitoring mobile transmissions

It is possible that a wanted mobile unit (Mobile A) will be located significantly further from the monitoring site than the user's own base site (Base A). Therefore the received signal strength may be less than the monitoring threshold value set, although strong enough at the intended base site to be useable (see Fig. 2).

FIGURE 2
Monitoring mobile transmissions
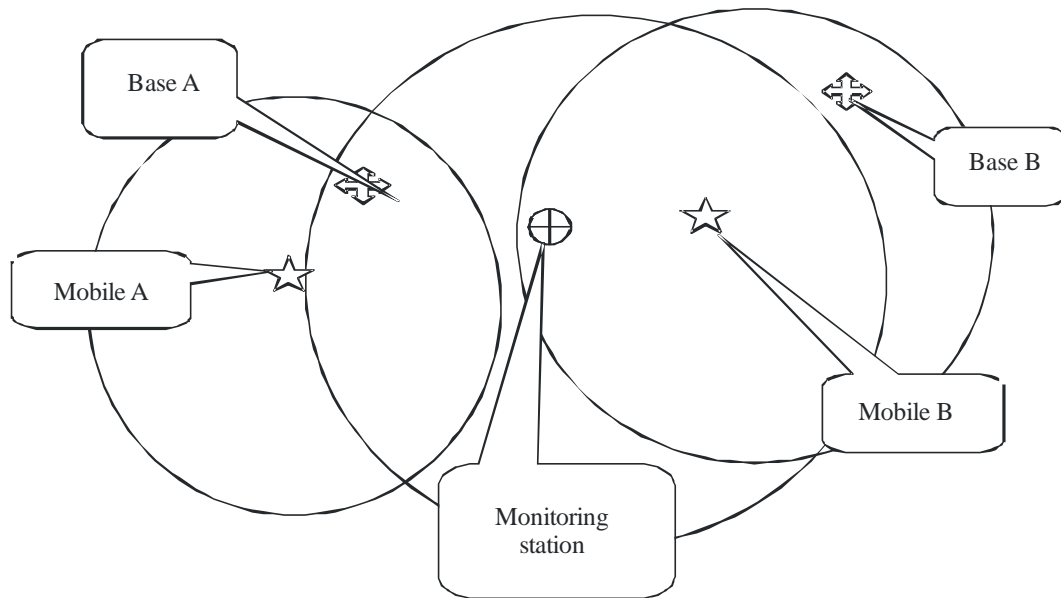
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Conversely, a mobile unit from an out-of-area co-channel user (Mobile B) may be received at the monitoring site but not heard at the main user's base site.

Either of the above situations might lead to misleading results since the occupancy results might not be representative for the entire mobile network, but only of the region covered by the monitoring site.

3.5.3 Propagation

Propagation conditions should also be considered when setting receiver threshold levels and propagation should be monitored during the measurement period.

3.6 Presentation and analysis of collected data

The results can be stored every 5, 15, 30 or 60 min as required. From this data it is possible to generate presentations based on tables, textual graphs, line/bar graphs and maps. After the desired information is extracted, these raw sampled data can be discarded.

The presentation system should, as a minimum, contain the location of the monitoring site, date and period of measurement, frequency, type of user(s), threshold level used, occupancy in the busy hour and revisit period.

3.6.1 Representative example of field strength used to discriminate between different users

If field strength is recorded, additional information can be extracted from the measurement.

The left plot in Fig. 3 is a commonly used way to present the occupancy with a resolution of 15 min, normally with only one curve. The red curve in the left plot represents the total occupancy caused by all users on that channel. The green curve is the occupancy caused by the station received with about 49 dB(μV/m) (see right side plot) and the blue curve is the occupancy caused by all the other users, in this case the second user received with about 29 dB(μV/m).

The plot in the middle represents the received levels over time. Only received levels above the threshold level (here: 20 dB(μV/m)) are evaluated.

The right plot shows the statistical distribution of the received field strength levels. In this example 49 dB(μV/m) has been measured about 380 times in a 24-hour period, 50 dB(μV/m) about 350 times, etc.

FIGURE 3

Enhanced processing of occupancy data
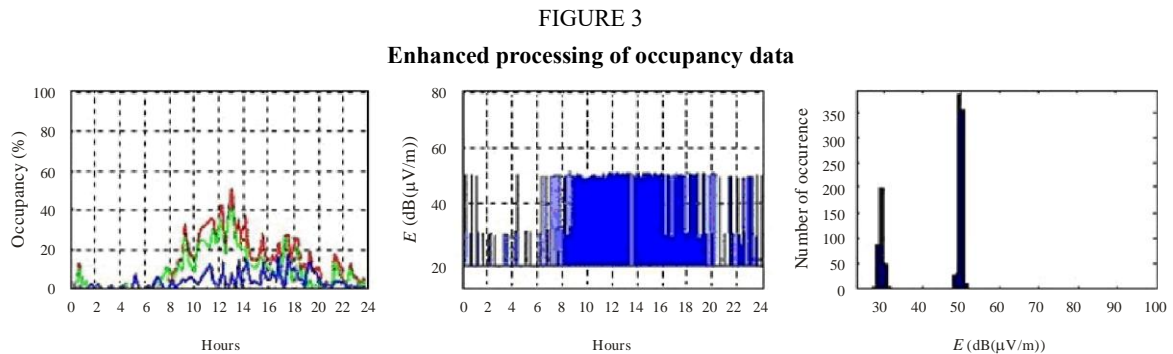
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3.6.2 Representation of frequency band occupancy by percentage

Instead of presenting only the occupancy from every single channel, the occupancy of the whole measured frequency band should also be presented.

Figure 4 shows the average occupancy over 24 h from every single frequency step.

FIGURE 4

Average occupancy over 24 h

Δf = 2.5 kHz f (MHz) threshold = 21 dB(μ V/m) occupancy = 20.18%
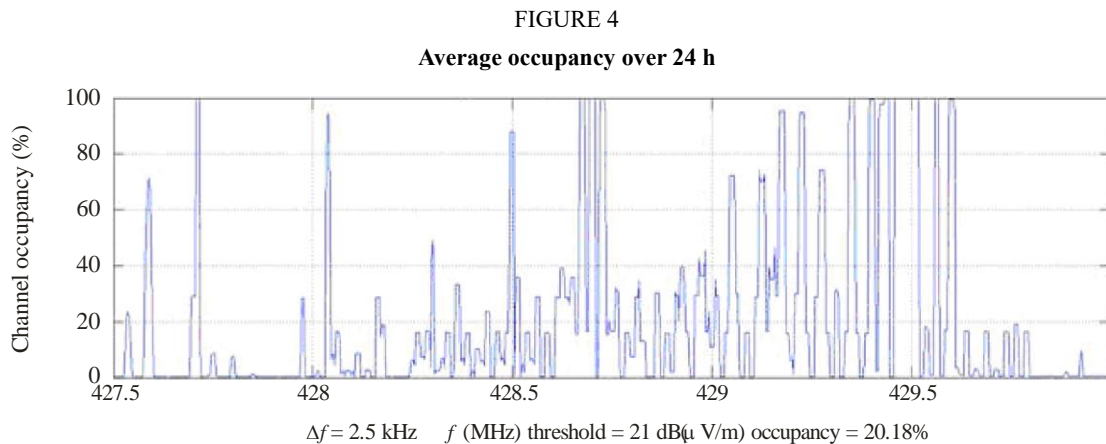
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As an example, assuming that a frequency band can be scanned in 1 000 steps in 10 s. From every step, 8 640 field-strength values are available in a period of 24 h. If, in this case, 4 320 times the threshold level on a channel/step is exceeded the occupancy will show 50%. In the resulting plot, as above presented, there is no time information left and there is no indication when this 50% occupancy was observed. This limitation should be considered when using this type of presentation.

3.6.3 Representation of frequency band occupancy by colours

To get a quick overview the occupancy can also be expressed by presenting a colour per channel per chosen resolution in time (normally 15 minutes). An example is given in Fig. 5.

In this presentation the time information is still available (96 values/24 h). The colour bar is presenting the occupancy (and not the field strength). The left Y-axis gives time, not in hours but in 96 periods of 15 min.

FIGURE 5

Frequency band occupancy using colours (spectrogram)

Channels: 80   Separation: 2 kHz   Frequency (MHz)
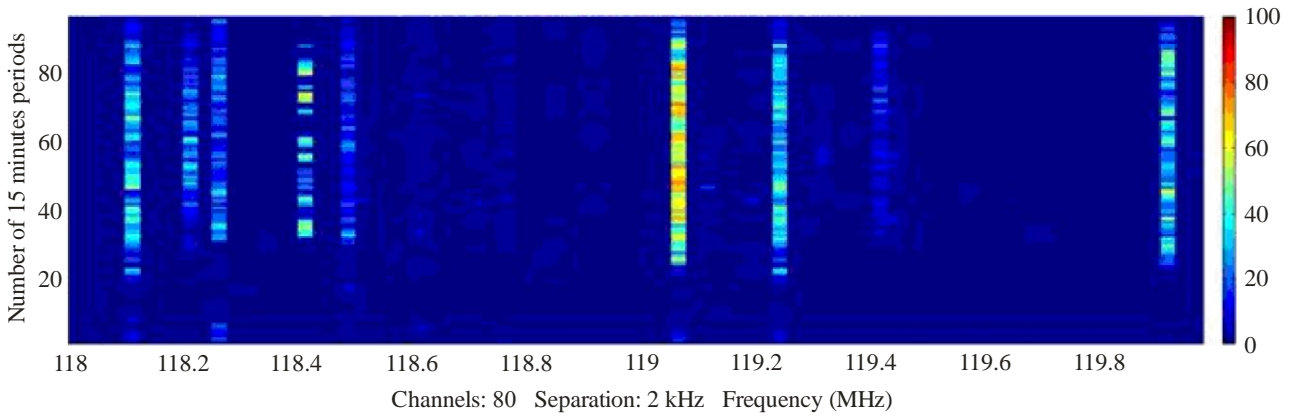
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Annex 2

Determination of required samples for different sampling methods

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1   Sampling methods

A practical aim of occupancy measurements is to achieve accurate results with minimum measurement effort. If a frequency channel could be measured continuously for the whole monitoring period, there would be an absolute accurate result for its relative occupancy. However, this would produce an unnecessary amount of data and normally would not allow monitoring multiple channels concurrently with the same monitoring equipment. For practical reasons it is therefore common to take only "snapshots" (samples) of the occupancy state of a frequency channel in more or less equal time intervals. These time intervals are the revisit time, the reciprocal value is the sampling speed. It

is obvious that the higher the sampling speed and the more samples are collected, the more accurate the occupancy result will be. It can be mathematically proven that, among other parameters, the required minimum number of samples to reach a given accuracy and confidence level depends on "dependent" or "independent" sampling. The difference between these two sampling methods, when applied to channel occupancy measurements, mainly lies in the fact whether it is possible to catch every single transmission on the channel or not. This is explained with the following two examples. They also show that in practical occupancy measurements, both cases can occur, and it is sometimes difficult to determine which sampling method is applied.

1.1   Dependent sampling

The example used here assumes an analogue frequency channel where average transmission lengths (and also the pauses between them) are in the order of seconds. This may be called a channel with "lengthy signals". Modern fast monitoring equipment is used which is capable of measuring thousand channels per second. So if 100 frequency channels are measured concurrently, the revisit time on each channel will be 100 ms. This means that every transmission on each of the ten channels will be detected. In fact it is oversampled because a transmission of 1 s length is captured 10 times.

FIGURE 6

**Sampling of a frequency channel with lengthy signals**
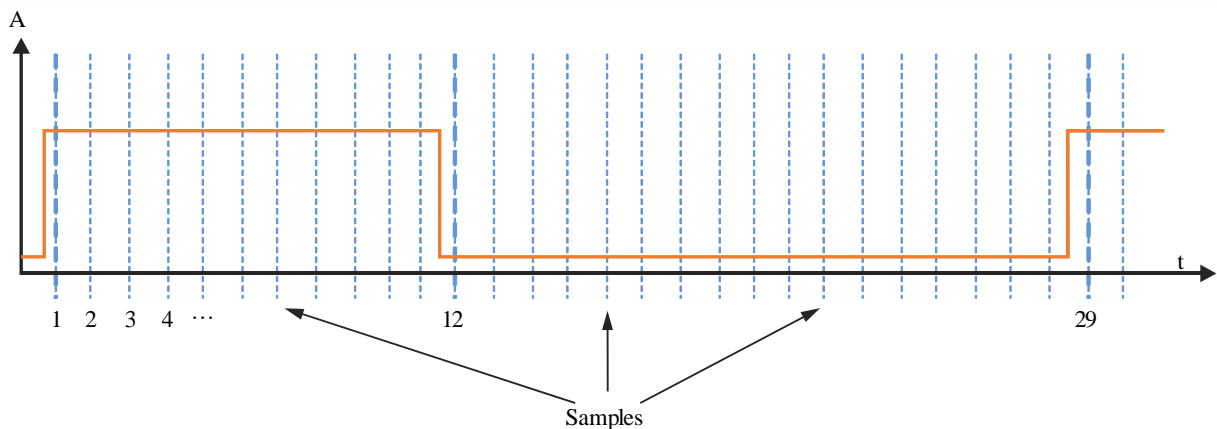
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In the example in Fig. 6, only samples 1, 12 and 29 detected a state change (from occupied to not occupied or vice versa) and therefore have a different value than their previous samples. The other 27 samples show the same state than their predecessors. Statistically speaking, the chance of a sample having the same state than the previous sample is much higher than hitting a state change. So, the value of a sample is dependent on the value of the previous sample.

1.2   Independent sampling

The example used for independent sampling assumes a channel with pulsed digital signals. Even with fast monitoring receivers, the burst times are often much shorter than revisit times. It is therefore not possible to capture each single burst (transmission) on each channel. The bursts are rather captured only by chance.

FIGURE 7

Sampling of a frequency channel with pulsed signals
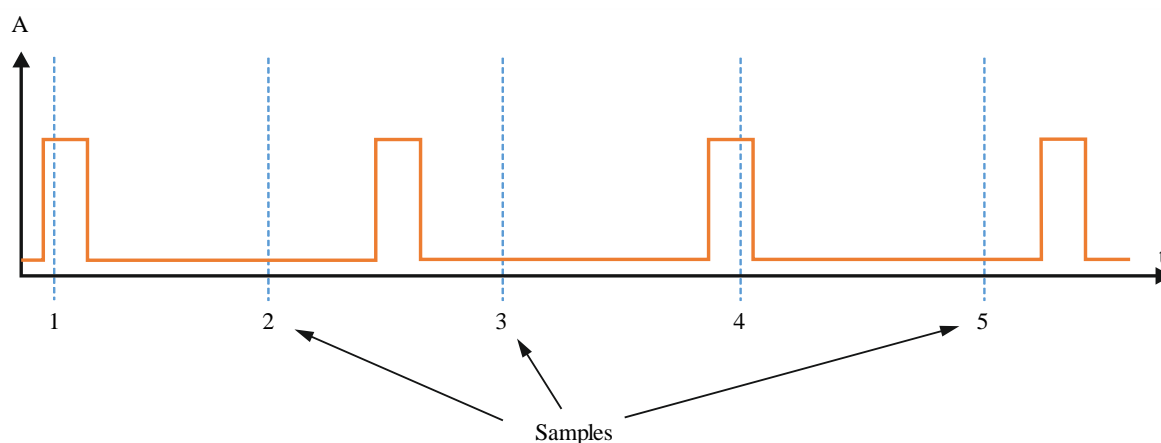
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Because the sampling is normally not synchronized with the burst rate, each sample in Fig. 7 hits a burst or a pause on a random statistical basis. The chance for each sample to show the channel occupied is only dependent on the timing of the signal itself, but not on the state of the previous sample. This situation is called "independent sampling".

2 Calculation of the minimum required samples

The transmission occupancy of a selected channel is defined as a two-state random process. The first state is labelled "occupied" and is defined as the event that, during an observation, the signal strength at a monitor receiver is above a given threshold.

The complementary event is that the signal strength is below this threshold. Because the state of the channel is random, its state at any given measurement time cannot be predicted. However, its state can be described in terms of a probability law [1].

Consider the two-valued random process: $X(t)=1$, if signal at time t is above threshold level, and $X(t)=0$, otherwise [1].

Let $X(n) = x_i$, so that the sequence of measurements x_1, x_2, x_3, …, x_n is represented by a sequence of 0's and 1's, where 1 means the detected strength in the channel exceeds a given threshold, and 0 means that the detected strength in the channel does not exceed that threshold. Here x_i is a sample of $X(t)$, regardless of the time interval.

From a statistics point of view, the result of spectrum occupancy measurement is an estimate or statistical value, thus it has accuracy and reliability attributes. As mentioned earlier, the key issue of the occupancy measurement is how to get enough information with spending less work in a certain confidence level, so the relative accuracy and confidence level are crucial.

2.1 Independent sampling

Also from a statistics point of view, the independent and identical distribution of samples is obviously the simplest case.

The basic idea of this method is to take the samples of x_i to estimate the true value of spectrum occupancy (SO) over the current integration time.

The variable $X(n)$ obeys to the 0-1 distribution with the parameter ρ (the probability of the detected strength in the channel exceeds a given threshold), so the probability density function of $X(n)$ is given by:

$$f(x,\rho) = \rho^x (1-\rho)^{1-x} \quad x = 0,1 \quad 0 < \rho < 1$$

In spectrum occupancy measurements, the modern receivers or spectrum analysers are widely used. Due to their high speed, a huge quantity of data will normally be produced in a certain given integration time, which exactly provides the basis of using the central limit theorem, so for x_i,

$$\frac{\sum_{i=1}^{n} X_i - n\rho}{\sqrt{n\rho(1-\rho)}} = \frac{n \bar{X} - n\rho}{\sqrt{n\rho(1-\rho)}} \sim N(0,1)$$

where $\bar{X}$ is the mean value of the samples, and is also the spectrum occupancy calculation result *(SOCR)*.

The confidence level P_{SOC} is given by

$$P_{SOC} = P\{-\mu_{\frac{\alpha}{2}} \leq \frac{n \bar{X} - n\rho}{\sqrt{n\rho(1-\rho)}} \leq \mu_{\frac{\alpha}{2}}\} = 1-\alpha$$

where $\mu_{\frac{\alpha}{2}}$ is upper value with the significance level α of the standard normal distribution (with mean = 0 and standard deviation = 1).

The confidence level is denoted as $1 - \alpha$.

Solving for ρ, there is $A \leq \rho \leq B$, [A, B] is the interval estimation of ρ.

The mean value of samples $\bar{X}$ with n scans (measurements) and m detections is given by

$$\bar{X} = \frac{\sum_{i=0}^{n} X_i}{n} = \frac{m}{n}.$$

Then, the relative accuracy of occupancy is

$$\delta_{SO} = \frac{B - A}{2 \bar{X}}$$

For the example of a relative accuracy of 10% and a confidence level of 95%, the number of required independent samples versus different spectrum occupancy is shown as Fig. 8.

FIGURE 8

Spectrum occupancy versus number of samples
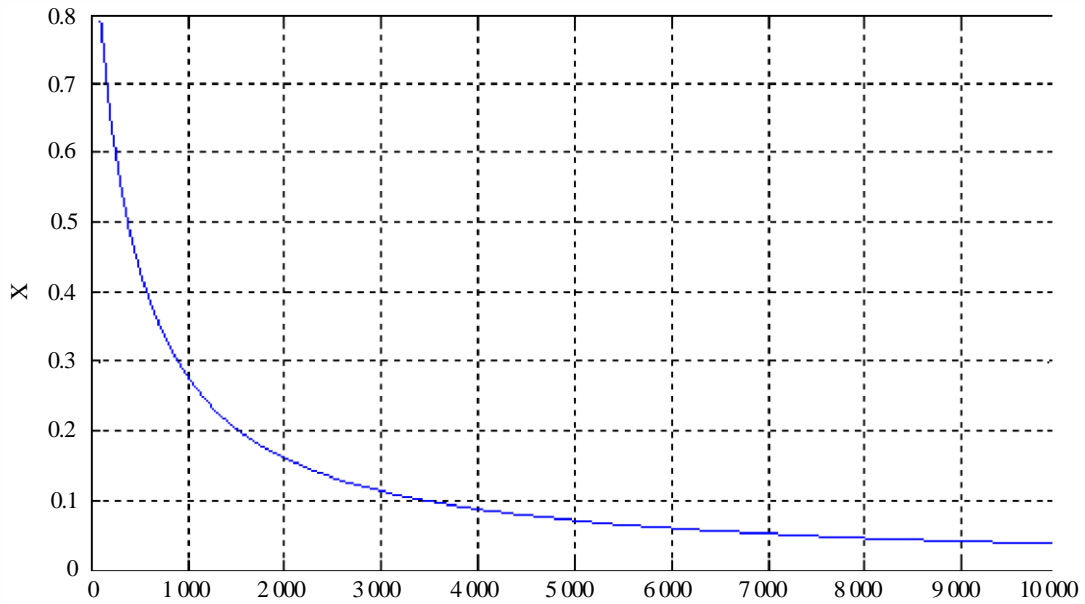
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2.2 Dependent sampling

For dependent sampling, the sequence can be represented by a Markov-chain of first order. Although more complicated mathematical models can also be used, for the situations of interest to monitoring, the results from such complex models differ little from first-order Markov results [1]. The resulting number of required samples for an accuracy of 10% and 95% confidence level for various occupancy figures are given in Table 1 in Annex 1 to this Recommendation. It can be seen that the number of required dependent samples is about three times higher than with independent sampling.

References to Annex 2

[1]   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.