Electronic Communications Committee (ECC)
within the European Conference of Postal and Telecommunications Administrations (CEPT)

ECC RECOMMENDATION (06)01

Bandwidth measurements using FFT techniques

Recommendation approved by the "Working Group Frequency Management" (WGFM)

Introduction

The occupied bandwidth is one of the most important parameters to characterize an emission. The implementation of powerful FFT algorithms even in low cost analysers allows to perform more accurate and quicker measurements of the occupied bandwidth compared to conventional methods. This recommendation specifies those parameters which are essential to achieve correct and mutually acceptable results.

"The European Conference of Postal and Telecommunications Administrations,

considering

a) that the bandwidth is an important parameter to characterize known and unknown signals;
b) that there is an increasing number of different signal types that have to be measured by radio monitoring services;
c) that FFT techniques allow to perform accurate measurements of the occupied bandwidth for nearly all types of signals;
d) that the number of low cost digital signal analysers using FFT techniques being capable of performing accurate bandwidth measurements is increasing;
e) that bandwidth measurement methods using FFT techniques offer advantages over conventional methods in terms of accuracy, storage of spectrum data, reproducibility and speed;
f) that FFT techniques better measure time varying (gated, pulsed, or transient) signals and complex modulated dynamic signals by processing all frequencies of the measured spectrum simultaneously.

recommends

that the method and setup specifications described in the Annex are used for bandwidth measurements using FFT techniques.

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ANNEX

1   GENERAL

Among all the different definitions of bandwidth used in ITU-R Recommendation SM.328, there are only two which can directly be measured and hence are important for radio monitoring services. These are:

- The 99% (or β -%) occupied bandwidth:

    This is the frequency range in which a certain percentage of the total spectral power of a signal falls. The residual part of the total power being denoted as β, which, in cases of symmetrical spectra, splits up into β/2 on each side of the spectrum. Unless otherwise specified, β/2 is to be taken as 0.5%. The related measuring method is known as the β/2 method.

- The x-dB bandwidth:

    The frequency range outside which the level of all spectral components of the signal is less than x dB below a predetermined 0 dB reference level. The related measuring method is known as the x-dB method.

FFT techniques can be used for both measuring methods. Compared with swept spectrum analysers, FFT offers advantages when measuring the occupied bandwidth in terms of speed and accuracy. For example, if a 10 kHz spectrum is to be analysed with 10 Hz resolution, a swept spectrum analyser will need over a minute, whereas the FFT analyser can present a result in less than a second.

2   PRINCIPLE OF MEASURING THE OCCUPIED BANDWIDTH USING FFT TECHNIQUES

Basic system setup
The following principle components are needed to measure the occupied bandwidth using FFT techniques:
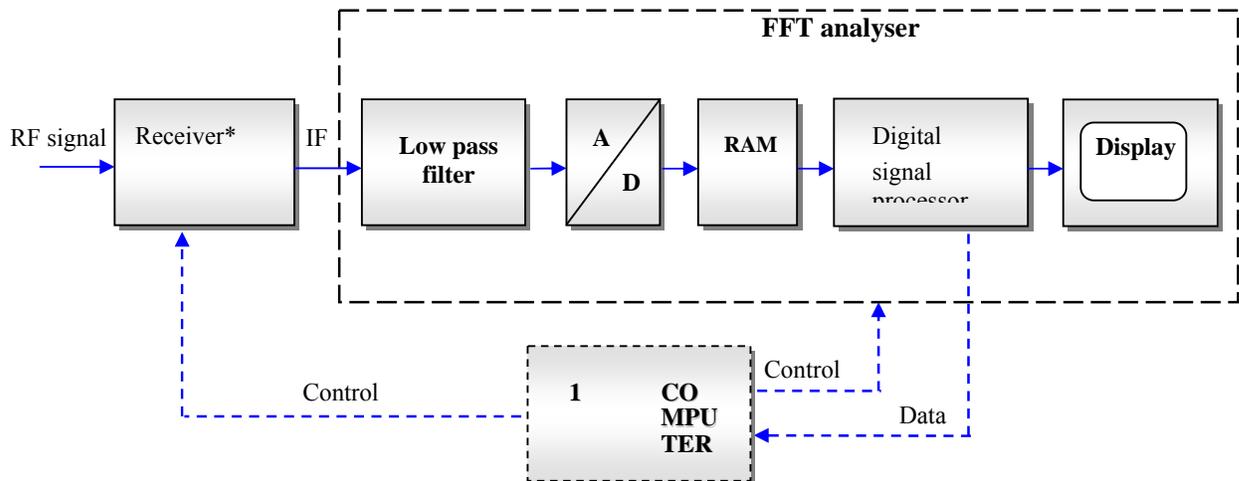
* The FFT analyser can also include the receiver unit.

The above-mentioned block diagram represents only a simplified FFT analyser. Practically, most of the FFT analysers apply zoom-FFT to magnify the frequency range of interest in cases, when a small frequency band of the spectrum is needed to be analysed. Zoom-FFT is a process where the input signal is mixed down to a baseband and the decimated and resampled prior to passing it into the standard FFT unit. Zoom operation makes it possible to reduce the frequency span while maintaining a constant center frequency and focus the measurement anywhere within the analyser frequency range.

Functions and settings

Receiver

The RF signal is first fed into a receiver that converts the frequency band to be analysed into an IF frequency range that the following analogue/digital converter samples. Considering the speed of modern A/D converters, this down-conversion of the RF may be unnecessary.

The required dynamic range of the receiver components should be at least 60 dB.

The receiver IF bandwidth should be the nearest value to 150% of the estimated bandwidth of the signal being tested. To produce accurate results, the flatness of the IF frequency response curve has to be within 1 dB over the whole IF bandwidth.

Low pass filter

For digitalising the analogue signal, it must be sampled at regular intervals. During this process, mixed frequencies are generated from the input signal and the sampling frequency are generated that can fall into the input frequency range of the FFT analyser, making the measurement result false (aliasing effect). The signal therefore has to be passed through a low pass anti aliasing filter before being sampled. The filter has to be designed such that the IF signal can pass but signal components of frequencies higher than half the sampling rate of the following A/D converter are suppressed.

A/D converter

The A/D converter converts momentary amplitudes of the signal into a digital data stream. The dynamic range of the A/D converter should be just greater than the amplitude of the IF signal. Complete reconstruction of a waveform for accurate representation of the incoming signal is only possible with sample frequencies taken at a rate greater than twice the highest frequency-harmonic component (f_{inmax}).

RAM

A certain number of the sampled data has to be temporarily stored in memory (as a 'time record') before the actual FFT process can be performed. The minimum duration of the time record is the reciprocal value of the lowest frequency to be processed.

Digital signal processor

This unit performs the actual FFT processing, which converts the complete blocks of time records into amplitude vs. frequency signals. The resulting spectrum is then mathematically analysed in the frequency domain to calculate the bandwidth.

Display

In order to achieve valid results, several conditions have to be met in terms of signal-to-noise ratio and interference. Furthermore, the channel width in which order the expected bandwidth lies has to be entered manually, because automatic detection of the signal boundaries is unreliable, especially when multiple signals and/or signals on adjacent channels are received, or interference is present. Therefore, automatic bandwidth measurements showing only a figure as a result cannot be recommended. It is absolutely necessary to have a display showing the spectrum of the measured signal in the frequency domain. This display has to include the current markers that the system uses to calculate the occupied bandwidth.

Data storage

An optional computer can be used to control receiver and FFT analyser and store measurement data. There are two different stages in which signal data could be stored:

- The resulting data is stored underlined after the FFT process (i.e. in the frequency domain). This method takes up only little storage space, but later measurements can only be repeated with the same FFT settings.

- The time domain samples of the signal are stored <u>before</u> the FFT process. This method allows later measurements with different FFT settings (acquisition time, resolution), but takes up a very large amount of storage capacity.

Storing the data allows measurements at a later time ("off-line"), making it unnecessary for the operator to wait for temporary emissions to come up, and ease bandwidth measurements of very short (pulsed) emissions.

Processes of bandwidth measurement

The spectral components of an analogue modulated signal continuously change over time. Because a sweeping analyser also needs time to perform a sweep, the right end of the resulting spectrum shape will show a signal recorded later than the left end. FFT techniques, however, is able to capture all spectral components simultaneously and gives the possibility to average the successive momentary bandwidth values over the time records.

<u>The 99% bandwidth</u> is calculated from each time record as follows:

The spectral power (or level) of each frequency line inside the stored sample is added throughout the whole recorded frequency range to give the 100% reference power. In a second calculation, starting from the lowest frequency recorded, the spectral power of each frequency line is again added up until the sum reaches 0.5% of the predetermined total power. At this point, a marker is set. The same calculation is then performed starting from the highest frequency recorded (the right end of the display) until again 0.5% of the total power is reached and a second marker is set. The 99% bandwidth is the frequency difference between the two markers.

<u>The x-dB bandwidth:</u>

The FFT process can also be used to measure the x-dB bandwidth, regardless of the definition of the 0 dB reference level. In the annex to ITU Recommendation SM.328, this reference level is defined for many analogue modulations and often has to be measured with a different resolution bandwidth (RBW) than used for the actual bandwidth measurement. In cases where the total power sometimes returns to the carrier, the 0 dB reference level can also be measured with the same narrow RBW as is used for the actual recording of the spectrum, using a max hold function. With the noise-like digitally modulated signals, the 0 dB reference level is the peak of the spectrum curve recorded with narrow RBW.

After entering the desired value for x-dB, the resulting bandwidth can easily be calculated from the power levels of each spectral line.

FFT parameters

<u>Window function</u>

For exact bandwidth measurements it is necessary to achieve good frequency resolution of the FFT. Since the FFT process looks at a signal only for a limited time (the acquisition time), it assumes the signal to be non-existent or at least periodic outside the calculation <u>'window'</u>. This, however, results in certain errors when in fact the amplitude of the signal is not zero at the beginning and the end of each time record. To force this behaviour, a so-called window function has to be mathematically applied to the signal.

From the FFT theory it can be proven that no ideal filter exists that results in an exact reproduction of the signal in the frequency domain. All windows are compromises and are optimised for either good amplitude accuracy or good frequency resolution. Assuming that the amplitude distortion of a frequency-optimised window function is equal for all spectral components inside the range to be analysed, this type of window is best for bandwidth measurements, because the whole calculation only works with relative and not absolute levels.

The most common window functions that are optimised for frequency resolution is the Hanning (sometimes also referred to as "Han") window, which should therefore be used in bandwidth measurements.

<u>FFT resolution</u>

To achieve good accuracy, the spectral resolution of the FFT process should be at least 200 lines, although modern FFT analysers normally provide 512 lines or more. The required frequency resolution is often determined through setting of a resolution bandwidth. For a maximum of accuracy, if the FFT resolution is 512 lines, the optimum resolution bandwidth is about 1/500 of the frequency span that is analysed. Higher values for the RBW would waste FFT resolution capability, smaller RBW would only result in slower performance because the necessary acquisition time increases.

<u>Time record (acquisition time)</u>

The duration of each time record has to be at least as long as the period of the lowest modulating frequency of the signal to be analysed (f_s). However, it also depends on the required frequency resolution and on the frequency span. The higher required FFT resolution and span, the longer is the minimum acquisition time. In practical FFT analysers, the acquisition time is automatically adjusted to the lowest possible value depending on the user's setting of the other parameters.

Time record length (T)

$$T = N \times \Delta t$$

where N is the number of sample points and Δt is the sample time ($= 1/f_s$).

<u>Real-time bandwidth</u>

This value is the performance indicator of the analyser. Real-time bandwidth is the frequency span at which the FFT processing time equals the time-record length. There is no break between the end of a time record and the start of the next.

Specifications summary

Dynamic range of the receiver	$\geq$ 60 dB
IF bandwidth	$\sim$ 150% of the signal bandwidth, if adjustable
Cut-off frequency of the low pass filter	$\geq$ IF plus 75% of the signal bandwidth < 0.5 * A/D converter sampling frequency
A/D converter sampling rate	> 2 * 150% of the signal bandwidth
A/D converter resolution	$\geq$ 16 bit
Window function	Hanning (Han)
FFT resolution	$\geq$ 512 lines

Frequency span
As mentioned earlier, it is necessary that a certain amount of spectrum outside the occupied bandwidth is included in the calculation process. The necessary frequency span is therefore around 1.5 times of the signal bandwidth.

Making the span too wide, however, may result in influences from emissions on adjacent channels and will also reduce the accuracy as less spectral lines in the wanted channel can be used for calculation.

Signal level
The received signal level has to be high enough in order to obtain a reasonable accuracy. When measuring the 99% bandwidth, the peak signal level should be at least 30 dB above the noise floor. When measuring the x-dB bandwidth, the markers used to calculate the occupied bandwidth have to be at least 5 dB above the noise floor or any interfering signals. The operator can check this prerequisite by looking at the spectral display while the measurement is performed.

Signal detection function

In FFT systems, the signal detection function is implemented through software in the frequency domain. If the bandwidth is not constant due to modulation, the maximum bandwidth is of interest. The following signal detection functions have to be used:

Signal type or class of emission	Signal detection function
A1x, A2x, F1x, F7x	ClearWrite (momentary bandwidth)
F3E, A3E, J3E, H3E, R3E	MaxHold (maximum bandwidth)
Continuous signals with digital modulation (xPSK, x-QAM, MSK, OFDM)	ClearWrite
Pulsed signals with digital modulation (TDMA)	MaxHold

3   LIMITATIONS AND ACCURACY

One limitation inherent to the $\beta/2$ method is that the noise level has to be well below $\beta/2$ of the signal level to produce accurate results. Otherwise, the spectral power of the noise, which will be interpreted as parts of the actual signal, may add up significantly resulting in an increased value for the occupied bandwidth. The actual measurement error due to increased noise cannot be generally quantified, because it depends on the spectrum shape. Also, the $\beta/2$ method does not allow for any interfering signals inside the selected span.

When measuring the x-dB bandwidth, the signal-to-noise ratio does not need to exceed x dB by more than 5 dB which is sometimes less than the requirement for the $\beta/2$ method. Also, the x-dB bandwidth can tolerate the presence of interfering signals, provided their spectrum does not mask one of the x-dB points.

The frequency accuracy of the FFT bandwidth measurement depends on the FFT resolution (and therefore, indirectly, on the time record length). Assuming the suggested FFT resolution of 512 lines and a frequency span of 150% of the signal bandwidth, the accuracy of the result can be better than 1% in terms of measured bandwidth.