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# MODULATION QUALITY MEASUREMENTS IN BLUETOOTH™ SYSTEMS THROUGH TIME-FREQUENCY REPRESENTATIONS

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**Abstract** − A digital-signal-processing method for assessing bluetooth transmitters modulation quality is presented and validated. Thanks to the use of the Short Time Fourier Transform (STFT), a typical time-frequency representation (TFR), the instantaneous frequency trace of the bluetooth signal is first attained; the most significant parameters peculiar to modulation quality are then measured through straightforward procedures. The influence on measurement results of different choices of the STFT parameters is exhaustively analysed. The optimal tuning of the parameters, capable of granting the lowest experimental standard deviations, is finally found.

Keywords: Time Frequency Representation, binary-GFSK modulation, frequency deviation measurement, frequency drift measurement, initial carrier frequency tolerance measurement.

## 1. INTRODUCTION

Bluetooth is an emerging technology for wireless short-range interconnectivity of two or more devices. It principally aims at the realization of personal area networks, named piconets, connecting a variety of electronic devices regularly used in our daily life. [1-3]

Several appliances complemented with bluetooth interfaces, such as cordless headsets, cell-phones, personal digital assistants (PDA), keyboards, printer adapters, have already reached the market, and many others are expected to follow the rush of numerous proposals of new applications. Bluetooth interfaces can be employed, in fact, to replace cable connection, to remotely control facilities used in domestic environment, etc.

As the bluetooth system uses interference-dominated RF channels, its proper functioning mainly relies on transmitters and receivers performance, which has to satisfy several constraints imposed by RF standard specifications [1-3]. At present, the methodologies for testing and verifying bluetooth equipment require a large set of dedicated and expensive instruments, such as vector signal analysers, power meters and swept spectrum analysers complemented with suitable personalities. Above all, they are continuously subject to improvements or changes, thus, they will differ from those will be adopted in the next future [4-5].

The authors, who have already proposed with success the use of Time-Frequency-Representations (TFR) [6] for testing telecommunication equipment in other wireless systems, such as GSM (Global System for Mobile Communications), cdma2000, and UMTS (Universal Mobile Telecommunication System) [7-9], intend to show that TFR's can be employed for assessing the modulation quality of bluetooth transmitters as well.

Specifically, they define and validate a measurement method based on the use of a particular TFR, the Short-time Fourier-transform, highlighting, throughout a number of experimental tests, that accurate results can be afforded only suitably tuning the parameters affecting TFR outcomes. Furthermore, they also establish the optimal set-up of TFR parameters capable of minimising the standard deviation of measurement results.

The proposed method exhibits comparable performance with respect to that granted by other solutions already available on the market. Moreover, demodulation of the transmitted signal is not required by the measurement procedure with a consequent benefit on the measurement time. Still, one-button measurements, which do not require qualified users, are assured by the fully automatic test capabilities shown by the method.

## 2. BLUETOOTH MEASUREMENTS: AN OVERVIEW

### *A. Fundamentals of bluetooth technology*

The *bluetooth* system operates within the licence-free industrial scientific and medical (ISM) frequency band, that ranges from 2400 up to 2483,5 MHz, divided into 72 1-MHz bandwidth channels.

Due to the 1 MHz available channel bandwidth, the maximum bit rate allowed is 1 Mbps.

The system uses the Gaussian-filtered binary frequency shift keying (2-FSK) modulation technique, characterised by 160 kHz nominal frequency deviation: positive and negative frequency deviations with respect to the carrier are produced in correspondence of input digits 1's and 0's respectively.

Information is divided into packets that are transmitted by means of bursts, within suitable time slots: each time slot engages the channel for a limited time interval (625 μs).

For overcoming the interference problems characterising the deregulated ISM band, consecutive bursts are transmitted using different channels. This mechanism, named hopping, makes the carrier vary with step variations at regularly spaced instants.

Each packet contains both an informative bit-stream and short bit-sequences included for synchronisation and general management tasks. Several packet formats characterised by different length and, as a consequence, by different time duration are available in bluetooth system. They can need one or more consecutive time slots of the assigned channel to be transmitted: there are packets that use a single slot, three slots, or five slots. All adhere to a general format represented in Fig.1, in which three major fields can be recognized: an access code (72 bits), containing a preamble, a synchronisation word, and a trailer; an inner block named header (54 bits); and a payload of variable length (0-2745 bits), which contains the informative bit stream.

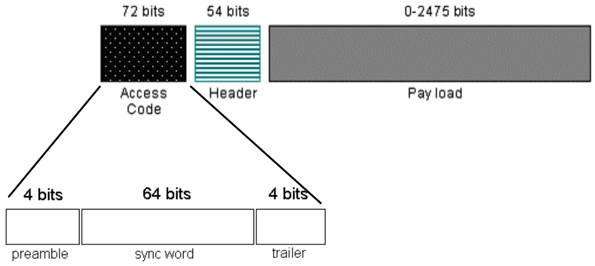


Fig.1. The general format of a *bluetooth* packet

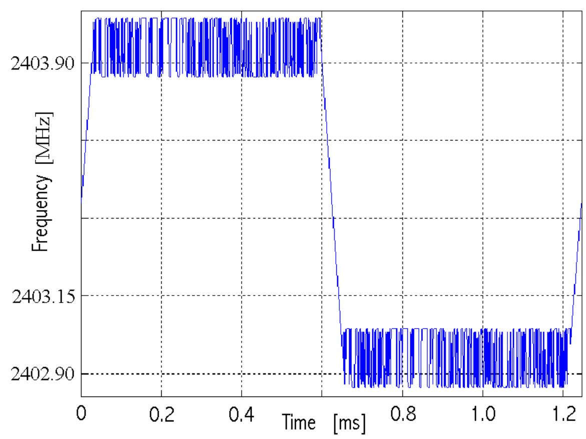


Fig.2. The time domain evolution of the instantaneous frequency characterising a bluetooth signal in normal operation

For the sake of clarity, a generic instantaneous frequency trajectory of a *bluetooth* signal is shown in Fig.2: the carrier frequency characterising the first slot (2404 MHz), successively hops to the centre frequency of another available channel that is far 1 MHz apart (2403 MHz).
In normal operation (packets occupying a single slot) hop-speed is 1600 hops per second, however, it can vary depending upon packet length.

*B. Modulation quality measurements*

*Bluetooth* RF specifications [1-3] suggest detailed tests for assessing transmitter modulation quality. In particular, attention is paid to the measurement of:

*a) maximum frequency deviation,*
*b) carrier frequency drift,*
*c) initial carrier frequency tolerance (ICFT).*

*a)* Maximum frequency deviations should be measured in the presence of two different payloads: a first one made up of repeating 8-bit sequences 00001111; a second one of repeating 8-bit sequences 01010101. These two different test sequences provide different stress mechanisms for testing both the modulator performance and the premodulator filtering. For each 8-bit sequence, both the average frequency of the signal and the maximum deviation from it, $\Delta f_{1max}$, are measured. The average of the maximum deviations, $\Delta f_{1avg}$, in the whole packet is also evaluated. According to RF specifications, in the presence of the 00001111 sequences, $\Delta f_{1avg}$ has to meet the two constraints

$$140kHz < \Delta f_{1avg} < 175kHz . \qquad (1)$$

In the case of the 01010101 sequences, instead, the maximum frequency deviation, named $\Delta f_{2max}$, has to satisfy only the constraint

$$\Delta f_{2\max} > 115kHz . \qquad (2)$$

At the same time, the average value of the maximum deviations, $\Delta f_{2avg}$, has to be compared to the value, $\Delta f_{1avg}$, and the relation

$$\Delta f_{2avg} / \Delta f_{1avg} > 0.80 , \qquad (3)$$

should be satisfied.

*b)* Frequency drift has to be evaluated in the presence of packets containing payloads made up of repeated 8-bit sequences 01010101. In particular, the measurement of the average frequency characterising the first 4 bits (preamble) of the packet, which are 1010, furnishes the value of the carrier at the beginning of the burst. Then, the average frequencies that characterise all 10-bit sequences 0101010101 repeated in the payload are also measured. The difference between each average frequency and that characterising the preamble gives the frequency drift value. The frequency drift-speed during burst transmission, which is given by the difference between the average frequencies of two adjacent 10-bit sequences can also be highlighted. Frequency drift tests have to be carried out for the lowest, central and highest channel frequency in the ISM band, both in the presence and absence of frequency hopping. According to the aforementioned standard specifications the maximum frequency drift revealed in a packet occupying 5 slots has to be inferior to 30 kHz.

*c)* ICFT refers to a frequency offset between the nominal frequency and that really produced by the transmitter. ICFT measurement is performed in the presence of payloads characterised by pseudo random sequences, which simulate actual traffic. Tests are required both in the presence and absence of frequency hopping. In particular, the measurement of ICFT requires the analysis of the first four bits, which form the preamble of the transmitted packet (1010). To this aim, the difference between the average frequency measured in correspondence of the aforementioned four bits and the nominal value is evaluated.

## 3. PROPOSED METHOD

The proposed method allow the assessment of the modulation quality of bluetooth transmitters throughout three fundamental stages, which are (i) downconversion and digitisation, (ii) instantaneous frequency evaluation, and (iii) parameters estimation.

### *A. Downconversion and digitisation*

The RF bluetooth signal produced by the transmitter under test is first downconverted to intermediate frequency, in order to be digitised by a suitable data acquisition system. The digitised signal is then passed to a suitable digital signal processing unit.

### *B. Instantaneous frequency evaluation*

The instantaneous frequency trajectory of the signal is evaluated by applying the STFT.

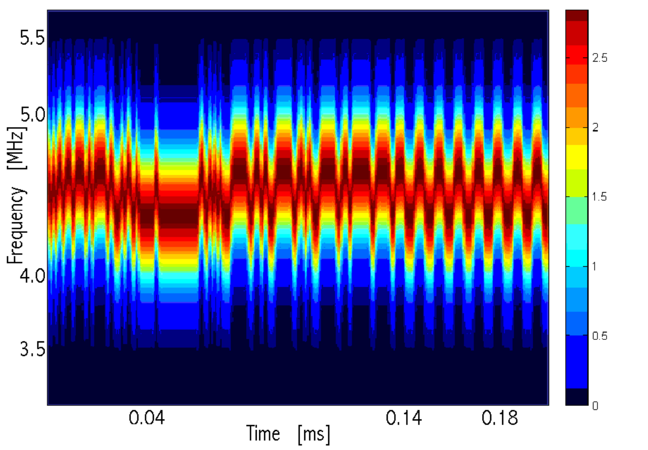


Fig.3. Planar representation of the spectrogram of a bluetooth signal downconverted to intermediate frequency; different brightness is associated to different values of the power

STFT results are taken in modulus and squared in order to attain the spectrogram [10-11]. Spectrogram is represented by means of a matrix whose values are dependent of time (column indexes) and frequency (row indexes). Through the spectrogram, the evolution versus time of the power spectral density of the analysed signal can be highlighted. As an example, Fig. 3 furnishes a graphic of the spectrogram of a bluetooth signal: in the planar map different brightness is associated to different values of the power density; time is reported on the x-axis; frequency is reported on the y-axis.

As the maximum power density in each time instant is associated to the instantaneous frequency of the signal, the frequency trajectory of the signal can be evaluated by applying peak location algorithms to the spectrogram. Specifically, peak location algorithms operate on the columns of the matrix, which contain the values of the power spectral density of the signal at the particular instant associated to the column index. For each column the row index in correspondence of which the power density is maximum is collected in an array that shows the evolution versus time of the frequency of the analysed signal.

It is worth highlighting that STFT results vary according to the type and length of the window adopted by the transform. As an example, Fig.4, Fig.5, and Fig.6 show the frequency trajectory extracted from three different spectrograms of a signal containing a live-traffic test sequence. The signal under test is downconverted to 3.6 MHz and digitised with a sample rate of 20 MSamples/s. In particular, Fig.4 shows the results attained by a spectrogram calculated using Hanning window characterised by 750 ns time duration, Fig.5 shows the results attained using 2 μs Hanning window, and Fig.6 shows the results attained by means of 750 ns Hanning window. Both the nominal and the measured traces are displayed in order to highlight as both the 2 μs Hanning window and the 750 ns Hamming window produce greater deviations between the nominal trajectory and the measured one (Fig.5 and Fig.6) than the 750 ns Hanning window.

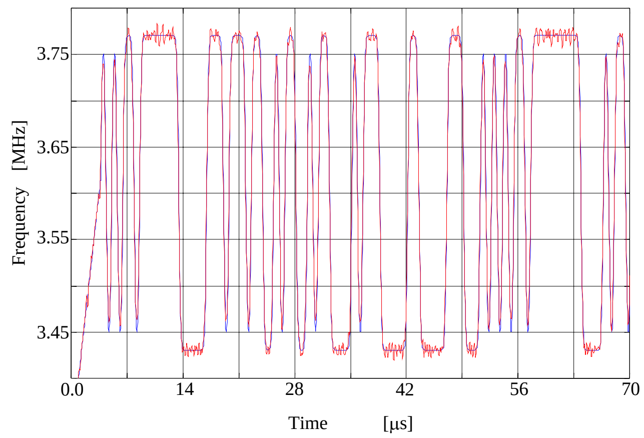


Fig.4. The frequency trajectory attained through the use of 750 ns Hanning window is displayed overlapped to the nominal trajectory.

### *C. Modulation quality assessment*

Once the evolution of the instantaneous frequency of the signal under test has been evaluated, all parameters, which have been introduced in section 2 for assessing modulation quality of bluetooth systems, are estimated in a very straightforward manner.

- For frequency deviations measurement, attention is focused on the payload of the signal, specifically, on consecutive sections containing 8 bits (8 μs time duration). In detail, according to the sample rate adopted for the digitisation of the signal, the array is divided into several small sub-arrays: as an example, in the presence of a signal acquired at 20 MSamples/s, each sub-array contains 160 sample points. For each sub-array the average and the maximum deviation from the average are estimated; only the set of values of the maximum deviations $\{\Delta f_{max}\}$ is stored. Finally, the average of the maximum deviations, $\Delta f_{avg}$ is computed.

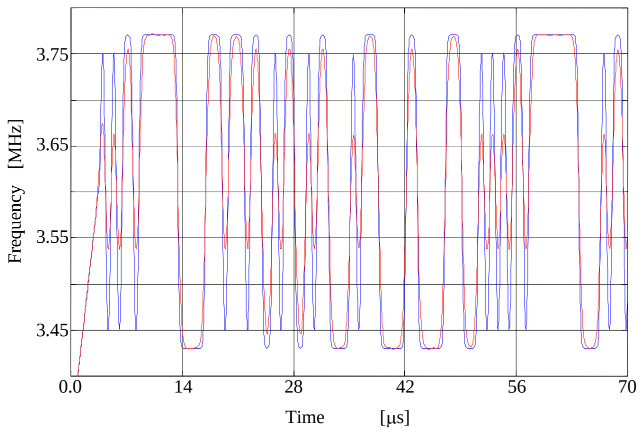


Fig.5. The frequency trajectory attained through the use of 2 µs Hanning window is displayed overlapped to the nominal one.

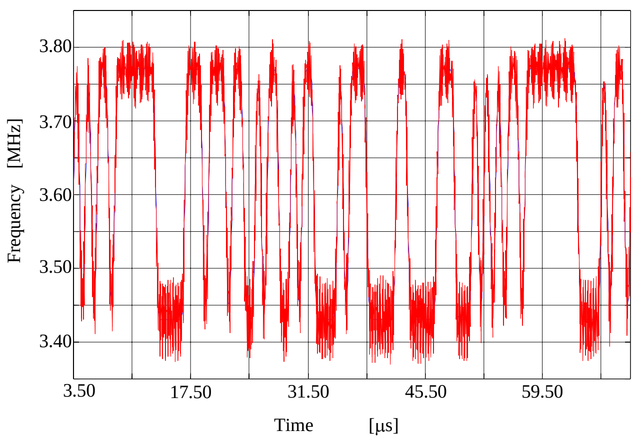


Fig.6. The frequency trajectory attanied through the use of 750 ns Hamming window is displayed overlapped to the nominal one.

- For frequency drift measurements, the preamble and the payload of the acquired packet are first recognised in the array of the instantaneous frequency trace. The sub-array corresponding to the bits of the preamble and all consecutive sub-arrays made up of 10 bits belonging to the payload are separated and processed. In particular, the average of each sub-array is first calculated, then the difference between the average frequencies that characterise all 10-bit sequences and that of the preamble are determined. The results are collected in a new array that shows the frequency drift of the signal versus time. Taking the first order difference of this new array highlights the drift-speed.

## 4. EXPERIMENTAL SET-UP

A suitable measurement station has been set up in order to verify the reliability of the method, and, contemporaneously, highlight the performance enhancements produced by different tunings of TFR parameters.

### *A. Measurement station*

The measurement station adopted for the experimental tests includes a dual channel arbitrary waveform generator (12-bit D/A resolution), an RF signal generator (100 kHz-2.0 GHz), a data acquisition system (8 bit vertical resolution, 1 GHz bandwidth, 4 GSamples/s maximum sample rate), and two swept spectrum analysers, both used in zero span mode as downconverters: the first (9 kHz-2.9 GHz) allowing downconversion to 21.4 MHz intermediate frequency, the second (9 kHz-2.2 GHz) to 3.6 MHz intermediate frequency.

### *B. Signal generation*

The first step for the experimental activity has been the generation of test signals according to bluetooth RF modulation specifics. These signals have been arranged performing I/Q modulation. In particular, the baseband I and Q components of the binary-GFSK signal have been digitally synthesised, and, then, produced in analogue form by means of the arbitrary waveform generator. Then, the analogue baseband components (I and Q) are passed to the I and Q input channels of the RF signal generator that produces the bluetooth signal. Due to the limited output range of the signal generator, the carrier frequency selected for the signals used in the tests ranges from 1.8 GHz up to 2.0 GHz, which is below the ISM band.

### *C. Data acquisition*

The analogue signal is first downconverted and then digitised. The sample rate selected for the digitisation depends on the frequency of the downconverted signal. In particular, 20 MSamples/s sample rate is adopted in the presence of signals downconverted to 3.6 MHz, while 100 MSamples/s sample rate is adopted in the presence of signals downconverted to 21.4 MHz.

## 5. TUNING OF THE MEASUREMENT ALGORITHM

The experimental activity has considered four different windows, specifically, Hanning, Hamming, Gaussian and Blackmann windows. For each window the measurement of the instantaneous frequency trajectory of the test signal has been repeated holding on the window and varying its length. The values of peak error and rms error characterising the difference between the measured instantaneous frequency and the nominal one attained in the presence of live-traffic test sequences are reported, respectively, in Fig.7 and Fig.8.

In this experiments the signal under test is downconverted to 3.6 MHz and digitised with a sample rate of 20 MSamples/s. As it is shown in Fig 8 the minimum peak error is attained by Hanning window characterised by 750 ns time duration; due to the 20 MSamples/s sample rate the window is made up of 15 coefficients. The minimum rms error is attained, instead, by means of Hanning window characterised by 650 ns time duration (13 coefficients). It is worth noting, however, that the rms error attained by means of 750 ns Hanning window is only slightly greater than the absolute minimum (650 ns).

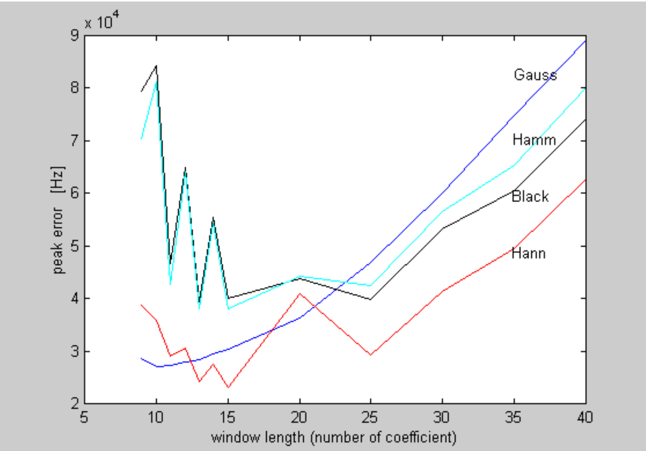


Fig.7. Peak error comparison in the presence of live-traffic bit sequences. Gaussian, Blackmann, Hanning and Hamming windows are considered.

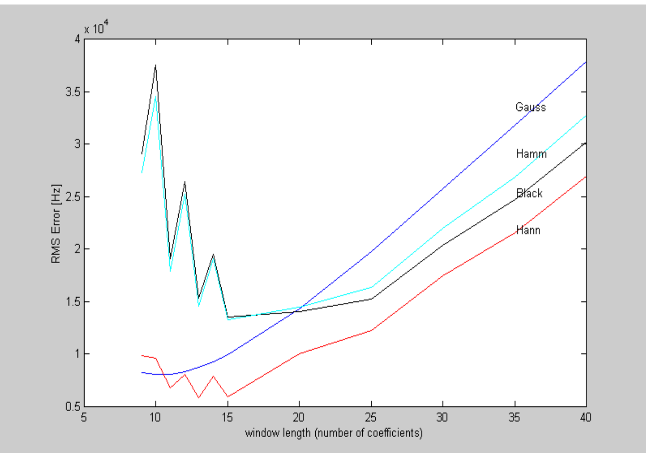


Fig. 8. Rms error comparison in the presence of live-traffic bit sequences: Gaussian, Blackmann, Hanning and Hamming windows are considered.

Different test arrangements demonstrate that these results are independent both of the carrier frequency of the test signal and the intermediate frequency to which the signal is downconverted. Moreover, experiments show that 750 ns Hanning window is also the optimal set-up of parameters to be used in the presence of signals characterised by repeated 8-bit 01010101 test sequences. On the contrary, in the presence of frequency variations imposed by repeated 8-bit 00001111 sequences, the minimum peak error is granted by Gaussian window characterised by 750 ns time duration, while the minimum rms error is assured by Gaussian window characterised by 650 ns.

## 6. EXPERIMENTAL RESULTS

*a)* Table I shows the results obtained by applying the proposed method to a signal containing a payload that consists of the repetition of the pattern 00001111. In these experiments the STFT has been performed adopting 750 ns Gaussian window. In particular, Table I shows the results of the analysis of 10 packets: for each packet the value $\Delta f_{1avg}$ is measured. Repeated measurements on the same packet have been carried out in order to highlight the experimental standard deviation of the measured data, $\sigma(\Delta f_{1avg})$, which is also given in Table I. The results achieved in the presence of a payload made up of repeated 01010101 8-bit sequences are shown, instead, in Table II. The STFT has been performed adopting 750 *ns* Hanning window. Table II shows the values of $\Delta f_{2avg}$, and of its standard deviation, $\sigma(\Delta f_{2avg})$.

The proposed method evaluates the ratio in (3) offering results characterised by an experimental standard deviation, $\sigma(\Delta f_{2avg}/\Delta f_{1avg})$ which is, in the worst case and in percentage relative terms, inferior to 2,5%.

*b)* Furthermore, experimental tests carried out on test signals affected by a known frequency-drift demonstrate that frequency-drift measurements attained by means of the proposed method are characterised by an experimental standard deviation that is inferior to 0,7% of the measured value.

**Table I**

| Packet | $\Delta f_{1avg}$ [kHz] | $\sigma(\Delta f_{1avg})$ [kHz] |
|---|---|---|
| 1 | 160,38 | 0,72 |
| 2 | 160,35 | 0,74 |
| 3 | 160,44 | 0,73 |
| 4 | 160,42 | 0,77 |
| 5 | 160,39 | 0,71 |
| 6 | 160,39 | 0,77 |
| 7 | 160,36 | 0,74 |
| 8 | 160,36 | 0,72 |
| 9 | 160,45 | 0,78 |
| 10 | 160,35 | 0,72 |

**Table II**

| Packet | $\Delta f_{2avg}$ k[Hz] | $\sigma(\Delta f_{2avg})$ [kHz] |
|---|---|---|
| 1 | 140,0 | 2,3 |
| 2 | 140,0 | 1,3 |
| 3 | 138,9 | 1,9 |
| 4 | 139,3 | 2,9 |
| 5 | 141,3 | 2,0 |
| 6 | 137,8 | 2,4 |
| 7 | 140,6 | 2,7 |
| 8 | 139,8 | 2,2 |
| 9 | 140,7 | 1,6 |
| 10 | 137,5 | 2,2 |

*c)* Finally, Table III presents the results of ICFT measurements in the presence of a signal characterised by frequency hopping. Two consecutive slots of the signal under test, which, due to frequency hopping, are spaced 2 MHz apart from each other, are acquired and analysed. As downconversion moves the input RF signal to 3.6 MHz, the carrier frequency of the downconverted signal resides at 2.6 MHz in the first slot and hops to 4.6 MHz in the second slot. The signal is acquired with a sample rate of 20 MSamples/s. Each test has been repeated about one hundred times and a statistical analysis has permitted the estimation of the standard deviation of the measured data. In these tests different values have been imposed to the initial frequency offset. In particular, Table III shows the results obtained when ICFT nominal values of 350 Hz and 500 Hz are imposed, respectively, to the carrier of the first slot and to that of the second slot.

**Table III**

| | *downconverted carrier 2.6 MHz* | | *downconverted carrier 4.6 MHz* | |
|---|---|---|---|---|
| ***ICTF [Hz] Nominal*** | ***ICFT [Hz] measured*** | ***std-dev [Hz]*** | ***ICFT [Hz] measured*** | ***std-dev [Hz]*** |
| ***350*** | ***347*** | ***16*** | ***350*** | ***14*** |
| ***500*** | ***501*** | ***16*** | ***501*** | ***13*** |

The experimental standard deviation is comparable to that of dedicated instruments available on the market [4-5].

It is worth highlighting that the experimental standard deviation of the measurement results includes various contributions produced by different sources, such as the dual channel arbitrary waveform generator, the RF signal generator, the data acquisition system, and the measurement algorithm. Anyway, if the specific contributions of the arbitrary waveform generator and the RF signal generator are neglected with respect to that of the data acquisition system and the measurement algorithm, as it is the case of the adopted measurement set-up, the experimental standard deviation confirms the reliability and efficacy of the proposed method.

## 7. CONCLUSIONS

In this paper a measurement method for the evaluation of the parameters assessing the modulation quality of bluetooth transmitters has been presented. The method is based on a digital signal processing approach that uses a particular Time Frequency Representation, the Short Time Fourier Transform. The method has been refined and validated throughout a great number of experimental tests.

An optimisation study addressed to the recognition of the optimal set-up of TFR parameters has put in evidence that standard deviation of measurement results is minimised by, respectively, 750 ns Hanning window, in the presence of live-traffic or 01010101 bit sequences, and 750 ns Gaussian window, in the presence of 00001111 test sequences.

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