XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

A WAVELET PACKET TRANSFORM-BASED APPROACH FOR INTERFERENCE MEASUREMENT IN SPREAD SPECTRUM WIRELESS COMMUNICATION SYSTEMS

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Abstract − The paper mainly concerns interference measurement in spread spectrum, wireless communication systems. A new digital signal-processing method is proposed, which proves non intrusive and independent of the specific system considered. Thanks to the nice properties of the wavelet packet transform, the method is capable of extracting the occurred interference from the spread spectrum signal, thus ensuring accurate interference magnitude and frequency estimates also in critical conditions: interference level much smaller than that characterizing the spread spectrum signal, and interference spectral content very close to the carrier centre frequency of the considered system.

Keywords: *Interference measurement*, *RF measurement*, *Spread spectrum systems*, *Wireless systems, Wavelet packet transform*.

1. INTRODUCTION

Spread spectrum systems have encountered the favour of wireless communication engineers and researchers for a long time [1],[2]. They are nowadays playing a fundamental role in most third-generation (3G) telecommunication proposals [3]. The reason of this success relies essentially on superior operation in multipath environments, better flexibility in the allocation of channels, and increased capacity in bursty or fading channels with respect to conventional narrowband systems.

Although spread spectrum systems have the inherent interference suppression capability, in the strong, non-stationary and sometimes hostile electromagnetic environment, receiver operation may be very disturbed by the presence of interferers, which are often an unavoidable problem [4],[5]. The interference, both intentional, as in military communications, and non-intentional, as in a spectral overlay system [4], can regularly reach such an intensity as to make the processing gain of the system insufficient for the extraction of the desired information from the received spread spectrum signal [6]. Thus, with the aim of pursuing maximum system performance, accurate interference measurements can prove very helpful for a reliable characterization of communication channels, and, consequently, for a proper optimisation of receiver design.

This kind of measurement is not an easy task. In most spread spectrum systems, in fact, streams of data are encoded on a single carrier using a pseudo-random code, with a resulting high and variable crest factor (ratio of peak power to average power) and a power spectrum exhibiting white-noise-like features [7],[8].

Referring to the scientific literature, neither methods nor techniques, expressly devoted to interference measurement, seem to be described; the only solutions of interest are those forming the input section of a variety of receivers, optimised for interference excision [6],[9]-[11]. These solutions, always based on a digital signal-processing approach and often mandated to a preliminary estimation of the interference and a subsequent subtraction of it from the received signal, differ from one another in the domain (time [9], frequency [10], or time-frequency [6],[11]) they operate. Those involving a two-dimensional (time-frequency) domain have recently captured a great deal of interest due to their inherent capability of ensuring good performance also in the presence of non-stationary interference, thus overcoming a relevant limitation of all solutions based on a one-dimensional (time or frequency) approach. Nowadays, in fact, most interferers, including communications signals, radars or jammers, and even impulsive noise bursts, are in some way characterized by a localized time-frequency content [6],[11].

Moreover, at the best of the author's knowledge, few apparatuses, expressly devoted to interference measurement in spread spectrum systems, seem to be available on the market. Some of them, however, need to disable traffic on the channel to be measured, with a consequent inefficiency for final users (intrusive measurement) [12],[13]. Others of them need to demodulate the RF signal in order to apply suitable error vector magnitude (EVM)-based measurement procedures, thus becoming wholly dependent on the specific spread spectrum system considered [14].

The paper proposes a digital signal-processing method for interference measurement in spread spectrum, wireless communication systems. By combining the use of the wavelet packet transform (WPT), one of the most promising time-frequency approaches for interference mitigation [15], and coherent structure extraction (CSE) algorithm [16], the method (i) proves totally independent of the specific spread spectrum system considered, (ii) allows non intrusive measurements, and (iii) assures satisfying accuracy for different types and levels of interference.

The results of many laboratory tests, carried out on spread spectrum signals affected by different types of interferers, carrier wave interference, chirp carrier wave interference, and narrowband interference show the reliability and efficacy of the method.

2. INTERFERENCE IN WIRELESS SYSTEMS

Interference can be categorized by its sources, as well as its effect on the desired communications [12],[13].

- Concerning the sources, there is a long list of possible offenders capable of creating signals that accidentally or intentionally interfere with wireless RF signals. Here are a few of the most common sources.
  - ✓ *Improperly configured transmitter*
    Another operator is transmitting on the frequency of interest. Most often, this is the result of a fault or an incorrect setting in the offending transmitter.
  - ✓ *Unathorised transmitter*
    The offending operator is intentionally working in the frequency band considered, usually because he has no license at all.
  - ✓ *Cell overlap*
    A cell from the considered network, or others, exceeds specified coverage in one or more channels.
  - ✓ *Intermodulation*
    It can be the result of one or more external RF signals entering the offending transmitter's non-linear final amplifier stage. The external signals mix with each other and with the transmitter's own signal, creating intermodulation products that appear as new (and often very undesirable) frequency components in the communication band.
  - ✓ *Harmonics*
    Signals provided by high-powered sources, such as commercial broadcast stations, may contain harmonics of the fundamental frequency, which are strong enough to cause interference with nearby wireless communications. The identification of the source is often very difficult. The multiplication process that creates the harmonic alters the spectrum signature as well; its width and deviation are multiplied by the same factor as the carrier frequency.
- With regard to the effect of the interference on the communications, a distinction should be made between two major classes of interference.
  - ✓ *Off-frequency interference*
    This class includes strong signals that are not at the exact centre frequency of the communication channel, but are strong enough to affect the input of any receiver.
  - ✓ *On-frequency interference*
    This second class of interference refers to signals (weak or strong) that are at the same frequency as the intended communication signals.

3. THEORETICAL BACKGROUND

The basic idea underlying the proposed method is to decompose the spectral content of the signal under analysis into uniform frequency subbands, according to the desired frequency resolution, and, then, to treat them individually in order to detect and extract from the original signal the interference eventually occurred. To this aim, the use of the

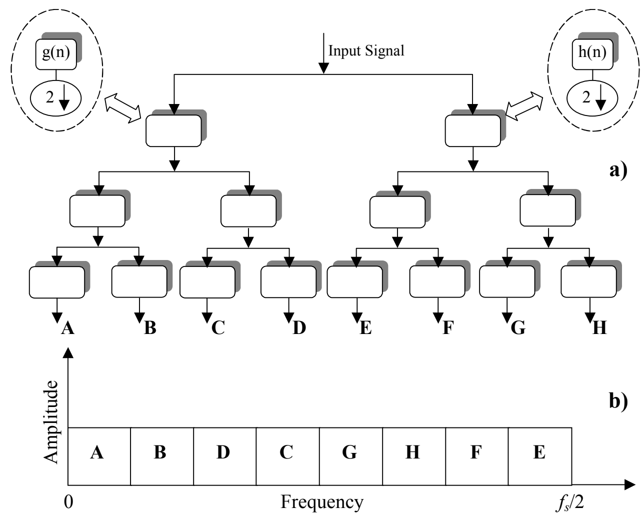

Fig.1. a) WPT analysis tree: the decomposition of the input signal into uniform frequency subbands is pursued. The correspondence between each sequence (from **A** to **H**) obtained at the end of the last decomposition level and the frequency subband containing the related spectral content is highlighted in b).

wavelet packet transform (WPT) as a powerful digital signal-processing (DSP) tool has shown itself very appropriate.

The WPT, a natural extension of the wavelet transform, provides a level-by-level decomposition of the input signal from the time domain to the frequency domain according to a full binary tree, also called analysis tree. The decomposition is obtained by simple cascade filtering and downsampling: the signal is filtered using two analysis filters and subsampled by a factor of two, yielding two new sequences. This process is iterated over and over again on the newly created sequences; as the levels are being computed from top-down, the temporal resolution of the decomposition decreases, while its frequency resolution increases. For the sake of clarity, an example of three-level analysis tree is given in Fig.1a.

Each level of the decomposition uses the same couple of filters: a low-pass one, whose impulse response is generally denoted by $g(n)$, and its mirror version (high-pass), whose impulse response is $h(n)$. The result is a uniform decomposition in frequency subbands, which cover the interval extending from 0 Hz up to the half of the sample rate, f_s, adopted in digitising the input signal (Fig.1b).

Once the last decomposition level is over, the coefficients of each created sequence (from **A** to **H** in Fig.1), also called WPT coefficients, can further be processed through specific DSP algorithms, or simply reconstructed by means of the inverse wavelet packet transform (IWPT), which is implemented through a synthesis tree whose structure is very similar to that of the analysis tree [17].

A worthy algorithm often applied to the WPT coefficients is known as coherent structure extraction (CSE) [16]. It allows the separation, in the time domain, of two signals having different power levels and sharing the same frequency subband; the lower the correlation between the two signals, the better the results of the algorithm (the sharper the separation). Specifically, the theoretical dimension, N_0, of the analysed sequence is first evaluated according to

$$N_0 = e^H \quad , \tag{1}$$

where H is the normalized entropy of the related coefficients, c_i, expressed as

$$H = -\sum_i \frac{|c_i|^2}{\|C\|^2} \cdot \log \frac{|c_i|^2}{\|C\|^2} \quad , \tag{2}$$

and

$$\|C\|^2 = \sum_i |c_i|^2 \quad . \tag{3}$$

The value of N_0 may range from 0 up to the sequence length, N; it is a kind of information cost describing how many of the coefficients are significant to reconstruct the original signal as reliable as possible. Then, after arranging the coefficients in decreasing values, a fraction of N_0, $N_0' = \delta \cdot N_0$, is established according to a threshold, δ, the value of which is inside 0-1 and *a priori* known. The N_0' big coefficients and the remaining $(N_0 - N_0')$ small ones are thus singled out. The reconstruction of the big coefficients yields the higher level signal, also called coherent part, while the reconstruction of the small ones produces the lower level signal, also called remainder part. The combined application of the WPT and CSE algorithm can be iterated on the newly created remainder parts in order to make the separation between the two signals much sharper.

4. PROPOSED METHOD

The fundamental steps of the proposed method are roughly sketched in Fig.2. In the following, their description is given with references to an application example.

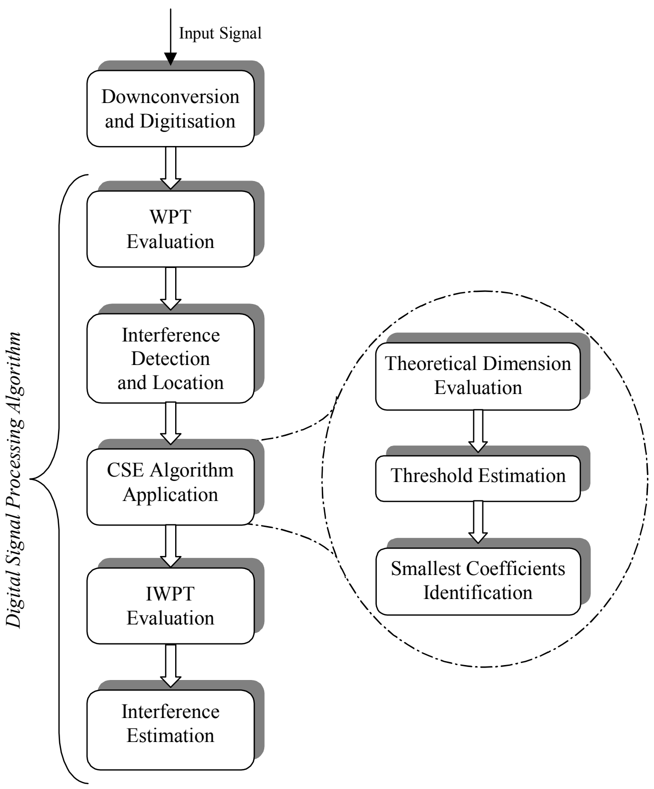

Fig.2. Block diagram of the proposed method.

4.1. Downconversion and digitisation

The input signal is at first downconverted to a suitable intermediate frequency value according both to the maximum sample rate and memory depth of the data acquisition system mandated to its digitisation.

As an example, Fig.3 concerns magnitude spectrum estimates related to wideband code domain multiple access (W-CDMA) signals, downconverted to 21.4 MHz and digitised at a sample rate, f_s, of 50 MS/s. W-CDMA signals exhibit spread spectrum features, and they are peculiar to the universal mobile telecommunication system (UMTS), the European proposal of a third generation (3G) telecommunication system. Fig3a accounts for a signal free from interference, while Fig.3b refers to the same signal affected by low-level carrier wave interference (CWI). The root mean square (rms) value of the W-CDMA signal is equal to 1.6 V, the spectral content of the interference is positioned in the centre of the transmission channel (on-frequency interference), and the interference-to-signal ratio (ISR) is equal about to 0.05. It can clearly be noted that singling out the occurred interference through an accurate examination of the magnitude spectrum of Fig.3b is an extremely, or even impossible, task. No valuable difference between the two spectra of Fig.3a and Fig.3b can, in fact, be appreciated.

4.2. WPT evaluation

The wavelet packet transform of the acquired signal is evaluated according to the analysis tree described in the

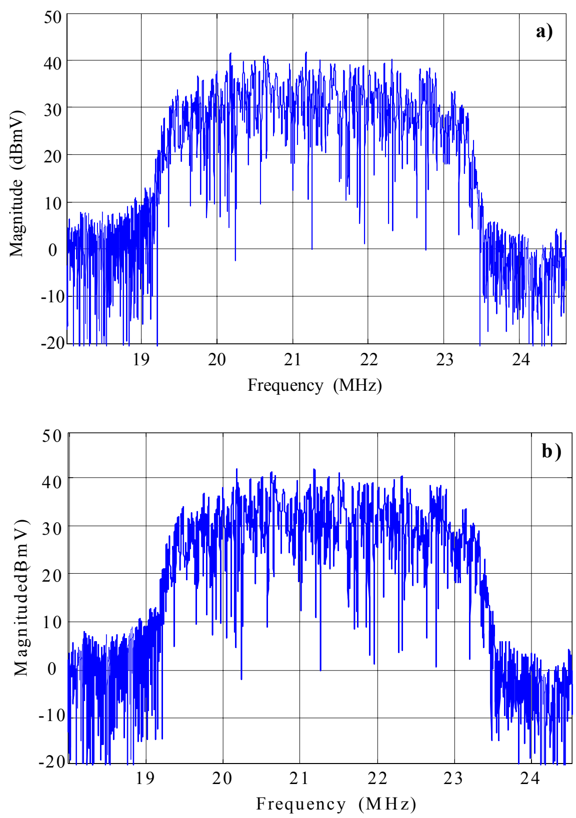

Fig.3. Magnitude spectrum estimate of a W-CDMA signal a) not affected and b) affected by low-level carrier wave interference. No valuable difference between the two spectra can be appreciated.

previous section. The number of levels has to be established according to the desired frequency extent of the subbands that result when the analysis process is over; it is worth stressing that subband extent halves at the end of each decomposition level. The chosen extent ultimately stands for the frequency resolution achievable in interference detection and related spectral content location, the goal of the successive step.

In the considered example a five-level analysis tree has been adopted, thus gaining a frequency resolution of about 780 kHz.

4.3. Interference detection and spectral content location

To check the presence of interference and locate its spectral content, a straightforward idea has been made operative. It relies upon a nice property of most spread spectrum signals: their white-noise-like nature makes the power spectrum approximately flat all over the channel bandwidth.

Among all frequency subbands obtained at the previous step, only those covering the transmission channel of interest are selected for successive analysis. In particular, the power level, p, characterising the coefficients of each of them is first evaluated according to

$$p = \sum_{i=1}^{N} \left| c_i \right|^2 \quad . \qquad (4)$$

For what stated above, it can be expected that, in the absence of interference, each selected subband roughly exhibits the same value of p. If, instead, interfering signals affects one or more of the selected subbands, the related value of p raises with respect to that characterising all the other subbands. Consequently, after evaluating the average power level, p_m, according to

$$p_m = \frac{1}{M} \sum_{j=1}^{M} p_j \quad , \qquad (5)$$

where M is the number of the selected subbands and p_j is the power associated to a generic one, interference detection is accomplished by singling out those subbands, also called offended subbands, whose p_j is greater than p_m of a certain amount, K, the user can fix as a percentage of p_m itself. Furthermore, it is also reasonable to suppose that most spectral content of the occurred interfering signals falls inside the so-determined offended subbands (spectral content location).

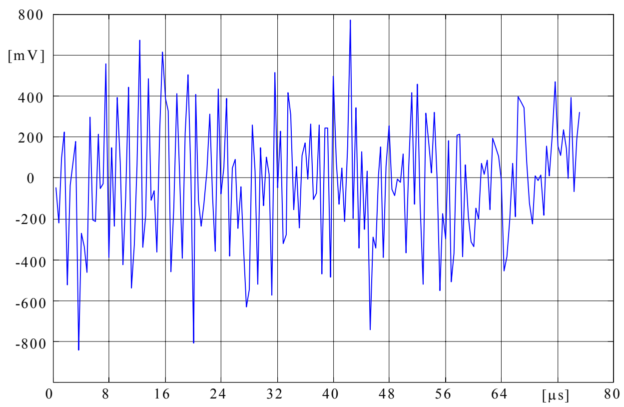

Fig.4. Time domain representation of the content of the frequency subband in which the carrier wave interference has been located.

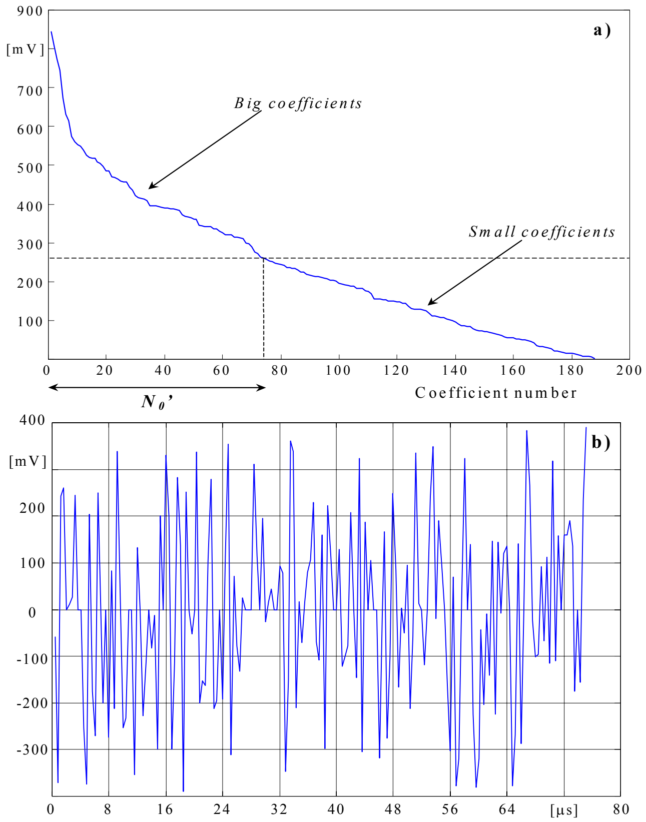

Fig.5. a) The value of N_0' allows the selection of the coefficients of interest (small coefficients), the time domain evolution of which is given in b).

Due to the frequency resolution achieved in the given example, only five subbands are needed to cover the UMTS channel bandwidth (about 4 MHz). Through the application of the described procedure, the imposed CWI has correctly been located in the subband characterised by the frequency interval 21.094 – 21.875 MHz. The time domain representation of the offended subband is shown in Fig.4.

4.4. CSE algorithm application

After calculating the theoretical dimension, N_0, of each offended subband according to the relations (1), (2) and (3), the attention has to be paid to the associated threshold δ.

The results of many experiments, described in detail in Section V, have suggested an heuristic rule, according to which the value of δ has to be equal to the reciprocal of the peak-to-average ratio (PAR) characterising the power spectrum of the specific subband. A fair power spectrum estimate can be attained through the application of reliable and well-known digital signal-processing algorithms, such as weighted overlapped segment averaging (WOSA) estimators or multitaper approaches [18], to the WPT coefficients of the subband.

Once the value of δ is known, the small coefficients of the offended subbands can be pointed out. As stated in Section III, it is reasonable to suppose that these coefficients contain only the information connected to the occurred interference.

Concerning the treated example, the value of the threshold δ has been established by applying a WOSA

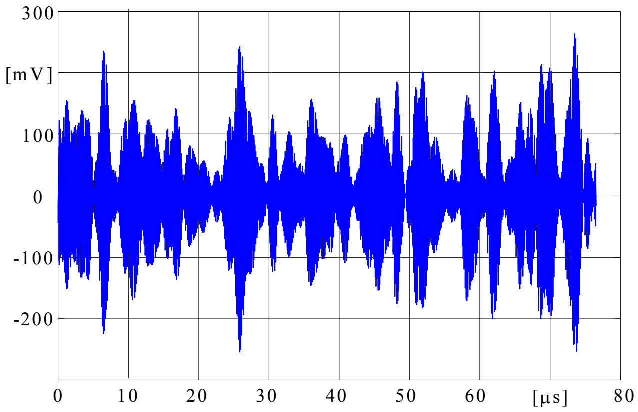

Fig.6. Time domain evolution of the signal obtained from the application of the IWPT synthesis procedure to the small coefficients depicted in Fig.5b.

power spectrum estimator to the WPT coefficients of the offended subband. In particular, δ has resulted equal to 0.625, thus implying for N_0' a value of 75 (N_0 is equal to 120). Fig.5a shows the aforementioned coefficients arranged in decreasing values; the fundamental role played by N_0' in the selection of the small coefficients is also highlighted. For the sake of completeness, the time domain evolution of the small coefficients is given in Fig.5b.

4.5. IWPT evaluation and interference estimation

The inverse wavelet packet transform (IWPT synthesis procedure) is applied to the small coefficients of each offended subband. The reconstructed signal roughly accounts for the time domain evolution of the interference affecting the subband. A frequency domain representation of

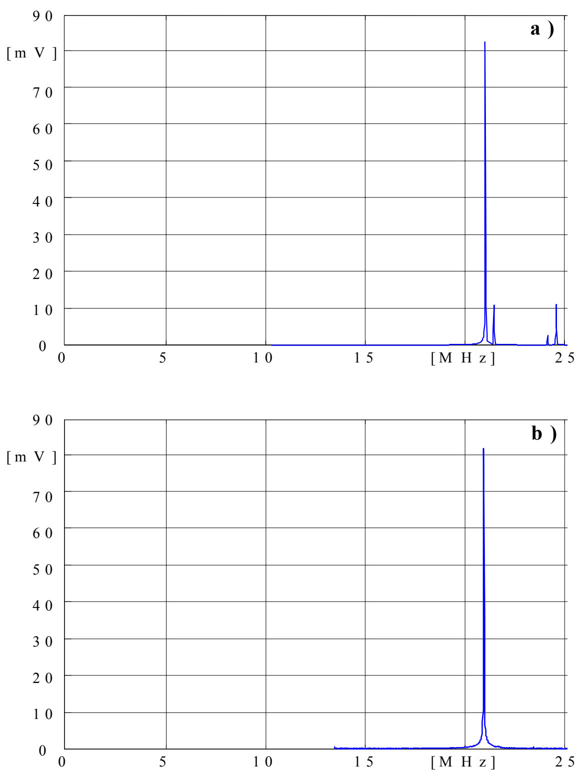

Fig.7. Magnitude spectrum of the a) reconstructed signal and b) originally imposed on-frequency interference.

the interference could be very helpful in straightforwardly measuring its magnitude (generally rms value) as well as fundamental or centre frequency, f_i.

The synthesis process applied to the small coefficients depicted in Fig.5b has furnished the results given in Fig.6. The magnitude spectra of the reconstructed signal and the originally imposed interference are given in Fig.7a and Fig.7b, respectively. Both spectra have been attained through a fast Fourier transform-based algorithm with the use of a rectangular window. It is worth noting that the fundamental frequency of the interference has correctly been located around 21.4 MHz, while a rms value (about 83 mV) matching well with the original one has been experienced.

5. METHOD VALIDATION

The performance of the proposed method has been assessed through a number of experiments on emulated spread spectrum signals affected by known interference (known values of the centre frequency as well as ISR). The emphasis has been put on (i) W-CDMA spread spectrum signals because of the fundamental role they nowadays play in telecommunications, and (ii) three types of common interferers [4]-[6],[9]-[11]: carrier wave interference (CWI), chirp CWI, and narrow band interference (NBI).

To this aim, a suitable measurement station has been set up. It consists of (i) a processing and control unit, namely a personal computer, (ii) a digital radiofrequency (RF) signal generator, *Agilent Technologies E4431B*^{TM}, (250 kHz-2 GHz output frequency range, I/Q analog inputs) with arbitrary waveform generation (AWG) capability (14-bit vertical resolution, 1 Megasample memory depth, 40 MHz maximum generation frequency), (iii) a spectrum analyzer, *Agilent Technologies HP 8594E*^{TM}, (9 kHz-2.9 GHz input frequency range, 21.4 MHz IF output), and (iv) a data acquisition system, *LeCroy LC 584AL*^{TM}, (8-bit resolution, 1 GHz bandwidth, 8 GS/s maximum sample rate); they all are interconnected by means of an IEEE-488 interface bus.

Baseband (I/Q) components, compliant with W-CDMA recommendations and affected by known interference, have first been produced numerically, and then downloaded into the internal memory of the signal generator, which have translated them to RF through quadrature amplitude modulation (QAM). The so obtained RF signals have been downconverted to a tune frequency of 21.4 MHz by the spectrum analyzer, to be, subsequently, routed to the input of the data acquisition system (f_s = 50 MS/s). The digitized samples have been retrieved from the memory of the data acquisition system by the processing and control unit, and passed to the digital signal-processing software implementing the proposed method. To prevent the inherent periodicity of the emulated signals affecting the measurement results, the repetition period of the AWG section of the RF signal generator have been fixed in such a way as to be greater than the time interval covered by the acquired record, to which the proposed method has been applied. Furthermore, due to the fine frequency resolution they assure, the couple of Daubechies filters with 88 coefficients [16] has been adopted both in the analysis and synthesis stage of the WPT.

Adding numerically the interference at baseband has given the opportunity of easily adjusting the related spectral content as well rms value. In particular, chirp CWI interference has been produced using a sinusoidal signal with a frequency that sweeps over a narrow band included in the channel of interest. NBI interference has, instead, been originated using a noise generator filtered by a 8th order bandpass elliptic filter.

The three types of interferers have always been configured as on-frequency interference. For each of them, the considered centre frequency, f_i, values (20 MHz, 21.4 MHz, and 23 MHz) have always been positioned inside the UMTS channel bandwidth around the adopted 21.4 MHz intermediate frequency. Moreover, with regard to stationary CWI, four ISR values (0.075, 0.1, 0.2, and 0.3) have been taken into account. Concerning chirp CWI as well as NBI, four values of the ratio, ISBW, between ISR and the bandwidth of the occupied narrow band (0.35 MHz^{-1}, 0.5 MHz^{-1}, 1 MHz^{-1}, and 1.5 MHz^{-1}) have been examined; the considered bandwidths have ranged in 50 kHz-400 kHz.

For each couple of values, f_i and ISR for CWI or f_i and ISBW both for chirp CWI and NBI, the proposed measurement algorithm has processed about 100 W-CDMA signals. The extremes of the offended subbands singled out along with the rms amplitudes of the imposed interference have been collected. The formers have given the possibility of checking the correctness of interference spectral content location; the latters have been examined with the aim of evaluating i) the difference, Δ, between their mean value, μ, and the nominal one in order to single out possible bias, and (ii) the experimental standard deviation, σ. In all tests, a five-level decomposition tree has been adopted for WPT analysis, and the value of K has been fixed equal to 10%.

For the sake of brevity, only the results concerning NBI are illustrated. In particular, the values of Δ and σ, both expressed in percentage relative terms, are given in Table I, and no failure in locating the spectral content of the interferer in the right subband has been experienced. From Table I, the following considerations can be drawn.

- The smallest Δ and σ are obtained both for increasing ISBW values and for interference centre frequencies not so close to the middle of the channel of interest.
- The performance the method exhibits in critical conditions is satisfying if compared to that granted by most measurement solutions available on the market.

Very similar results have been obtained for the other types of interfering signals.

Table I. Values of Δ and σ, in percentage relative terms, obtained in the tests on emulated W-CDMA signals affected by narrow band interference.

	ISBW			
	0.35 MHz^{-1}	0.5 MHz^{-1}	1 MHz^{-1}	1.5 MHz^{-1}
	f_i =20 MHz			
Δ [%]	4.8%	4.9%	3.2%	1.2%
σ [%]	0.72%	0.53%	0.53%	0.48%
	f_i =21.4 MHz			
Δ [%]	7.0%	6.5%	4.1%	1.5%
σ [%]	0.85%	0.66%	0.62%	0.55%
	f_i =23 MHz			
Δ [%]	5.1%	4.5%	3.4%	1.0%
σ [%]	0.64%	0.57%	0.54%	0.46%

6. CONCLUSIONS

Thanks to the combined use of the WPT and CSE algorithm, the proposed method for interference estimation in spread spectrum systems succeeds in overcoming some notable limits of most measurement solutions. It has proved both non invasive and completely independent of the spread spectrum system analysed.

Moreover, preliminary tests on emulated signals have highlighted that the method could assure a measuring accuracy in critical conditions (6-7%) comparable to that offered by other instruments, already available on the market and expressly devoted to interference measurement.

Future research activity is mainly oriented to enlarge the set of spread spectrum signals to be used in the tests, and assess the performance of the method also in the presence of more than one interfering signal.

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