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INTERFERENCE SENSITIVITY OF AN AUTOMATIC MODULATION CLASSIFIER

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Abstract – In this paper, the experimental evaluation of the prototype of an automatic digital modulation classifier, carried out in a shielded chamber, is described. In this particular environment, immune to external interference, the prototype has been tested against different types of out-of-band RF interfering signals, in order to assess its robustness. The results present good success percentages with a small reduction, in comparison with those achieved in absence of interference.

Keywords - Classification, digital modulations, shielded chamber measurements.

1. INTRODUCTION

Wireless communications history started in the 19^{th} century, since the first electric signal was transmitted through air and successfully by the advent of the radio and telegraph telecommunication systems. Today, there is a wide use of wireless technologies for daily ordinary tasks, with a fast growing list of applications, including TV and radio broadcasting, mobile phone, home automation, Internet access, voice and data transfer and many others. In particular, technologies such as GSM (Global System for Mobile Communications), Wi-Fi (Wireless Fidelity) and Bluetooth have become very popular, but also other technologies, such as UMTS (Universal Mobile Telecommunication System) and WiMAX (Worldwide interoperability for Microwave Access) are emerging rapidly in this increasingly wireless-oriented context.

In this scenario, every wireless technology has its own space in the Radio Spectrum. At any given time, there are thousands of radio frequency (RF) emissions. Therefore, it could be necessary to constantly monitor the radio spectrum, both for civil and military purposes. In the first case, monitoring is needed to avoid interference among systems that operate on the same frequency (ZigBee, WiFi, Bluetooth, TV transmitters, and so on), in the second case to understand the identity of an unknown RF source and to recognize the presence of any enemy force. In order to deal with such necessities, a system able to capture an unknown signal without any a priori information and to identify automatically the type of transmission has been proposed in [1]. An overview of several methods trying to solve the modulation classification problem is included in [1], [2]. Among those cited, the main classification methods rely on a statistical approach [3], [4], neural networks [5], [6], time-frequency representations [7], [8] and zero-crossing techniques [9], to achieve the target. However, the most part of them are able to identify a restricted number of modulations or they are processing power and/or time consuming. The general method, proposed in [1], to automatically classify almost all kinds of digital modulation schemes adopted in the current digital telecommunication systems, has been specialized in [2], by presenting two classification methods, according to the possible hardware architectures of the classification instrument. One of the methods is able to work on direct acquisition systems as those included in Waveform Digitizers (WDs). This method does not require the knowledge of the carrier frequency [2]. The second method works on I-Q based demodulation and acquisition systems, as those included in Vector Signal Analyzers (VSAs). This last method has been already implemented and experimentally validated on a Real Time Spectrum Analyzer (RTSA) [10]. The purpose of this paper is to present the implementation of the second method on a WD-based hardware architecture and its experimental evaluation versus narrow- and wideband interference. The work is intended as an additional step of a precise develop sequence containing: simulations [2], emulations [10] and experimental tests, involved in absence of interference [11]. The achieved experimental results have been compared with those achieved on the VSA by means of the tests carried out by wiring directly the generator to the classifier in absence of interfering signals and presented in [10].

In the following section, a description of the method proposed in [1] is given. Subsequently, in Section III, an explanation of the novel measurement instrument prototype is presented and, in Section IV, a brief description of the test bench and the test procedure adopted to evaluate prototype interference sensitivity in a shielded environment is reported. Finally, in Section V, a detailed description of the tests and the discussion on the achieved results in comparison with the ones coming from the VSA-based architecture is reported.

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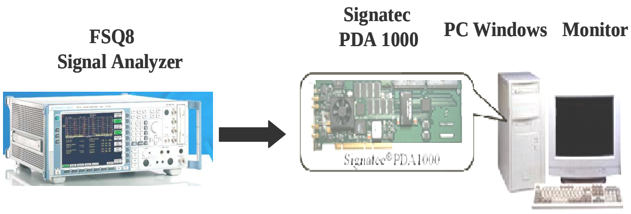

Fig. 2. Modulation Classifier Prototype.

2. THE ADOPTED METHOD

The method for the recognition of digital modulations proposed in [2] is able to recognize classical single carrier modulations such as M-ary Phase-Shift Keying (PSK), M-ary Frequency Shift Keying (FSK), M-ary Amplitude Shift Keying (ASK) and M-ary Quadrature Amplitude Modulation (QAM), as well as Orthogonal Frequency Division Multiplexing modulations, such as those used for IEEE 802.11g [12], Digital Video Broadcasting Terrestrial (DVB-T) [13] and HyperLAN [14]. It is based on a hierarchical decision tree, whose branches are selected starting from the root, and evaluating some signal parameters, as shown in Fig.1.

In this structure, the classification tree is composed by 8 decision points. First, the method selects the modulation type between the single-carrier (SC) and multiple-carrier (MC) ones (*step 1*), then, among the SC signals, it chooses between signals with or without frequency modulation (*step 2*). In the *step 3*, the classification method selects the modulation type among signals with one, two or 4-8 phase levels. The signals with one phase level are classified as Carrier Wave (CW). Finally, in the last steps, the recognition of the modulation type is carried out:

Among the SC 2-phase modulated signals, a module discriminates between Unlimited Bandwidth (UB) 2 PSK signals and amplitude modulated signals (*step 4*).

Among the SC 2-4-phase modulated signals, a module discriminates between 4-8 PSK UB signals and amplitude modulated signals (*step 5*).

Among the SC 2-phase amplitude modulated signals, a module discriminates between 4-8 ASK and Limited Bandwidth (LB) 2PSK signals (*step 6*).

Among the amplitude modulated signals with more than two phases, a module discriminates between QAM and LB-MPSK modulated signals (*step 7*).

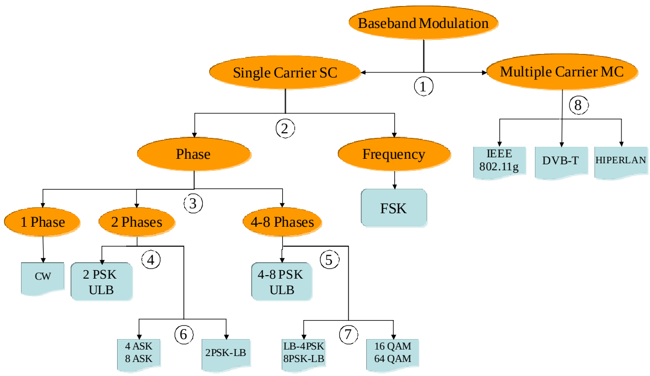

Fig. 1. Hierarchical three structure of the method.

Among the MC-modulated signals, a module has been developed to identify OFDM modulated signals with cyclic extension and to distinguish among signals compliant to IEEE 802.11g, DVB-T and HIPERLAN standards (*step 8*).

The method has some advantages: (i) the hierarchical approach allows dividing the classification problem in smaller and smaller sub-problems, saving processing resources; and (ii) the modularity makes the method flexible, by allowing to add or to remove steps of the recognition process, in order to adapt it to different modulation types.

This method requires an acquisition section, operating on the incoming RF signals directly or after a preliminary conversion to an intermediate frequency (IF). Therefore, it does not require the knowledge of the carrier frequency.

3. IMPLEMENTATION OF THE DIGITAL MODULATION CLASSIFIER

For the realization of the modulation classifier prototype, able to work on a WD, a device that could be programmed with a standardized and well known programming language, has been chosen in order to achieve the highest degree of hardware independence. In this way, in fact, the software controlling the instrument and executing the classification can be used on several data acquisition devices available on the market. For such a reason, the analog front-end necessary to process the incoming RF signals has been implemented externally to the classifier by means of a Rohde&Schwarz FSQ8 signal analyzer. Thanking to two Intermediate Frequency (IF) outputs at 20 and 400 MHz and an IF bandwidth up to 120 MHz, the FSQ8 is able to downscale the carrier frequency while keeping the whole modulating signal bandwidth. The signal analyzer operates the impedance match, the input band-pass filtering and amplification, as well as the wideband frequency down-conversion from RF to IF. The A/D conversion has been achieved by means of a Signatec PDA1000 Data AcQuisition board (DAQ) [15], shown in Fig.2. It provides an analog bandwidth of 500 MHz starting from DC, digitization rates of up to 1 GSa/s and an on board memory depth of 256 MB for capturing extremely long events. The PDA1000 has been installed in a PC, equipped with the Windows operating system, a Pentium IV processor with 1.8 GHz clock frequency and 256 MB of RAM.

The automatic modulation classifier executes the following algorithm:

(i) the FSQ8 center frequency, the number of records to acquire (N), the record length (M), the sampling frequency (f_s) and the start command is expected from the user;

(ii) N records of M samples each are acquired at f_s from the IF signal and stored in the DAQ memory;

(iii) the acquired records are transferred to the PC memory, by means of the PCI bus;(iv) the choice of the records to classify is expected from the user;

(iv) the Modulation Classifier automatically executes all the steps of the classification process on each selected record;

(v) the results are returned to the GUI and presented to the user;
(vi) a new classification cycle can be executed, starting from the step (i).

The IF filter center frequency and bandwidth should be manually set on the FSQ8 by the user.

A typical classification result contains a record number, the record acquisition start time, the record length, the acquisition sampling frequency, the A/D converter resolution, the detected modulation type and an estimation of the signal carrier frequency.

During the software design, it has been attempted to maintain the level of complexity low, such to make easy the maintenance and further expansions. The complexity issue becomes of primary importance when the classifier works with wideband signals and with large sample records, because the number of operations required by the software increases.

In order to allow a remote control of the modulation classifier, an additional software module has been integrated into the prototype. This additional module, designed to have server features, is able to receive a Transmission Control Protocol (TCP) connection and provide remotely some functionalities of the instrument, such as the signal acquisition and classification.

4. TEST DESIGN

For this test phase, the prototype has been validated by means of radio transmitted signals. Tests have been conducted in a shielded environment, in order to be immune from any external interference. The developed classifier prototype has been validated at the *TLC Sannio Testing Lab* [16]. This laboratory has been created thanks to the collaboration between the University of Sannio and the Province of Benevento, to provide testing services to companies involved in telecommunication equipment manufacturing. The activities of this laboratory are mainly focused on electromagnetic compatibility (EMC) measurement and on telecommunication equipments characterization and measurements.

The shielded chamber of the *TLC Sannio Testing Lab*, has the following dimensions: 7m length, 4m width, and 3,20m height, and it has been used as shielded environment for the experimental validation of the prototype by limiting the carrier frequency of the generated signals below 1 GHz.

In order to emulate a radio frequency telecommunication system, in absence of external interfering signals, a suitable test bench with a transmitting and a receiving section has been realized (Fig.3).

The transmitting section is composed by:

- a Rohde & Schwarz SMIQ03B vector signal generator, able to generate signals compliant with the most used digital modulation schemes, with a carrier frequency below 3 GHz and a maximum output power of 13 dBm;
- an Agilent E8663B Analog Signal Generator, able to generate a modulated sinusoidal interfering signal;
- a transmitting wideband Rohde & Schwarz HL562 ultra-log antenna;
- a transmitting wideband Rohde & Schwarz HL040 log-periodic dipole antenna;
- two RF broadband amplifiers Teseq CBA-1G-018 with a 44 dB gain, connected between each generator and the corresponding transmitting antenna in order to give the adequate power to the antennas.

The receiving section is composed by:

- a receiving wideband Rohde & Schwarz HE300 active directional antenna;
- the modulation classifier prototype.

The transmitter antennas were centered with respect to the walls and were positioned at a distance of 3m from the receiver one. The signal generators and the radio frequency amplifiers have been placed outside of the chamber and have been connected to its external shielding insertion by RF cables. The external insertions have been directly connected to the transmitting antennas placed into the chamber. The modulation classifier prototype has been also placed outside of the chamber and has been connected to the receiving antenna output by another external shielding insertion.

In order to have an automatic control of all the instruments and to ensure a fixed Signal to Interference Ratio at the receiving antenna, a LabVIEW virtual instrument has been developed. It was able to control both signal generators and spectrum analyzer and, by automatically changing the interference amplitude level, it was able to fix the Signal to Interference Ratio (SIR) at a wanted value.

The virtual instrument has a front panel divided in three sections (Fig. 4):

- the first section (Fig. 4a) controls the SMIQ03B vector signal generator, by setting amplitude level, center frequency, digital modulation, different kinds of filter and filter parameters;
- the second section (Fig. 4b) controls the E8663B analog signal generator, by setting amplitude level,

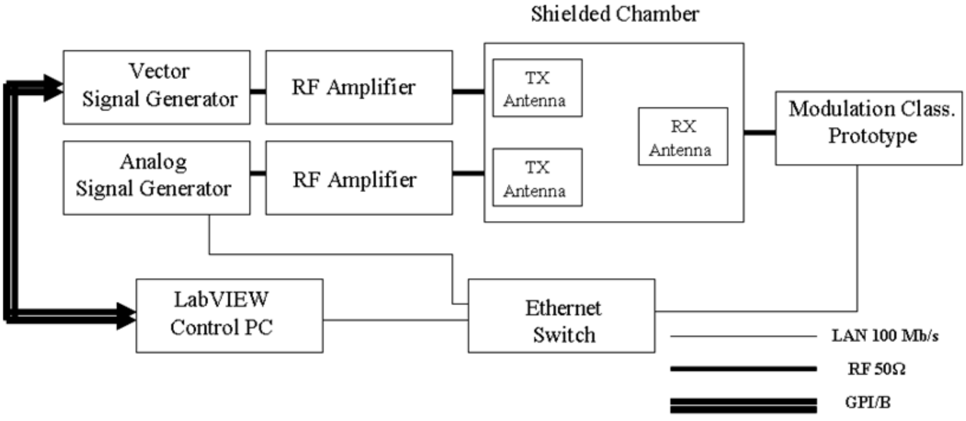

Fig. 3. Test bench setup.

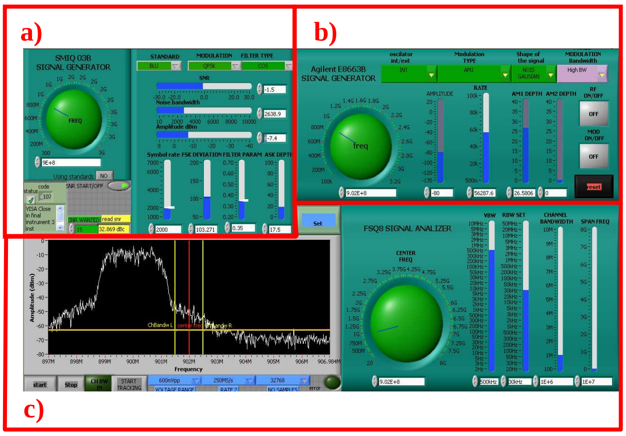

Fig. 4. The VI front panel, divided in three sections: (a) SMIQ03B controls, (b) E8663B controls, (c) FSQ8 and prototype controls.

center frequency and if the interference should have a narrow band or a wideband;

- the third section (Fig. 4c) controls (i) the FSQ8 signal analyzer, by setting: span, resolution bandwidth, video bandwidth and channel bandwidth and by displaying the signal spectrum before down-conversion; (ii) the E8663B and FSQ8, by setting the desired SIR; (iii) the modulation classifier prototype by setting the classification parameters (M,N, f_s) and starting the classification.

In order to achieve a given SIR, a tracking function has been developed, which automatically modifies the interference amplitude until the wanted value has been reached. Inside the tracking loop, the SIR has been calculated by means of the Carrier to Noise (C/N) measurement function of the FSQ8.

With the aim of characterizing the entire system and to verify its repeatability, a set of preliminary verifications has been executed, as follows:

1) Several signals have been generated by means of the SMIQ03B generator at a fixed carrier frequency of 900 MHz, amplified and sent to one transmitting antenna. In this phase the modulation type, the filter type and parameter and the amplitude have been varied, according to the values shown in Table 1.

2) The interfering signal, consisting of either a CW or a wideband interference, has been generated by means of the E8663B generator, amplified and sent to the other transmitting antenna. In order to achieve values of the SIR ranging from 15 to 40dB, the amplitude of the interference has been varied manually,

3) The spectra of the signal before the down-conversion have been observed on the FSQ8 and compared to those achieved in the digital domain, by means of the DFT (Discrete Fourier Transform) of the samples acquired from the PDA1000. It has been verified, in particular, that the interference did not overlap with the signal and that the signal spectrum was not distorted by the transmission and down-conversion process.

In order to validate the method, several tests on actual signals have been carried out in the chamber.

In this case the following procedure has been followed:

1) For each test signal, the modulation type, the amplitude, the carrier frequency, the symbol frequency, the filter type and the filter parameter have been set;

2) Then, the frequency with the interference type between CW and wideband have been selected;

3) After setting signal parameters, the spectrum of the received signal was checked and both the frequency span and the channel bandwidth for the calculation of the SIR were set;

4) A desired value of the SIR was selected and the SIR tracking loop was started;

5) When the SIR tracking loop reached the desired value with an accuracy of ±0.5 dB, the classification was started.

The classification results were stored in a Microsoft Excel file for further processing.

5. TEST RESULTS

In this section, the results obtained by classify actual RF signals, are presented and compared with those results previously achieved by the alternate method proposed in [10].

The validation phase has been carried out on sets of 100 trials for each different modulation type and parameter. In order to simplify the result table representation, the following acronyms have been used: *ULB* and *LB* for the unlimited bandwidth and limited bandwidth modulations, respectively; *cos 0.35* to indicate the use of a raised cosine pulse-shaping filter with a roll-off factor of 0.35; *gauss 0.30* to indicate the use of a Gaussian pulse-shaping filter with a BT parameter equal to 0.30. All the tests have been performed with two different kind of interfering signal: CW and wideband inteference.

The wideband interference has been generated by enabling the *modulation on/off* control button and by selecting *wideband modulation* from the menu ring of the E8663B section of the VI front panel (Fig.4b). Its spectrum is shown in Fig.5b.

The wideband interference is obtained by phase modulating a sinewave carrier with a wideband Gaussian noise generated internally by the E8663B.

The results are shown in Table 2. The symbol rate has been fixed to 1 or 2 MSymb/s and the SIR has been set to 20 dB. The interfering signal is a CW. In Table 3, the results in the case of wideband interference, are shown. In both tables. each row reports in the first cell the modulation type of the

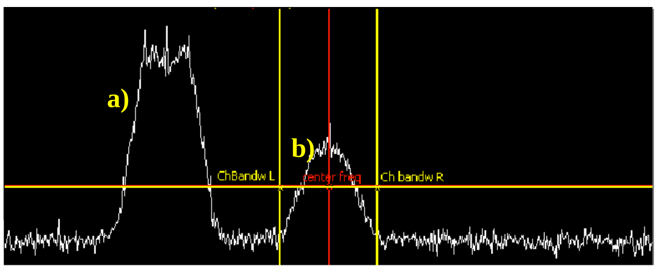

Fig. 5. PSK modulated signal (a) and wideband noise modulated Signal (b) spectra.

test signal, in the second cell the kind and the frequency of the interference signal, in the third and fourth cell, the symbol rate and the measured SIR respectively, and, in the other cells, the number of classified modulations for each input signal.

With reference to Table 2, as an example, the LB-2PSK has been recognized properly as LB-2PSK, with a percentage of 74%; it has been wrongly recognized as QAM, with a percentage of 26%.

As it can be seen from Table 2 and Table 3, all modulations were recognized with high percentages, with exception of the 2FSK with frequency deviation of 4 MHz, in presence of CW interference. In this case, the estimation of the frequency hops, corresponding to the FSK symbol transition, has a poor resolution, due to the low ratio between the sampling frequency and the carrier frequency. As a consequence, the frequency hops are too low to be estimated.

By comparing these results with those previously obtained in [10], the latter ones present higher correct identification percentages. As an example, in [10] the LB-2PSK has been properly recognized with a percentage of 97%, while, a 74% success percentage has been obtained with the currently implemented method, in presence of CW interference. An 81% success percentage has been obtained in presence of wideband interference.

Furthermore, both LB-4PSK and LB-8PSK were correctly identified in [10] with a percentage of 100%. Instead, they reach, in this validation phase, classification percentages of 72% and 73%, in presence of CW interference and 97% and 93%, in presence of wideband interference, respectively.

Also FSK modulations reach lower success percentages than in [10], even if the obtained values remain above 72%

Very good results have been obtained with QAM modulation classification. In this case, as shown in Table 2 and in Table 3, the success percentage is closer to the 100%

Tab. 1. Values of the parameters used during the assessment tests.

Carrier frequency		900 MHz
Interference frequency range		[885-915] MHz
Signal to Interference Ratio		[15-20-25-30-35-40]dB
Interference Signal		Sine wave
Filter type	UB-PSK	Rectangular
	LB-PSK, QAM	Root cosine, α=0.35
	FSK	Gaussian, BT=0.30
FSK frequency deviation		[1 – 5] MHz
Level	PSK, FSK	[-20 – 0] dBm
	QAM16	[-20 – 0] dBm
	QAM64	[-20 – 0] dBm

obtained in [10].

As shown by the obtained results, the out-of-band interference, added to the radio transmitted signals has a relevant impact on the PSK and FSK signal classification only, while keeping the success percentage better than 72% in all cases. Moreover, the success percentage decrease is much weaker in the case of wideband interference than in presence of CW.

6. CONCLUSIONS

In this paper, the interference sensitivity of an automatic modulation classifier has been evaluated. This work is intended as an additional step of a precise develop sequence containing: simulations, emulations and experimental tests involved in absence of interference. In order to ensure a controlled interference, all the evaluation tests were performed using radio transmitted RF signals in a shielded chamber. A virtual instrument, able to control the test bench and to ensure a fixed Signal to Interference Ratio at the receiving antenna has been realized.

The modulation classifier prototype has been tested by means of several actual signals adding both narrowband and wideband interference.

Table 2. Results obtained in the validation phase with CW interference. Each row reports in the first cell the modulation type of the test signal, in the second cell, the kind and frequency of the interference signal, in the third and fourth cell, the symbol rate and the measured SNR, respectively and in the other cells, the percentages of identification of each modulation.

Test signal type	Test interference frequency [MHz]	Symbol Rate [MSymb/s]	Measured SIR [dB]	Modulation recognition percentages							
				LB-2PSK	LB-MPSK	UB-2PSK	UB-MPSK	FSK	QAM	ASK	CW
Cos BPSK 0.35	CW 903 MHz	2	19.9	74	0	0	0	0	26	0	0
Cos QPSK 0.35	CW 903 MHz	2	20.4	3	72	0	17	8	0	0	0
Cos 8PSK 0.35	CW 903 MHz	2	19.9	1	73	0	19	7	0	0	0
Gauss FSK2 4MHz	CW 906 MHz	2	20.4	0	0	0	0	23	77	0	0
Gauss FSK2 5MHz	CW 907.5 MHz	2	19.9	0	0	0	0	100	0	0	0
Gauss FSK4 3MHz	CW 908 MHz	1	19.5	0	0	0	0	72	28	0	0
Gauss FSK4 4MHz	CW 909 MHz	1	20.0	0	0	0	0	96	4	0	0
Gauss FSK4 5MHz	CW 910 MHz	1	19.7	0	0	0	0	100	0	0	0
Cos QAM64 0.35	CW 903 MHz	2	19.5	1	0	0	0	5	94	0	0
Cos QAM16 0.35	CW 903 MHz	2	20.1	1	0	0	0	5	94	0	0

Table 3. The results obtained in the validation phase with modulated by wideband noise interference.

Test signal type	Test interference frequency [MHz]	Symbol Rate [MSymb/s]	Measured SIR [dB]	Modulation recognition percentages							
				LB-2PSK	LB-MPSK	UB-2PSK	UB-MPSK	FSK	QAM	ASK	CW
Cos BPSK 0.35	Wideband PM 906.5 MHz	2	20.1	81	0	19	0	0	0	0	0
Cos QPSK 0.35	Wideband PM 906.5 MHz	2	19.7	2	97	0	1	8	0	0	0
Cos 8PSK 0.35	Wideband PM 906.5 MHz	2	19.9	3	93	1	19	1	2	0	0
Gauss FSK2 4MHz	Wideband PM 907.5 MHz	2	19.5	0	0	0	0	81	19	0	0
Gauss FSK4 3MHz	Wideband PM 908.5 MHz	2	19.8	0	0	0	0	75	25	0	0
Cos QAM64 0.35	Wideband PM 906.5 MHz	2	19.6	1	0	0	0	0	99	0	0
Cos QAM16 0.35	Wideband PM 906.5 MHz	2	19.7	0	0	0	0	0	100	0	0

It has been shown that the presence of interference causes a limited decrease in the classification success percentages. Such decrease is higher in the case of narrowband interference.

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