17th Symposium IMEKO TC 4, 3rd Symposium IMEKO TC 19 and 15th IWADC Workshop
Instrumentation for the ICT Era
Sept. 8-10, 2010, Kosice, Slovakia

A Portable Automatic Digital Modulation Scanner

Luca De Vito[1], Daniele Domenico Napolitano[1], Sergio Rapuano[1],
Maurizio Villanacci[1], Domenico Luca Carnì [2]

[1] *Dept. of Engineering, University of Sannio, Benevento, Italy*
{devito, danapoli, rapuano, maurizio.villanacci}@unisannio.it
[2] *Dept. of Electronics, Computer and System Science, University of Calabria, Rende (CS)*
dlcarni@deis.unical.it

Abstract- In this paper a portable automatic digital modulation scanner is described. This novel instrument has been designed including a pre-processor, able to divide the spectrum in sub-bands and to detect the incoming signals in each band, and a classifier, able in processing the detected signals and estimating their modulation types. The new instrument has been evaluated by several experimental tests, carried out in different operating conditions by varying the Signal to Noise Ratio (SNR) and by emulating different real scenarios.

I. Introduction

The modern telecommunication systems require a very large bandwidth for high speed data transmission in order to provide an increasing number of digital services. However, the range of radio frequencies (RF) is not an unlimited resource and, therefore, a dynamic spectrum allocation will soon be necessary to avoid a chaotic interference scenario. As a consequence, new measurement instrumentation for telecommunication systems should be suitably designed to characterize signals whose spectrum and even modulation change dynamically without any a priori information. Such features would be a great advantage in signal integrity or signal intelligence applications.
In this scenario, it could be very useful a device able to: (i) scan the spectrum in order to detect sub-bands with the presence of one or more signals without any a priori information; (ii) detect, for each sub-band, the carrier frequency and extract the corresponding signals; and (iii) classify, for each extracted signal, the modulation type and other parameters such as the symbol rate and the type of pulse shaping filter.
A method capable to classify the signal modulation has been already proposed [1], implemented in an instrument and successfully validated [2], [3]. However, the method and the corresponding instrument have a fundamental limitation: they cannot scan a wide spectrum in order to detect the signal presence; therefore, it is necessary to know the frequency band of the unknown waveform to capture and classify it.
In this paper, a portable automatic digital modulation scanner able to overcome such limitation is proposed. The instrument includes both the signal detection [4] and the modulation classification [1] functions. In particular, it provides: (i) the division of an assigned frequency range in a given number of sub-bands; (ii) the automatic selection of the frequency sub-bands including an unknown signal; and (iii) the automatic modulation classification, based on the method [1], of the detected unknown signals.
The signal detection phase is provided by implementing an eigenvalue-based method proposed in [5] for cognitive radio applications and successfully applied to unknown signals in [4].
The method [1] is able to automatically classify several kinds of digital modulation schemes such as M-ary Phase Shift Keying (MPSK), M-ary Frequency Shift Keying (MFSK), M-ary Quadrature Amplitude Modulation (MQAM) and Ortogonal Frequency Division Multiplexing (OFDM).
An experimental evaluation phase on standard telecommunication signals has been carried out to validate the proposed instrument.
The paper is structured as follows: the hardware design criteria will be explained in Section II. In Section III, the software implementation of the novel instrument will be discussed. Finally, in Section IV, a detailed description of the experimental test bench and a complete discussion of the obtained results will be shown.

II. Hardware section

A. Design criteria

In order to design a suitable hardware architecture to implement the automatic portable digital modulation scanner, a lot of requirements have to be satisfied. The ideal instrument for characterizing a dynamically changing radio spectrum for signal intelligence or telecommunication applications should be deployed on the field, therefore, it should be relatively compact, transportable on a vehicle, robust enough to operate in an uncontrolled environment, modular and easy to maintain on the field. The system should be able in acquiring and processing the real time wide-band RF spectrum, and, at the same time, capable of satisfying the following needs: (i) easy package, carriage and usage; (ii) high degree of scalability in terms of power supply, power management and system integration; (iii) modular structure to match with possible hardware add-ons due to research enhancements; and (iv) high interoperability with the most common test and measurement control software. Hardware platforms satisfying such requirements already exist; therefore, the hardware design phase consisted in choosing the most suitable one.

The most used modular instrument platforms are the VMEbus eXtension for Instrumentation (VXI) [6] and the PCIbus eXtended Instrumentation (PXI) [7] ones. Both platforms include several measurement modules in a shielded chassis connected by means of dedicated high throughput data connections and the possibility of being interfaced to a PC as external processing unit, when it is necessary. The main hardware module required for the digital modulation scanner, a Vector Signal Analyser (VSA) is available from different manufacturers for both the platforms. Moreover, both platforms allow the set-up of integrated test systems including in the same shielded rack a RF signal generation section for the experimental evaluation of the prototype scanner.

The main advantage of the PXI platform versus the VXI one is about dimensions and weight, that on a portable system is decisive: for such a reason the PXI platform has been chosen. As reported in [8], for commercial and military systems, and in [9] for mobile applications, the PXI-based instrumentation assure all the previously reported requirements. Moreover, such measurement systems are suitable for both civilian and military critical applications where systems operate without the guarantee of a reliable power source and are surrounded by hard environmental conditions.

An external control and processing unit executing the digital modulation scanner software has been chosen in order to allow an easier adjustment of the processing power for new processors during the research phase. Due to the instrument employment, a laptop is the best external processing unit. A slot-in processing unit can be easily added in a further production phase.

For the aforementioned reasons the automatic digital modulation scanner has been implemented in a PXI chassis including a VSA and a module able to connect it to a laptop by means of a PCI Express Card. The complete PXI-based prototype will be described in the next sub-section.

B. Developed prototype

The developed prototype of the portable automatic digital modulation scanner is an instrument whose hardware section is in charge of (i) scanning the unknown spectrum, (ii) selecting the sub-bands, (iii) translating them to baseband, (iv) digitizing the signals, and (v) transferring the acquired waveforms to a digital signal processing unit. The hardware configuration implementing such functions is shown in Fig.1. It is composed of (i) a Sony VGN-CR240E laptop (Intel Core Duo 2GHz and 2 GB of RAM), with the roles of control and processing unit, (ii) a PXI chassis that includes a Vector Signal Analyser (VSA) PXI-5663 from National Instruments, able to operate the frequency down-conversion and the A/D conversion, and (iii) a PXIe-8360 module for connecting the chassis to the laptop.

The PXI Express chassis PXI-1036 provides up to 2 GB/s per slot dedicated bandwidth and highly accurate timing. These features are obtained by using a differential system clock, and differential signalling, whose increase the noise immunity for instrumentation clocks and the ability to transmit at higher frequency clocks, both characteristics needed for an instrument that should work on the field with wireless telecommunication signals. The slots in the chassis permit to achieve in the same shielded rack the down conversion of the RF input signal and its acquisition by using the VSA.

In particular, the PXI-5663 VSA guarantees a Real Time RF Bandwidth of 20 MHz and a very wide frequency range (10MHz – 6 GHz). During the present research phase a 220 V ac power supply unit has been chosen for the prototype as the metrological capability was under investigation only. A 12V dc power supply unit can be adopted for the field operation without requiring an external dc/ac converter.

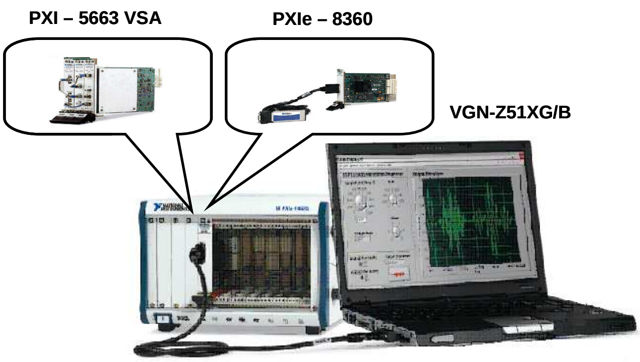

Fig.1. Digital modulation scanner hardware architecture.

III. Software section

The software section of the proposed instrument is composed of three modules: (i) a control module, managing the signal down-conversion and acquisition in order to scan the whole frequency range of analysis in multiple steps, (ii) a signal pre-processor aiming to detect the signals within a single frequency sub-band, and (iii) a digital modulation classifier, able of identifying the modulation type for each incoming signal.

The control module, a Virtual Instrument (VI) developed in LabVIEW and installed on the laptop, is able to perform the following tasks: it divides the spectrum to be scanned in sub-bands, and, for each sub-band, it executes iteratively the following actions;

1. it down-converts the signals in each sub-band to the data acquisition bandwidth;
2. it digitizes the signals with a specified oversampling ratio;
3. it calls the signal detector module;
4. if a signal is detected, it calls the modulation classification module, otherwise the acquired record is discarded;
5. it stores the results.

After the procedure has been completed for all the sub-bands, the results are displayed to the user.

The configuration of the digital modulation scanner as well as the result displaying are done by means of the VI graphical user interface (GUI), where the frequency span ΔF and the sub-band width Δf can be chosen. The number of sub-bands to be analysed is obtained as $m=\Delta F/\Delta f$, where m is an integer number.

The signal detector module implements a method proposed in [5] based on the eigenvalues of the received samples covariance matrix.

The method, as reported in [5], is composed by the following steps:

i) to calculate the sample covariance matrix of the received signal, denoted as $R_X(N_S)$, where N_S is the number of stored samples;
ii) to obtain the maximum and minimum eigenvalues of the matrix $R_X(N_S)$, that is, Λ_{MAX} and Λ_{MIN};
iii) to decide: if $(\Lambda_{MAX} / \Lambda_{MIN}) > \gamma$, signal exists; otherwise, signal does not exist.

The threshold γ is chosen from the probability of false alarm P_{FA}, that is the probability of the method having detected a signal when there is none.

It can be shown that γ can be obtained as a function of L, the effective number of columns of the covariance matrix, the number of the receiving antennas, N_S and P_{FA} [5]. In the present work, a single antenna receiving hardware has been chosen. Then, by choosing experimentally the best trade-off between N_S and L for a given P_{FA}, it has been possible to find the target γ for very low false alarm probabilities.

The method has been implemented in a MATLAB function that can be called from the control module.

The modulation classifier module implements, in a MATLAB function, the method for the recognition of digital modulations proposed in [1]. It 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 like those specified in IEEE 802.11g [10], Digital Video Broadcasting Terrestrial (DVB-T) [11] and HyperLAN [12]. The method is based on a hierarchical decision tree, whose branches are selected starting from the root depending on the signal characteristics.

The hierarchical approach allows the division of the classification problem in smaller and smaller sub-problems, saving processing resources. 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 approach allows the classification of the modulation type by simply acquiring the signals directly at a RF, or, possibly, after a preliminary conversion to an intermediate frequency (IF). In this case the whole signal in the time domain should be acquired, comprising both the carrier frequency and its modulating information.

IV. Experimental validation

A. Signal generation

In order to evaluate the automatic digital modulation scanner, several experimental tests with different combinations of emulated signals, have been carried out. Digitally modulated signals have been generated by means of a PXIE-5641R Transceiver and then frequency shifted by means of a PXI-5610 up-converter.

In Fig.2, the block scheme of the experimental test bench is shown. Both the signal generation PXI modules have been installed in the same chassis as the digital modulation scanner, and have been controlled by means of a test executive software developed in LabVIEW to automatically execute all the tests in a closed loop.

Multiple signals have been generated simultaneously, on different frequency channels, according to 5 different scenarios. In order to emulate a real spectral environment, each scenario includes three signals with different modulations with an overall bandwidth of 40 MHz. The signal parameters used for the considered scenarios are reported in Table 1. The signals in each scenario are 2-PSK, 4-PSK, 8-PSK, 16-QAM and 64 QAM, each one with different carrier frequency, bandwidth and amplitude. In the first, second and fourth scenario, the signals have been generated at 2373 MHz, 2383 MHz and 2387 MHz. In the third scenario, the 2-PSK signals the 4-PSK and the 16-QAM signals have been placed into adjacent channels, therefore the carrier frequencies are nearer. The second scenario reproduces the first one with different amplitude ratios among the signals. The amplitude has been varied and, signals have been generated and mixed in software within the MATLAB environment. An

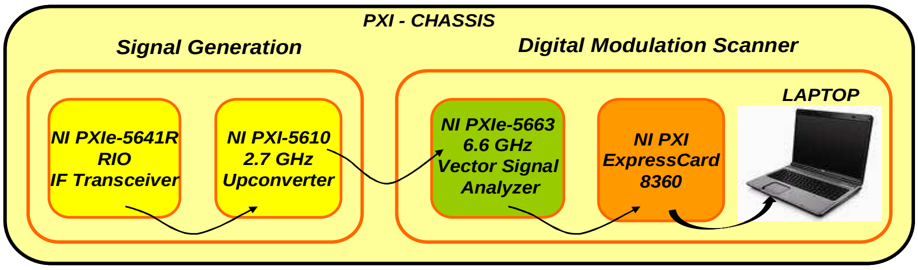

Fig. 2. Block scheme of the experimental test bench.

Table I. Test scenarios parameters: generation.

a)

Modulation	Carrier frequency [MHz]	Symbol frequency [kSymb/s]	Filter	Rolloff factor	Amplitude (to highest one) [dBm]
4PSK	**2373.0**	**500**	**Raised cosine**	**0.22**	**-3**
16QAM	**2383.0**	**1000**	**Raised cosine**	**0.35**	**-20**
2PSK	**2387.0**	**100**	**Raised cosine**	**0.20**	**0**

b)

Modulation	Carrier frequency [MHz]	Symbol frequency [kSymb/s]	Filter	Rolloff factor	Amplitude (to highest one) [dBm]
4PSK	**2373.0**	**500**	**Raised cosine**	**0.22**	**-6**
16QAM	**2383.0**	**1000**	**Raised cosine**	**0.35**	**-25**
2PSK	**2387.0**	**100**	**Raised cosine**	**0.20**	**0**

c)

Modulation	Carrier frequency [MHz]	Symbol frequency [kSymb/s]	Filter	Rolloff factor	Amplitude (to highest one) [dBm]
4PSK	**2373.0**	**500**	**Raised cosine**	**0.22**	**-6**
16QAM	**2375.0**	**1000**	**Raised cosine**	**0.35**	**-25**
2PSK	**2385.4**	**100**	**Raised cosine**	**0.20**	**0**

d)

Modulation	Carrier frequency [MHz]	Symbol frequency [kSymb/s]	Filter	Rolloff factor	Amplitude (to highest one) [dBm]
4PSK	**2373.0**	**500**	**Raised cosine**	**0.22**	**-3**
64QAM	**2383.0**	**1000**	**Raised cosine**	**0.35**	**-20**
2PSK	**2387.0**	**100**	**Raised cosine**	**0.20**	**0**

e)

Modulation	Carrier frequency [MHz]	Symbol frequency [kSymb/s]	Filter	Rolloff factor	Amplitude (to highest one) [dBm]
8PSK	**2371.0**	**500**	**Raised cosine**	**0.22**	**-6**
64QAM	**2381.0**	**1000**	**Raised cosine**	**0.35**	**-25**
4PSK	**2387.0**	**100**	**Raised cosine**	**0.20**	**0**

additive white Gaussian noise with an SNR varying in the range [6-20] dB has been added to the signals, too. The samples of the so obtained mixed signal have been then transferred to the NI PXIe-5641 IF Transceiver.

B. Signal acquisition

All the generated scenarios were sent to the digital modulation scanner by means of a cabled connection, as it can be seen in Fig.2, and they have been acquired, by means of the developed prototype and sub-divided in m=10 slots. The acquisition parameters, common to all considered scenarios are shown in Table II.

Table II. Test signal parameters: acquisition.

Parameter	**Value**
Center Frequency	2380 MHz
VSA Sampling Frequency	8 MSa/s
VSA Record Length	50000 samples
Frequency Span ΔF	40 MHz
Single Slot Bandwidth Δf	4 MHz

C. Test phase and results

The whole digital modulation scanner evaluation phase has been structured in three phases: (i) signal detector test; (ii) modulation classifier test; and (iii) whole digital modulation scanner test.

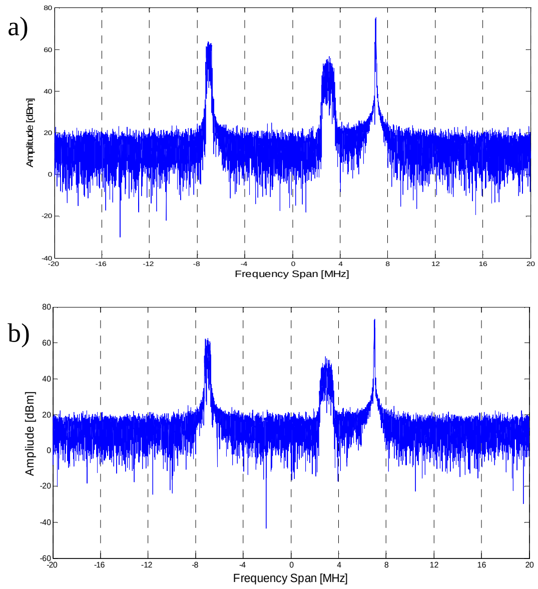

Fig. 3. Spectra of the scenario 1 (a) and scenario 2 (b) divided in 10 slot of 4 MHz.

To fix the detection algorithm parameters such as N_s and L, a preliminary test phase, as in [4], has been conducted. A lot of combinations has been tested and because of the limited slot samples (50000), N_s and L was fixed respectively to 100 and 4.

Signal detector test phase

In this phase each of the 10 frequency slots for scenario has been analysed by the detector module, by varying P_{FA} for 0.01, 0.005 and 0.001 values and with N_s and L parameter fixed to 100 and 4 respectively.

As an example, in Table 3 the detection percentage on 100 trials for the first and the second test scenario, with a fixed P_{FA} of 0.001, are shown slot by slot. As it can be seen from the corresponding spectra, observed during the tests, in Fig. 3a) and 3b), the detector should find a signal in the IV, VI and VII frequency slots only. From Table 3 it is possible to verify that for SNR values of 10dB and higher, the detector selects correctly all the effectively occupied slots, while a maximum experimental false alarm rate of 0.02 (slot VIII with an SNR fixed to 6dB) was obtained.

Table III. Detection percentage for the first and the second scenario generated with SNR variable in the range [6-20] dB.

Scenario 1											Scenario 2										
	Frequency Slots											Frequency Slots									
SNR [dB]	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**SNR [dB]**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
6	0	0	0	100	0	0	100	2	0	0	**6**	0	0	0	100	0	100	78	0	0	0
10	0	0	0	100	0	100	100	0	0	0	**10**	0	0	0	100	0	100	100	0	0	0
14	0	0	0	100	0	100	100	0	0	0	**14**	0	0	0	100	0	100	100	0	0	0
18	0	0	0	100	0	100	100	0	0	0	**18**	0	0	0	100	0	100	100	0	0	0
20	0	0	0	100	0	100	100	0	0	0	**20**	0	0	0	100	0	100	100	0	0	0

Modulation classifier test phase

In this test phase each slot in which the signal was detected in the previous phase has been sent to the modulation classifier, while the others have been discarded. During this phase over 750 modulated signals have been tested. Table 4 shows the correct classification percentage for all the acquired and detected signals in the first two scenarios for 100 trials.

As shown in the table, the correct classification percentages are very good for SNR greater than 10dB, where the correct classification percentages are always equal or higher than 85%.

Table IV. Modulation classification percentage for the first and the second scenario detected signal.

Scenario 1				Scenario 2			
SNR [dB]	**4-PSK**	**16-QAM**	**2-PSK**	**SNR [dB]**	**4-PSK**	**16-QAM**	**2-PSK**
6	50	90	0	6	100	100	0
10	95	90	0	10	100	100	0
14	95	95	100	14	100	100	85
18	100	95	100	18	100	100	85
20	95	100	100	20	100	100	90

Whole instrument evaluation at fixed SNR

In order to evaluate the whole system robustness another scenario has been designed. According to Table I, the fifth scenario has the slot III, VI and VII occupied by 8-PSK, 64-QAM and 4-PSK signals, respectively. The spectrum, sub-divided in 10 slots, of the corresponding acquired signals is shown in Fig.4. In this last evaluation, an additive white noise with SNR fixed at 20dB has been added to the signals. In Table V both the detection results (*ok*, if a signals was detected, *no* otherwise), for each acquired slot, and the correct modulation classification percentages, for each detected signal, are shown. As it can be seen from the table, the occupied sub-bands have been correctly detected while the other seven free sub-bands have been discarded: furthermore, the detected modulated signals have been perfectly classified as MPSK (M>2) and QAM.

Table V. Signal detection percentage and correct modulation classification percentage for scenario 5.

SNR [dB]	Signal Detection									
	I	II	III	IV	V	VI	VII	VIII	IX	X
	no	no	ok	no	no	ok	ok	no	no	no
20	Modulation Classification									
	8-PSK (slot III)			64-QAM (slot VI)			4-PSK (slot VII)			
	ok			ok			ok			

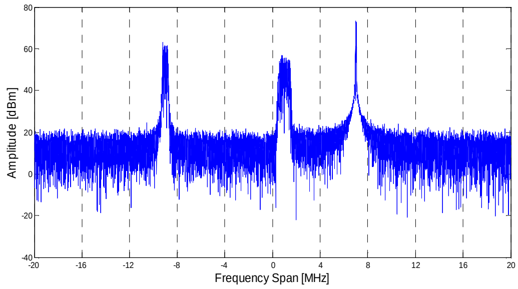

Fig. 4. Spectrum of the scenario 5.

V. Conclusions

In this paper, a portable automatic digital modulation scanner has been described and experimentally tested. The modulation scanner has been designed as a single block including a pre-processor, able to divide the spectrum in sub-bands and to detect the incoming signals in each band, and a classifier, able in processing the detected signals and estimating their modulation types. To develop this novel instrument, a PXI-based architecture controlled by a digital signal processing unit has been chosen. The new instrument has been evaluated by several experimental tests, in which a lot of different actual scenarios have been generated by varying the SNR. The instrument has been validated by means of three different test phases: signal detector evaluation, modulation classifier evaluation and whole instrument evaluation. The results were good, with an high percentage of correctly detected sub-bands and an high percentage of correct modulation classification. The next research step will consist in estimating physical layer signal parameters and in improving the automatic modulation scanner processing rate.

Acknowledgments

The authors wish to thanks Prof. Pasquale Daponte and Prof. Domenico Grimaldi for their helpful suggestions during all the phases of the research work.

References

[1] L.De Vito, D.Grimaldi, S.Rapuano, “An automatic digital modulation classifier for measurement on telecommunication networks”, IEEE Trans. on Instrum. and Meas., vol.56, No.4, Oct. 2007, pp.1711-1720.

[2] L.De Vito, S.Rapuano, M.Villanacci, “Real Time Spectrum Analyzer including an automatic digital modulation classifier”, Proc. of IEEE Int. Instrum. and Meas. Tech. Conf. (I^2MTC), Victoria, Canada, May 2008, pp.1582-1587.

[3] L.De Vito, D.Napolitano, S.Rapuano, M.Villanacci, “Interference sensitivity of an automatic modulation classifier”, Proc. of IMEKO World Congress, Lisbon, Portugal, Sept. 2009, pp.562-567.

[4] L.De Vito, D.Napolitano, S.Rapuano, M.Villanacci, “Eigenvalue-based signal detector for an automatic modulation classifier”, IEEE Int. Instrum. and Meas. Tech. Conf. (I^2MTC), Austin, USA, May 2010, pp.1131-1136.

[5] Y.Zeng, Y.Liang, “Eigenvalue based spectrum sensing algorithms for cognitive radio”, IEEE Trans. on Commun., vol.57, No.6, Jun. 2009, pp.1784-1793.

[6] IEEE, IEEE Standard 1155, “VMEbus Extensions for Instrumentation”, 1992.

[7] PXI Systems Alliance, PXI Specification Overview - The PXI Modular Instrumentation Architecture, available at http://www.pxisa.org.

[8] C.D.Ziomek, D.C.Robinson, “Testing commercial & military RF systems with PXI instrumentation modules”, Proc. of IEEE Systems Readiness Technology Conference AUTOTESTCON, Anheim, USA, 22-25 Sept, 2003, pp.139-143.

[9] C.Chuang, “A portable platform for mobile applications”, Proc. of IEEE Systems Readiness Technology Conference AUTOTESTCON, Anheim, USA, 22-25 Sept. 2003, pp.104-107.

[10] IEEE, “IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, 2007.

[11] ETSI, “Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television”, EN 300744, v.1.6.1, 2009.

[12] ETSI, “Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Physical (PHY) layer”, TS 101475, v.1.3.1, 2001.