Telemeasurement and Circuit Remote Configuration Through Heterogeneous Networks: Characterization of Communications Systems

Oreste Andrisano, *Member, IEEE*, Andrea Conti, *Member, IEEE*, Davide Dardari, *Member, IEEE*, and Alberto Roversi

***Abstract*—The telemeasurement through heterogeneous networks to characterize systems and devices is addressed in this paper. The methodology is generally valid and applied to characterize communication systems. Both dedicated circuits and digital-signal-processor (DSP)-based realizations are taken into account; in the latter case, the remote definition of the system is also considered. The wide-sense telemeasurements concept is introduced in this paper as the general case in which both circuits and instruments are remotely defined and configured. This approach is particularly useful for two opposite situations: the case in which few valuable instruments are available only in some particular laboratories and the educational case where the number of instruments available is not sufficient with respect to the potential number of users. An integrated Web server architecture to manage both instruments and DSP platforms has been developed for educational purposes.**

***Index Terms*—Code division multiple access (CDMA), heterogeneous communication networks, remote control, software radio (SWR), telemeasurements.**

I. Introduction

IN THE last few years, the trend of laboratory research centers both inside and outside Europe has been to develop few but high-level laboratories (also called excellence centers) where sophisticated measurements can be done by means of high-cost instruments. Since 1994, the Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT) [1] in Italy has been founded to create a research network able to improve the research activity among universities and the results obtained. In particular, the Laboratorio Nazionale di Comunicazioni Multimediali (LABNET) [2] has been created in Naples with the aim of defining a methodology for remote access to complex instrumentation and a test bed concerning communication systems and networks. A way to increase the relevance of these centers is to make available their capabilities regardless of the physical location of the users. To this aim, the remote measurement (telemeasurement) gains a particular interest allowing setup, monitoring, and data postprocessing from a remote location. The increasing amount of the number of potential users is important since small laboratories do not have the instrumentation but can remotely utilize the instruments of these specialized centers. The concept of the telemeasurement is well known: In fact, several commercial products, like general purpose interface bus-ethernet (GPIB-ENET) [3] make it feasible, also via the Web, providing a "bridge" between the IEEE 488.1 [4] and Transmission Control Protocol (TCP)/IP [5]. Moreover, software packages like LabView and Visual Engineering Environment [6]–[9] enable the virtual-instrument technology [10]. In particular, this allows the realization of the virtual-instrument concept, where functionalities of different real instruments can be collected and made remotely available as a new virtual interface.

Recently, the characterization of communications systems by means of measurements gained a lot of interest due to their market penetration [e.g., cellular systems and wireless local area networks (WLANs)] and the increasing complexity that makes the performance evaluation a relevant topic. In this field where several standards have to coexist on the same device, the software-radio (SWR) technology is going to play a fundamental role since it moves typical hardware functionalities into software by means of general-purpose platforms as a digital signal processor (DSP), a field programmable gate array (FPGA), etc. [11], [12].

In this paper, the telemeasurement concept is extended in such a way where not only the instruments, but also the devices under measurement, are remotely defined and controlled. This can be realized in the context of the SWR technique. In particular, we developed a DSP-based architecture in which the algorithms that realize system functionalities can be remotely uploaded, through the communication network, to the SWR platform connected to the instrumentation. This approach opens an interesting scenario in which a user will remotely configure both circuits and instruments, realizing a "wide-sense" telemeasurements paradigm.

Possible applications of this architecture range from educational, where many people access the measurement test bed (e.g., a class with many students) [13]–[15] to advanced research where people access valuable instrumentation. In particular, we report our experience in telemeasurements of

Manuscript received July 8, 2003; revised November 16, 2005. This work was supported by MIUR, Rome, Italy, within the project VICom.

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Digital Object Identifier 10.1109/TIM.2006.870335

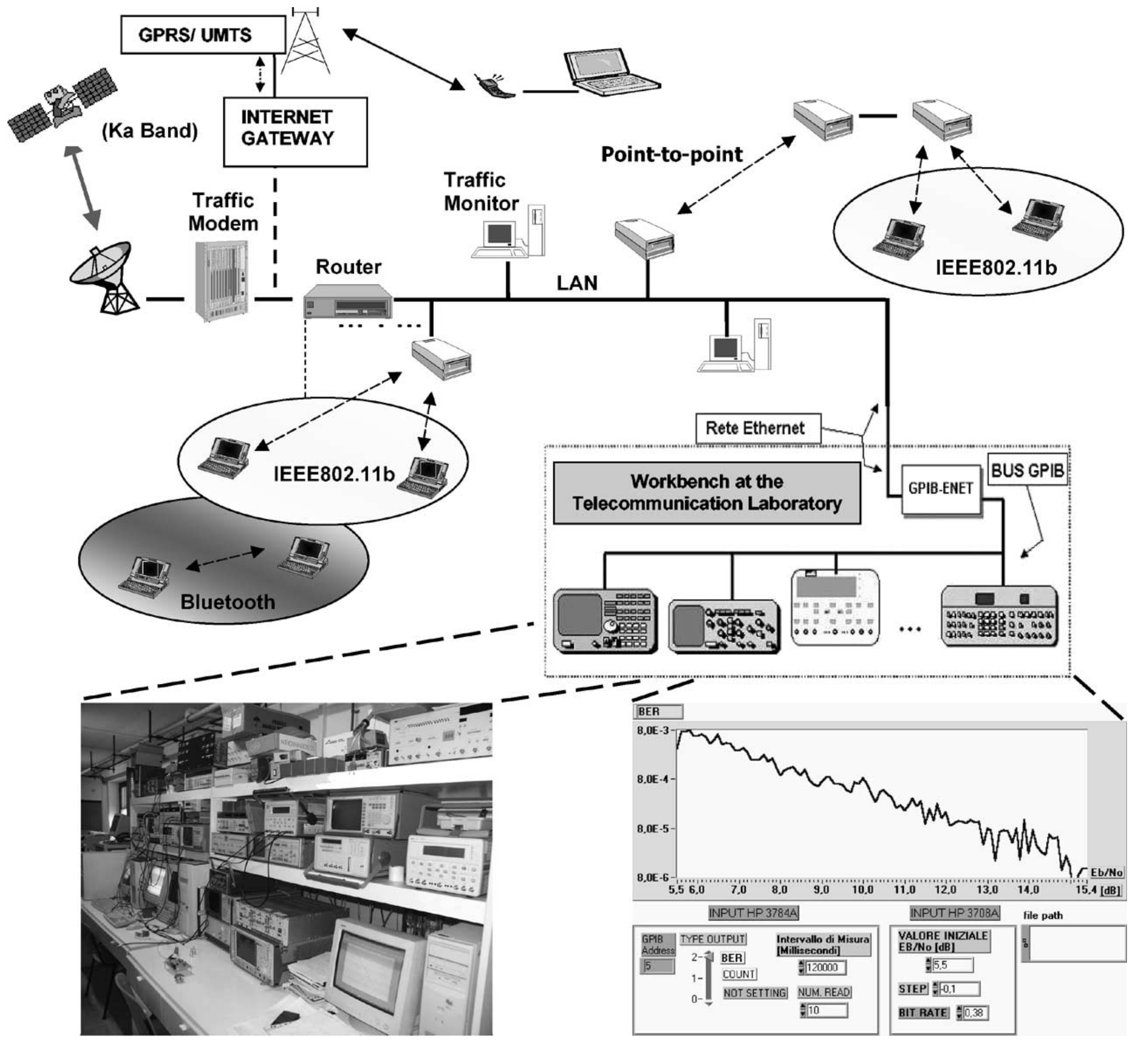

Fig. 1. Telemeasurement through a heterogeneous network (WiLab, IEIIT-BO/CNR, University of Bologna, Italy).

SWR-based platforms through heterogeneous networks from the Wireless Communication Laboratory (WiLAB),[1] University of Bologna, Italy. In fact, an intensive research activity on wireless communication systems has been developed in this paper with both theoretical analysis and experimental characterization through a measurement test bed open to the Internet.

The paper is organized as follows. In Section II, a description of the network and the resource-reservation-server (RRserver) architectures for telemeasurement is provided. In Section III, the SWR technology and the remote circuit definition are treated; in Sections IV and V, examples of wide-sense telemeasurements are given for educational and industrial applications, respectively. Finally, our conclusion is given in Section VI.

II. Telemeasurement Network Architecture

A snapshot of the network architecture present in the WiLAB at the IEIIT-BO/CNR is shown in Fig. 1. Different access technologies are supported: Ethernet, IEEE 802.11, Bluetooth, general packet radio service (GPRS)/universal mobile telecommunications system (UMTS), and the Internet in general. The connection to the workbench is also possible by means of a 2.5-G mobile radio system (GPRS) and by a Ka-band satellite backbone made available by CNIT for the interconnection of excellence centers. In particular, the IEEE 488.2 instrumentation bus is connected to the LAN through the GPIB-ENET device [3], which permits the access to the measurement bench both from wired and wireless remote users. As an example, for educational purposes, this structure enables the access to the measurement bench from students that are in remote laboratories belonging to the Faculty of Engineering at the University of Bologna or from a professor in a class through wireless connected laptops. Moreover, by means of a Web cam, a complete view of the real workbench is available in real time to allow the student the view of both the remote interface and the real instrumentation. Obviously, real-time video capability is possible only when the required network bandwidth is available. In Fig. 2, a typical workbench configuration for the characterization of digital-communication transmission chain is shown. It is mainly composed of a digital transmission analyzer (for data generation and error-rate analysis), mixers (for baseband to RF conversion and vice

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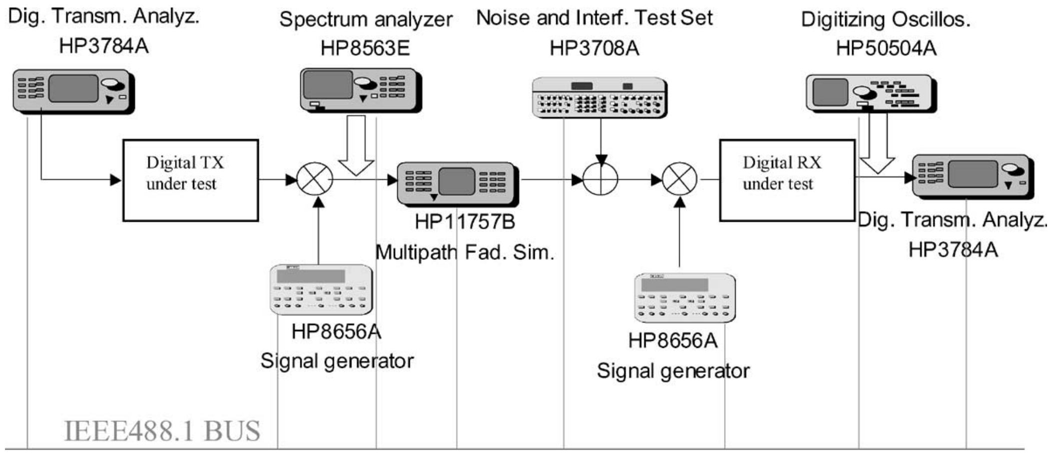

Fig. 2. Typical workbench configuration for the characterization of communication transmission chain.

versa), signal generators, multipath channel fading simulators to emulate different multipath propagation conditions, noise and interference test set (NITS) to insert different disturbances, e.g., additive white Gaussian noise, and oscilloscopes and spectrum analyzers for signal observations in time and frequency domains. Several virtual interfaces have been developed to make available all the instrumentation functionalities through the network. The instrumentation chain can be accessed via the Web as a virtual instrument depending on the type of system characterization to be performed. Each involved instrument is provided by its own virtual-instrument panel with basic functionalities for each developed application; if necessary, it is very easy to add other functionalities. A typical virtual interface for the bit-error-rate (BER) measurement, developed by using LabView [8], is reported in the bottom of Fig. 1: The performances of digital transmission systems through the analysis of BERs, eye diagrams, constellations, and spectra both at baseband or at the radio frequency (RF), with or without multipath propagation and disturbances (e.g. cochannel interference and thermal noise), are reported. In this case, the BER curve is automatically obtained once the user changes system parameters like the range of the signal-to-noise ratio (SNR) and the number of information bits transmitted.

A. Architecture Implementation Details

We addressed the study, the design, and the realization of a server-based architecture that is capable to manage the instruments and programmable devices on the measurement workbench at the IEIIT-BO/CNR, Bologna. When a remote user approaching the telemeasure platform is interested in using a particular instrument, he must know which instruments are available, choose and reserve the resources, and finally obtain the remote controls. From the point of view of a remote user, the complete availability of a resource means that it must be turn ON and nobody else will get the control of the resource. Here, we describe a server-based architecture represented in Fig. 3 and developed in our laboratories, which is able to handle multiple access of remote users to the instruments and programmable devices present in the laboratory. In the proposed solution, the RRserver shows the remote user the availability of instrumentation, reserves and gives the user the remote control of the chosen instruments, and keeps continually upgraded a special table containing the state of the resources. The architecture is composed by a first level of two different classes of resources: the instruments connected to each other by the GPIB bus and interfaced to the second level through a GPIB-ENET and the programmable devices connected to the second level by an integrated network interface or by the use of a dedicated host PC. The second level is composed by the reservation resource manager that is based on a parallel architecture of three servers.

1) A Web server Apache [17] of which the role is to dialog with the clients. It contains both static (HTML language) and dynamic (hypertext preprocessor (PHP) language) pages, which can be visited by the remote user.
2) A database server MySQL [18] of which the role is to keep, manage, and upgrade information about the instrumentation and the programmable devices present in the laboratory every time there is a query of availability. The MySQL database server dialogs only with the Apache Web server.
3) A LabView server [8] of which the role is to keep and send to the clients the executable virtual panel to control the chosen instruments.

When a client connects to the RRserver to know the availability of resources, a script computer graphic interface (CGI) is run by the Apache server. The CGI queries to the GPIB-ENET and to the dedicated network interfaces which instruments and programmable devices are turned ON; these information are returned to the Apache RRserver and the status of the resources, containing also information about passed reservations, is updated on a MySQL table. The Apache server collects all information about the availability of the resources and sends to clients a PHP page containing a list of available resources. Thus, the client chooses the resources, reserves them for a specific time slot, and downloads from the LabView server the virtual-instrument panels embedded in an HTML page as an ActiveX object with the permission to control the selected instrumentation and the HTML page to run different configuration files on the SWR devices. In this way, the number of users that can access the resource reservation system is not limited.

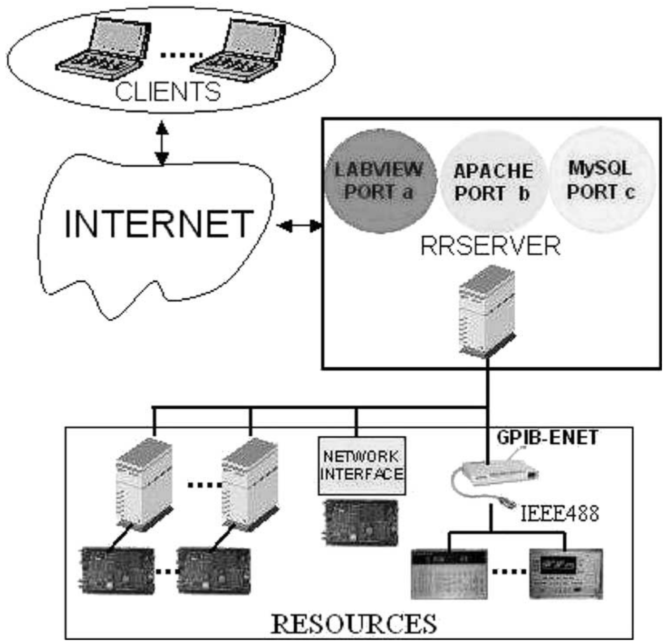

Fig. 3. Resource-reservation-system architecture.

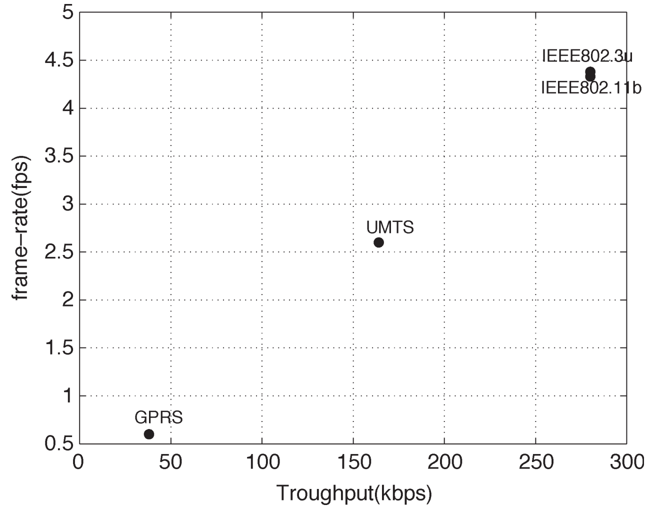

Fig. 4. Bandwidth performance characterization.

Only the number of clients connected to different virtual-instrument panels is limited to 20 (upgradable to 50), this is due to the number of remote panel connection licenses on the LabView server. The reservation system is multiple-user access while the control of each virtual panel and of programmable platforms is possible by a single user. The development of a resource scheduler is anticipated in order to make available the resources in different times. The implemented system has atomic characteristics so that, when multiple users want to reserve more instruments involved in a particular experience, only one user will be able to reserve all desired resources in one shot. Since different hardware technologies and platforms are used, the choice of a particular programming language is not unique, but it is strictly related to the constraints imposed by the hardware technology. In particular, the C language has been used to develop the CGI interfaces taking advantage from the application program interface (API) libraries offered by the National Instrument for the GPIB-ENET device. The realization of the virtual-instrument panels using LabView language is due to its wide use in the community and the wide range of instrument drivers already available for this platform. However, these implementation aspects are completely hidden to the final user of which the interface is entirely based in HTML pages representing the chosen experience and the results of the telemeasure process.

B. System Performances

We reported in Fig. 4 an example of the measured bandwidth versus the frame rate of the virtual-panel display, using the digital oscilloscope [16] in a typical measure experience. In this way, we can have an idea of the data-rate requirements of the application. Obviously, some data-rate-consuming functionalities, such as a Web cam, cannot work through low-data-rate network accesses (e.g., GPRS). A rigorous measurement of the response time is a very hard task because of the variety of hardware, software, and network technologies involved. However, qualitative experiments show that the response is immediate (less that 1 s) when using wired and WLAN accesses to open one virtual-instrument panel. The timing response increases when the traffic generated by the opened virtual-instrument panels saturates the GPIB-ENET/100 interface (maximum rate of 100 kB/s of TCP/IP traffic).

III. Remote Circuit Definition

As previously stated, the trend in communication-system implementation is going toward the SWR concept. General-purpose hardware platforms, based on programmable devices like DSPs and FPGAs, will allow the migration of signal processing from hardware to software not only at baseband, but also at an intermediate frequency (IF) or at an RF (the so-called "multimode radio") [11], [12]. In this context, the main object under measurement is a general-purpose hardware with functionalities implemented via software. Hence, we set up a DSP network connected to the workbench that permits the characterization and definition of different systems only by carrying the software through the network without any hardware movement. This allows a new telemeasurement concept (the wide-sense telemeasurement) in which both instruments and circuits (the objects under measurements) are remotely configured and, most importantly, defined.

In Fig. 5, our wide-sense telemeasurement platform is depicted, where the system under analysis is composed by a general-purpose DSP network. This platform is connected through the network to a Web server integrated with virtual interfaces of instruments and a Web cam. Functionalities like the system definition (e.g., software upload to DSPs), the system control, the parameters exchange, the instruments configuration, and the observation of the workbench by the Web cam are possible. The Web server Apache [17] has been used to make available virtual interfaces, DSP commands, and the Web cam in the same Web HTML page. This integration is possible by means of new features of recent versions of LabView and

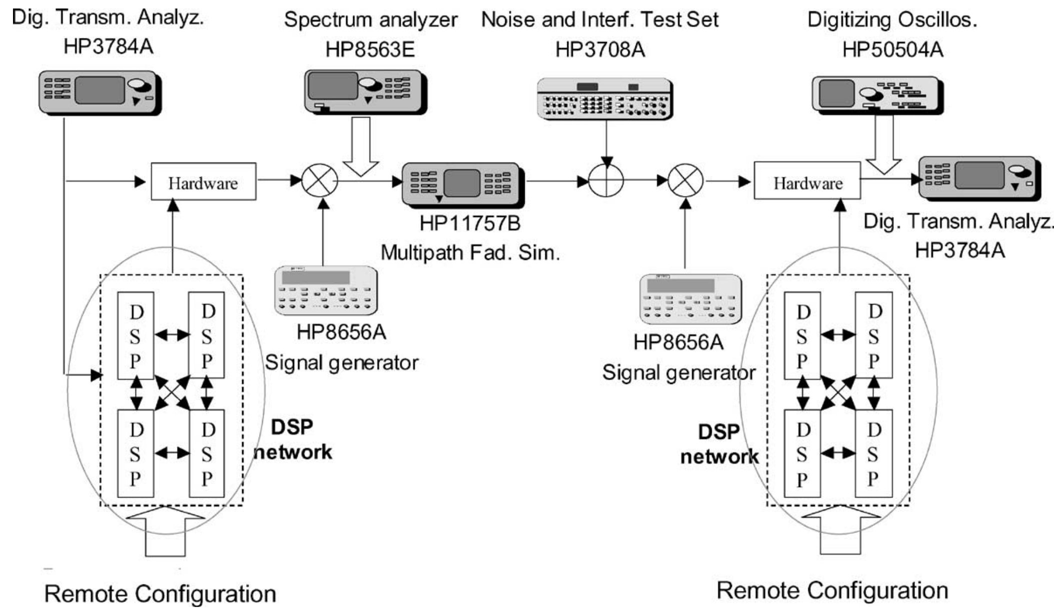

Fig. 5. Wide-sense telemeasurement platform.

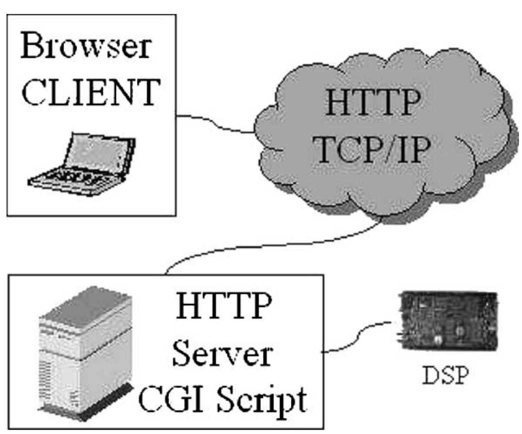

Fig. 6. Interaction between the Web server and the programmable platforms.

the development of *ad hoc* CGI for the communication with the DSP platform (see Fig. 6).

In particular, Texas Instruments DSP modules have been connected to different computer hosts. Within a predefined book, a user chooses an experience and the virtual interfaces of instruments that are involved appear in the HTML page. There are also links to CGI scripts from which commands to the DSP module are permitted, such as commands to transfer the software to the DSP internal memory for circuit definition and execution control commands like Reset and Run.

This platform has many advantages, such as the cost reduction due to the absence of hardware movements that are required and the reduction of time consumption for workbench setup and measurements (it is possible to schedule batch measurement sessions on different circuits without any real-time human iteration). As a consequence, the utilization efficiency of excellence centers increases. The CGI to communicate with DSP platforms were written using C language and libraries are offered by Texas Instruments Code Composer Studio, taking advantage from the Dynamic Link Library that permits to control the execution of commands on the DSP board through the local host port interface [23]. The source code running on programmable devices is written in C language, taking advantage from the standard DSP American National Standards Institute (ANSI) C libraries called Chip Support Libraries.

IV. Examples of Educational Applications

The wide-sense telemeasurement platform that has been set up is useful for research purposes in excellence centers (which have few replicas of very expensive instruments) and for all cases where a large number of instruments that are not necessarily valuable are required to satisfy a huge number of users. This is the case of a class of students accessing the workbench in order to make educational experiences. Remarking that experiences performed directly on real instrumentation remains necessary to complete the educational training, a virtual access to an instrumentation can represent a useful way to give the possibility of making a remote laboratory experience (e.g., distance learning). This is particularly true in the case of digital signal processing courses where a lot of time is spent in developing and debugging the DSP software.

Through the telemeasurement platform described in the previous section, a pilot experiment of laboratory distance learning has been developed and tested. Courses at different levels can take advantage from this experiment (e.g., from basic electrical communications to advanced digital transmission masters). Based on the course level addressed, experiences with three degrees of complexity and flexibility have been considered: driven, predefined, and student developed. In the first case, the tutor is the only user who controls the instrumentation and students remotely observe his lesson, e.g., to learn basics of communication-system performance evaluation. In the second case, students access to a menu of predefined experiences to familiarize with DSPs and the instrumentation. In this case, the student plays an active role in the use of the instrumentation and the system configuration without entering into details of the system definition. In the third case, which is more complex and flexible, students of advanced courses directly access both the instrumentation and the DSP platforms for system definition and configuration; they are enabled to create new DSP applications and to upload the software on the DSP platform. As an example, the following predefined experiences have been made available to students.

1) [Digital filter design and characterization]. Design via MatLab toolboxes [19], [20] and DSP realization of finite- and infinite-impulse-response filters with measures of magnitude and phase characteristics.
2) [Digital transmission chain characterization]. Generation of a multilevel pulse-amplitude-modulation signal, with pseudorandom information-bit sequence and different transmission rates, followed by a product modulation at 70 MHz to obtain a multilevel amplitude-shift-keying signal, demodulation, and lowpass filtering (from a simple RC filter to raised-cosine equalizer with different cut frequencies): Spectra, eye diagrams, and effects of intersymbol interference can be measured.
3) [Digital phase-locked loop circuit]. Definition and characterization of a digital phase-locked loop.
4) [BER measurement]. Characterization of a code-division multiple-access (CDMA) modem (transmitter and receiver with I-Q product modulation at 70 MHz), signal analysis at different sections, and BER measurement with thermal noise (at different SNRs) and multipath propagation. The data sequence elaborated and transmitted can be a pseudorandom bit sequence or an unformatted file audio. In the last case, an analysis of the user perceived quality of service for different conditions and error rates is also possible and useful for educational purposes in order to evaluate a relationship between the quality of service and the quality perceived by the user.

The executable files running on the DSP were obtained using the C compiler offered by Code Composer Studio [25], [26]; the source files were written using C language, taking advantage from the standard ANSI C libraries also called Runtime Support Libraries and the low-level routines supporting on-chip peripherals also called Chip Support Library [24] offered by Texas Instruments Software Foundation Libraries.

In Fig. 7, a snapshot of the Web server with the book of educational experience and an example of an access to an experience from a student are shown. It is important to remark that, in all cases, this is a way to permit students the use of real instruments and circuits through their remote interface. At this point, it is important to remark that an important challenge is the optimization of the multiple access to the workbench by a suitable policy and resource sharing management algorithm (e.g., [13]). In this paper, we put more emphasis on the realization of the wide-sense telemeasurement platform (remote configuration of devices and instrumentation), giving a solution to the multiple access of the instrumentation described in Section II-A.

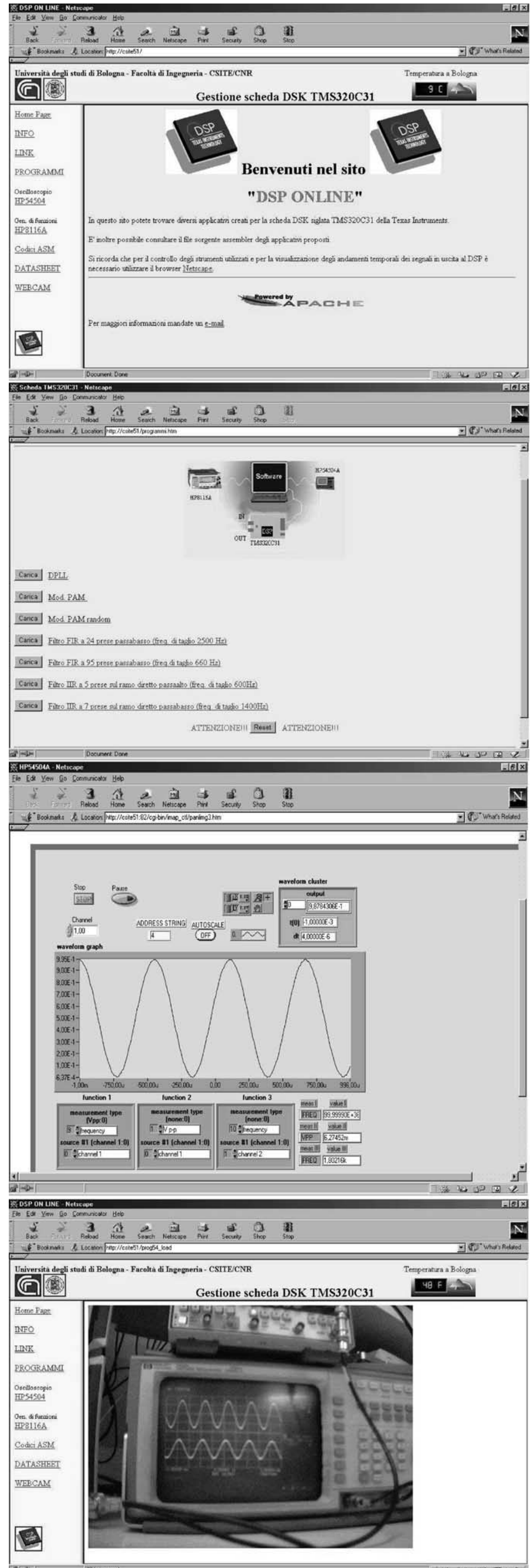

Fig. 7. Web server for the book of educational experiences.

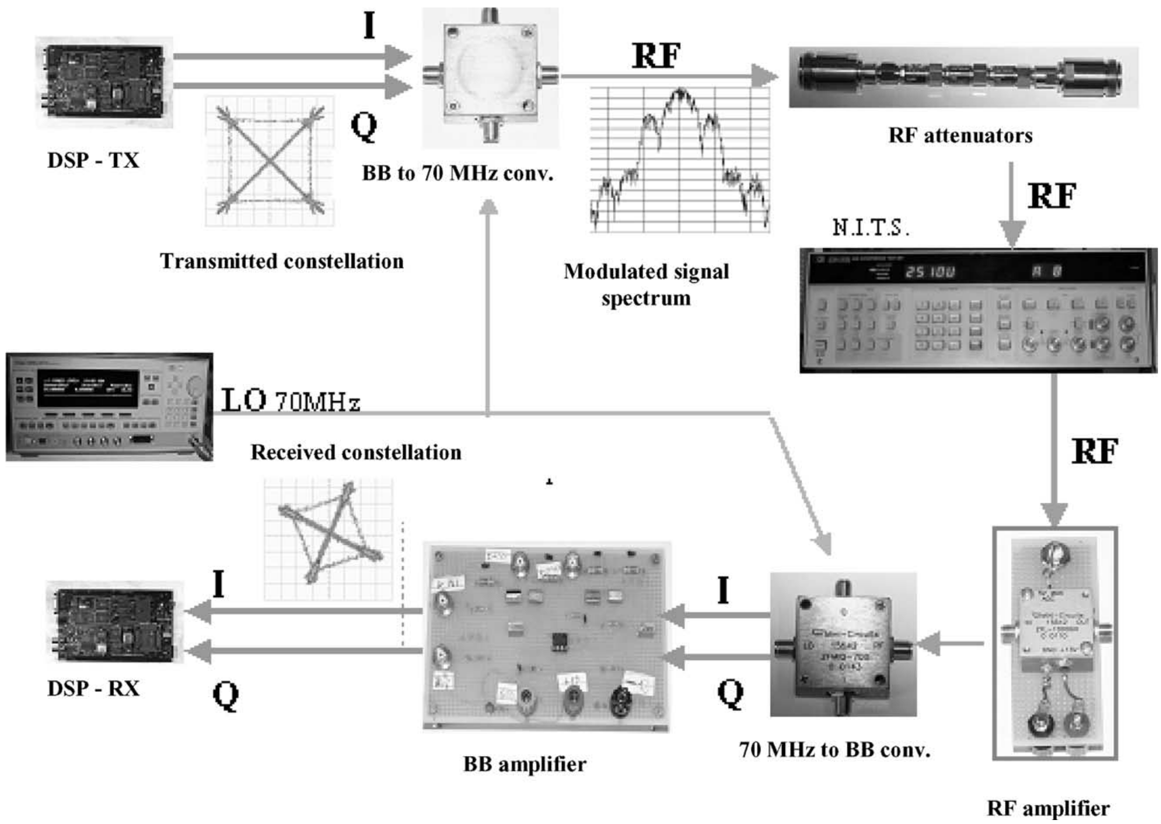

Fig. 8. CDMA-modem performance characterization by telemeasurement.

V. Example of an Industrial Application: A CDMA-Modem Characterization

In the forthcoming mobile-radio-system standards, the necessity to extend high bit-rate services to an increasing number of users sharing the same limited radio bandwidth drove the recent research activity to efficient multiple-access techniques to the channel. In this context, the CDMA scheme [21] gained great interest as the key technology for third-generation mobile radio systems [22]. Hence, it is important to measure the system performance in complex scenarios that take into account the principal transmission impairments like thermal noise, interference, and multipath propagation.

Within the CNIT-Italian Space Agency (ASI) project "Integration of Multimedia Services on Heterogeneous Satellite Networks," an SWR-based CDMA modem for satellite transmissions has been developed and tested [27]–[29]. One of the aims of the project was to provide CDMA to earth stations that are distributed on the entire Italian territory connected through the Ka-band satellite link. In this scenario, it is important to give the possibility of an excellence center to remotely define the functionalities and measure the performance of geographically distributed modems. The wide-sense telemeasurement concept previously introduced, with the remote configuration of the programmable platform, allows this kind of system characterization. In fact, any change in modem algorithms can be uploaded to the geographically distributed DSP platforms and can be evaluated through the telemeasurement network.

Examples of tests and measurements on CDMA communication systems can be found in [30] and [31]. In the following, a performance characterization by means of measurements of a constellation, an eye diagram, a spectrum, and a BER will be given for a CDMA modem employing differential-quadrature phase-shift-keying (DQPSK) modulation, Gold sequences with a spreading factor of 7, and acquisition, tracking, and frequency offset recovering implemented via software using the algorithms proposed in [29]. The transmission chain implemented is depicted in Fig. 8. It is comprehensive of the CDMA transmitter (realized on a DSP platform), an I/Q product modulator with the local oscillation at 70 MHz generated by a function generator, an NITS to add white Gaussian noises with different SNRs, a product I/Q demodulator, and the receiver implemented on a different DSP platform. In each section, attenuators or amplifiers are inserted to adjust the signal level, and the signal in time and frequency domains can be measured. At the receiver, the measurement of the BER for each value of the SNR set is performed and compared with theoretical results. In Fig. 9, the measures of the baseband signal constellation and the eye diagram at the transmitted side are reported, whereas the telemeasured spectrum of the modulated RF signal is reported in Fig. 10. The measure of the constellation of the baseband received signal before despreading, in which it is possible to appreciate the addition of thermal noises and the phase shift between the carriers at the transmitter and at the receiver, is reported in Fig. 11. As far as the complete characterization of the system is concerned, the BER has been measured for different values of the SNR. As an example, Fig. 12 shows the measured BER versus SNR and its comparison with theoretical results for the DQPSK scheme.

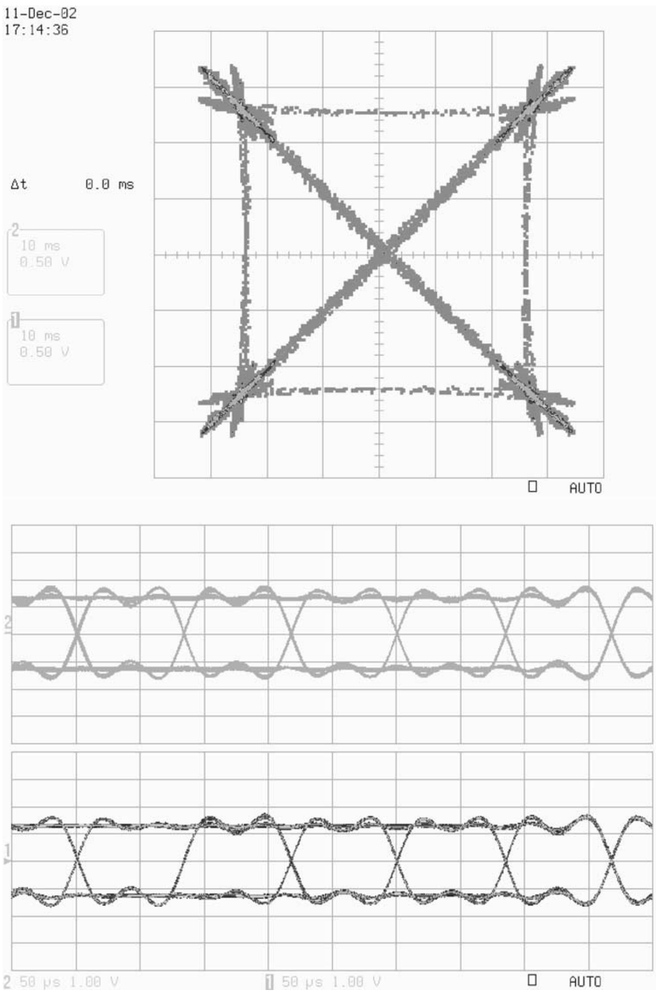

Fig. 9. Measured constellation and eye diagram at the transmitter side.

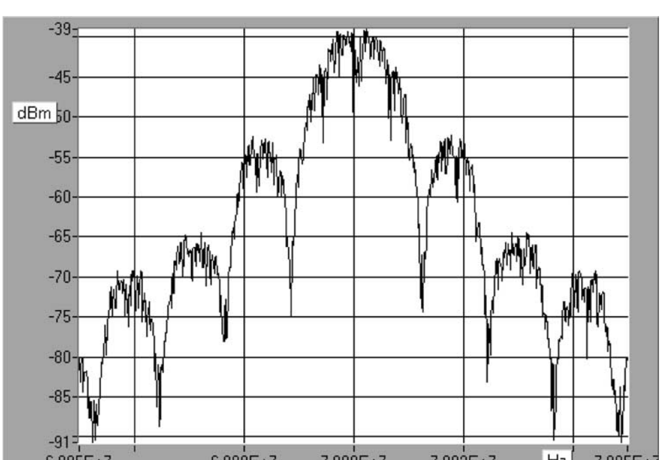

Fig. 10. Telemeasured RF-signal spectrum.

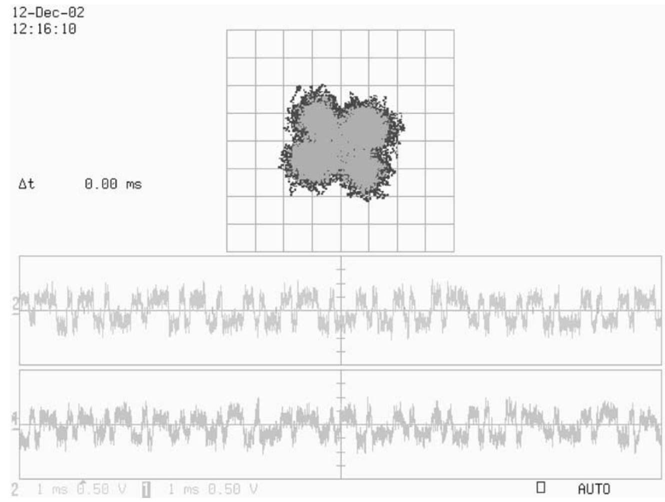

Fig. 11. Measured constellation and eye diagram at the receiver side before despreading.

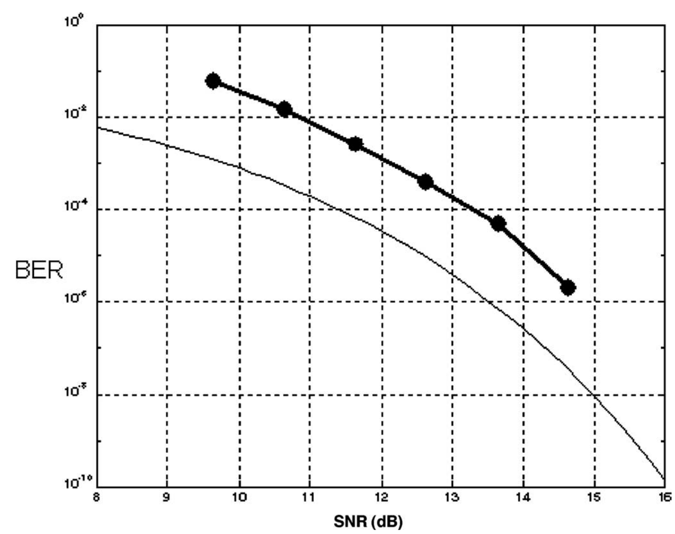

Fig. 12. Theoretical and measured BER versus SNR.

VI. Conclusion

In this paper, a wide-sense telemeasurement methodology for the characterization of communications devices and systems through heterogeneous networks has been proposed. This approach consists of the remote configuration of the instrumentation (classical telemeasurement approach) and the addition of the remote definition of circuits realized on programmable platforms. This methodology is particularly useful both for the case in which valuable instrumentation is necessary (research purposes) but only available in some particular laboratories (excellence centers) and for the case of a class of students (educational purposes) performing remote measurement experiences (distance learning). In particular, we reported the experience made in the WiLAB at IEIIT-BO/CNR, in which a Web server configured to manage both instruments and DSP platforms has been developed. As an example of the application, a book of experiences is provided for students that access via Web by a heterogeneous network composed of wireless and wired links. A CDMA-modem characterization, in terms of the telemeasurement of the constellation, the eye diagram, the spectrum, and the BER, has been given as an example of an industrial or a research application.

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