Practical Papers, Articles and Application Notes

Robert G. Olsen, Technical Editor

In this issue you will find three practical papers on the topic, "EMC and Wireless Devices" that should be of interest to members of the EMC community. The first is a short editorial paper entitled, "Coexistence of Converged Wireless Communications Devices" by M. Foegelle. In this paper Dr. Foegelle discusses a different kind of EMC issue in which the testing focuses on degradation in performance of one wireless link due to the interference from the other types of wireless radios. The second paper is entitled, "Challenging Research Domains in Future EMC Basic Standards for Different Applications" by N. van Dijk, P. Stenumgaard, P. Beeckman, K. Wiklundh and M. Stecher. In this paper, the authors discuss some of the problems in developing standards that are relevant for emerging wireless technologies. It is a nice complement to the first paper in this section. The third paper is entitled, "Ultra Wide Band Propagation Measurements in Indoor Working Environments and Through Building Materials," by C. Buccella, F. Graziosi, G. Manzi, M. Feliziani, M. Di Renzo, and R.Tiberio. Ultra Wide Band is one of the emerging wireless technologies for which standards will be developed. To develop these standards, it will be necessary to understand this technology and this article will be helpful toward that end. The second and third papers were first presented at the EMC Europe Workshop 2005 entitled, "Electromagnetic Compatibility of Wireless Systems" in Rome, Italy and have been reprinted here by permission of the Workshop Committee.

The purpose of this section is to disseminate practical information to the EMC community. In some cases the material is entirely original. In others, the material is not new but has been made either more understandable or accessible to the community. In others, the material has been previously presented at a conference but has been deemed especially worthy of wider dissemination. Readers wishing to share such information with colleagues in the EMC community are encouraged to submit papers or application notes for this section of the Newsletter. See page 3 for my e-mail, FAX and real mail address. While all material will be reviewed prior to acceptance, the criteria are different from those of Transactions papers. Specifically, while it is not necessary that the paper be archival, it is necessary that the paper be useful and of interest to readers of the Newsletter.

Comments from readers concerning these papers are welcome, either as a letter (or e-mail) to the Technical Editor or directly to the authors.

Coexistence of Converged Wireless Communications Devices

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Introduction

With the proliferation of wireless technologies, a new type of electromagnetic compatibility issue has arisen which is considerably different than those addressed by traditional EMC testing. Termed coexistence, this field addresses the issues related to having one device with multiple wireless technologies that are expected to be active at the same time. More loosely, it can also refer to use of different wireless technologies at the same location. In traditional EMC testing, unintentional radiation, including spurious emissions (out-of-band harmonics) of intentional radiators, is required to be below some regulatory limit to pass the device. In coexistence testing, the testing focuses on degradation in performance of one wireless link due to the interference from the other types of wireless radios.

Background

Traditional EMC limits are intended to protect the spectrum from interference by unintentional radiators. The presumption there is that the interferer and the radios being interfered with are separate entities with some physical separation. Test limits are specified as field levels at a fixed distance from the EUT. These levels were chosen at a time when radio communications were primarily analog in nature and the effects of RF interference were obvious with respect to the quality of the communications link. The common EMC solution published with most electronics refers to a user solution of moving either the interferer or the "interferee" to rectify an interference situation. By changing the proximity and relative orientation of the devices, the interference can be reduced to a level that usually eliminates the obvious effects of the unwanted signal.

Converged Devices

Now consider a wireless device such as a laptop or mobile phone, which is likely to have radios for cellular phone, 802.11 (Wi-Fi), and Bluetooth, just to name a few technologies. The antennas and radio circuitry for each of these radios is in a fixed location in these devices. The user cannot move them with respect to each other, and they are all in extremely close proximity to each other. Thus, it's immediately apparent that any interference caused by one of these radio interfaces on any of the others while in operation cannot be alleviated by the methods mentioned above. It should also be apparent that due to the proximity of the different radios to each other, the out-of-band signals of a radio that passes traditional EMC requirements will be much higher than the limit at the input to the other radios in the device. Even if the out of band signal is 100 dB down from the intentional radiation (pretty impressive for most band-pass filters in today's digital electronics) then a cell phone radio transmitting at +33 dBm can easily pass today's spurious emissions requirements, and still result in interference levels at the input to a Wi-Fi radio that are well above the ~-85 dBm sensitivity level of a typical 802.11b radio. The loss of even a few dB of sensitivity can have drastic effects on the available range and overall performance of a wireless device. The reality is that without careful design, the level of interference can be much worse than this simple example. And unfortunately, the only way to eliminate the interference is to disable the interfering radio.

There are many ways the various radios can interfere with each other. For example, it's obvious that technologies like Bluetooth (802.15) and Wi-Fi (802.11), both of which share the unlicensed ISM band at 2.4 GHz, are likely to interfere with each other if both radios are in use simultaneously. Transmission from one radio easily couples into the input of the other, possibly overloading the input or otherwise interfering with reception of a desired signal. The 2.4 GHz band is an even multiple of the 800 MHz cellular band, allowing harmonics of cellular communication to show up in the 2.4 GHz band. Both cellular and PCS (1.8-2 GHz) mobile phone bands, as well as the 2.4 GHz ISM band have harmonics in the 5-6 GHz ISM band used for 802.11a. Note that this doesn't necessarily go just from lower bands to higher bands, as the principal signal in a higher band can leak into the lower band receiver as an out-of-band signal that is not sufficiently reduced by the receiver's band pass filter. Even when harmonics don't appear in the overlapping bands, there can still be interference. Signals can leak into the IF stages of the radio, or the sums of the filters of both radio output and input are still not enough to drop an interfering signal below the sensitivity of the receiver being interfered with.

To address these issues, a new arena of coexistence testing is being developed. These tests are being introduced as modifications to over-the-air (OTA) performance tests for these wireless devices. The concept for this type of testing is pretty straightforward. The radiated performance of the EUT is determined for a given technology (i.e. with only one radio active). The receiver performance (sensitivity) of the radio under test is evaluated in an OTA arrangement to ensure that the effects of digital circuitry and other "self-jamming" behaviors are present when the radio is tested. A conducted (cabled) test might not show these effects. Once the "best" performance is determined, the other radio(s) are enabled, and traffic is sent over those links while the OTA sensitivity measurement is repeated for the radio being tested. Any difference between this result and the original result indicates the level of desensitization caused by the other technologies. Ideally, no desensitization would occur. Depending on the configuration of the EUT, this process can be repeated with each single radio enabled or any combination thereof. Once the desensitization is determined for the given technology, the same test can be repeated for each additional radio technology supported by the EUT to determine the level of desensitization present for that technology.

At this time, these types of tests aren't regulatory in nature, and haven't been standardized for any certification programs either. For the moment, manufacturers are interested in them to ensure they're providing a good product. Industry organizations like the Cellular Telecommunications and Internet Association (CTIA) and Wi-Fi Alliance recognize the proliferation of so-called "converged" devices and are looking at this type of testing as part of their certification programs. Various standardization groups are looking at coexistence in the broader sense, either in terms of their own standards (such as 802.19, which will look at ensuring that various 802.X standards coexist) and broader efforts, that are looking at coexistence issues between emerging technologies such as ultra-wideband (UWB, which uses spread spectrum signals below traditional EMC limits) and cognitive radio (which can monitor the spectrum and switch to unused bands to avoid interference) and their effects on both the licensed (TV, cellular, etc.) and unlicensed bands that these devices are likely to operate in.

Conclusion

The nature of electromagnetic testing is changing. The average person now owns at least one device that has an antenna in it for some form of digital communication, and most would probably be surprised to realize that they're surrounded by many more than that. We are no longer limited to the basic communication model around which most EMC standards were written. Ten or fifteen years ago, the average household might have had a couple of AM/FM radios, possibly some rabbit ears on their TV, and maybe an analog cordless phone. Today, we have mobile phones, PDAs, and laptops with a mix of Cellular, Wi-Fi, and Bluetooth technologies, wireless keyboards and mice, wireless speakers and headsets, wireless networks, digital walkie-talkies, etc., with more on the way. If it used to have a wire for communication, it can typically be provided wireless today. Other technologies such as Wi-Max/UWB are poised for introduction, and it seems that new technologies are being invented faster than engineers can figure out how to use them. 60 GHz transceivers are on the horizon! With the proliferation of digital communication, the issues of EMC can be expected to change considerably. With a focus on performance of the communication products, and emerging concepts such as cognitive radio, it becomes apparent that the definition of EMC may move from "electromagnetic compatibility" to "electromagnetic coexistence." See page 111 for more information.

Innovative Software Tools Improve EMI/EMC Design

Dr. Bruce Archambeault, Gene Garat

Where has all the current gone?

Today's high speed PCB's have many layers and are very complex. Who has the time to examine each critical signal looking for a good returning current path? Well, if you don't, your computer does. It can use automated EMC rule checking tools. These tools uncover the hidden schematic, examining each net in turn regardless of the PCB complexity. Fortunately, there are a set of software tools, developed by **IBM** EMC Engineers for internal use, that are now available outside the company for you to take advantage of. They have over 25 years of research and a proven track record.

EMSAT with Allegro Violation Viewer

EMI/EMC Design Rule Checking

EMI/EMC design has traditionally been performed using a try-it-and-see approach. This design strategy often results in products that fail the EMI/EMC requirements - resulting in multiple design iterations, adding costs to the product, and delays to market introduction.

The EMC performance of a printed circuit board is mostly based on the location of various components and the location of critical I/O nets/traces. Manual checking of all the multiple layers on today's high speed circuit boards is extremely time consuming and prone to error. **EMSAT** relieves the tedium and removes the human error by checking each EMC critical net for violations of any selected set of EMC design rules in minutes or hours. After CAD board files are imported, the user selects EMC rule(s) based on specific nets/traces or components that are critical for EMC, such as I/O nets, power nets, ground, etc. Violations of the EMC rules can be graphically viewed either in Allegro, or as an HTML document

EM Simulation

State-of-the-art fullwave EM solvers, **PowerPEEC,** based on the Partial Element Equivalent Circuit (PEEC) technique, providing simulations in both the time and frequency domain, and **EMSIM,** based on Methods of Moments (MOM), both provide insight to help make the EMI design trade-offs before the product is built. **CZ2D** is a quasi-static EM simulation tool best used for electrically small models when RLC extraction is required.

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Biography

Dr. Michael D. Foegelle received his Ph.D. in Physics from the University of Texas at Austin, where he performed theoretical and experimental research in both Condensed Matter Physics and Electromagnetic Compatibility (EMC). He performed contract EMC research with Dr. J. D. Gavenda of the University of Texas for IBM and RayProof where he helped to develop a semi-anechoic chamber modeling system. In 1994, he began working for EMCO in Austin, Texas (now ETS-Lindgren in Cedar Park, Texas), where he is currently the Senior Principal Design Engineer. In this position, he has been integral to the development of products, software, and test methods for Wireless, RF, and EMC testing. He has been involved in numerous national and international standards committees and is currently involved in the work being done to improve antenna calibrations and site validations per the ANSI C63 standards, as well as the CTIA Certification Program Working Group on over-the-air performance testing of wireless devices and the IEEE 802.11 TGT for wireless performance prediction of Wi-Fi devices. He is co-chair of the CTIA's Converged Devices ad-hoc group and is a member of the Wi-Fi Alliance's Wi-Fi/Cellular Convergence group. He has authored or co-authored numerous papers in the areas of Electromagnetics, EMC, and Condensed Matter Physics.

Challenging Research Domains in Future EMC Basic Standards for Different Applications

Nico van Dijk, Peter F. Stenumgaard, Pierre A. Beeckman, Kia C. Wiklundh, Manfred Stecher

Abstract — *The EMC area was once born due to radio interference problems. It is likely to assume that wireless issues will once again cause a strong development of the EMC area. The rapid development within multimedia and wireless systems has lead to a large need in development activities in order to make the current EMC product standards relevant for these emerging technologies. The complexity of these development issues is, however, large and includes several challenging research activities to be carried out. In this paper, examples of such research activities are presented to give an overview of future needs within some technical areas.*

I. INTRODUCTION

The background of the EMC area may be found in the 1920s, when broadcasting services started to reach the general public. Quite soon it became evident that control of the generation of electrical noise and similar man-made disturbances was essential in order to guarantee a good quality of the new broadcasting services. However, imposing limitations on electrical equipment and household appliances could cause trading problems if different countries applied significantly different norms. This problem was soon realised on national levels, which led to the foundation of the International Special Committee on Radio Interference (CISPR). The International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU) were cofounders [8]. The first standard produced was at a national level when the BS613 (1935) concerning components for radio disturbance suppression devices was published in England. In 1937, the BS727 concerning characteristics of an apparatus for measuring of radio disturbance was published. This standard had a major impact on the standardisation work within CISPR. Since then, the EMC area has undergone tremendous growth with the birth of a large amount of sub areas. Today, the EMC area is a well-established engineering and scientific domain all over the world. In the near future, it is expected that wireless interference issues once again will lead to several challenging new research activities within the area of EMC. Examples of such activities will be presented and discussed.

Two emerging domains can be identified as driving forces behind the need of these research activities. The first is the on-going development of dynamic flexible wireless networks, or software defined radios (SDR) based on software communication architectures. SDR is a key element in the design of mobile ad-hoc networks for future civilian and military command and control systems. One development path within SDR is Cognitive Radios (CR). Cognitive Radios are "smart" radios that easily adapt to their operating environment, seizing spectrum bandwidth whenever it becomes available.

The second important domain is the area of multimedia products for the wireless home. A general trend can be observed that traditionally different markets are converging, namely: the Personal Computer (PC) market, the telecom market, the gaming market, and the consumer electronics market. In addition, the digital communication systems (WiFi, Bluetooth, Ultra Wide Band (UWB)) converged in the multimedia equipment will in general operate at frequencies above 1 GHz, while the current CISPR norms are defined up to 1 GHz only. All these extreme changes in the electronic market highlight the need for new and more research activities, which are necessary to facilitate a fast acceptance of wireless applications in multimedia equipment. In this paper, we will discuss some research items which are, in our opinion, of large importance:

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- Extension of radiated emission measurements above 1 GHz;
- Weighting detectors for future emission standards;
- Development of new statistical techniques (e.g. APD) for the processing of radiated emission measurement results;
- Extension of radiated immunity tests above 1 GHz;
- Extension of radiated immunity tests by using digitally modulated signals;
- Development of alternative measurement methods;
- Development of a new multimedia standard.

In this paper, each of the above listed research items are summarized together with some state-of-the art results. The goal of the paper is to give a well-defined overview of current and near-future activities which are important for the development of a new EMC product standard for multimedia equipment. This multimedia standard (Emission: CISPR 32, Immunity: CISPR 35) is under consideration in CISPR/I and will be the successor of CISPR 13, 20, 22, and 24 in future.

II. RADIATED EMISSION MEASUREMENTS ABOVE 1 GHZ

These days, a lot of electronic products or systems operate above 1 GHz. This means that either intended RF- transmitters and/or receivers are applied at frequencies above 1 GHz or that internally electronic functions are realized using signals above 1 GHz, e.g. a clock signal. Consequently, new interference scenarios may occur in the frequency range above 1 GHz, which will affect the emission and immunity performance of products. This paragraph will address the developments related to the radiated emission measurement method above 1 GHz. Paragraph V describes the issues related to the immunity tests above 1 GHz.

Many years ago, the FCC established radiated emission limits up to 40 GHz. The method of measurement of these emissions above 1 GHz is specified in ANSI C63.4-2003 [1]. The ANSI C63.4 description of the radiated emission measurement method above 1 GHz is based on measurement of maximum radiated electric field at a certain distance from the EUT. The FCC considers an emission measurement site that is valid for use below 1 GHz also suitable for emission measurements above 1 GHz. The measurement method applies near-field region scanning of the EUT where the scanning depends on whether the main beam of the receive antenna sufficiently encompasses the EUT. The FCC/ANSI >1 GHz measurement method is a pragmatic extension from the <1 GHz radiated emission measurement method. The uncertainty and reproducibility aspects of this FCC/ANSI method are not known. In the past years, within CISPR, different sub committees are or were dealing with several 1-18 GHz-related standardisation projects. CISPR/A deals with the radiated emission measurement method, the validation of test sites and the receiver specification above 1 GHz, while both CISPR/I & /H address the radiated emission limits from 1-18 GHz. It is impossible to discuss the status of these projects in detail in the context of this paper. The situation can be summarized as follows:

- The radiated emission measurement method (1-18 GHz) is recently published in Amendment 1 of CISPR 16-2-3 [2],
- A 6th CD (!) [3] has been published on the evaluation of 1-18 GHz test sites,
- A CDV [4] for CISPR receiver specifications has been voted positively and will soon be registered as an FDIS,
- The work on setting interference limits from 1-18 GHz is pending within CISPR/H,
- Limits for 1-6 GHz [5] have been accepted for publication in CISPR 22, but the proposed limits between 6-18 GHz has been voted down (CISPR/I/106A/CDV).

From this status overview it is clear that the different CISPR >1 GHz projects are progressing at different speeds. The measurement method is published, but the site validation method and receiver specifications are still underway, and the rationale for limits is lacking. The slow progress of some of the >1 GHz work is due to the complicated technical aspects involved with the radiated emission measurement method >1 GHz. Some of these issues are [6]:

1) The measurement method has been developed without explicit statement on what the measurand above 1 GHz should be. The present measurement method and procedure is such that for many types of EUTs the maximum emission will not be captured [6], which is due to the directivity of EUT emission patterns [15] and near-field region effects.
2) The present scanning procedure [2] is based on heuristic considerations, rather than on results of adequate modelling or measurements. A height-scan procedure related to the radiation properties of the EUT (instead of physical height) would be more appropriate and consistent (with the azimuth scan procedure).
3) Compared to <1 GHz measurement method, other uncertainty factors play a role and the level of uncertainty (reproducibility) is probably much larger. Accurate antenna calibration [7] and site validation is difficult. Uncertainty factors are not investigated systematically and no uncertainty budget is available yet.
4) New interference scenarios become important with the proliferation of wireless and digital products ‘operating’ above 1 GHz. It may well be that for these interference scenarios other types of disturbance parameters should be considered for limitation (total radiated power instead of maximum electric field at a certain distance).

The present >1 GHz emission measurement method is based on extrapolation of the <1 GHz method, which is a deterministic method with the aim to measure the maximum electric field at a specified distance from the EUT. Several of the abovementioned issues may be solved if in the > 1 GHz region, statistical based methods will be applied and if a measurand is used that fits better with the interference scenarios that are relevant in this >1 GHz frequency range. For example, a challenging research domain in this respect is the application of the reverberating chamber measurement method [14],[16] to determine the total radiated power of an EUT as relevant disturbance figure of merit (see also paragraph VI).

III. WEIGHTING DETECTORS FOR FUTURE EMISSION STANDARDS

A. Origin and function of the quasi-peak detector

When broadcasting services started to enter homes in the early times of radio, it became obvious that radio interference had to be limited in order to enable an acceptable reception of the new service. As a consequence, CISPR was founded in 1934 [8] for the development of measuring equipment and procedures.

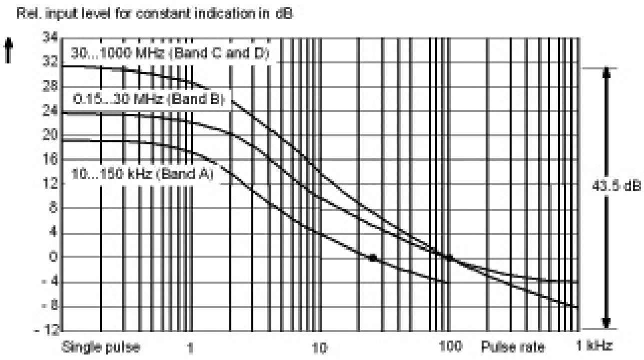

Fig. 1: Weighting curves of quasi-peak measuring receivers for the different frequency ranges as defined in CISPR 16-1-1 [9].

Until 1967, the CISPR quasi-peak detector had been established up to 1000 MHz as depicted in Fig. 1. The effect of narrowband interference was found to be higher than that of broadband interference, which was taken into account by different limits for narrowband and broadband disturbances.

B. Other standard detectors

Besides the QP detector, other detector functions have been standardized in [9]. The peak detector follows the signal at the output of the IF envelope detector and holds the peak value. The average detector measures the average output of the IF envelope detector. The RMS detector is described in [9], but it has no practical use in EMI measurements up to now. Recent measurement and simulation results have shown that the RMS (Root-Mean-Square) detector exhibits a response that can be correlated to the interference impact on digital communication systems. All modern radio services use digital modulation schemes. This is not only true for mobile radio but also for audio and TV. Procedures for data compression and processing of analog signals (voice and picture) are used together with data redundancy for error correction. Usually, up to a certain critical bit-error rate (BER) or bit-error probability (BEP), the system can correct errors so that perfect reception occurs. The RMS-value resulting in constant BEP for different values of the pulse repetition frequency, f_p, of the disturbance signal has been shown to be approximately [10] as shown in Fig. 2, where P_0 is the chosen value of the constant BEP and RS is the symbol rate of the digital communication system. This result has been shown to be valid for several digital modulation schemes [17]. If error-correcting codes are used in the communication system, the behaviour differs from the uncoded case only by a change of the 7.5 dB/decade region [11], see Fig. 3 so that it is smaller.

C. A new weighting detector

The question of weighting to digital radio communication systems is of interest to both CISPR and ITU-R. The work to do is to determine the interference effect and find a compromise solution for a weighting detector including measurement bandwidth. While the pulse repetition frequency is varied, the required pulse level has to be varied in order to keep the BER constant (see Fig. 4). In [12], an RMS/Average weighting receiver has been proposed for international standardisation in order to more realistically measure the interference potential of emissions on digital radio communication systems. In Fig. 5, this detector is compared to some standard detector. Further studies have been made to support the new detector.

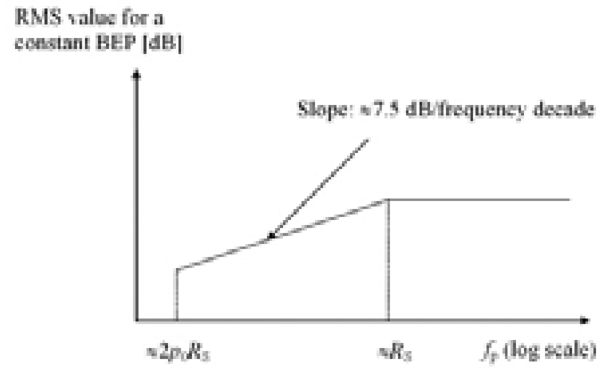

Fig 2. The RMS value for constant BEP.

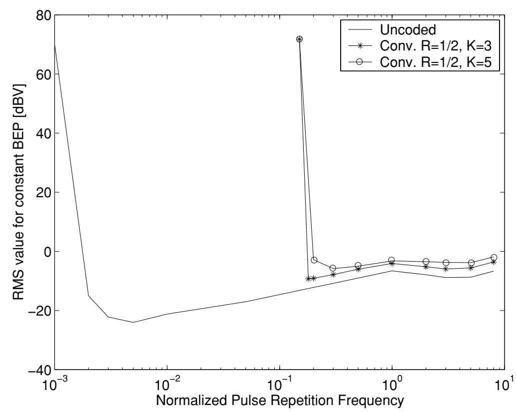

Fig 3. The RMS level for constant BEP for two, rate.

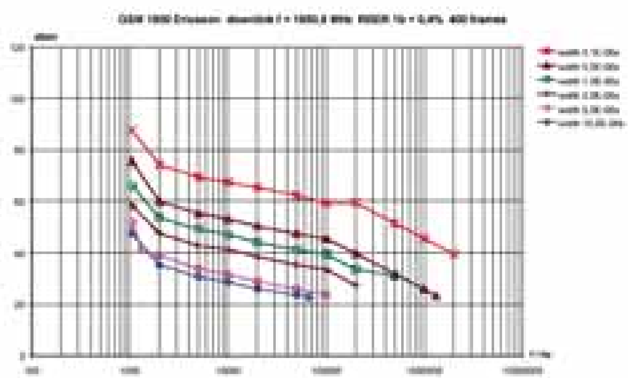

Fig. 4: Example of a measured weighting function (RBER 1b of GSM). The curves are characteristically rising below 2 kHz PRF.

IV. DEVELOPMENTS IN STATISTICAL TECHNIQUES FOR RADIATED EMISSION MEASUREMENTS

The impact on modern digital communication systems of complex radiated interference environments can be very difficult to

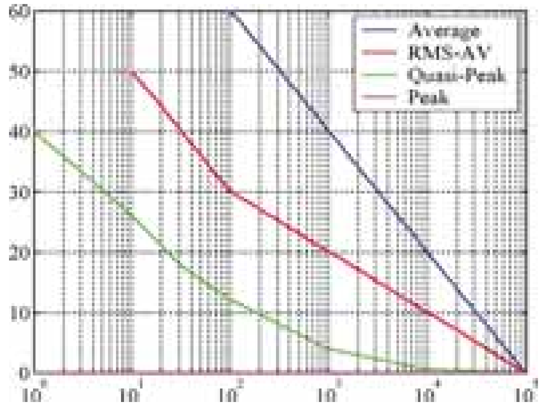

Fig. 5: The proposed weighting detector (in blue) for CISPR bands C and D (30 to 1000 MHz) with existing detectors (Pk/QP/AV).

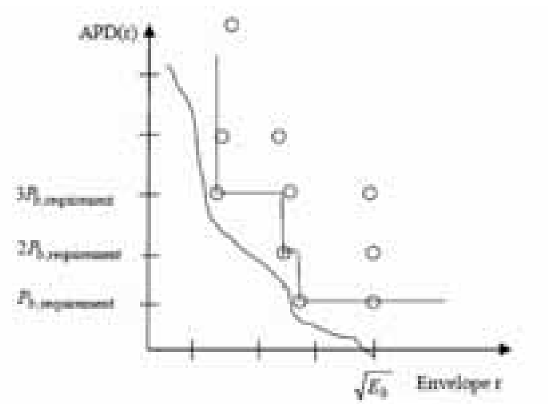

Fig. 6: Example of limit lines in APD graph.

analyse with present methods, see paragraph II. This raises the question of modelling these environments in another way, by the use of statistical methods in order to get models that are more suitable for interference-impact analyses on digital communication systems. The Amplitude Probability Distribution (APD) is a measure, which characterizes the interference envelope distribution after the IF filter. The APD is defined as the part of time the measured envelope exceeds a certain level [17]. The measure has been discussed within CISPR as a possible measurement method of radiated interference [18], since it has been demonstrated to be correlated to the BER of a digital receiver. This has been shown in [17] by simultaneous measurements of the APD and the performance of a certain radio receiver and in [19], in which a theoretical description between the APD and BEP is presented. In [20], a possible approach to use the APD for emission requirements is proposed. This can be performed by putting restrictions on the measured APD. A similar solution has been discussed within CISPR [21]. By using the relation between the maximum BEP and the APD of an interference signal, the requirement can be implemented as points in an APD diagram, see Fig. 6, under which the measured APD must lie below [20]. Since radio receivers with different modulation schemes withstand interference signals differently well, each considered systems results in a certain point in the APD diagram. If the measured APD lies below the requirement points, it is guaranteed that the BER not exceed the determined one for the radio systems considered. In these references, the communication system is assumed to be uncoded. However in [22], correlation is shown between the APD and the BEP for a coded and more complex communication system, although this is demonstrated with measurements only for some selected systems. Consequently, there are no general results of whether or how the APD is connected to the BEP for coded and more complex communication systems. Therefore, the following points need to be investigated:

- The approximate connection between the APD and the BEP for coded systems.
- How can this relation be used to derive emission requirements?
- What is the penalty of using more simple approximations of the interference as the Gaussian approximation, when studying coded and complex communication systems? That is, for which situations and for which systems do we need information from the APD to get a reliable estimate of the BEP?

V. RADIATED IMMUNITY TESTS ABOVE 1 GHZ

In this paragraph we will look at the immunity aspects of the increasing multimedia and wireless market. As explained in the introduction, a converging of different markets can be observed. This will result in multimedia equipment consisting of, among other things, wireless communication systems. Therefore, this trend means that a lot of new and generally digitally modulated communication signals will be present close to all other multimedia electronics. So, a new type of threat will be present due to the digitally modulated communication signals. For that reason, the immunity tests of electronic equipment should be extended. In classic (and current!) immunity tests, electronic equipment is tested on its robustness only against a 1 kHz 80% Amplitude Modulated (AM) signal which should be representative for analogue of radio signals. In order to find a test signal which is representative of digitally modulated communication signals, we need to investigate the behaviour of digital wireless communication signals. First, results point out that the digitally modulated signals themselves are not distinguishable of Average White Gaussian Noise (AWGN) in a lot of cases. However, the digital communication systems generally use data bursts, also called time-slots.

Actually, these data bursts mean that the modulated signal will be pulsed modulated with a Pulse Repetition Frequency (PRF) equal to the time-slot frequency (e.g. 217 Hz for GSM 900). The pulsed modulated character may cause low frequency demodulation and can subsequently cause considerable interference in audio and video applications. Further research on the behaviour of digitally modulated signals is needed in order to derive one representative test signal. One representative test signal, also called the Unified Disturbance Source (UDS), will prevent a tremendous amount of tests, which saves time and keeps the immunity tests simple. It is expected that the APD (paragraph IV) can be very useful for this signal characterization. Besides the threat of wireless communication signals, also the threat of PCs (spread spectrum clocks) and high-speed data buses are substantial, which are already in the above GHz range. At the moment, proposals for immunity tests above 1 GHz are not submitted, while representative immunity tests become very important for a satisfactorily functioning of wireless and multimedia equipment.

VI. ALTERNATIVE MEASUREMENT METHODS

As mentioned in the introduction, a general trend can be observed of increasing operating frequencies above 1 GHz of both the communication systems as well as other electronic equipment such as PCs, high-speed data buses and other multimedia applications. For this reason, it was already mentioned that an extension of both the immunity tests and emission measurements above 1 GHz is necessary. As mentioned in paragraph II, there are new proposals for emission measurements above 1 GHz in a Fully Anechoic Room (FAR). Up to now, proposals concerning immunity tests above 1 GHz were not submitted, while a lot of new interference threats are present in that frequency range (see paragraph V). EUTs have different radiation behaviour at higher frequencies. At lower frequencies (roughly below 1 GHz) especially the cable is the dominating source of radiation. At higher frequencies (roughly above 1 GHz) the equipment itself with its apertures and slits is the dominating source of radiation. Mostly this type of radiation will result in complex radiation patterns, i.e. grating lobes are present. The radiated emission of EUTs with radiation behaviour with narrow lobes is very difficult to measure in anechoic types of chambers like Semi Anechoic Rooms (SAR) and FARs. Therefore, alternative measurement methods like the reverberation chamber are interesting to investigate. In general, we can distinguish established and alternative measurement methods. Established methods are methods which are described in so-called basic standards and which are referred to in product standards. Alternative measurement methods are also described in basic standards but not (yet) referred to in product standards. For example, the OATS radiated emission measurement can be seen as established, because it is described in CISPR 16 (basic standard) and referred to in CISPR 22 (product standard). However, the reverberation chamber is described in IEC 61000-4-21 (basic standard) but not yet in a product standard. The IEC 61000-4-21 standard [14] is developed in a joint task force of CISPR/A and TC77B. The basic standard for TEM-cell measurements is also developed in a joint task force. In practice, there are various reasons to use alternative measurement methods:

1) Better high frequency performance;
2) Better reproducibility;
3) Reduced measurement time;
4) Low investment.

Besides many application-specific workbench measurement methods, well-known examples of alternative measurement methods are the already mentioned reverberation chamber, the FAR, and the TEM-cell. One important issue concerning the acceptance of alternative measurement methods is the limit that should be used. In that context, important work is performed in the ad-hoc group for alternative measurement methods in working-group 2 (WG 2) of CISPR/A. The results of this ad-hoc group are published in a Committee Draft (CD), CISPR/A/603/CD and 637/A/CC [13], which describes a well-defined correlation procedure for limits. The correlation procedure consists of the following steps:

1) Choice of physical reference quantity;
2) Obtain emission results by using both the established and the alternative measurement method;
3) Calculate the difference between results (step 2) obtained by the established method and the reference quantity (step 1);
4) Calculate the difference between results (step 2) obtained by the alternative method and the reference quantity (step 1);
5) Calculate the correlation by subtracting the two differences obtained in step 3 and step 4.

Although step 1 seams trivial, it is the most important step because it defines the relevance of the measurement method, mostly radioprotection. In principle, the correlation is EUT specific. Therefore, speaking about 'the correlation' is a mistake. We can only define useful correlations for specific EUTs or classes of EUTs. The above-mentioned correlation procedure is especially suitable to derive the correlation between the alternative measurement results and the established measurement results for classes of EUTs. In the mentioned correlation procedure, the so-called intrinsic uncertainty of the measurement method is an important factor. The intrinsic uncertainty defines how well the measurement method is suitable to measure the physical reference quantity of interest, i.e. the physical reference quantity. This makes clear how important a useful and relevant measurand will be in practice. In the 603/CD and 637/A/CC, an example is given of a comparison between the FAR and the SAR at various measurement distances. Moreover, working-group documents were published concerning comparisons between the reverberation chamber and both the FAR and the SAR. Although further research, including more types of EUTs and measurement results, is necessary, we can give the following correlation estimates for the reverberation chamber and FAR, where the maximum electric field was used as physical reference quantity:

- FAR (3 m) → SAR (3 m) ≈ 4 dB
- Reverberation chamber → SAR (3 m) ≈ 4 dB
- Reverberation chamber → FAR (3 m) ≈ 0 dB

Actually, in the reverberation chamber, the total radiated power is measured [14][16]. In accordance with the standard, this power is transformed to electric field by using the (free-space) Friis formula. For that reason, the FAR and the reverberation chamber are both free space types of measurements. One essential aspect in reverberation chamber measurements is the necessary estimation of the directivity of the EUT when the total radiated power is transformed to free space electric field. However, in [15] a useful formula is derived to approximate the directivity:

$$\langle D_{max} \rangle = \begin{cases} 1.55, & \text{if } ka \leq 1 \\ \frac{1}{2}\left[0.577 + \ln(4(ka)^2 + 8ka) + \frac{1}{8(ka)^2 + 16ka}\right], & \text{if } ka > 1 \end{cases}$$

where k is the wave number and a is the largest dimension of the EUT. Further research on correlation of results from alternative and established measurement methods is important in order to disclose alternative methods for future application.

VII. CONCLUSION AND OUTLOOK

As addressed in the introduction, tremendous changes in the consumer electronic market can be observed by the introduction of wireless communication systems and the convergence of different functionalities in one application. The current EMC product standards include the audio and video standards

(CISPR 13 and 20) and the information technology standards (CISPR 22 and 24), all under auspices of CISPR/I. Due to the rapidly changing electronic market with its typical new aspects such as higher frequencies, ad-hoc networks, convergence of various functionality in one application, etc., it is necessary to reconsider and extend the current standards. The most important technological challenges for the relevant extensions or adaptations are discussed is this paper. The extensions should result in a new multimedia standard (Emission: CISPR 32, Immunity: CISPR 35) in approximately the coming five years. Then the new multimedia standard will be the successor of the current audio, video, and information technology standards.

REFERENCES

[1] ANSI C63.4-2003: "Methods of measurement of radio noise emissions from low-voltage electrical and electronic equipment in the range of 9 kHz to 40 GHz," 2003.

[2] [Amendment 1 of IEC CISPR 16-2-3, "Specification for radio disturbance and immunity measuring apparatus and methods – Methods of measurement of disturbances and immunity – Radiated disturbance measurements," 2005-05.

[3] CISPR/A/531/CD, "Site evaluation above 1 GHz," 2004-06-04.

[4] CISPR/A/554/CDV, "Maintenance of CISPR 16-1-1, proposed amendment of clauses 5, 6 and 7: Extension of the measuring receiver frequency ranges above 1 GHz," 2004-10-29.

[5] CISPR/I/151/FDIS, "CISPR 22 Ed. 5: Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement Amendment 1: Emission limits and method of measurement from 1 GHz to 6 GHz," 2005-4-22.

[6] P.A. Beeckman: "Sources of uncertainty for emission measurements above 1 GHz," workshop on advances in site validation techniques above 1 GHz, 16th Zurich Symposium on EMC, Feb. 2005.

[7] N. van Dijk, "Uncertainties in 3-m Radiated Emission Measurements Due to the Use of Different Types of Receive Antennas," IEEE Transactions on Electromagnetic Compatibility, Vol. 47, No. 1, pp. 77-85, Feb. 2005.

[8] D. Heirman and M. Stecher, "A history of the evolution of EMC regulatory bodies and standards," Proc. 16th Zurich Symposium on EMC, Feb. 2005.

[9] IEC CISPR 16-1-1/2003-11: Specification of radio disturbance and immunity measuring apparatus and methods. Part 1-1: Radio disturbance and immunity measuring apparatus – measuring apparatus.

[10] Peter F. Stenumgaard, "Using the RMS Detector for Weighting of Disturbance According to its Effect on Digital Communication Services," IEEE Transactions on Electromagnetic Compatibility, Vol. 42, No. 4, pp. 368-375, Nov. 2000.

[11] Peter F. Stenumgaard, "A Possible Concept of How Present Radiated Emission Standards Could be Amended in Order to Protect Digital Communication Services" IEEE Transactions on Electromagnetic Compatibility, Vol. 46, No. 4, pp. 635-640, Nov. 2004.

(12) CISPR/A/628/CD: Weighting of interference according to its effect on digital communications services.

[13] CISPR/A/603/CD, Conditions for the use of alternative test methods, 2004-05-28.

[14] IEC 61000-4-21, Testing and measurement techniques – Reverberation chamber test methods, 2003-08.

[15] G. Koepke, et al., "Directivity of the test device in EMC measurements," Proc. 2000 IEEE International Symposium on EMC, Washington, pp. 535-539, Aug. 2000.

[16] C. L. Holloway, et al., "Total radiated power limits for emission measurements in a reverberation chamber," Proc. 2003 IEEE Symposium on EMC, Boston, pp. 838-843, Aug. 2003.

[17] Y. Yamanaka, T. Shinozuka, "Measurement and estimation of BER degradation of PHS due to electromagnetic disturbance from microwave ovens," Trans. IEICE, B-II, no. 11, Nov. 1996.

[18] Additional information on APD measuring equipment and draft CD for the amendment to CISPR 16-1 Clause 6.2, CISPR/A/WG1, July 1998.

[19] K. C. Wiklundh, "A method to determine the impact from disturbing electrical equipment on digital communication systems by using APD," Proc. EMC Europe, pp. 93-97, Sorrento, Sep. 2002.

[20] K. C. Wiklundh, "A New Approach to derive Emission Requirements on APD in order to protect Digital Communication Systems," Proc. 2003 IEEE International Symposium on EMC, Istanbul, May, 2003.

[21] Guidance for applying APD method to the compliance test and developing APD limits, CISPR/A/WG2/(Ymanaka-Shinozuka) 2003-01, June 2003.

[22] Radio-interference measurements and statistical methods, committee draft (CD), CISPR/A/447/CD.

Biographies

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Peter Stenumgaard was born in Sweden in 1964. He received the M. Sc in Applied Physics and Electrical Engineering from the Linköping Institute of Technology in 1988 and the Ph.D. degree in radio communications from the Royal Institute of Technology, Stockholm in 2001. Until 1995 he was a systems development engineer at Saab Military Aircraft, Linköping, where he worked with electromagnetic compatibility issues in aircraft design. Dr. Stenumgaard is currently a deputy research director and project manager at the Swedish Defence Research Agency (FOI) in Linköping, Sweden. He also works as an educator in the development of Command & Control Systems for the new Swedish Networked Based Defence. Dr. Stenumgaard has also worked as a project manager for several research projects concerning the application of commercial electronic products in military applications. He has also been the Deputy Head of the Communication Systems Department.

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Manfred Stecher was born in Munich, Germany in 1942. He received the Dipl.-Ing. degree in electrical engineering in 1967 from the Technical University of Munich. In 1967, he joined Rohde & Schwarz, Munich. He was engaged in the development and market introduction of EMI and signal monitoring test receivers and field strength meters, became group leader in 1980, and was responsible for the development of test receivers and accessories - hard and software. Since 1985, he has been a member of various German national standardizing committees (of the DKE, see below) on EMI instrumentation and measurement methods and since 1990 he has been an active member of various CISPR Subcommittees (mainly CISPR/A on measurement instrumentation and methods, but also CISPR/D on automotive emission testing, CISPR/H on emission limits and CISPR/I on information technology and telecommunication equipment) and is contributing to the ITU-R Study Groups on radio monitoring (mainly Study Group 1). Since 1997, he has been Chairman of CISPR/A/WG2, the CISPR Working Group on EMI measurement methods. He has published approximately130 papers in the field of EMC and signal monitoring, besides holding professional seminars and workshops. He is a member of the German VDE (Verein Deutscher Elektrotechniker) and the DKE (German commission for standardization in the field of electronics and electrical engineering) and is among the first recipients of the DKE needle (award received in 2005 for outstanding work in the field of standardization). He is also a senior member of the IEEE EMC Society.

Consultants Network

Ultra Wide Band Propagation Measurements in Indoor Working Environments and Through Building Materials

C. Buccella, F.Graziosi, G. Manzi, M. Feliziani, M. Di Renzo, R.Tiberio

Abstract—*In Ultra Wideband Impulse radio systems, the short duration of transmission enables a very fine time resolution in the receiver and therefore the opportunity to take great advantage of multipath diversity. However, unlike common narrowband channels, UWB channels are frequency selective. In fact, in typical UWB channels interaction with the environment (e.g. scattering, reflection, etc.) is frequency dependent and can introduce distortion on the received pulse shape, independently from multipath propagation. In this paper, we performed a series of measurements in an Indoor Working Environment (D.E.W.S. LAB and EMC LAB of the University of L'Aquila) with the purpose to show the effects of ultrawide band frequency selectivity on the propagated pulse. To this aim, measurements in Frequency Domain have been performed in order to characterize the frequency selectivity of UWB channels for a variety of Non Line-of-Sight propagation conditions.*

Index Terms—*UWB, Frequency Domain Measurements, Indoor Measurements, NLOS propagation.*

I. INTRODUCTION

ULTRA Wide Band (UWB) Impulse Radio (IR) is a Radio Frequency (RF) technology used in radio-communications to transmit binary data [1]. It is referred to as "baseband," "impulse" or "carrier-free" technology because it makes use of extremely short-duration and low-energy pulses, which are transmitted, in an extremely wide range of frequencies, without a dedicated radio channel. In this context, low transmission power, combined with the use of spreading codes and a very large bandwidth, enables, at least in principle, the coexistence of UWB systems with narrow-band and wide-band systems overlapped in frequency, without unacceptable mutual interference effects. The introduction of UWB radio-communication promises an excellent indoor alternative to narrowband technologies due to the expected through-the-wall propagation capabilities [2]-[6].

The short duration of transmitted pulses in UWB-IR enables fine time resolution in the receiver and allows exploitation of multipath diversity [7]. However, unlike narrowband channels, UWB channels are typically frequency selective [6], thus significantly altering the shape of the transmitted pulse.

In order to characterize this pulse distortion, we present an analysis of the indoor UWB propagation channel in a typical office environment with dense multipath and in the presence of some frequency selective walls (e.g. common building materials), obstructing the Line-of-Sight (LOS) path.

Measurements have been performed in frequency domain by using a vector Network Analyzer (NA) in the frequency range 1-18 GHz. The wide frequency range has been chosen to ensure an accurate evaluation of the UWB signals that must be restricted between 3.1 GHz and 10.6 GHz according to the FCC rules [5]-[6].

Frequency domain measurements for typical situations encountered in indoor environments are presented, i.e. point-to-point communications in the presence and in the absence of penetrable walls.

The aim of the measurements is to collect data to help the research for the characterization of the indoor working environment in UWB-IR communications. Two different kinds of measurements with two different setups are presented. The first series of measurement is carried out to characterize the field attenuation produced by walls of penetrable materials, which are often present in a typical indoor environment such as stucco and glass. Then the measurements are performed in a typical office environment with many building materials obstructing the LOS path in the surrounding area of Transmitter (Tx) and Receiver (Rx).

In this paper, only a part of the measurement results will be presented. Other measurements results will be presented in a future work of the authors.

II. UWB SIGNAL PROPAGATION IN PRESENCE OF PENETRABLE WALLS

The influence of the penetrable walls on the UWB signal propagation is investigated. We want to characterize the field attenuation produced by penetrable walls of stucco and glass in the frequency range of interest for UWB-IR communications. For this application, the proposed measurement setup, shown in Fig. 1, is similar to that used to characterize shielding properties of materials.

TABLE I. MATERIAL THICKNESS

MATERIAL	PANEL THICKNESS t
STUCCO	5 mm
GLASS	10 mm

TABLE II. USED INSTRUMENTATION

Network Analyzer (NA) mod. Wiltron 37247A.
2 Horn Antennas EMCO 3115 (1-18 GHz)
2 Coaxial Cables SUCOFLEX_101 (L=8m)
1 Personal Computer (PC)

The wall is assumed to be a finite dimension panel $l \times w$, placed at a fixed distance h from the ground and separated from the two antennas by an equal distance d. The different materi-

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als under examination are panels of stucco and glass. The setup has been defined with the following parameters: h=1 m; l=1 m; w=1 m; h_a=1.5 m and d=0.25 m giving $D=2d+t$ (where t is the thickness of the panel). The materials and the thickness t of the considered panels are reported in Table I.

All measurements are performed in the frequency domain (FD) by using the equipment shown in Table II. The measurements are carried out in the frequency domain in the range 1-18 GHz to cover all the frequencies of UWB signals. The two ports of the NA are connected to the antennas by using coaxial cables. The NA is connected to a PC to collect measurement data as shown in Fig. 2. The Network Analyzer is set with the following parameter: Center frequency f_c=9.02 GHz; Bandwidth B=17.960 GHz (i.e. 40 MHz – 18 GHz); Number of frequency points N=1601; Frequency step Δf=11.225 MHz (i.e. Δf=B/(N-1)); Max. excess delay τ_{max}=89.087 ns (i.e. $\tau_{max}=1/\Delta f$); Sweeping time t_{sw}=800 ms.

To extract the propagated signal through a penetrable panel, we need to perform two different measurements. The first measurement is carried out with the transmitted and received antennas separated only by air. The second measurement is performed with the panel introduced between transmitting and receiving antennas [5]. The panel under test has been placed over a wood support, as shown in Fig. 3, able to fix and hold constant its position.

In the tests, we measure the scattering parameter S_{21}, i.e. power received by the port #2 transmitted by the port #1. We denote as $S_{21}(\omega)$ the measured transmission parameter value in the presence of the panel and as $S^0{}_{21}(\omega)$ the measured transmission parameter without the panel. The frequency domain response $H(\omega)$ is obtained as:

$$H(\omega) = \frac{S_{21}}{S_{21}^{0}(\omega)} \tag{1}$$

To remove effects due to noise, frequency domain (FD) measurements are convenient [4]-[6]. For this reason, the measurements in FD have been performed in the same configuration, but in two different ways: by a single measurement of the scattering parameter S_{21} and by averaging S_{21} over 1000 measurements. The results of the frequency domain measurements (single measurement and average value), in the geometrical configuration described above, are shown in Fig. 4 for a stucco panel

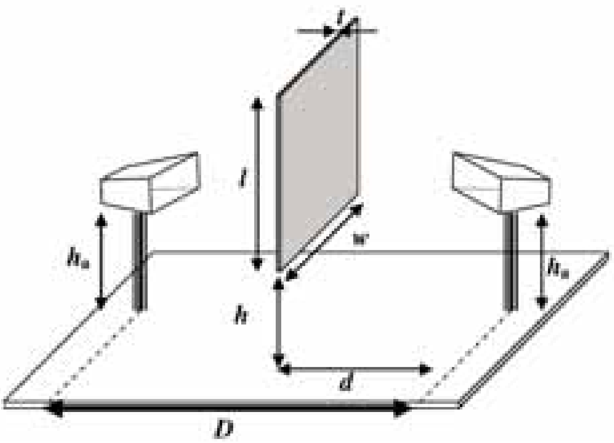

Figure 1. Experimental setup for obstacle propagation measurements.

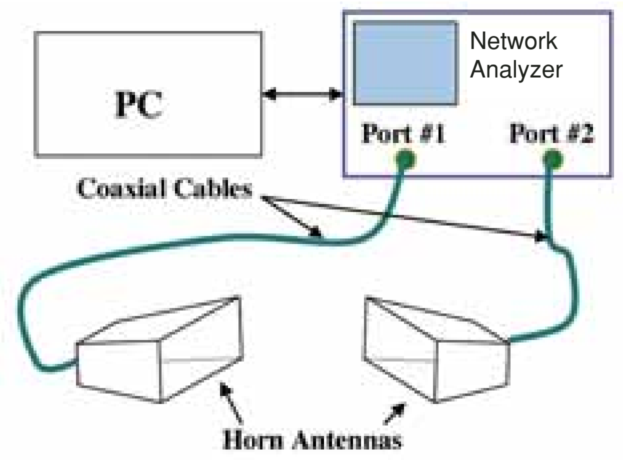

Figure 2. Measurements setup network analyzer antenna connection.


Figure 3. Photo of the experimental setup for propagation measurements, in presence of obstacle.

of thickness t=5 mm. Then the measurements have been repeated, in the same configuration of the stucco panel, for a glass panel with thickness t=10 mm and the average results are shown in Fig. 5.

In the case of stucco, by applying the Inverse Fast Fourier Transform (IFFT) to the frequency domain results, the time domain impulse response of the UWB propagation has been obtained as shown in Fig. 6, where a comparison is carried out between free space propagation (absence of an obstacle), single measurement, and averaged measurements.

III. UWB CHANNEL CHARACTERIZATION IN INDOOR ENVIRONMENT

The measurements have been also performed to characterize the UWB channel in a real complex indoor environment in the presence of penetrable and impenetrable walls, which cause reflections, and transmissions giving rise to a considerable multipath effect. In the following, we define the antenna connected to the port #1 of the NA as the transmitter antenna and the antenna connected to the port #2 as the receiver antenna. The setup is designed with the antennas placed in two different positions as shown in Fig. 7. Two series of measurements have been performed. The first with the transmitter antenna in position Tx1 with the receiver antenna in positions Rx P1 and Rx P2; the sec-

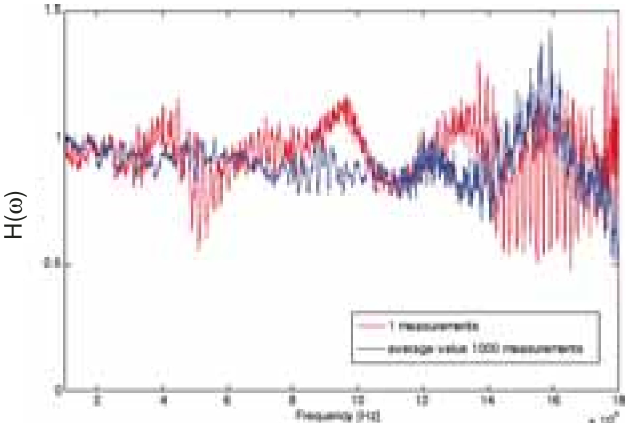

Figure 4. Measured H (ω) for a stucco panel (average and non-average values).

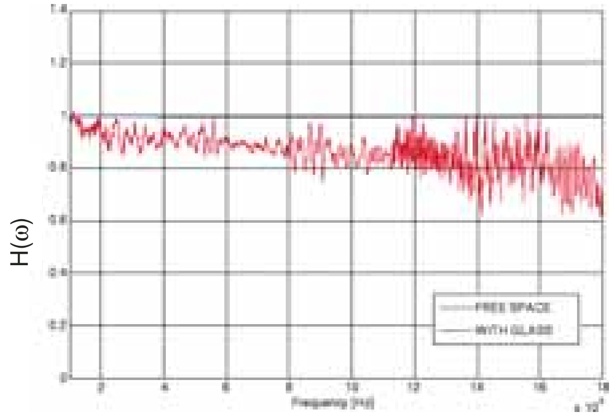

Figure 5. Frequency domain measurement in case of presence of glass obstacle (average values).

ond with the transmitter antenna in position Tx2 and the receiver in positions Rx P1 and Rx P2. The multipath effects on the pulse propagation have been evaluated together with the field attenuation. A picture of the test setup is shown in Fig. 8.

For this kind of experimental tests in the frequency domain, the same measurement procedure described in the previous section has been used.

Many measurements have been carried out in the frequency domain. Here, for the sake of brevity, we report only the computed time domain response obtained by IFFT for the case of the propagation between the points Tx1 and RxP1 in indoor

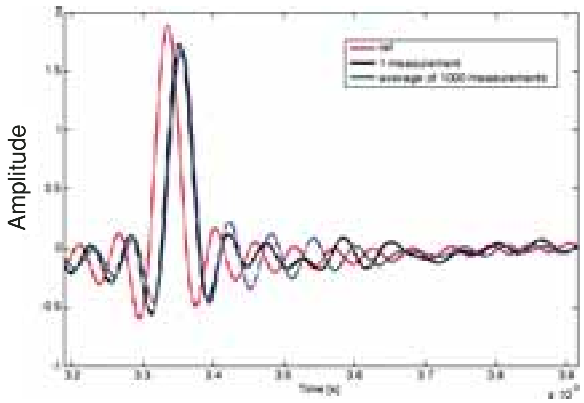

Figure 6. Time domain impulse response of a UWB pulse in the presence of stucco obstacle.

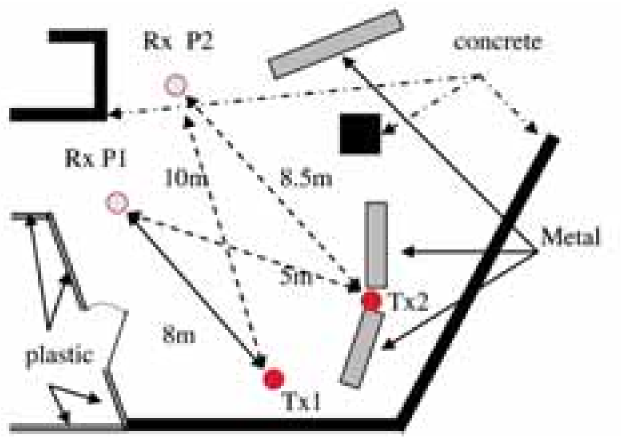

Figure 7. Indoor measurements scenario.

Figure 8. Photo of the setup to measure the UWB propagation in indoor environment.

environments as shown in Fig. 9.

IV. MEASUREMENTS ANALYSIS

A correlation analysis between the received pulse and the transmitted one has been carried out in order to investigate the effects on the received pulse produced by obstacles (i.e. penetrable panels) or a dense multipath (i.e. complex indoor environment). The correlation is the degree to which two or more quantities are linearly associated. In a two-dimensional plot, the degree of correlation between the values on the two axes is quantified by the so-called correlation coefficient. Information about the correlation coefficient is useful to evaluate the effect on the performances of a correlation based UWB receiver [1], [8], [10].

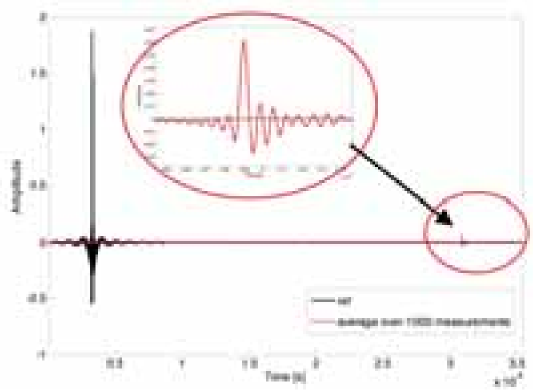

Figure 9. Time domain impulse response of the indoor environment in the case $T \times 1 \rightarrow R \times P1$

The correlation r coefficient, [13], of a set of n datapoints (x_i, y_i) is given by

$$r^2 = \frac{ss_{xy}^2}{ss_{xx}ss_{yy}} \qquad (2)$$

where ss_{xx}, ss_{xy} and ss_{yy} are defined in [13].

By calculation, we have obtained the following results:

- r = 0.9937, for the case of UWB propagation with the presence of stucco panel obstacle;
- r = 0.8357, for the case of indoor environment propagation between point Tx1 and RxP1

It should be noted that the value of the correlation coefficient of the indoor propagation is lower than that produced by a penetrable wall. This means that the multipath effect is more dangerous for UWB-IR communications than that produced by a penetrable wall, at least for the examined test cases.

V. CONCLUSION

Frequency domain measurement has been performed to evaluate the propagation in an indoor environment and to investigate the presence of an obstacle between transmitting and receiving antenna. The measurements show that the presence of an obstacle along the propagation channels introduces mainly a delay in the pulse propagation together with attenuation and a small distortion. On the other hand, the propagation through an office environment gives a delay with a distortion higher than that due to the presence of an obstacle.

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REFERENCES

[1] M.Z. Win, R.A. Scholtz, "Impulse Radio: How It Works", IEEE Communications Letters, Vol. 2, No. 2, February 1998, pp 36-38.

[2] Chia-Chin Chong, Youngeil Kim, Seong Soo Lee, Samsung Advanced Institute of Technology (SAIT), "UWB Channel Measurement Results in Indoor Residential Environment –High-Rise Apartments", doc.: IEEE 15-04-0282-00-004a, May 2004, Korea.

[3] R.J.-M. Cramer, R.A. Scholtz, M.Z. Win. "Evaluation of an ultra-wide-band propagation channel", IEEE Transactions on Antennas and Propagation, vol. 50, no. 5, pp. 561-570, May 2002.

[4] Karedal, J., Wyne, S., Almers, P., Tufvesson, F., Molisch, A.F., "UWB Channel Measurements in an Industrial Environment", IEEE Global Telecommunications Conference (GLOBECOM), Vol. 6, pp. 3511-3516, November 2004.

[5] Ahmad Safaai-Jazi, Sedki M. Riad, Ali Muqaibel, and Ahmet Bayram, "Through-the-Wall Propagation and Material Characterization"; DARPA NETEX Program: Ultra-wideband Propagation Measurements and Channel Modeling, November, 2002.

[6] I. Cuinas, and M. Sanchez, "Building Material Characterization from Complex Transmissivity Measurements at 5.8 GHz," IEEE Transactions on Antennas and Propagation, vol. 48, no. 8, August 2000.

[7] R. Alesii, M. Di Renzo, F. Graziosi, F. Santucci, A. Scarano, P. Tognolatti, "A Low-Complexity Receiver for Ultra Wide Band Communications", IEEE Euro Electromagnetics Congress (EuroEM), Magdeburg, Germany, 12-16 July 2004.

[8] R.A. Scholtz, M.Z. Win, "Impulse Radio", Personal Indoor Mobile Radio Conference, Helsinki, Finland, September 1997.

[9] R.A. Scholtz, "Multiple Access with Time-Hopping Impulse Modulation", IEEE Military Communications Conference: Communications on the Move, Vol. 2, 11-14 October 1993, pp. 447-450.

[10] J. Kunisch and J. Pamp, "Measurement results and modeling aspects for the UWB radio channel," IEEE Conference on Ultra Wideband Systems and Technologies, Digest of Technical Papers, 2002, pp. 19–23.

[11] A. S. Y. Poon and M. Ho, "Indoor multiple-antenna channel characterization from 2 to 8 GHz," in Proc. Int. Conference on Communications, May 2003.

[12] C.R. Anderson, T. S. Rappaport, and et. al., "In-building wideband multipath characteristics at 2.5 & 60 GHz", IEEE 56th Vehicular Technology Conference, 2002 Proceedings. VTC 2002-Fall, Vol. 1, pp. 97-101, 2002.

[13] Kenney, J. F. and Keeping, E. S. "Linear Regression and Correlation." Ch. 15 in Mathematics of Statistics, Pt. 1, 3rd ed. Princeton, NJ: Van Nostrand, pp. 252-285, 1962.

Biographies

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