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EXPOSURE ASSESSMENT PROCEDURES IN PRESENCE OF WIDEBAND DIGITAL WIRELESS NETWORKS

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The article analyses the applicability of traditional methods, as well as recently proposed techniques, to the exposure assessment of electromagnetic field generated by wireless transmitters. As is well known, a correct measurement of the electromagnetic field is conditioned by the complexity of the signal, which requires dedicated instruments or specifically developed extrapolation techniques. Nevertheless, it is also influenced by the typology of the deployment of the transmitting and receiving stations, which varies from network to network. These aspects have been intensively analysed in the literature and several cases of study are available for review. The present article collects the most recent analyses and discusses their applicability to different scenarios, typical of the main wireless networking applications: broadcasting services, mobile cellular networks and data access provisioning infrastructures.

A correct assessment of population exposure to radiofrequency emissions requires the identification of reliable procedures for the measurement of electromagnetic fields, especially in the presence of complex modulations. The first measurement techniques developed for this purpose were derived from the standard procedures applied for electromagnetic compatibility radiated measurements, where the object of the measurement is a sequence of incoherent, narrowband, non-modulated signals. On the other hand, last generation radio services make use of more and more complex modulations that limit or even preclude the use of those procedures that often lead to inadequate results.

For this reason, in the last years, many researches have been carried out and published, to verify the limits of traditional measurement techniques and to propose alternative and more efficient ones. This article analyses and discusses the methods that have appeared in the literature for the measurement of an electromagnetic field modulated with complex wideband (spread-spectrum) digital signals.

SPREAD-SPECTRUM DIGITAL MODULATIONS

During the decade 2000–10 digital modulations have definitively arisen as the state of the art in telecommunications. Data digitalisation, based on a numerical representation of the information, allows the optimisation of the channel, owing to compression, strengthening and protection of data that correspond to a substantial improvement of the transmission resource. After the introduction of numerical transmission techniques, spread-spectrum modulations have been widely applied, optimising and enhancing the use of the frequency spectrum, with relevant improvements for all communication systems based on radio transmissions. For this reason, in the near future wideband digital communications are going to substitute analogue and narrowband digital techniques, in favour of more and more efficient radio transmissions.

Wideband digital radio networks are generally classified into three main categories: radio-phonic or radio-television broadcasting networks, mobile cellular networks and data access/exchange networks. Year after year (standard after standard), the differences among all these categories are becoming less and less evident. As a consequence, transmission standards evolve rapidly towards integrated platforms, converging to a unique architecture applicable to multiple services.

Spread-spectrum transmissions are widely exploited for any kind of wireless implementation, from broadcasting to cellular and networking services. Digital Audio Broadcasting, Digital Radio Mondiale and Digital Video Broadcasting make use of orthogonal frequency-division multiplexing (OFDM). Third generation mobile networks make use of (wideband) code division multiple access ((W)-CDMA), although the next generation (long-term evolution) is adopting OFDM. Body, personal, local, metropolitan and regional wireless networks (WBAN, WPAN, WLAN, WMAN and WRAN) make use of direct sequence spread spectrum (DSSS) and OFDM, although frequency hopping spread spectrum (FHSS) is exploited by former WLAN standards and Bluetooth.

Among all these applications, (W)-CDMA, DSSS and OFDM-based systems are the ones characterised by higher radiated powers. Consequently, an

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electromagnetic field exposure assessment in the presence of such services can be required and adequate procedures must be available.

EXPERIMENTAL METHODS FOR EXPOSURE ASSESSMENT TO RADIOFREQUENCY SIGNALS

All methods available for the measurement of non-ionising radiation in the radiofrequency and microwave bandwidths can be grouped in two main categories[1]: the first involves the use of broadband field probes, although the second implies selective investigations by means of spectrum analysers. Both categories can be implemented for short-term (spot) measurements or long-term (continuous) ones, even if narrowband analyses are rarely carried out over long periods.

BROADBAND MEASUREMENTS BY USE OF FIELD PROBES

Electromagnetic field measurements are typically performed by means of broadband probes, to characterise the cumulative value of electromagnetic noise over a wide portion of the frequency spectrum. The acquisition is realised by means of a detector that can be constructed either by the use of temperature detectors or diode rectifiers[2]. Temperature or bolometric detectors are characterised by a linear response over a large dynamic range, but their cost grows exponentially as the desired sensitivity decreases. On the other hand, diode detectors exhibit better sensitivity for much cheaper prices, but, making use of non-linear devices, offer very limited dynamic ranges[3].

Independently from the choice of the detector, to construct a direct relationship between the incident field and the detector output, a calibration process is used. This procedure allows a partial extension of the dynamic range over a wider interval especially for probes making use of diode detectors, but it is valid only if the dynamics of the modulation is limited. The calibration is performed by exposing the probe to continuous wave (CW) electromagnetic fields of an increasing level, in a certain dynamic range and at pre-determined frequency values. The look-up table consequently defined allows the use of the probe over large dynamic ranges, independently of the detector input/output relationship. Probes are solely calibrated in the presence of CW signals, but the process also works for modulated signals with limited dynamics, like the ones implemented for analogue transmissions or for digital ones with limited bandwidth.

The presence of additional measuring uncertainties due to the effect of a modulation, even an analogue one, is intensively discussed in the literature[2,4]. For example, the presence of two analogue signals may produce overestimations of the effective field value[5]. Nevertheless, many international standards take into consideration the use of field probes as a first means for an initial assessment of human exposure.

Concerning wideband digital modulation, some articles show that diode detectors may overestimate digital signals implemented for (W)-CDMA communications[6,7]. For this modulation, where the transmission is never intermittent and the minimum transmitted power is never less than the 10 % of the maximum one, the overestimation increases as the field amplitude grows. This is mainly due to the fact that signal amplitudes are described by a Gaussian complementary cumulative distribution function (CCDF) and the effective signal power is always larger than the most probable signal amplitude values[6]. Recently, an experimental procedure for an accurate estimate of the additional measurement error due to the use of field probes in the presence of a complex modulation has been introduced[8]. This error has been referred to as Modulation Additional Error (MAE) and it has been calculated as the ratio E_{mod}/E_{CW}, where E_{mod} is the field value indicated by the probe in the presence of the digital modulation and E_{CW} is the field value indicated by the probe in the presence of the CW signal, for a constant RMS value of the radiated signal. Confirming results reported in[6], it has been demonstrated that, in the presence of continuous transmissions[9], the MAE takes the form of an overestimation that increases with the field value; the output increment depends mainly on the signal intensity, and additionally it varies slightly, for different typologies of signal modulation: spread-spectrum sequences and signal bandwidth.

Figure 1 taken from[9], shows the MAE behaviour of a wide selection of field probes as a function of

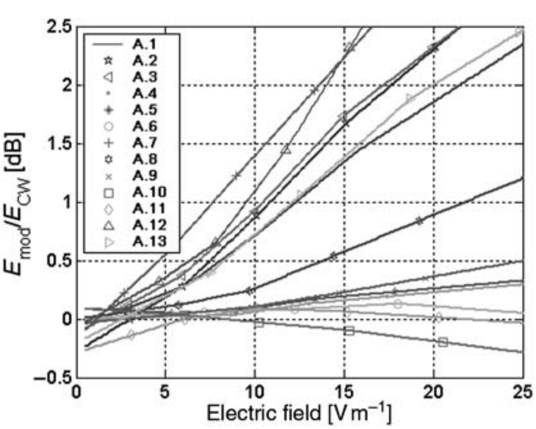

Figure 1. MAE as a function of Electric Field Amplitude; experimental values measured with 13 different probes in presence of continuous OFDM modulation (font[9]).

field amplitude, in the presence of continuous OFDM sequences, typical of broadcasting communications. Detailed characteristics of probes are listed in[9]; these results confirm the mentioned characteristics. Similar results are reported for DSSS and (W)-CDMA sequences. A limited set of probes evidences slight underestimations, normally due to an inefficient use of probes below 3 GHz, even if they are designed for very high frequency ranges.

Moreover, some preliminary results reported in[9] demonstrate that discontinuous signals can produce an underestimation that grows with the field amplitude. This underestimation emerges when the time constant of the integrating circuit of the detector is too low to follow the signal time variations that can range down to 1/32 of the transmission frame. Figure 2, taken from[9], reports results measured in the presence of Worldwide Interoperability for Microwave Access (Wi-MAX) signals (OFDM), with intermittent transmissions, down to one-sixteenth of the full frame duration.

Field probes making use of diodes with extended dynamic range are typically expensive but mostly effective for the measurement of spread-spectrum modulated signals. A valid alternative is represented by probes making use of variable attenuators adaptable to modulation dynamic range above the detector. In this way the detector input is kept within its quadratic dynamic range and the error is efficiently reduced[9].

In general, the use of field probes for the assessment of human exposure to last generation digital radio services may produce unreliable results. To avoid this, a complete pre-characterisation of the MAE is essential prior to an on-field exploitation of the instrument.

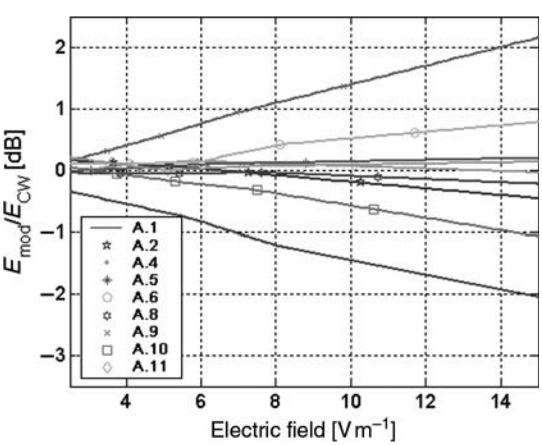

Figure 2. MAE as a function of Electric Field Amplitude; experimental values measured with nine different probes in presence of intermittent OFDM modulation (font[9]).

SELECTIVE MEASUREMENTS BY MEANS OF SPECTRAL ANALYSIS

The most effective instrument for an accurate measurement of digital signals is the vector signal analyser[10–16]. This is a normal receiver, or spectrum analyser, mounting a digital demodulator able to measure all modulation characteristics. Figure 3 reports the output of a measurement performed using such an instrument, on a Wi-Max signal with bandwidth 24 MHz, centred at 3.5 GHz. As shown, it is possible to evaluate the signal power, not only the one associated with the full signal, but also the one associated with separate channels (or codes). In particular, the power associated with control channels can be easily identified. In case the transmission scheme implements power control or discontinuous transmissions, it is possible to measure the peak and the average power values. Moreover, a modulation analysis of the constellation can be performed, as well as CCDF monitoring, useful to characterise the signal dynamics. Last but not least, the instrument outputs the frame duration and the periodicity of active bursts.

To perform these operations, several signal parameters (bandwidth, numerical modulation characteristics and sequence, maximum interval between consecutive synchronisms, approximate estimate of the maximum signal level, scrambling code for UMTS networks, etc.) must be input in advance. In the presence of standard signals, many of these parameters are already stored in the instrument, and a suitable demodulation procedure can be run almost automatically. Even so, additional effort is required to measure real signals, especially in the presence of propagation fading and/or background noise.

Despite their applicability to any kind of digital signal, vector signal analysers are expensive, difficult to transport and they require strong expertise of the operator. For these reasons, they cannot be regularly used for exposure assessment and they are mainly dedicated to laboratory measurements. The alternative is represented by the use of traditional spectrum analysers without a numerical demodulator on board.

By using a spectrum analyser, it is possible to measure with adequate accuracy the electromagnetic field, averaged during the period of measurement. For simplicity, in the following this value will be referred as 'instantaneous'. Several procedures are available to characterise the average signal power by means of a spectrum analyser. For example, publication[17] reports a method applicable to the measurement of (W)-CDMA signals.

With such an instrument, the simplest way to measure the instantaneous power is represented by an acquisition in either the frequency or time domain, performed by means of intermediate frequency (IF)

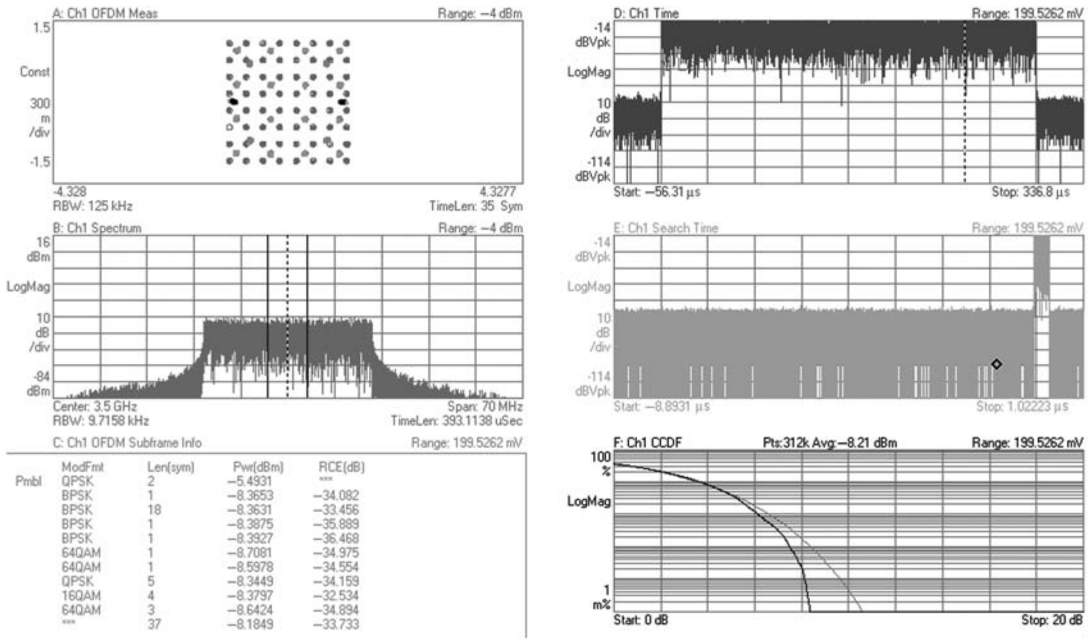

Figure 3. Typical output of a vector signal analyser applied to the measurement of a Wi-Max signal. Top left: constellation; mid left: channel spectrum; bottom left: power associated with different bursts; top right: frame analysis (zoomed); mid right: frame analysis; bottom right: signal CCDF (compared with the ideal one).

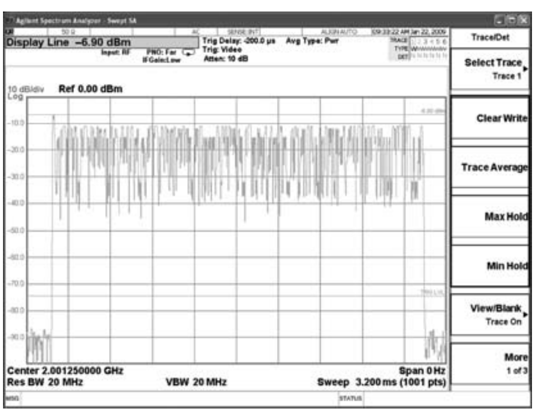

Figure 4. Example of acquisition of a WLAN signal in time domain, by use of a traditional spectrum analyser equipped with digital IF filters. For a more representative readout, a single-sweep trace is reported.

filters larger than the full signal bandwidth. The trace must be averaged in the linear (power) domain for a time long enough to be statistically representative of signal power variations. Figure 4 reports an example of a measurement of a WLAN signal in time domain. The one shown in the picture is an intermediate stage: a single-sweep trace is reported; once the instrument has been set as it is shown, the averaging procedure should be started, together with a continuous-sweep acquisition.

Traditional Gaussian IF filters are sufficient only if the signal is adequately separated by the adjacent ones (or the adjacent ones carry a negligible power). In the presence of strong adjacent channels, like the ones illustrated in Figure 5, square wave filters are necessary.

Alternatively, if square wave filters are not available, channel power measurements can be performed. For this purpose, the following conditions should be satisfied:

- the IF bandwidth should be a small percentage of the trace span (up to 4 %);
- the IF bandwidth should preferably be larger than the distance between two consecutive trace points;
- the video bandwidth should be larger than the IF one (typically, 10 times);
- an average (RMS) detector should be used; if not available, a sample detector can be exploited.

Figure 6 shows a measurement example, applied to a standard WLAN signal carrying OFDM modulation (IEEE 802.11 g standard), whereas Figure 7 reports a similar one, applied to a complex WLAN signal carrying an hybrid DSSS/OFDM modulation

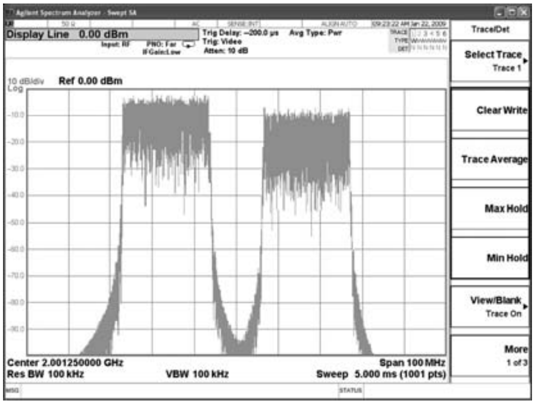

Figure 5. Spectra of two Wi-MAX (OFDM) signals with 20 MHz bandwidth and 10 MHz channel separation. The acquisition has been performed by means of a spectrum analyser in the frequency domain.

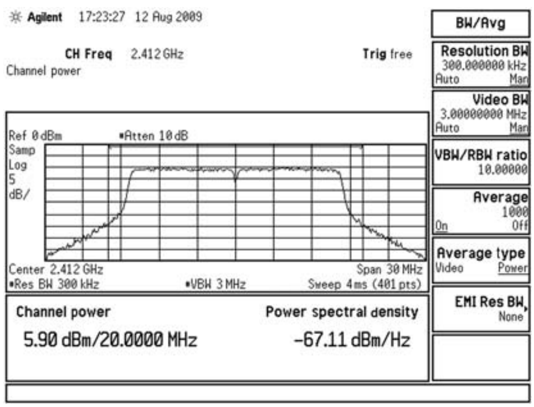

Figure 6. Screen shot taken on a traditional spectrum analyser during a channel power measurement of a WLAN signal carrying a pure OFDM modulation (IEEE 802.11 g standard).

(IEEE 802.11b together with IEEE 802.11 g standard).

EXTRAPOLATION TECHNIQUES

According to National Regulatories and Technical Standards, the result of exposure assessment analysis should be not only the ‘instantaneous’ field value but also a suitable ‘exposure indicator’ corresponding to the maximum reachable field value, in the presence of full time transmissions and the worst power control corrections. The indicator should represent a realistic conservative estimate avoiding excessive and unreasonable overestimations when compared with the typical behaviour of the transmission standard.

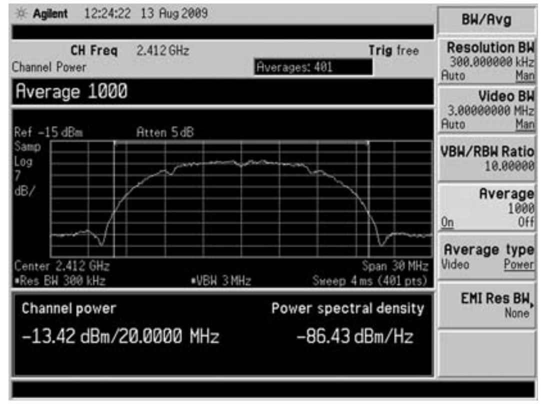

Figure 7. Screen shot taken on a traditional spectrum analyser during a channel power measurement of a WLAN signal carrying an hybrid DSSS/OFDM modulation (IEEE 802.11b and IEEE 802.11 g standards).

This operation can be easily performed by measuring a referable quantity (when identifiable), and then calculating the exposure indicator, with simple mathematical steps directly derived from the transmission standard itself. In many practical cases, the referable quantity can be the signal peak (e.g. all modulations used for analogue television broadcasting), but in a few other cases, it can be the signal average level (e.g. frequency modulated signals used for radio-phonic broadcasting).

In case of spread-spectrum signals based on code division use (e.g. (W)-CDMA networks), additional information should be collected from the network operator to know the ratio between the power associated with the control channel and the maximum transmitted one. Nevertheless, when this value is not accessible, it is still possible to apply some conservative coefficients derived from the standard.

The referable quantity can be easily measured by means of signal demodulators. As different radio services exist, each with its own modulation, a signal analyser should implement several demodulators, raising up the equipment cost. For this reason, the technical standards accept and identify solutions that avoid the use of demodulators.

Making use of a simple spectrum analyser, the measurement of the peak of the signal, if the peak is transmitted periodically and with constant power (e.g. the synchronism in many amplitude analogue modulations), represents the easiest, fastest and most reliable approach for the characterisation of the modulation and the consequent extrapolation of an indicator. The synchronism itself acts as an easy referable quantity, irradiated periodically with constant power, even if for short time intervals. Once the synchronism is measured (e.g. by means of the MAX-HOLD option and a suitable choice of the SWEEP-TIME value in the spectrum analyser), the average value and the exposure indicator can be calculated, applying the ratios disciplined by the transmission standard.

When the field carries amplitude modulations that do not implement synchronisms, the measurement of the peak cannot be performed deterministically, and a statistical approach must be used; i.e., making the measurement last for a time interval long enough, to catch at least one peak. The choice of the observation interval length can be based on the CCDF of the particular transmitted signal. The alternative is represented by the measurement of the signal average, again extending the observation time until an adequate mean value is obtained.

Again, the described procedures are easily applicable if the signal is adequately separated by the adjacent ones (or the adjacent ones carry negligible power). Moreover, the procedure can even be applied in the presence of strong adjacent channels, if square wave filters are available. For both cases, the analyser must be provided with IF filters larger than the full signal bandwidth. In this case, it is possible to set the instrument SPAN to ZERO and use it as a time domain analyser.

If a SPAN ZERO analysis cannot be performed, there is still the possibility of making a channel power measurement. However, this option can be applied to single carrier signals, e.g. a (W)-CDMA one, but it becomes impracticable with multi-carrier modulations (e.g. an OFDM one), since the statistical analysis should be performed separately on each subcarrier. For this purpose, a simple and efficient procedure has been recently proposed[18] for an immediate extrapolation of the maximum power associated with OFDM signals. It is based on the measurement of the synchronisms associated with preamble subcarriers, easy to identify and distant enough from the adjacent subcarriers.

Finally, average measurements are unsuitable for broadband access technologies based on Time Division or Frequency Division MAC schemes (the majority of Wireless Local Loop systems), since the mean signal level at the receiver side is affected by the presence of two or more intermitting transmissions whose behaviour is determined by the traffic statistic. To overcome this problem, a simplified procedure, applicable by means of standard spectrum analysers, has been recently proposed[19].

CONCLUSIONS

Measuring wideband digitally modulated signals requires the use of advanced exposure assessment techniques, if compared with the traditional ones. Despite their cost and usage complexity, the most accurate measurement is obtained by using a vector signal analyser equipped with digital demodulators. Nevertheless, the literature reports several examples and cases of study that avoid the use of such instruments, owing to the application of techniques based on an exact knowledge of the transmission standard.

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