I. Angulo et al., "An Empirical Comparative Study of Prediction Methods for Estimating Multipath Due to Signal Scattering From Wind Turbines on Digital TV Services," in IEEE Transactions on Broadcasting, vol. 57, no. 2, pp. 195-203, June 2011,
doi: 10.1109/TBC.2011.2131430.

An Empirical Comparative Study of Prediction Methods for Estimating Multipath Due to Signal Scattering from Wind Turbines on Digital TV Services

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***Abstract* — Several authors have theoretically studied the effect of wind turbines on the propagation of electromagnetic waves in the UHF band. The International Telecommunication Union also proposes a simplified model to evaluate the impact caused to television reception by a wind turbine in the Recommendation ITU-R BT.805. This paper presents an empirical study of the above mentioned prediction methods for estimating signal scattering from wind turbines in the UHF band, comparing predicted values with empirical data obtained from a DTV measurement campaign carried out in Spain. As signal scattering is independent of the transmission standard or modulation, the results are applicable to any broadcasting and wireless communication signals in the UHF band that may be affected by the multipath interference caused by a wind farm.**

***Index Terms*— Digital TV, Electromagnetic scattering, UHF propagation, Wind farms**

I. Introduction

In the late 70s, coinciding with the beginning of the modern wind energy industry, some situations of interference in the reception of analogue television were found when a wind farm was installed near television transmitters or receivers. Since then, several studies have been carried out to characterize signal scattering from wind turbines. These studies are fundamentally theoretical, and they aim to provide some simple scattering models to estimate the impairment that a wind turbine may cause to television reception [1]-[7].

The International Telecommunication Union (ITU) also proposes a simplified model to evaluate the impact caused to television reception by a wind turbine in the Recommendation ITU-R BT.805 [8]. However, a more recent ITU Question [9] considered that further study of the conditions for a satisfactory television service in the presence of reflected signals was needed, including several aspects such as methods of calculation to determine the ratio and displacement of the direct and reflected signals, different effects of scattering signals on analogue and digital television systems, variability of the scattered signals, etc. As a result, several amendments to Recommendation ITU-R BT.805 will be included in the development of a New Recommendation [10].

The objective of this paper is to present a comparative study of the existing prediction methods for estimating signal scattering from wind turbines in the UHF band, in order to evaluate their accuracy and determine their suitability for estimating the potential effects of the scattering signals on the broadcasting services. The study focuses on comparing predicted values with empirical data obtained from a DTV measurement campaign in Spain. It should be noted that this study is based on DVB-T field data, but signal scattering is independent of the transmission standard or modulation. Therefore, the results are applicable to any broadcasting and wireless communication signals in the UHF band that may be affected by the multipath interference caused by a wind farm.

Section II of this paper describes the theoretical scattering models of wind turbines; Section III outlines the main characteristics of field trials and Section IV exposes the methodology for data analysis. Finally, Sections V and VI include the results and conclusions derived from the study.

II. Theoretical Scattering Models

This section describes the five theoretical scattering models for the comparative study. The last subsection summarizes the main limitations of these scattering models.

A. Recommendation ITU-R BT.805

The ITU-R Recommendation includes a simplified model that only accounts for the scattering from the blades, which are considered metallic rectangular plates [8].

In the case of a free-space path of length d (km) between

Manuscript received November 24, 2010.

This work was supported in part by the Basque Government under both the SAIOTEK program and the program for the training of the researcher staff (BFI08.230).

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the wind turbine and the receiving location, the unwanted field strength from the wind turbine may be calculated according to (1)

$$FSWT + RF + RA - 20\log d \quad (1)$$

where

$FSWT$: field strength at the wind turbine site

RF: reflection factor

RA: relative amplitude

The "reflection factor" RF includes the free-space path loss for the first km of the path from the wind turbine site to the receiving location R. The maximum value of this reflection factor due to the wind turbine blades is given by (2)

$$RF = 20\log\left(A/\lambda \right) - 60dB \quad (2)$$

where

A: blade area (m^2)

λ: wavelength (m)

The "relative amplitude" RA depends on the scatter region where receiver is located, following the pattern shown in Fig. 1. Two scattering regions are defined: the general scatter region and the forward scatter region.

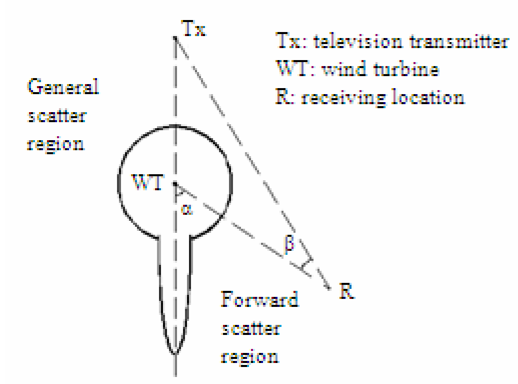

Fig. 1. Plan view of the Rec. ITU-R BT.805 model [8]

In the general scatter region, the "relative amplitude" is taken to be a constant value of -10 dB (not theoretically justified). In the forward scatter region, the "relative amplitude" is given by (3)

$$20\log\frac{\sin(\pi \cdot W / \lambda \cdot \sin\alpha)}{\pi \cdot W / \lambda \cdot \sin\alpha} \quad (3)$$

where W is the blade width (m).

Therefore, the "relative amplitude" RA to calculate the unwanted field strength according to (1) is given by

$$\max\left(-10 \, , 20\log\frac{\sin(\pi \cdot W / \lambda \cdot \sin\alpha)}{\pi \cdot W / \lambda \cdot \sin\alpha} \right) \quad (4)$$

So that the largest of -10 dB and the relative amplitude of the forward lobe defines the scatter region where receiver is located.

B. ITU-R Preliminary Draft New Recommendation

The Preliminary Draft New Recommendation for the assessment of impairment caused to digital television reception by a wind turbine [10] aims to overcome some of the limitations of the Rec. ITU-R BT.805. Firstly, the scattering model is based on a triangular blade, an assumption that is closer to the actual shape of the blades than rectangular. Secondly, the scattering model depends on the incident and scattering angles of the signal with respect to the rotation plane of the blades, and therefore, it considers the wind turbine orientation against the wind. Fig. 2 shows the plan view of the general wind turbine problem.

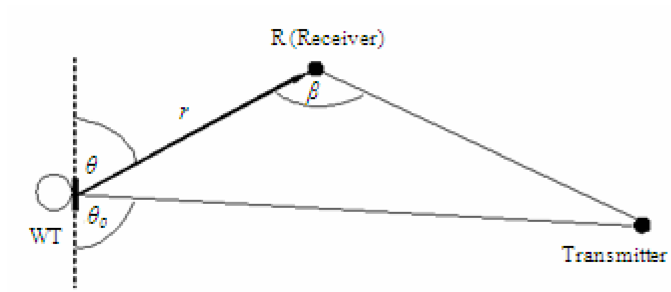

Fig. 2. Plan view of the Prelim. Draft New Rec. ITU-R model [10]

A "scattering coefficient", ρ, which includes the free-space path loss for the path from the wind turbine site to the receiving location, may be defined as:

$$\rho = \frac{A}{\lambda r} g(\theta) \quad (5)$$

where

$$g(\theta) = \mathrm{sinc}^2\left(\frac{\overline{W}}{\lambda}(\cos\theta - \cos\theta_0) \right)\sin\theta \quad (6)$$

and

$\overline{W}$: mean width of the blade (m)

A: blade area (m^2)

λ: wavelength (m)

θ_0: angle of the incident signal at the blade

θ: angle of the scattering signal from the blade

The scattering coefficient ρ only accounts for backscatter from the blades. According to the plan view of Fig. 2, this corresponds to situations where receiver and transmitter are located at the same side of the semiplane limited by the rotation plane of the blades. Hence, a certain reception location can be in the backward or forward region of the blades depending on the wind direction.

It should be noted that the backscatter region defined in this model does not coincide with the backscatter zone of Rec. ITU-R BT.805, which is defined according to the location of the wind turbine and independently of its orientation against the wind.

According to the Preliminary Draft New Recommendation, the metallic mast also contributes significant static backscatter. Furthermore, the forward scatter from the blades may be significant, but has lower amplitude than backscatter. Nevertheless, the model does not determine the method for estimating these scattered signals.

C. Sengupta

Sengupta theoretically obtains the scattered field using the physical optics approximation to calculate the moments of the induced electric dipoles on the blade surface [1].

For a more practical approach, Sengupta proposes a "idealized signal scatter ratio", Z_I, as the ratio of the field strength amplitudes of the scattered signal at the receiver to the direct signal at the wind turbine, assuming that the blades of the wind turbine are positioned for optimum signal reflection (or shadowing) from the transmitter [1]-[5]. The "idealized signal scatter ratio" is then given by (7).

$$Z_I = \frac{\eta_S}{2}\frac{D}{\zeta}\cos(k\phi_S) \tag{7}$$

where

$$k = \begin{cases} 0.5 & -0.8\pi \le \phi_S \le 0.8\pi \quad \textit{(Backward Zone)} \\ 2.0 & 0.8\pi \le \phi_S \le 1.2\pi \quad \textit{(Forward Zone)} \end{cases}$$

and

η_S: signal scattering efficiency of the blade compared to a flat metallic plate (η_S=0.27, empirically obtained for fiberglass blades [1])

D: rotor diameter (m)

ζ: distance from the receiver to the wind turbine (m)

ϕ_S : azimuthal scatter angle (rad)

The "idealized signal scatter ratio" pattern is shown in Fig. 3.

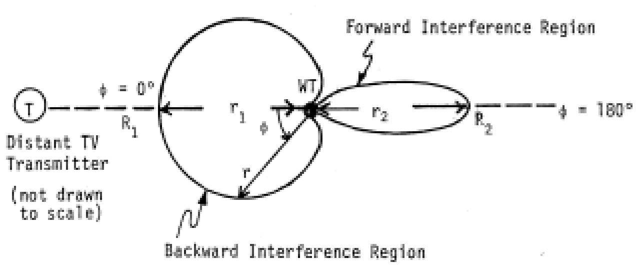

Fig. 3. Interference zone proposed by Sengupta [4]

D. BBC Research Department

The BBC Research Department adopts in [6] the method previously proposed by Sengupta to obtain estimations of the scattered signal for planning purposes.

The model proposed by BBC Research Department is based on a flat conducting plate representation for the blades and in the worst-case assumption of specular reflection condition [6]. With these simplifications, the magnitude of the re-radiated free-space field E_r (V/m) is given by (8):

$$E_r = \frac{EA\sin\phi}{\lambda D_2} \times 10^{-3} \tag{8}$$

where

E: strength of the incident wave (V/m)

A: area of plate (m^2)

λ: wavelength (m)

D_2: distance between wind turbine and viewer (km)

Path geometry is illustrated in Fig. 4, where S is the source (transmitter), V a viewer and R the wind turbine.

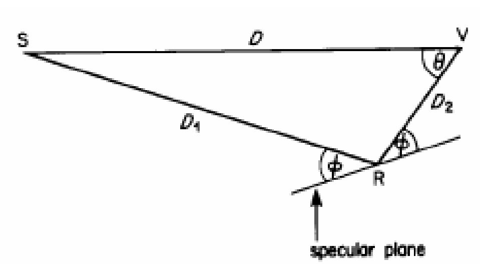

Fig. 4. Path geometry proposed by BBC R.D. [6]

E. Van Kats

Van Kats applies the Radar Cross Section (RCS) concept [11] to characterize signal scattering from the wind turbine [7].

A "co-ordination area" is defined to establish the area surrounding a wind turbine where television quality may be affected. The geometrical configuration of the "co-ordination area" is shown in Fig. 5.

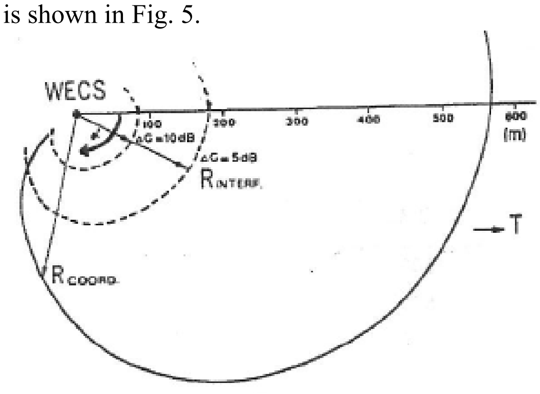

Fig. 5. Geometrical configuration of the co-ordination zone proposed by Van Kats [7]

For this co-ordination area, the blade is approximated by a rectangular perfectly conducting screen and the worst-case scattering characteristics of the wind turbine are assumed. The RCS of the wind turbine is thus given by (9).

$$\sigma(\alpha) = \left[\frac{4\pi}{\lambda^2} A^2 \left(\frac{1+\cos\alpha}{2} \right) \right] \tag{9}$$

where

A: effective area of the blade (m^2)

λ: wavelength (m)

As previously defined by Sengupta in [4], the effective area of the blade A is related to the projected geometrical area A_p via the scattering efficiency η_S:

$$A = \eta_S \cdot A_p \tag{10}$$

F. Limitations of the Theoretical Scattering Models

The theoretical scattering models have some limitations that should be considered in the subsequent empirical analysis of their prediction errors. Several limitations are common to some of the scattering models, as they are based on the same assumptions.

Variability Due to Blades Rotation

Van Kats, Sengupta and the BBC Research Department include in their references measurements of scattering signals as blades rotate. These measured scattering signals feature variations of several dB [5]-[7]. The Preliminary Draft New Recommendation ITU-R also states that the scattering pattern changes by at least 10 dB due to blades rotation. However, for practical purposes, all the models are static, i.e., they do not model the variations of the scattered signals as blades rotate.

Variability Due to Rotor orientation

The model included in the Rec. ITU-R BT.805 and the models proposed by the BBC Research Department, Van Kats and Sengupta are based on worst-case assumptions with respect to rotor orientation. They all assume that the scattering signal will be greatest when the rotation plane of the blades is oriented so that the specular reflection condition is fulfilled, but this will only occur for some proportion of the time. Only the model included in the Preliminary Draft New Recommendation ITU-R considers rotor orientation in the scattered signal estimation.

Mast Contribution to the Scatter Signal

Despite the fact that the wind turbine tower is a large metallic structure (similar in size to rotor diameter), all the estimation models are merely based on the scattering from the blades.

The Preliminary Draft New Rec. ITU-R indicates that it is necessary to include static backscatter from the mast, but it does not provide a method or reference values to estimate it [10]. The BBC Research Department states that the magnitude of the signal from the support structure will depend on its size and form, but then proposes, for a general case, to increase 3 dB the value of the re-radiated field to take account of its presence.

Variability of the Scattering Pattern in the Vertical Plane

None of the scattering models accounts for the difference in height of transmitter, wind turbine and receiver locations, although some theoretical studies demonstrate that the wind turbine scattering pattern is directive in the vertical plane [1].

It should be considered that most of these models were proposed at an early stage of the wind industry development, and the wind turbines structures have dramatically evolved ever since. For example, Sengupta and Van Kats in [5] and [7] refer to two-blade machines, whereas current wind turbines are normally three-blade. In [6], the support structure is said to be a large lattice or concrete tower, whereas actual mast are tubular towers made of steel with heights of up to 100 metres.

III. Field Trials

An extensive measurement campaign was planned and conducted by the authors in order to obtain empirical values of scattered signals from wind turbines. The field trials were carried out in the surrounding area of a wind farm in the North of Spain during spring of 2009. Wind turbines are aligned along the crest of a mountain forming two groups, and between them, there are two television transmitters providing DVB-T services in the UHF Band. Fig. 6 shows a terrain profile with the location of the two transmitters and the nearest wind turbines.

DTV signal measurements were carried out in 38 different locations distributed around the wind farm. In most locations, signals were recorded in several days to gather information of different operation conditions of the wind farm.

Reception locations fulfill the following criteria:

- Rural or semi-urban reception environment to avoid additional effects on DTV signal.
- Line of sight to the transmitters and, at least, the wind turbines located closest to them.
- Minimum distance between transmitter and receiver limited by near field effects (2 km) and maximum distance limited by coverage area (14 km).

Further details on field trials planning and description can be found in previous references from the authors [12]-[13].

IV. Methodology

This section describes the methodology used for the comparison of the estimated values by the scattering models outlined in Section II with the empirical values obtained in the measurement campaign.

A. Data Selection

For the study presented in this paper, only signals scattered by the nearest wind turbines located at the south-east of the transmitters are used (WT 1 to WT 4 in Fig. 6). Thus, cumulative effects of wind turbines located in the shadow area of other turbines are avoided.

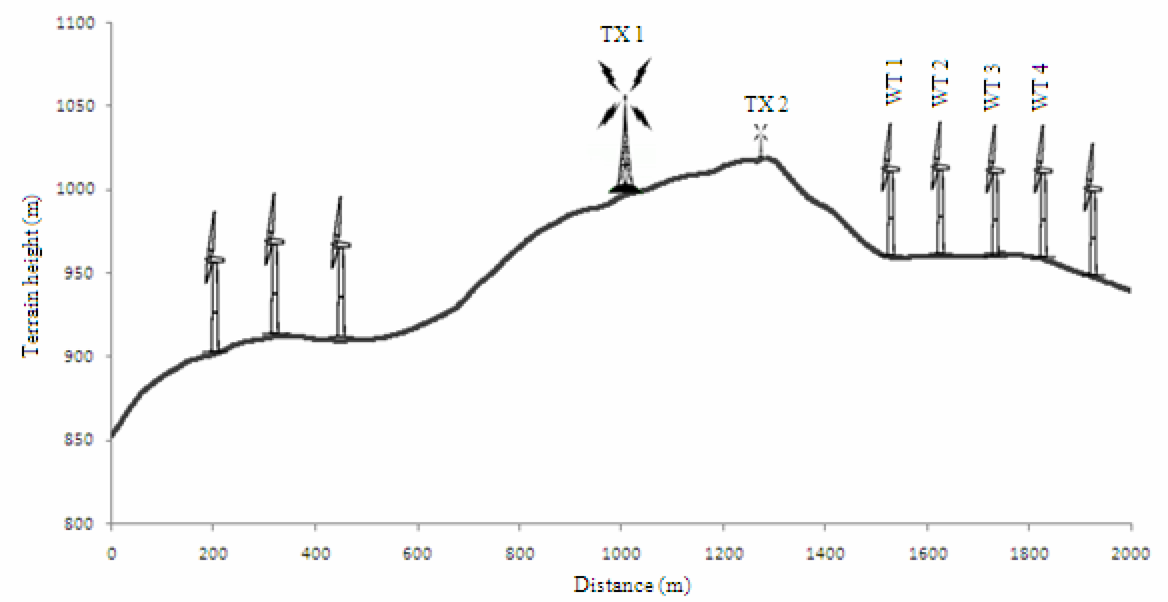

Fig. 6. Terrain profile showing the relative location of DTV transmitters and nearest wind turbines

The model of the Preliminary Draft New Recommendation ITU-R depends on the orientation of the blades with respect to transmitter and receiver sites. The orientation of the rotation plane of the blades is perpendicular to the wind direction in case of normal operation of the wind farm. Thus, only measurement data corresponding to wind turbines with rotating blades are selected. Data about wind conditions (direction and speed) is provided by the meteorological station of the wind farm.

According to previous conditions, 339 measurements of signals scattered by WT1 to WT4 in 26 different locations are selected. The number of data samples used for the evaluation of the model included in the Prelim. Draft New Rec. ITU-R is reduced to 234 due to the fact that this model does not provide signal estimations for the forward scattering area of the blades.

B. Use of the Channel Impulse Response

In presence of a wind farm, the received Channel Impulse Response (CIR) is composed of a direct path from the transmitter and a series of attenuated, time-delayed, and phase shifted replicas due to signal scattering on the wind turbines. Theoretical calculation of scattered delays allows the identification of the contribution of each wind turbine to the impulse response. Therefore, the amplitude of the signals scattered by each wind turbine of the wind farm can be obtained from the CIR [14].

The CIR is estimated from the pilot carriers of the DVB-T signal by applying an Inverse Fast Fourier Transform every four DVB-T symbols, and thus it contains amplitude and phase values of all the pilot carriers [15]-[18]. For the DVB-T configuration used in Spain, this corresponds to obtaining the amplitude of the scattered signals every 4 ms [19]. Hence, the proposed methodology allows an accurate characterization of the time variability of the scatter signals, for example, as blades rotate.

It should be noted that it is not possible to distinguish the contributions of the scattered signals when the transmitter, the wind turbine and the receiver are located almost in line. In these cases, the scatter signals are overlapped by the direct signal from the transmitter in the Channel Impulse Response. These situations correspond to the forward scattering region of the wind turbines as defined in the Rec. ITU-R BT.805 and in Sengupta model.

C. Simulation Tool

The simulation tool used for the case under study has been developed by the University of the Basque Country (UPV/EHU). This software tool analyzes potential interferences of a wind farm to telecommunication services (television broadcasting, radio links and radar, mainly).

Based on high-resolution altimetry maps, and considering the configuration of transmitter and receiver and the wind turbines dimensions, the simulation tool calculates the amplitude of the signals scattered by each turbine of a wind farm according to the theoretical models described in Section II.

This simulation tool provides valuable graphic results viewable on Google Earth. In addition to this, numerical results are calculated and stored for further processing. These numerical results are given as Carrier-to-Interference ratios (C/I) for each wind turbine, i.e., the ratio between the direct signal from the transmitter and the signal scattered by a certain wind turbine at each reception location, expressed in dB.

V. Results and Discussion

The accuracy of the models is statistically evaluated by comparing theoretical and empirical Carrier-to-Interference ratios for each reception point. Hence, the differences between the Carrier-to-Interference ratios obtained from the channel impulse responses of the measured DVB-T signal for each wind turbine (C/I_{meas}) and the ratios provided by the simulation tool for each wind turbine (C/I_{pred}) are calculated and analyzed.

As previously commented, Carrier-to-Interference ratios obtained from measured channel impulse responses feature variations of several dB due to blades rotation [12], whereas theoretical models provide static estimations. Therefore, it is necessary to choose a statistical value to characterize the measurement. For a first approach, median value is selected as a representative central value.

Hence, prediction errors are calculated as the difference between the median values of the empirical C/I ratios and C/I ratios estimated by the different prediction methods:

$$\text{Error} = \text{median}\{C/I_{meas}\} - C/I_{pred} \quad (9)$$

Positive errors mean that measured C/I are greater than estimated C/I, and thus, the prediction method is pessimistic. On the contrary, negative errors mean that the prediction method is optimistic as it underestimates the scattered signal contribution.

Prediction errors are statistically characterized by the mean absolute error, the standard deviation and the 5th and 95th percentiles. The mean absolute error is obtained from absolute error values to avoid compensation between positive and negative values. The standard deviation is a measure of the dispersion from the mean error value. The 5th and 95th percentiles indicate the lower and upper limits within 90% of error samples are located, and thus, they show if the scattering model is pessimistic or optimistic. Table I shows the obtained results.

TABLE I
STATISTICAL CHARACTERIZATION OF PREDICTION ERRORS OF THE SCATTERING MODELS WITH RESPECT TO THE CENTRAL VALUE OF C/I_{MEAS}

	Mean absolute error	**Standard deviation**	**5th percentile**	**95th percentile**
Rec. ITU-R BT. 805	8.68 dB	6.49 dB	-2.91 dB	19.10 dB
BBC	15.68 dB	6.43 dB	5.62 dB	26.61 dB
Van Kats	6.10 dB	6.43 dB	-5.75 dB	15.24 dB
Sengupta	6.24 dB	6.43 dB	-14.02 dB	7.00 dB
Prelim. Draft New Rec. ITU-R	32.28 dB	24.13 dB	-71.60 dB	10.38 dB

The main conclusions derived from the results are the following:

- The scattering models with lower mean error are Van Kats and Sengupta. These models apply the effective or equivalent scattering area of the blade instead of the physical area of the blade, so that they are less pessimistic.
- BBC, Van Kats and Sengupta models show the same standard deviation. It can be proved that these three models are mathematically equivalent in the backscattering zone with respect to the relative geometry between transmitter, wind turbine and receiver locations, as they all assume the worst-case condition of specular reflection.
- The model included in the ITU-R Preliminary Draft New Recommendation provides higher prediction errors, estimating scattering signals several orders of magnitude below measured signals. The new model is based on a scattering coefficient that is clearly specular, following a $sinc^2$ pattern with a narrow main lobe around the specular reflection direction (with respect to the rotation plane of the blades). For reception locations out of this narrow beam, the model provides scattered signals of very low amplitude. Consequently, according to this model, there is no significant scattered signal outside the main lobe. However, this effect is not observed in the measurements, as commented later. Moreover, the Prelim. Draft New Rec. states that blades made of fiberglass or other composite materials result in 6 to 10 dB less scattering than metallic blades. Taking this consideration into account, prediction errors would be even higher.

Following subsections analyze several aspects involved in the comparative study of the scattering models.

A. *Error Distribution by Wind Turbine*

Table II shows mean error values of the different prediction methods for each wind turbine separately. It can be observed that mean error values of each scattering model are in the same order of magnitude for the four wind turbines selected. Therefore, it can be concluded that cumulative effects amongst wind turbines do not seem to be significant.

TABLE II
STATISTICAL CHARACTERIZATION OF PREDICTION ERRORS OF THE SCATTERING MODELS FOR EACH WIND TURBINE

	WT1	**WT2**	**WT3**	**WT4**
Rec. ITU-R BT. 805	8.93 dB	9.51 dB	8.05 dB	8.51 dB
BBC	16.36 dB	17.08 dB	14.73 dB	15.13 dB
Van Kats	6.26 dB	6.32 dB	5.67 dB	6.29 dB
Sengupta	5.49 dB	4.70 dB	6.65 dB	7.53 dB
Prelim. Draft New Rec. ITU-R	33.75 dB	31.42 dB	32.77 dB	31.50 dB

B. *Variability Due to Blades Rotation*

As previously commented, scattered signals show time variability due to blade rotation. Considering that all theoretical models are based on worst-case assumptions, the 5th percentile is calculated as a lower limit of the measured C/I in order to characterize the blades position such that the maximum scattered signal is obtained. Fig. 7 shows an example of time variability of the C/I_{meas} as the blades of WT2 rotate, along with the 5th percentile and the median value of the registered values.

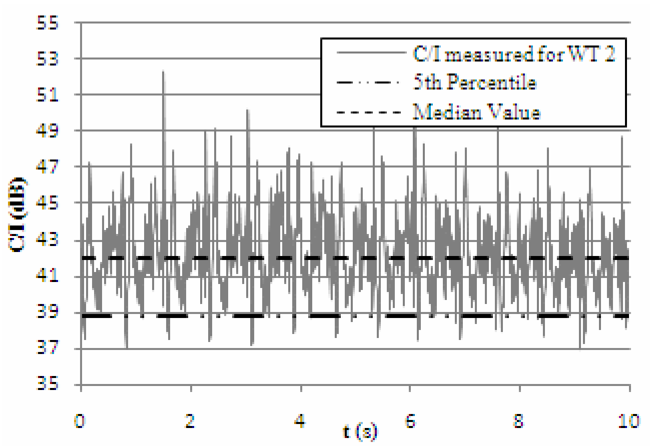

Fig. 7. Example of time variability of C/I_{meas} as blades rotate, median value and 5th percentile

Statistical characterization of the prediction errors obtained when considering the 5th percentile as the representative lower value of the measurement is shown in Table III.

TABLE III
STATISTICAL CHARACTERIZATION OF THE PREDICTION ERRORS OF THE SCATTERING MODELS WITH RESPECT TO THE LOWER LIMIT OF C/I_{MEAS}

	Mean absolute error	Standard deviation
Rec. ITU-R BT. 805	7.06 dB	5.86 dB
BBC	13.74 dB	5.76 dB
Van Kats	4.94 dB	5.76 dB
Sengupta	6.83 dB	5.76 dB
Prelim. Draft New Rec. ITU-R	33.84 dB	23.92 dB

Comparing Table I and Table III, it can be observed that the differences in the mean error values of each scattering model are low.

For instance, Fig. 8 shows time variability of the same C/I measurement of Fig. 7 along with C/I predicted by the scattering models. As shown in the figure, none of the predicted values coincide with the C/I measurement, although it presents variations higher than 10 dB.

Therefore, the representative value selected for the characterization of measured C/I ratios does not seem to be a significant factor in the high prediction errors obtained. However, this does not mean that time variability due to blades rotation should not be considered in a more complete scattering model, as this movement causes variations higher than 10 dB in the measured C/I ratios.

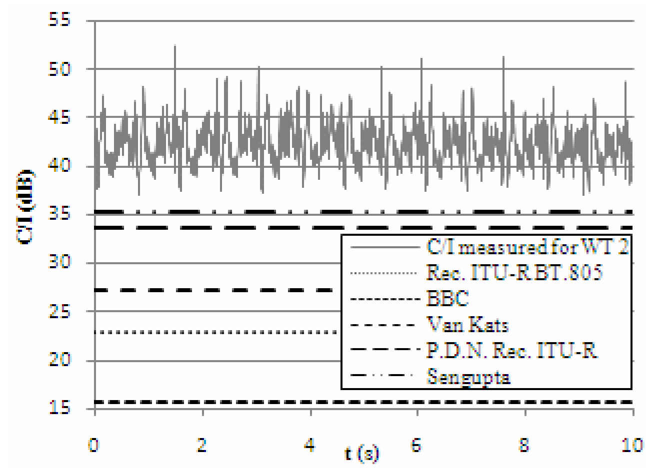

Fig. 8. Example of time variability of C/I_{meas} and C/I estimated by the different scattering models

C. *Variability Due to Rotor Orientation*

As commented in Section II, the model included in the Rec. ITU-R BT.805 and the models proposed by the BBC Research Department, Van Kats and Sengupta are based on worst-case assumptions with respect to rotor orientation.

Fig. 9 shows three measurements of C/I for different rotor orientations of WT1 in the same reception location, along with the results of the above-mentioned prediction methods.

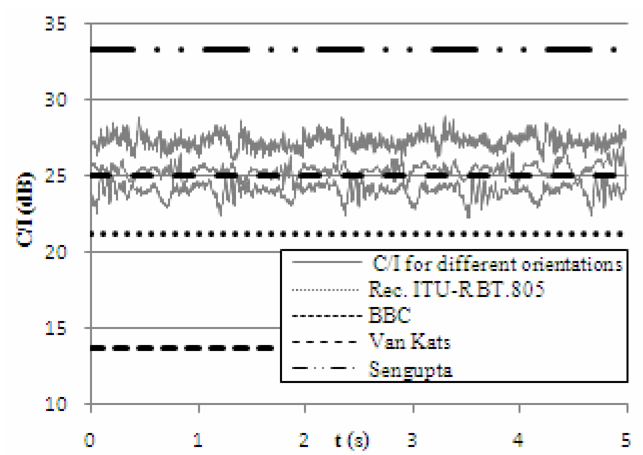

Fig. 9. C/I_{meas} for different rotor orientations of WT1 in the same reception location and C/I_{est} by the different scattering models

It can be observed that measurements with different rotor orientations differ in several dB, whereas the four scattering models provide constant values that correspond to the worst-case estimation of specular reflection condition.

Only the model included in the Preliminary Draft New Recommendation ITU-R considers rotor orientation in the scattered signal estimation. However, as previously stated, the "scattering coefficient" follows a $sinc^2$ pattern with a narrow main lobe around the specular reflection direction (with respect to the rotation plane of the blades). For a certain reception location, the specular reflection condition corresponds to a particular wind direction. As an example, Fig. 10 shows predicted results for a certain reception location as a function of wind direction (depicted in grey). Six C/I measurements corresponding to that reception location are also shown in the figure (depicted in black). More precisely, the vertical range of these values correspond to variations of the C/I measurements due to blade rotation.

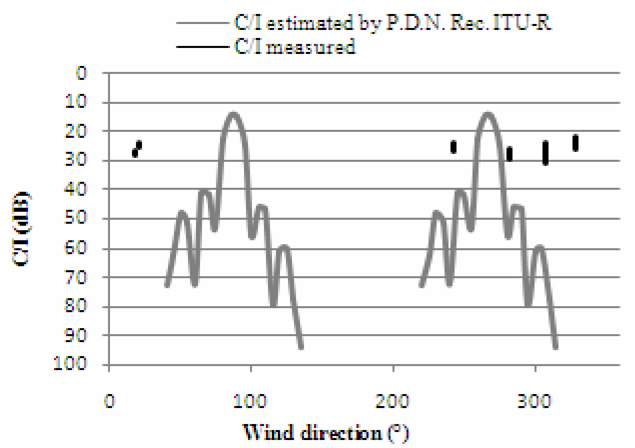

Fig. 10. C/I_{est} according to Prelim. Draft New Rec. ITU-R for a certain reception location as a function of wind direction

It can be observed that all C/I measurements are lower than their corresponding predictions. Thus, the prediction model clearly underestimates the scattered signal values. Moreover, even though measurements differ in several dB when varying rotor orientation, these differences do not present a specular behaviour as defined by the scattering model.

There are two main reasons for the variations not being as specular as the model proposes:

- Firstly, the actual shape of the blade is more complex than a triangular metallic flat plate.
- Secondly, the scattering model does not consider the contribution of the wind turbine mast. This contribution could be, at least, as important as the scattering from the blades, but static and independent of rotor orientation [20]-[22].

It should also be noted that there are three measurements that correspond to the "forward scattering" zone of the blades and therefore the method does not provide estimation values for these scattered signals. However, these signals feature significant amplitude, similar to the signals scattered in the backscatter region of the blades.

VI. Conclusions

The empirical evaluation of the scattering models demonstrates that they do not provide realistic estimations of scattered signals from wind turbines, as it can be stated from the high values of the mean absolute prediction errors (6 dB to 32 dB) and the standard deviations (6 dB to 24 dB) obtained. This lack of accuracy is due to some limitations of the theoretical models:

- None of the models considers the scattering pattern variation in the vertical plane.
- Despite the fact that some studies state the significant contribution of the mast in the scattered signal, none of the theoretical models includes it in the estimation methods.
- The models proposed by the BBC Research Department, Van Kats and Sengupta have the same theoretical basis and thus they feature some common limitations. All of them are based on specular reflection condition for maximum scattering from the blades. The high error deviations obtained are due to the fact that the models do not take into account the variability attributable to rotor orientation or blade rotation.
- The model included in Rec. ITU-R BT.805 has a constant value of -10 dB for the relative amplitude in the general scatter region that is not theoretically justified, and it is clearly pessimistic when compared to the measurements.
- The Prelim. Draft New Rec. ITU-R proposes a model based on a triangular blade, whose "scattering coefficient" depends on the rotor orientation. However, this "scattering coefficient" features a very directive lobe in the specular reflection direction that does not agree with the measurements. Moreover, the model does not provide signal estimations in the forward scattering zone of the blades.

It can be concluded that none of the analyzed methods seems to be accurate enough to provide realistic estimations of the signal scattered by the wind turbines. In conclusion, a more complete scattering model is needed in order to provide more practical estimations of the scattered signals and evaluate their potential impact on the broadcasting services. This model should include a characterization of the variability of the scattered signal due to the different movements of the modern wind turbines, as this variability may be of importance for the assessment of reception quality of the new telecommunication services in the UHF band.

Acknowledgment

The authors would like to thank the partners from Iberdrola Renovables, Itelazpi and Abertis Telecom for their kind collaboration in this work.

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