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Empirical Evaluation of the Impact of Wind Turbines on DVB-T Reception Quality

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***Abstract*— This paper describes the results of two extensive measurement campaigns for evaluating the potential impact of scattered signals from wind turbines on terrestrial DTV reception quality in the UHF band. A detailed description of the different propagation channels encountered is provided. Furthermore, empirical threshold carrier-to-noise requirements for Quasi Error Free reception in the DVB-T system in the area of influence of a wind farm are presented, and the situations where a significant degradation can be found are identified and characterized.**

***Index Terms*— Digital TV, Multipath channels, Quality of service, UHF propagation, Wind farms.**

I. Introduction

THE renewable energy sector has grown strongly and steadily for the last decade, as more wind power capacity is installed and firms continue to increase average turbine sizes and improve the involved technologies [1].

The effect of such huge structures near telecommunication infrastructures has been widely analyzed for some services such as analogue TV, radar or radiolinks [2]-[8]. The International Telecommunication Union (ITU-R) provides in Recommendation ITU-R BT.805 a simple scattering model to assess the impairment caused to television reception by a wind turbine [9]. However, the criterion included in the Recommendation only applies to analogue television. Hence, the ITU-R asked for new studies about the effects of reflected signals on digital television reception, with special attention to the variability of reflected signals due to movement of reflecting objects such as wind turbines [10].

The performance of the different DTV standards under this specific type of time varying multipath channel is yet to be assessed, and it will depend on the modulation and channel coding schemes used. The ATSC system was initially designed for MFN environment but technical advances have provided receivers able to handle strong multipath distortions [11]. The ISDB-T BST-OFDM system, which uses the same modulation and channel coding scheme as the DVB-T system, has performance advantages with respect to dynamic multipath distortion [12]. DMB-T systems seem to perform better under different channel fading models than both the practical 2K mode and the practical 8K mode DVB-T systems [13]-[15]. The DVB-T system can withstand high-level (up to 0 dB) long delay static and dynamic multipath distortion. However, a higher C/N will be needed to deal with such strong echoes [11].

In this context, DTV field measurements in the surrounding area of a wind farm were carried out in Spain in 2009 in order to evaluate the potential impact of wind turbines on terrestrial DTV reception quality. More precisely, empirical threshold carrier-to-noise ratios required for Quasi Error Free reception in the DVB-T system were obtained. The first results of these field trials were included in [16], and later referenced in the recently approved Recommendation ITU-R BT.1893 “Assessment of impairment caused to digital television reception by a wind turbine” [17].

In 2010, a new measurement campaign was conducted to add further data in different propagation scenarios around the wind farm.

This paper includes a detailed description of the different propagation channels encountered in the presence of wind farms, and the identification and characterization of the situations where a significant degradation might be found. The description of the propagation channels is independent of the transmission standard or modulation, and therefore it is valid for any broadcasting and wireless communication system. The study is based on empirical data from the two above-mentioned measurement campaigns, and thus includes definite and unpublished results.

Section II provides an overall description of the field trials. Section III analyzes the main characteristics of the propagation channels encountered in presence of a wind farm. Section IV presents the empirical threshold C/N ratios measured and relates them to the characteristics of the propagation channel.

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Finally, Section V summarizes the conclusions derived from the study.

II. FIELD TRIALS

The DTV field trials were carried out in the surrounding area of a wind farm in Spain during several months of 2009 and 2010.

A. *Overview of the Case under Study*

The wind farm is located at a mountain top with an elevation of 800 to 1000 m. The surrounding area at the south of the wind farm is quite flat, with a mean altitude of about 200 m. The area at the north of the wind farm is hilly, with altitudes between 200 and 450 m.

The wind farm is composed of 40 wind turbines forming two groups, and between them, there are two television transmitters providing independent program signals in several DTV channels within the UHF band.

The DVB-T configuration used in Spain is shown in Table I.

TABLE I
DVB-T CONFIGURATION USED IN SPAIN

Operational band	UHF
Carrier type	8K
Guard interval	1/4 (224 μs)
Code rate (FEC)	2/3
Modulation	64QAM
Transmission mode	Non-hierarchical
Channel bandwidth	8 MHz

B. *Selection of the Measurement Locations*

Measurements were taken in thirty six different reception locations placed between 2 and 13 km away from the transmitters, under normal operation of the wind farm. This implies that the blades are rotating with their rotation plane perpendicular to the wind direction when producing energy, or static in case of unfavorable wind conditions. In most locations, signals were recorded over several days to gather information regarding different operating conditions of the wind farm. These reception locations are distributed around the wind farm, being all of them in line-of-sight to the wind turbines.

Three different propagation scenarios are analyzed:

- In the *backscattering region* of the wind turbines, the channel impulse response at the measurement system will be composed of the direct path and a series of attenuated, time delayed, and phase shifted replicas caused by signal scattering on the wind turbines.
- The *forward scattering region* corresponds to locations where the transmitter, one or more turbines and the receiver are lined-up. In these situations, the relative delays of the scattered signals tend to zero. In general, the forward scattering from a target is stronger than the backscattering, but is nearly out of phase with the incident field. Consequently, the forward scatter is generally subtracted from the incident field, thereby creating a shadow region of reduced intensity behind the target [18].
- Due to the arrangement of the wind farm, there are some reception locations that are located both in the backscattering region of the wind turbines at the right of the transmitters and in the forward scattering region of the wind turbines at the left of the transmitters. This area is referred to as *forward-backward scattering region* for the sake of simplicity.

A total of 25 reception locations correspond to backscattering from the wind turbines, other 8 correspond to forward scattering and 3 to forward-backward scattering. Fig. 1 shows the selected reception locations around the television transmitters and the wind farm.

C. *Measurement Methodology*

In the backscattering region, measurements were carried out at each reception location pointing the antenna at different directions. The first measurement was recorded pointing the reception antenna towards the transmitter, and for successive measurements the antenna was misaimed in steps of 15º in azimuth. When the antenna is not pointing towards the transmitter, different gain values are applied to the signals scattered by the wind turbines. Therefore, for a certain location, the influence of different multipath levels in the reception quality can be evaluated. Altogether, 158 different backscattering situations are analyzed.

In the forward and forward-backward regions, measurements were carried out pointing the receiver antenna towards the transmitter. In total, 18 different situations of signals scattered in the forward region were measured, and 8 corresponding to the forward-backward scattering region.

D. *Measurement Equipment*

The measurement system was based on a RF recorder for a detailed characterization of the received signal. These signals were analyzed by using the DBA (Digital Broadcast Analysis) software receiver [19]-[20]. This tool was developed by the University of the Basque Country to provide the channel frequency response, the channel impulse response, the IQ constellation and the main quality parameters of the DVB-T signal. Additionally, a professional DVB-T test receiver was used to evaluate the effect of the scattered signals on the DVB-T reception quality.

Further details on field trials planning and description can be found in previous references from the authors [21]-[22].

III. ANALYSIS OF THE PROPAGATION CHANNEL

This section describes the methodology to estimate the channel impulse responses from the recorded DVB-T signal and outlines the main characteristics of the propagation channels depending on the scattering region. In the last

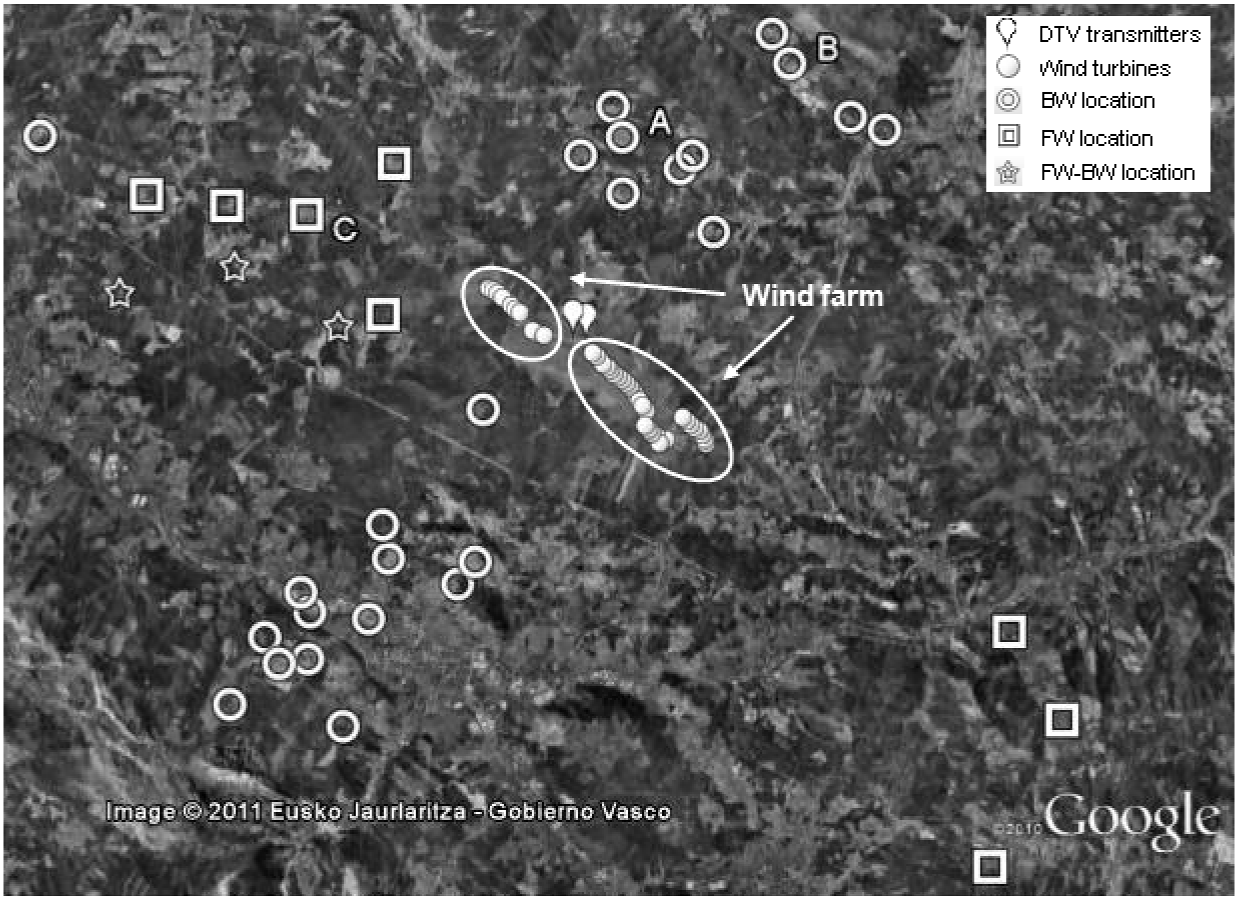

Fig. 1. Location of the wind farm, DTV transmitters and measurement locations

subsection, the parameters to characterize the multipath channels are defined.

A. Estimation of Channel Impulse Response

The impulse response is estimated from the pilot carriers of the DVB-T signal by applying an Inverse Fast Fourier Transform every four symbols, and thus it contains amplitude and phase values of all the pilot carriers [23]-[27]. The impulse response is normalized with respect to the direct path in order to characterize the propagation channel independently of the input received power.

The theoretical delays of the scattered signals can be calculated from the relative location of the transmitter, the receiver and each wind turbine. Thus, the amplitude and variation of these scattered signals are properly associated to each corresponding wind turbine and accordingly analyzed using the estimated channel impulse response, as described in [28]-[29].

B. Description of Representative Propagation Channels

The type of propagation channel encountered in the vicinity of the wind farm depends on the scattering region where the measurement system is located.

Backscattering Region

As an example, Fig. 2 shows 200 superimposed channel impulse responses (calculated from 800 consecutive symbols) corresponding to a reception location in the backscattering region (location A, see Fig. 1), when the wind farm was operating under normal conditions. The direct path from the transmitter and the multipath components due to the signals scattered by each wind turbine are distinctly differentiated. Changes in the amplitude of the different multipath components show that there is a significant time variability of the signals scattered by the wind turbines as blades rotate.

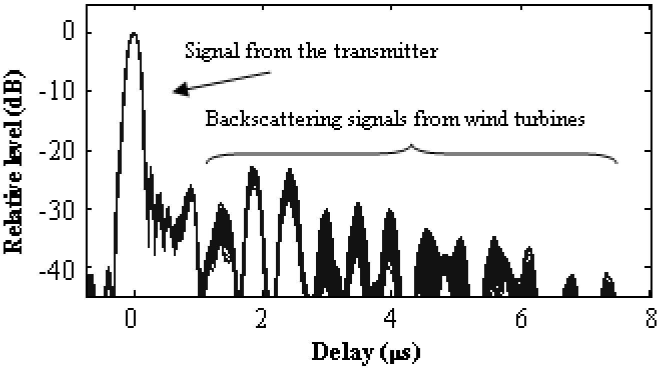

Fig. 2. Example of DVB-T channel impulse responses in the backscattering region (location A). Rotating blades.

This variability is clearly observed when representing the signal scattered by a wind turbine as a function of time. Fig. 3

shows the time variability of the signal scattered by one of the wind turbines (one of the multipath components) in the situation depicted in Fig. 2.

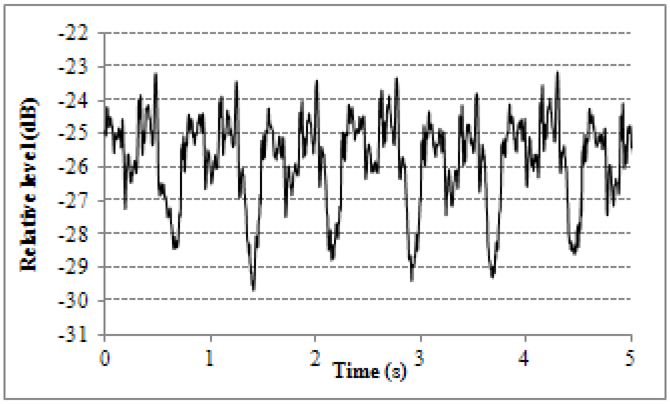

Fig. 3. Example of the time variability of the signal backscattered by a wind turbine as blades rotate

There is a periodic variation with a repetition period of approximately 1 s, corresponding to 1/3 of the rotation rate of the wind turbine, as expected for a three-blade rotor.

Both the multipath level and the time variability due to blade rotation are highly dependent on the orientation of the wind turbine with respect to the transmitter and the receiver. For instance, Fig. 4 shows 200 superimposed channel impulse responses corresponding to the same measurement location of Fig. 2 (location A), but for different wind conditions (and thus different orientation of the wind turbines with respect to the wind).

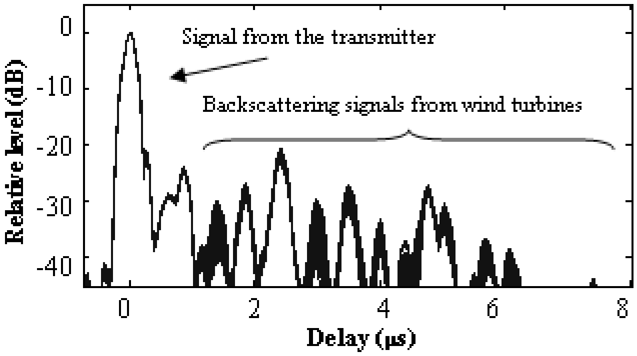

Fig. 4. Example of DVB-T channel impulse responses in the backscattering region (location A). Rotating blades with different rotor orientation.

As expected, the delay of the multipath components is maintained with respect to Fig. 2. However, the amplitude of the scattered signals as well as the time variability due to blade rotation is different. As an example, Fig. 5 shows the time variability of the signal backscattered by the same wind turbine of Fig. 3 but for the situation depicted in Fig. 4. It can be observed that both the mean multipath level and the variations due to blade rotation change significantly.

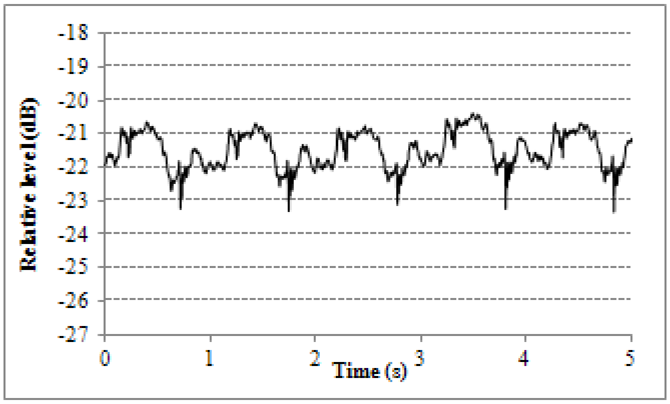

Fig. 5. Example of the time variability of the signal backscattered by a wind turbine as blades rotate. Different rotor orientation.

When there are no favorable wind conditions and blades are static, this variability is not observed. For instance, Fig. 6 shows 200 superimposed channel impulse responses corresponding to a different reception location in the backscattering region (location B, see Fig. 1) when the blades of the wind turbines were not rotating.

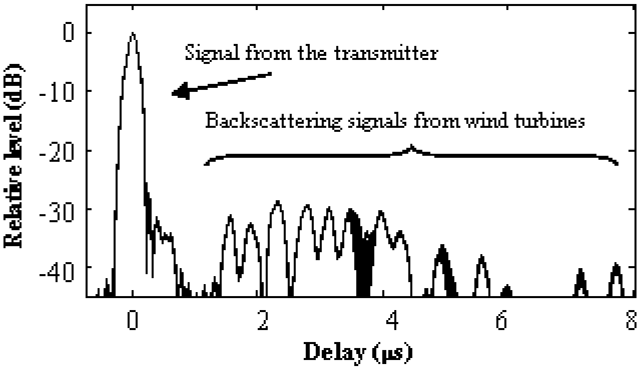

Fig. 6. Example of DVB-T channel impulse responses in the backscattering region (location B). Static blades.

If the normalized power of the signal scattered by one of the wind turbines of Fig. 6 as a function of time were depicted in a similar way to Fig. 3 and Fig. 5, no significant time variability would be observed, as the signal remains steady.

In conclusion, the main features of the propagation channel for stationary reception in the backscattering region of the wind turbines are the following:

- Multiple paths with constant delay, one for each wind turbine of the wind farm. The delays of the scattering signals can be theoretically calculated from the positions of the transmitter, the wind turbines, and the reception location.
- The amplitude of the scattering signals depends on the dimensions and materials of the wind turbine, as well as on the relative position between the transmitter, the wind turbine and the receiver.
- In general, the paths due to signal scattering are time-varying in amplitude. This variability is due to the

rotation of the blades and the different orientations of the turbine to face the wind direction.

- In contrast to other time-varying channel models, the direction of arrival of the multiple paths is fixed and known.

Forward Scattering Region

Fig. 7 shows 200 consecutive channel impulse responses corresponding to a reception location in the forward scattering region of the wind turbines located at the left of the transmitters (location C, see Fig. 1). As previously commented, in this area the transmitter, the wind turbines and the receiver are lined-up, and therefore the scattered signals are overlapped with the direct signal from the transmitter. Hence, their effect is not visible in the channel impulse response.

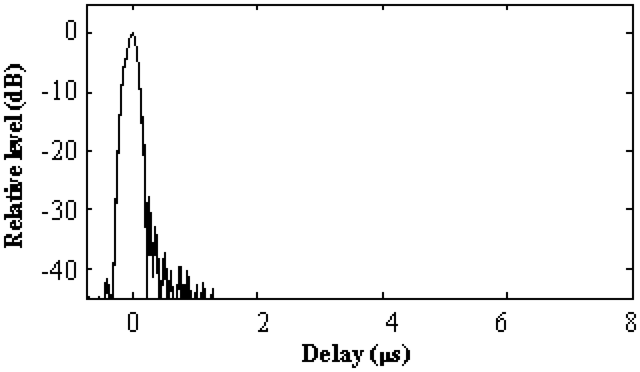

Fig. 7. Example of DVB-T channel impulse responses in the forward scattering region (location C)

To sum up, the propagation channel for stationary reception in the forward scattering region of the wind turbines is characterized by a shadow zone of reduced intensity behind the turbine, due to the sum of the incident field and the scattered field, of nearly equal strength but 180º out of phase. Nevertheless, the fields behind the target are hardly ever precisely zero because some energy usually reaches the shadow zone via diffraction from the sides of the obstacle [30].

Forward-Backward Scattering Region

In these locations, there is a combined effect of signals backscattered by the wind turbines located at the right of the transmitters, and signals scattered in the forward region of the wind turbines at the left of the transmitters. Therefore, the typical propagation channel in this case is a combination of the situations depicted in Fig. 4 or Fig. 6 and Fig. 7.

C. *Characterization of the Multipath Channel*

It is necessary to characterize the multipath channel in the backscattering region for further relating these characteristics to the obtained threshold C/N ratios.

Physically, multipath propagation characteristics imply multipath number, amplitude and path-length difference (delay) [31]. In this particular case, the characterization should consider the unique features of the dynamic multipath channel previously described: multiple paths with constant delay and time-varying amplitude depending on the working regime of the corresponding wind turbine. This is to say, the characterization should not only consider the amplitude of the multiple paths but also their time variability.

The first parameter selected takes into account the median level of the multipath due to signal scattering on wind turbines. Thus, it considers both the multipath number and the median amplitudes of these paths. To do so, the *multipath energy* of the channel, P_{mult}, is defined as the sum of the median received power from each wind turbine. The median value of each path is calculated as a representative central value of the path because, as previously commented, the scattering signals vary as blades rotate. Therefore, the *multipath energy* of the impulse response is given by (1).

$$P_{mult} = \sum_{i=1}^{N} median\left(P\left(\tau_i, t\right)\right) \tag{1}$$

where

$i=1$ *and* $i=N$: indices of the first and last paths above a threshold level of -45 dB with respect to the direct path

$P(\tau_i,t)$: normalized time-varying received power from path *i*

For example, the *multipath energy* corresponding to Fig. 2 (expressed in dB) is -20.32 dB.

The *mean standard deviation,* σ_{mean}, is calculated as the mean of the standard deviations of the time-varying signals scattered by each wind turbine in a certain measurement. Hence, it provides a measure of the time variability of the channel impulse response during the recording time. The *mean standard deviation* is given by (2).

$$\sigma_{mean} = \frac{\sum_{i=1}^{N} \sigma_i}{N} \tag{2}$$

where

$i=1$ *and* $i=N$: indices of the first and last paths above a threshold level of -45 dB with respect to the direct path

σ_i: standard deviation of the time-varying normalized received power from path *i*

For example, the mean standard deviation of the situation depicted in Fig. 2 is 0.26 dB.

Other parameters such as delay interval (length of the impulse response between two values of excess delay which mark the first time the amplitude of the impulse response exceeds a given threshold, and the last time it falls below it), number of multipath components [31] and rotor speed have also been calculated.

IV. EMPIRICAL EVALUATION OF THE DVB-T RECEPTION QUALITY

This section describes the methodology to obtain the threshold carrier-to-noise ratios for Quasi Error Free reception, the results obtained for the different propagation scenarios and their relation with the characteristics of the propagation channels.

A. *Methodology to Obtain C/N Thresholds*

The bit error rate (BER) as a function of carrier-to-noise ratio (C/N) is the most important figure of merit for any digital transmission system [32]. For comparative purposes, the C/N threshold for Quasi Error Free reception is estimated. This QEF condition corresponds to a BER after Viterbi equal to 2×10^{-4}.

The threshold C/N for QEF reception is usually measured lowering the C/N ratio until the BER after Viterbi equals 2×10^{-4}. There are two different techniques to obtain the threshold C/N ratios:

- To increase the noise level by means of an external source, and add this noise to the received DVB-T signal, in order to obtain the threshold C/N ratio.
- To progressively attenuate the DVB-T signal level in order to achieve a BER value close to the QEF threshold.

Both techniques were applied in the measurement methodology, providing similar results. In order to avoid redundant values, only the threshold C/N ratios obtained by means of the internal noise generator of the DVB-T test receiver are used in the subsequent analysis.

For the DVB-T configuration used in Spain (see Table I), the system has a theoretical threshold carrier-to-noise figure of 16.7 dB for a Gaussian channel, 17.3 dB for a Ricean channel and 20.3 dB for a Rayleigh channel [23]. These theoretical thresholds are based upon perfect channel estimation (without considering phase noise) and ideal receiver implementation, and thus in practical situations the C/N requirement for demodulation is increased by several dB [33]. For the DVB-T professional receiver, a margin of 2 dB corresponding to the receiver implementation losses and the use through a practical RF transmission system is considered. Thus, a threshold of 18.7 dB is taken as a reference value for the forward scattering region (Gaussian channel) and a threshold of 19.3 dB for the backward and forward-backward scattering regions (Ricean channel).

B. *Analysis of the C/N Thresholds for QEF Reception*

The results corresponding to the three different propagation scenarios (backscattering, forward scattering and forward-backward scattering) are analyzed separately.

Backscattering Region

Fig. 8 shows the bit error rate (BER) as a function of carrier-to-noise ratio (C/N) for the different situations measured in the backscattering region of the wind turbines.

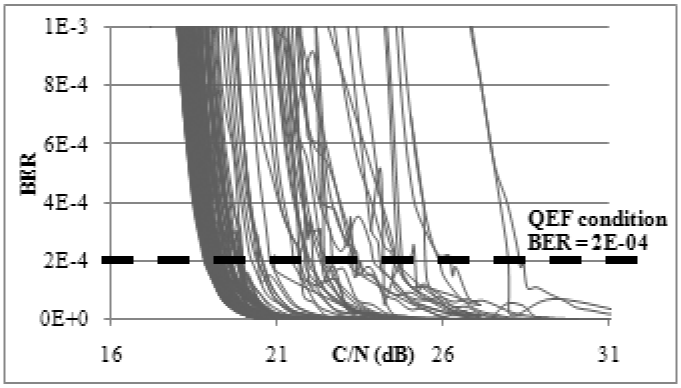

Fig. 8. Backscattering region - BER after Viterbi as a function of Carrier-to-Noise Ratio

It can be observed that most of the measurements feature threshold C/N ratios close to 19.3 dB. However, there are several measurements which show C/N threshold ratios higher than 19.3 dB and up to 28 dB.

Fig. 9 represents the C/N threshold ratios measured in the backscattering region as a function of the characteristics of the multipath channel. Required C/N ratios are shown with respect to *multipath energy* (expressed in dB). The size of the bubbles is determined by the values of the *mean standard deviation* of each measurement. The bubbles are also depicted from light grey to black as a function of the *mean standard deviation* to provide a clearer representation.

As it can be observed in the figure, there is a clear tendency between the increasing C/N ratios and the *multipath energy*. Moreover, measurements with the same level of *multipath energy* feature a higher C/N threshold ratio when the *mean standard deviation* is also higher.

As a significant result, all the measurements with *multipath energy* values higher than -15 dB have a C/N threshold ratio equal or higher than 19.3 dB, independently of their *mean standard deviation*. By contrast, Recommendation ITU-R BT.805 states that the effects of the wind turbines are reduced during periods when the wind turbines are not rotating. According to these results, this statement should be reconsidered.

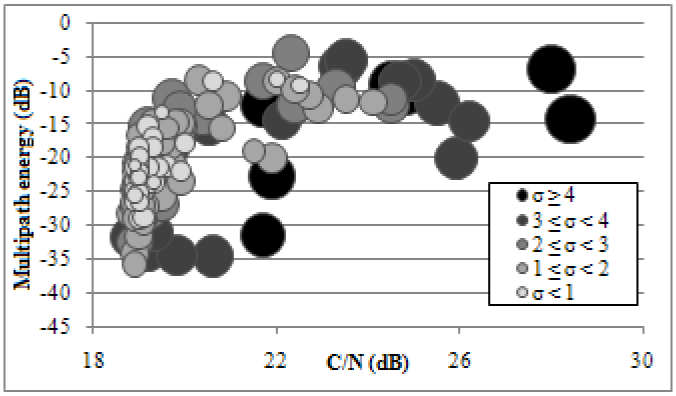

Fig. 9. Backscattering region. Required C/N ratios as a function of the characteristics of the multipath channel

For measurements with *multipath energy* values lower than -15 dB, the most significant increments over the theoretical threshold of 19.3 dB are obtained for the highest values of *mean standard deviation*. Moreover, all the measurements with *multipath energy* values lower than -25 dB and *mean standard deviation* values below 2 dB provide C/N ratios close to 19.3 dB.

Table II summarizes the maximum increments in the C/N threshold ratios with respect to the Ricean C/N threshold as a function of *multipath energy*.

TABLE II
MAXIMUM INCREMENT OF THE C/N THRESHOLDS OVER THE THEORETICAL RICEAN C/N THRESHOLD

Multipath energy	**Maximum increment of the C/N threshold over the theoretical Ricean C/N threshold**
$P_{mult} \geq -15$ dB	9.1 dB
-15 dB $> P_{mult} \geq -25$ dB	6.6 dB
-25 dB $> P_{mult} \geq -35$ dB	2.4 dB
$P_{mult} < -35$ dB	0 dB

The other parameters such as delay interval, number of multipath components and rotor speed proved to be less significant in the increase of the threshold C/N ratios.

It should be mentioned that levels of *multipath energy* above -15 dB are not usual when pointing the reception antenna towards the transmitter. In a general case, the use of an omnidirectional antenna will cause higher levels of *multipath energy* to be detected in the receiver. Moreover, DTV reception impairments could exist in the shadowed area where transmitter line-of-sight is blocked, while there is line-of-sight to the wind farm. Quality degradation may also be found in sites within the fringe of the coverage area. If a gap-filler is located in a potentially impaired region, its own coverage area might also be affected by quality degradation.

Forward Scattering Region

Fig. 10 shows the bit error rate (BER) as a function of C/N for the different situations measured in the forward scattering region of the wind turbines. It can be observed that all the measurements feature threshold C/N ratios in a narrow margin around the theoretical threshold for a Gaussian channel of 18.7 dB [23].

As previously commented, the forward scattering signals cast a shadow behind the wind turbines, although the fields behind the target are hardly ever precisely zero [30]. Moreover, at great distances from the obstacle, the angular width of the shadow becomes narrower [18]. For all the different situations measured, including several orientations of the wind turbines with respect to the wind direction (and therefore with respect to the transmitter-receiver path), the effect of the forward scattering seems to be negligible.

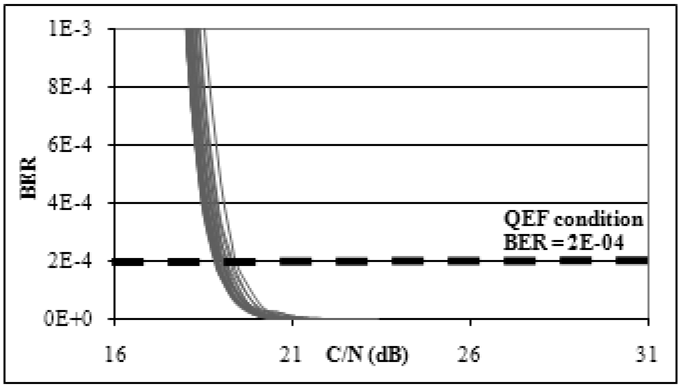

Fig. 10. Forward scattering region - BER after Viterbi as a function of Carrier-to-Noise Ratio

Forward-Backward Scattering Region

Finally, the measurements where a combination of forward and backward scattering effects is present are analyzed. To do so, the *multipath energy* and the *mean standard deviation* are calculated as explained in Section III.

Fig. 11 shows the obtained results overlapped to the ones previously depicted in Fig. 9, in order to compare measurements taken in the backscattering region to those obtained in the forward-backward scattering region.

As shown in the figure, the presence of the forward scattering signals does not seem to cause a further increment in the required C/N apart from that expected due to the backscattering signals.

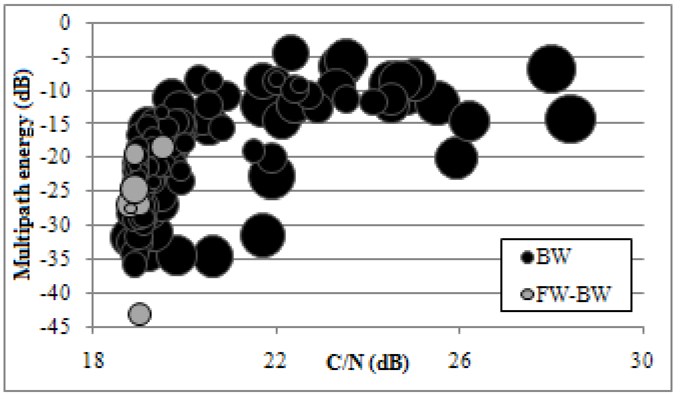

Fig. 11. Forward-Backward scattering region vs. Backscattering region - Required C/N ratios as a function of the characteristics of the multipath channel

V. CONCLUSIONS

Derived from the results of the field trials, it can be stated that the dynamic multipath channel observed in the backscattering region of wind turbines might be more demanding in terms of the C/N threshold ratio than a typical Ricean channel. The increases in the C/N threshold ratio depend both on the multipath level due to signal scattering from the wind turbines, and the time variability of these scattered signals as blades rotate.

As a significant result, all the measurement with *multipath energy* levels above -15 dB feature C/N thresholds higher than

19.3 dB (the theoretical threshold for a Ricean channel), even in those situations where the blades were static and thus the *mean standard deviation* was low. Broadly speaking, measurements with *multipath energy* levels below -15 dB feature higher C/N ratios for higher *mean standard deviation* values.

On the other hand, the effect of the scattering signals in the forward scattering region seems to be negligible.

Similarly, in the forward-backward scattering region, the increment in the required C/N corresponds to the threshold expected according to the characteristics of the multipath due to backscattering, with no noticeable effect of the forward scattering signals.

These results may be used as simple guidelines in order to estimate the potential degradation caused by a wind farm on a DVB-T service. The minimum C/N required at a receiver has a direct consequence on the required Effective Radiated Power (ERP) of a transmitter, which has to be increased correspondingly for a given coverage [34].

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