Impact of Wind Turbine Rotor Forward Scattering on 16-QAM Based Communication System

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***Abstract*—Rotor angle dependent amplitude and phase distortion of a radio signal is calculated using 2D Fresnel-Kirchhoff diffraction approach and verified by numerical field simulation using Uniform Theory of Diffraction (UTD). The corresponding instantaneous Modulation Error Ratio (MER) and raw data Bit Error Rate (BER) are investigated considering a 16-QAM system. Time-variant channel impulse response cannot be derived from the frequency domain model of the Fresnel-Kirchhoff formula due to inherent limitations of its approximation.**

Keywords—electromagnetic interference; radiowave propagation; diffraction; interchannel interference; wind turbine; wind farm;

I. Introduction

Wind turbine interference (WTI) of radio links can be imposed by reflection/scattering, diffraction, and/or near-field effects at the terminals [1],[2]. The diffraction in the so called forward scattering region causes areas of shadowing (obstacle loss) but also areas of obstacle gain [3]. Most investigations have been focusing on the backscatter region which was particularly addressed by the radar community due to severe clutter problems as well as desensitation [4]. As the blades of the wind turbine (WT) are rotating (most of the time) all the above stated interference mechanisms are non-stationary. Mitigation of WTI requires a profound modelling of these effects. Traditional exclusion zone models for coexistence of WTs and communication links are based on Fresnel zone clearance [5].

In [6] the authors presented a 1D Fourier diffraction approach for the calculation of the dynamic diffraction loss and phase modulation caused by tower and rotor of a WT. It has been shown, that the rotating blades cause a periodic frequency deviation of the diffracted signal. In contrast to numerical 3D field solvers Fresnel approximation offers a fast method to investigate a large number of propagation scenarios. However, this model had certain shortcomings, i.e. it did not account for the impact of an illuminated ground plane and it was only applicable for some selected geometries, i.e. a link geometry where the line of sight (LOS) path cuts right through the rotor swept area. This scenario is of particular interest for weather radars but it is less likely a scenario in the case of point-to-point radio links. In [7] a much more accurate 2D Fresnel-Kirchhoff diffraction approach has been applied to WT forward scattering avoiding all of the aforementioned shortcomings.

In this paper the impact of forward scattering of the rotor of a WT on the received signal of a higher order digital modulation system is studied in detail. Using 2D Fresnel-Kirchhoff diffraction approach for a WT rotor the performance of the received signal of a 16-QAM system is analysed. Modulation Error Ratio (MER) as well as Bit Error Rate (BER) of raw data with and without rotor is calculated with particular impact of the illuminated ground plane. The time-variant channel is characterised by periodic amplitude and phase distortions caused by the rotating blades, as well as by additive white Gaussian noise (AWGN). Scattering and multipath effects caused by objects other than the rotor or ground plane itself are not considered.

II. Calculation of BER Considering Time-Variant Channel Model

Fig 1 displays the channel model used for the investigation of the impact of WT rotor forward scattering on the MER and BER of raw data of a fixed link 16-QAM system. The signal $x(t)$ is modulated (and up converted) and transmitted via an antenna terminal (Tx) towards the receiver terminal (Rx). This Radio Frequency (RF) signal will experience a periodic amplitude and phase distortion represented by the function $c(\phi)$ before (down conversion and before) adding white Gaussian noise and demodulation, where ϕ is the time-variant rotor angle of the turbine (Fig. 2). The demodulated signal $y(t)$ is compared with $x(t)$ for calculation of MER and raw data BER. It is assumed that the spectrum of the distortion lies above the crossover frequency of the amplitude and phase control loops of the receiver (for the time-frequency spectrum of the distortion see e.g. [8]) but – on the other hand – will also not be affected by filtering in the RF receiver chain.

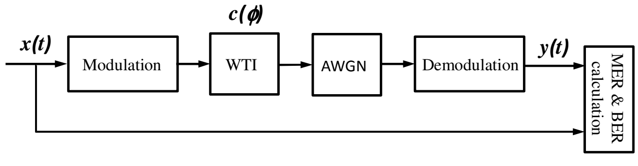

Fig. 1. Channel model used for BER calculation of 16-QAM system with wind turbine interference (WTI) und additive white Gaussian noise (AWGN).

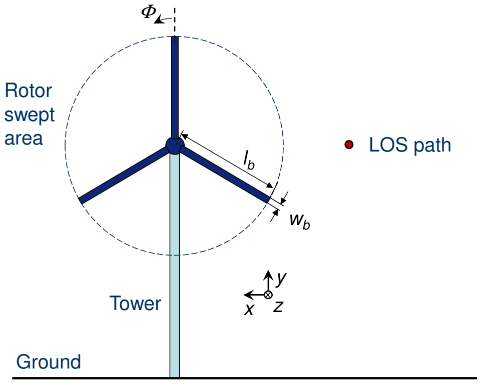

Fig. 2: Plane of obstruction: WT with 3-blade rotor in specular direction (head-on view from transmitter).

For narrowband RF signals the function $c(\phi)$ can be calculated for the carrier frequency ω_0 by Fourier-Kirchhoff diffraction approach or by time consuming numerical field simulation (i.e. UTD). With the knowledge of the function $c(\phi)$ at the carrier frequency ω_0 up- and down conversion of the signal has not to be considered any further. Fresnel-Kirchhoff diffraction formula [9] provides the resultant amplitude of the electric field E_P at a point P behind an aperture $A(x,y)$ from the superposition of all the Huygens' wavelets from the wavefront at the aperture

$$E_P = j\frac{E_S}{\lambda}\oiint A(x,y)\cdot F(\theta)\frac{e^{-jk(r_1+r_2)}}{r_1 r_2}\,\mathrm{d}x\,\mathrm{d}y \qquad (1)$$

where E_S corresponds to the amplitude of the transmit antenna, $F(\theta)$ is the obliquity factor which can be approximated by $F(\theta)\approx 1$ for the geometries considered, λ is the wavelength, k the wavenumber, r_1 (r_2) is the distance from the phase center of the transmit (receive) antenna to a point on the plane of obstruction.

This formula involves approximations (in particular $r_1, r_2 >> \lambda$) that limit the frequency range at the lower end and, thus, do not allow to calculate the (time-variant) impulse response of the channel. For the same reason a time-domain representation of the Fresnel-Kirchhoff diffraction formula cannot be derived (though technically it would be quite trivial for the integral in (1)). Besides the above mentioned limitations the curious phase shift factor $j=e^{j\pi/2}$ in front of the integral in (1) which compensates for the fact that the integral over all Fresnel zones provides a direct path longer than the line of sight (LOS) path is another difficulty. Therefore we stick to the frequency domain approach and assume a flat narrowband channel where $c(\omega)$ = const. Rotor angle dependent amplitude and phase distortion of $y(t)$ is calculated from the amplitude of the received field E_p comparing the case with and without rotor [7].

III. Simulation Results

In our first simulations the tower of the WT and the ground plane are omitted as we are in particular interested in the impact of the rotating blades. We are considering the following scenario: f = 1.30 GHz, rotor blade length l_b = 64 m, three

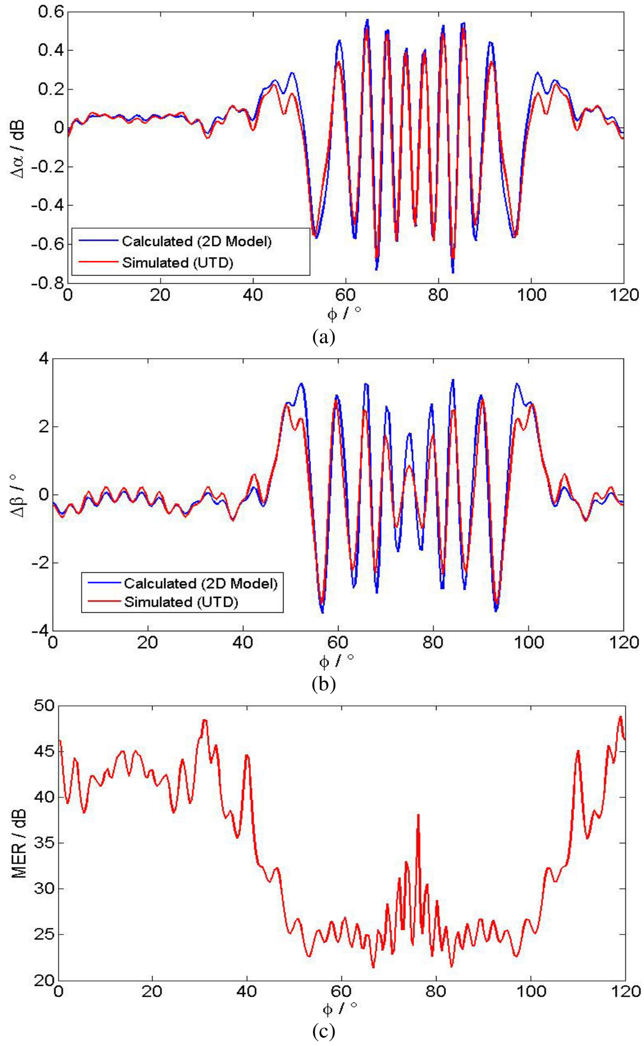

Fig. 3: Comparison of (a) diffraction loss Δα and (b) phase distortion Δβ vs rotor angle ϕ calculated by 3D numerical field simulations (UTD by FEKO) and 2D Fresnel-Kirchhoff approach. (c) corresponding instantaneous MER; f=1.30 GHz, d_1=d_2=4000m, l_b=64m, w_b=1.5m, signal axis 90m below and 90m to the right of rotor axis, no ground plane, SNR=∞.

rectangular blades of width w_b = 1.5 m. As a first step simulation results for the 2D Fresnel-Kirchhoff diffraction approach are compared to those obtained by 3D numerical field simulation (UTD by FEKO) for the example where the distance between Tx and WT (d_1) and between WT and Rx (d_2) is $d_1 = d_2$ = 4000 m. The LOS path is considered to be collinear 90 m below and 90 m to the right (from Tx point of view) of the rotor axis. This corresponds to a 7th Fresnel zone clearance of the link.

Figs. 3(a) and (b) display the calculated diffraction loss Δα and phase distortion Δβ vs rotor angle Φ. The 3-blade rotor causes a periodicity of the curves in Φ every 120°. The simulation results for the Fresnel-Kirchhoff diffraction formula and those for UTD method agree fairly well. Isotropic antenna pattern has been considered for simplicity. Maximum diffraction loss is in the order of 0.5 dB and maximum obstruction gain in the order of 0.7 dB. The phase distortion is in the range of -3.4° to +3.2 °. Though the LOS path lies

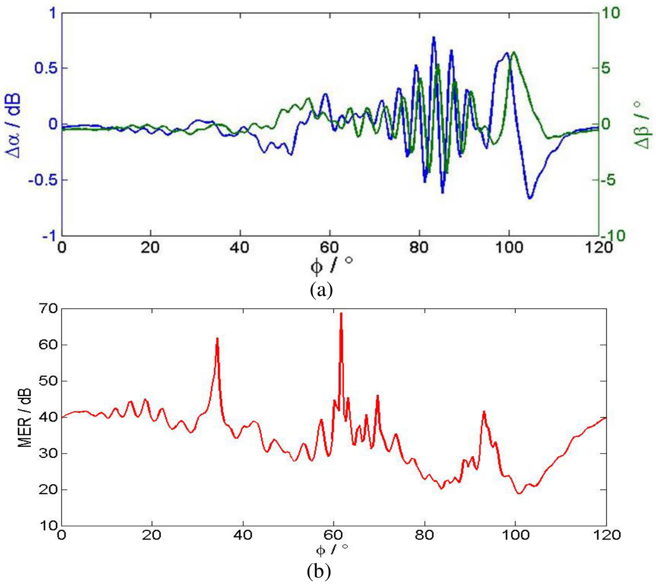

Fig. 4: Simulated (a) diffraction loss Δα and phase distortion Δβ vs rotor angle ϕ (b) corresponding instantaneous MER; f=1.30GHz, d_1=d_2=4000m, l_b=64m, w_b=1.5m, signal axis 90m below and 90m to the right of rotor axis, PEC ground (vert. pol.), SNR=∞, 'constructive' case (I).

outside the rotor swept area a typical diffraction pattern can be seen in Fig. 3(a). The maxima of the curve for Δα(Φ) are given for those rotor angles Φ where obstruction of the in-phase signal of the whole link reaches a relative maximum (blade orientation tangentially within an odd Fresnel zone which is interfering constructively with the overall signal of the link). The maxima of obstruction gain (minima of the curve Δα(Φ)) occur for blade orientations tangentially within an even Fresnel zone which is interfering destructively with the overall signal of the link [10].

Fig. 3(c) displays the corresponding instantaneous modulation error ratio (MER) for a Pseudo Random Bit Sequence (PRBS 2^{16}-1), Gray code mapping without considering any added noise. MER is a measure of the signal-to-noise ratio (SNR) in a digitally modulated signal. It is the ratio of the root mean square (RMS) power of the reference vectors to the power of the error vectors. As expected, the value of instantaneous MER decreases significantly for those rotor angles where amplitude and phase distortion are significant (Φ ≈ 50-100°). In that range of rotor angles MER value drops to about 25 dB. This level is still high enough to ensure that the link is error free (BER=0). The average value of MER is 33.4 dB.

Fig. 4(a) displays the calculated curves for Δα(Φ) and Δβ(Φ) for the case when a perfect ground plane (PEC) is inserted 100 m below the rotor axis (Tx and Rx height 10 m, vertical polarization). This case results in a constructive interference of LOS path and ground reflected path for the case without WT. In the following, the constructive interference scenario will be called case (I). Reflection of the radio wave can appear between Tx and WT and between WT and Rx. This is accounted for by the concept of a mirror Tx and a mirror Rx [7]. All other parameters are kept same as used for Fig. 3. In the case of constructive interference maximum diffraction loss and maximum obstruction gain are typically only slightly higher as compared to the case without ground plane. However, due to the additional ground reflected paths and the absence of the field for y<0 the curves for Δα(Φ) and Δβ(Φ) look quite different.

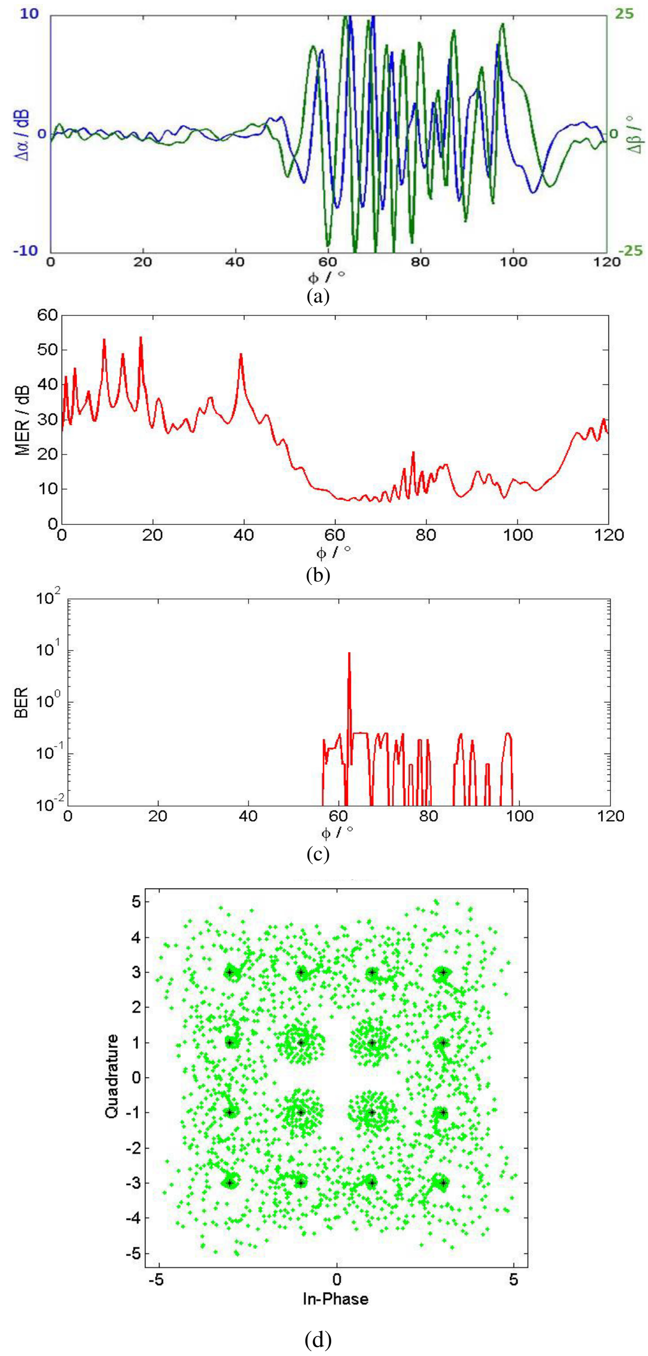

Fig. 5: Simulated (a) diffraction loss Δα and phase distortion Δβ vs rotor angle ϕ, corresponding instantaneous (b) MER, (c) BER, and (d) constellation diagram for a whole rotation; f=1.30 GHz (vert. pol.), d_1=d_2=4000m, l_b=64m, w_b=1.5m, signal axis 80m below and 90m to the right of rotor axis, PEC ground, SNR=∞, 'destructive' case (II).

Fig. 4(b) displays the corresponding value of instantaneous MER vs Φ. Minimum value of Instantaneous MER is slightly lower than in the case without ground plane which is expected from the slightly higher values for the maxima of Δα(Φ) and Δβ(Φ). The average value of MER is 30.9 dB and, thus, slightly lower than in the case without ground plane. The link remains error free (BER=0 for all values of Φ).

Fig. 5(a) displays the calculated curves for Δα(Φ) and Δβ(Φ) for the case with PEC ground when the heights of Tx and Rx are raised to 20 m (vertical polarization). This case results in an almost destructive interference of LOS path and ground reflected path for the case without WT. In the following, the destructive interference scenario will be called case (II). All other parameters are kept same as used for Figs. 3 and 4. Maximum diffraction loss (5.1 dB) and maximum obstruction gain (3.2 dB) are significantly higher as compared to those of case (I) or the case without ground plane.

Corresponding minimum value of instantaneous MER (Fig. 5(b)) is significantly lower than that in case (I) or in case without ground plane which is expected from the higher values for the maxima of Δα(Φ) and Δβ(Φ). The average value of MER drops to 21.2 dB and the link is no longer error free (Fig. 5(c)). Burst errors occur for those rotor angles where MER value is dropping significantly below about 21 dB which is the limit for $BER=10^{-6}$ for 16-QAM modulation. The corresponding constellation diagram (scatter plot) is shown in Fig. 5(d). Amplitude and phase distortion caused by the rotor can be clearly seen. As a next step Gaussian noise is added to the channel considering case (I) and case (II). A plot of the maximum as well as average value of Bit Error Rate (BER_{max} and BER_{avg}) calculated for the rotation angle interval Φ = 0-120° is shown in Fig. 6. Though the scenario of a 7th Fresnel zone clearance is considered a link setup with strong destructive interfering ground reflected path is very sensitive to amplitude and phase distortions caused by the rotor. Unacceptable low MER and significant high raw data BER values arise in this case.

IV. Summary and Conclusion

For the first time the impact of forward scattering of the rotating blades of a WT on a fixed radio link with higher order modulation scheme is analyzed throughout end-to-end. Instantaneous MER as well as instantaneous and average raw data BER are computed considering amplitude and phase distortion calculated by Fresnel-Kirchhoff diffraction formula. Regarding the WTI it is assumed that, firstly in base band the spectrum of the interference signal lies above the crossover frequency of the amplitude and phase control loops of the receiver and, secondly, in the RF domain the interference will not be affected by filtering in the RF receiver chain. The scenario considered is a link obstructed by a 3-blade rotor with a clearance as high as the first seven Fresnel zones. For the case of constructive interference of LOS path and ground reflected path (neglecting diffraction) amplitude and phase distortion are in general only slightly higher than in the case without PEC ground. Consequently MER values are only slightly lower. The link remains error free. However, for the undesirable case of (almost) destructive interference of LOS

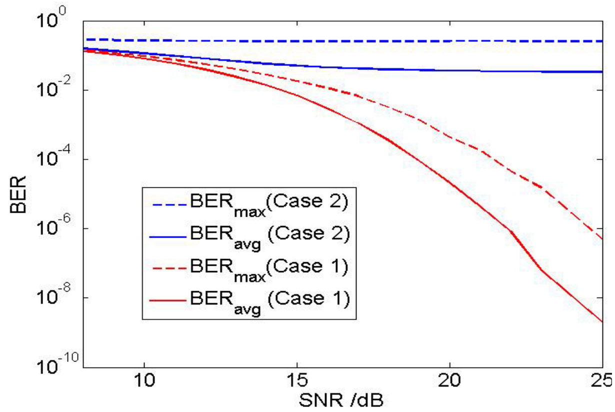

Fig. 6: Simulated average and maximum BER vs SNR of added AGWN for case (I) and (II).

path and ground reflected path (neglecting diffraction) amplitude and phase distortion are in average significantly higher than in the previous case as well as in the case without PEC ground. The example considering a 7 Fresnel clearance results in high amplitude (5.1 dB) and phase (26.5°) distortion and, thus, in burst errors for a wide range of rotor angles. Unacceptable low instantaneous MER values (as low as 6.3 dB) and high BER values as high as $2.78*10^{-1}$ occur in this case. This impact can only be mitigated by using pilot symbol assisted modulation.

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