Wind farms influence on radiocommunication systems operating in the VHF and UHF bands[*]

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The following paper discusses several aspects connected with the wind farms' impact on radiocommunication systems. The first part of this article is filled with the analysis of the ITU-R BT.1893 model, originally created for the analysis of the interaction between the wind turbines and digital TV receivers in the UHF band. A measurement campaign carried out by the authors confirmed that this model is also applicable for the lower, maritime VHF band. Utilizing the software implementation of this model, the authors conducted a thorough simulation analysis of the wind turbines' influence on radio systems working in both VHF and UHF bands. The results of these simulations are presented and discussed in the second part of the paper.

propagation, turbines, wind energy, wind farms

Introduction

In recent years, a significant growth of interest in renewable energy sources – including wind energy – has become a global trend. The recent statistics indicate that the number of operating power plants (usually referred to as wind farms) is growing constantly, as is the total power offered by these installations. At the end of 2013, the total (global) wind power capacity was 318 GW, and Europe accounted for 38% of that value [1].

The demand for the installation and exploitation of new wind turbines brings about the need to analyze and assess how these objects actually interact and affect their environment. In this context, it might be interesting to discuss the influence of the wind farm on radiocommunication systems. The potential interaction between them is mainly caused by the material the turbines are made of (composite/metal) and by the large dimensions of such constructions. Both the height of masts as well as rotor's ranges might be greater than 100 m. As a result, a wind turbine constitutes a substantial obstacle that could not only attenuate the radio signal but also reflect it. Out of these two phenomena, the latter seems to be of particular importance, but for many reasons it is also rather difficult to analyze. It might be surprising but the knowledge about the interactions between the wind turbines and radiocommunication systems is rather limited, as is the number of the subject literature (see e.g. [2]-[5]). Furthermore, very few mathematical models facilitate a formal description of the discussed issues. One of those is contained in the ITU-R Recommendation BT.1893 [6], but it generally concerns only the negative effects that can be caused by the farms to the digital TV systems operating in the UHF band.①

In 2013, the National Institute of Telecommunications (NIT) carried out an extensive study dedicated to the analysis of the wind farm influence on selected radio systems, with a particular attention paid to the systems operating in the maritime VHF band (156-162 MHz). This article presents and discusses several aspects of that research.

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[*] *Artykuł jest skrótem artykułu opublikowanego w kwartalniku JTIT nr 2/2015.*

① *The ITU-R has also issued a recommendation [6] dealing with wind farms' influence on analogue TV.*

The ITU-R BT.1893 Model

The ITU-R BT.1893 recommendation was originally created to provide evaluation methods of the impairments caused to digital television reception (UHF band) by wind turbines. The model contained in the recommendation facilitates a mathematical description of the primary propagation mechanism occurring at the wind turbines' sites, i.e. the radio signal reflection from the wind turbine blades. In the following paragraph, the major assumptions of this model will be presented and discussed.

Let us now assume the arrangement of the transmitter, receiver, and wind turbine as depicted in Fig. 1.

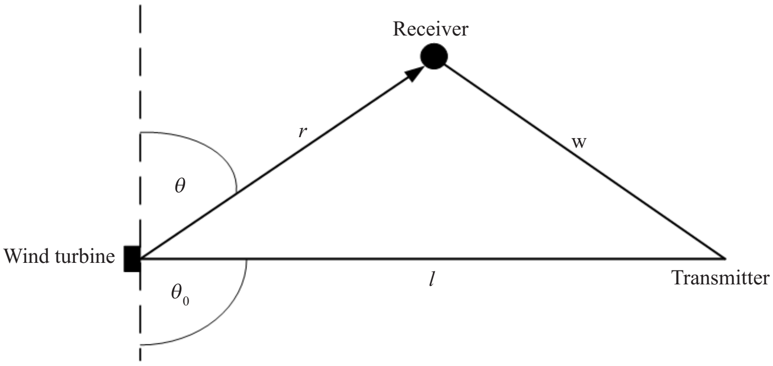

Fig. 1. *The arrangement of transmitter, receiver, and the wind turbine*

Under the assumption that the distance between the receiver and the wind turbine is r, the scattering coefficient ρ, which includes the free-space loss for the path between the turbine and the receiver can be expressed as follows:

$$\rho = \frac{A}{\lambda r} g(\theta) \quad , \tag{1}$$

where

$$g(\theta) = \mathrm{sinc}^2\left[\frac{S}{\lambda}(\cos\theta - \cos\theta_0)\right]\sin\theta \quad , \tag{2}$$

and

$$\mathrm{sinc}(x) \ = \frac{\sin(\pi \cdot x)}{\pi \cdot x}$$

A – total area of the turbine blades [m^2],
S – mean width of the blade [m],
λ – radio signal wavelength [m],
r – the distance between the wind turbine and the receiver [m],
θ – the angle between the receive direction and the plane of the rotor, i.e. the angle of the signal reflected (scattered) from the blades [°],
θ_0 – the angle between the transmit direction and the plane of the rotor, i.e. the angle of the incident signal at the blades [°].

The $g(\theta)$ function has values in the range of $-1\ldots1$.

It might be stated the coefficient ρ in Eq. (1) is an indicator of the amount of the incident signal that will be reflected from the blades towards the receiver. It should be underlined the above formula was defined under the assumption the wind turbine blades are approximately triangular and metallic. However, nowadays, a blade is typically made of fiberglass or another composite material, which results in the ρ coefficient being 6 to 10 dB lower than in the case of metallic blades. Consequently, if the analysis is conducted for the composite material blades, the scattering coefficient resulting from Eq. (1) should always be adjusted (decreased) accordingly.

The value of the ρ coefficient is maximum when the transmitter, receiver, and wind turbine are all in the same line, and when additionally this line is perpendicular (normal) to the rotor's plane. In such a case:

$$\rho = \rho_{max} = \frac{A}{\lambda \cdot r} \tag{3}$$

Let us now define the Field Strength at the Wind Turbine (FSWT) parameter as the strength of the signal directly at the wind turbine location:

$$FSWT = EIRP - L_l, \tag{4}$$

where EIRP – equivalent isotropical radiated power of the transmitter [dBm], L_l – propagation loss (attenuation) on the path between the transmitter and wind turbine (length l) [dB] .

If the length of the path between the receiver and wind turbine is r, then the unwanted signal power, i.e. the power of the signal that propagates from the transmitter to the receiver due to reflection from the turbine blades, can be calculated as:

$$UFSR = FSWT + 20 \log \rho \tag{5}$$

The Unwanted Field StRength (UFSR) is a key parameter, which allows analyzing the wind farm as the source of a secondary radiation.

Model Verification Measurement

The Measurement's Methodology

As it was mentioned before, the ITU-R BT.1893 model was originally intended for the analysis of the wind farms' impact on the UHF digital television systems. For the purpose of the works conducted by the NIT it was necessary to assess whether this model can also be applied to the systems operating in the maritime VHF Band. To do so, an extensive measurement campaign was organized in late 2013, which covered four selected wind farms located in the northern and central Poland.

The general methodology of the measurements was as follows: at the transmitter side, a 161 MHz① impulse was generated and repeated every 80 μs. This impulse, whose width was 8 μs, was then transmitted in the wind turbines direction. At the receiver side, the levels of two signals were measured:

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① *161 MHz is a frequency that belongs to the maritime VHF band. This particular value was selected and used during the measurements in order to avoid spurious emissions of the spectrum analyzer, which would be inevitable at 160 MHz. On the other hand, during the simulations, the value of 160 MHz was utilized.*

(a) the level of the direct signal, referred to as the Wanted Field StRength (FSR) in the ITU-R BT.1893 recommendation and (b) the level of the signal reflected from the turbine (UFSR). The results obtained this way – particularly the UFSR – were then compared with the theoretical data resulting from the model.

The concept of these measurements can be presented as in Fig. 2.

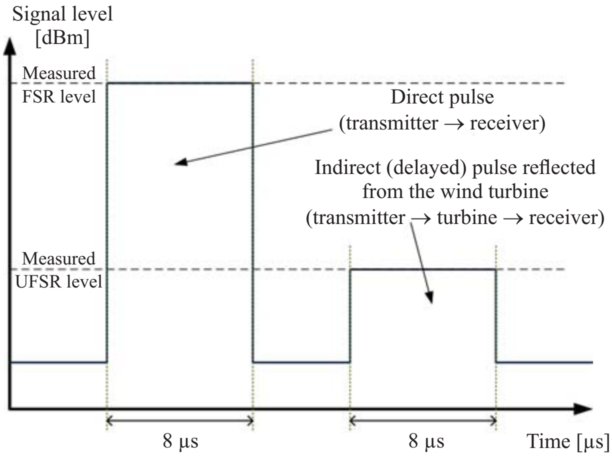

Fig. 2. *The concept of the measurements using the spectrum analyzer Zero Span function*

The Measurement Results

Before the campaign, a thorough mathematical analysis was conducted which considered the measurement equipment limitations as well as some dependencies which are true for the typical configurations of wind farms. The analysis of these factors resulted in a set of assumptions, conditions, and initial requirements for the campaign, such as the acceptable distances between the elements of the measurement equipment and the wind turbines. Obviously, each and every scenario that was actually carried out during the campaign satisfied those initial conditions. During the measurements, both transmit and receive directions were approximately normal to the rotors' planes, which was a highly desirable situation from the measurement's purposes point of view (it ensured a maximum reflection from the blades). Before a scenario was selected, it had also been verified that it exhibited a favorable terrain profile, i.e. the receiver was elevated, and the rotors were directly visible from both the transmitter's and receiver's locations.

In Table 1, the results obtained for all measurement scenarios have been presented. All those measurements were conducted for 161 MHz and included each of the four analyzed wind farms. In the table, the measurement data was compared with the theoretical (simulated) values resulting from the ITU-R BT.1893 model. It should be added, during the simulations, the propagation attenuations for the transmitter ↔ receiver and the transmitter ↔ turbine paths were calculated using the free-space loss model, whereas the Okumura-Hata model for open area was utilized in case of the turbine ↔ receiver path①. The measurement scenarios were selected in such a way, that conditions on the transmitter ↔ receiver and the transmitter ↔ turbine paths were as close to free space as possible (e.g. the transmitter placed on a hill, lack of obstacles between the transmitter and receiver, line of sight between the receiver / transmitter/ and the turbines and so on).

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① *Okumura-Hata model assumes the transmitter (base station) height in the range of 30-200 m and the receiver height in the range of 1-10 m. These assumptions were only satisfied for the turbine ↔ receiver path.*

Table 1. Measured vs. theoretical results obtained for the wind farms under consideration, at the frequency of 161 MHz

Farm (F) / Scenario (S)	Maximum measured UFSR level [dBm]	Theoretical UFSR value from the simulations [dBm]	Difference [dB]
F1 / S1	-80.7	-68.7	-12.0
F2 / S1	-82.5	-76.9	-5.6
F3 / S1	-86.1	-70.6	-15.5
F3 / S2	-82.2	-73.9	-8.3
F3 / S3	-79.5	-67.3	-12.2
F4 / S1	-86.3	-67.3	-19.0
F4 / S2*	-90.6	-126.2	35.6
F4 / S3	-88.2	-67.1	-21.1
Mean difference (error):			-13.4

*) The reference scenario – does not count towards the mean error value. In this case it was assumed that the angle between the rotors' planes and the transmit/receive direction was equal to 180°– i.e. unlike the other scenarios, it was not the case of the strongest reflection.
F1 – Gnieżdżewo wind farm (Pomerania Province)
F2 – Lisewo wind farm (Pomerania Province)
F3 – Kisielice wind farm (Warmia-Masuria Province)
F4 – Margonin wind farm (Wielkopolska Province)

As it can be observed in Table 1, the measured values of the received signal level (UFSR) at 161 MHz were less by 13.4 dB (on average) than the theoretical ones, calculated using the ITU-R BT.1893 model. The reasons of that discrepancy might be caused by a combination of the following factors:

- the model does not include actual obstacles in the signal propagation path,
- the planes of rotors during the measurements might not have been precisely normal (perpendicular) to the transmit and receive directions, so the observed reflection might not have been maximized,
- the material the rotors are made of actually reflects the signal weaker than some sources indicate,
- the parameters of the turbines employed in the calculations are not fully accurate,
- The ITU-R BT.1893 model is clearly pessimistic in case of the VHF band.

Additionally, it can also be seen in the table, that for the case of the maximum reflection, the theoretical values of UFSR were always greater than those obtained in the measurements. Consequently, the analyzed model can definitely be described as pessimistic, and very suitable for the worst-case scenario analysis, because in real conditions the reflected signal levels (UFSR) will most likely be lower than the values resulting from the model.

At this point, it should be recalled that propagation models (such as the one discussed in this paper) generally allow calculating the attenuation median (i.e. the received signal levels that are not exceeded in 50% of cases). Additionally, for wireless mobile system it is required to keep the so-called large-scale fading margin, which is about -13 dB (if we want to calculate the signal level exceeded in 99% of the cases) and +13 dB (if we want to calculate the signal level not exceeded in 99% of the cases)①. As we can see, this value is close to the average error indicated in Table 1. Consequently, it can be assumed that the ITU-R BT.1893 model simply takes into account the margin for the fluctuations of the propagation attenuation.

Given the observations above, it might be stated that despite some discrepancies between the simulated and measured values, the ITU-R BT.1893 model is sufficient for the analysis of the wind farms' influence on radio systems operating in the VHF band – especially for the worst case analysis.

The Simulation Analysis

Since it was verified that the ITU-R BT.1893 can be applied for both VHF and UHF bands②, the NIT created a software implementation of this model in order to perform a simulation analysis of the wind farms' impact on these two frequency bands. In the following paragraph, the authors shall present the simulations assumptions and the obtained results.

Simulation's Assumptions and Methodology

The simulations were conducted for two frequencies representing each of the analyzed bands:
160 MHz (VHF) and 400 MHz (UHF).

For the purpose of the simulation analysis, the location of three fictitious base stations (transmitters) in the vicinity of the wind farm in Margonin has been assumed. This arrangement is presented in Fig. 3 (base stations are marked in circles as BTS1, BTS2 and BTS3, respectively), and additionally in Tables 2 and 3, the parameters used during the simulations have been gathered [8]-[10].

In order to evaluate the level of negative interactions between the wind farms and the radiocommunication systems, two cases should be considered:

- the radio shadowing analysis – where a wind farm is considered to be a terrain obstacle in the radiowave propagation path.
- the interference analysis – where a farm is considered to be a source of interference in the form of the reflected (secondary) radiowaves. In this approach, a turbine should be analyzed as a hypothetical, equivalent "radio transmitter", which is operating with an equivalent EIRP power and is equipped with an equivalent antenna.

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① *Values derived on the basis of the ITU-R P.1546-5 recommendation for mobile wireless communications [12].*

② *Besides the 161 MHz band, the measurements conducted by the NIT covered the bands of 50 MHz and 400 MHz as well.*

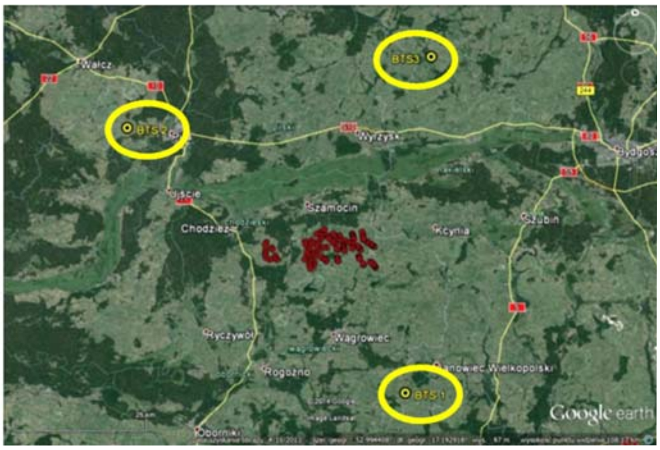

Fig. 3. *The location of the base stations around the Margonin wind farm*

Table 2. The parameters used during simulations

Transmit antenna height [m above terrain level]	50	
Receive antenna height [m above terrain level]	2	
Transmit signal frequency [MHz]	160	400
EIRP power of the transmit signal [dBm]	46	54
Receiver sensitivity [dBm]	-105	
SNR required level [dB]	10	
Propagation model	Okumura-Hata	
Environment type	Suburban	
Fading margin [dB]	0	

Table 3. Parameters of the turbines utilized at the analyzed wind farm

Number of turbines	105
Turbine's tower height [m]	100
Length of the blades [m]	45
Blades width at the hub [m]	3
Mean width of a blade [m]	1.5
Area of a single blade [m^2]	67.9
Number of the blades	3
Total area of the blades [m^2]	203.6
Material (blades)	Carbon skeleton covered with reinforced fiber glass
Turbines' layout (arrangement)	Non-uniform
Distance between the turbines [m]	418 - 1416
Note: Due to the non-metallic blades, the value of the scattering coefficient ρ used in the simulation was 6 dB less than the value resulting from Eq. (1).	

Due to the assumed arrangement of the base stations, the services ranges of all three stations overlap in the vicinity of the wind farm, and consequently it was not necessary to carry out the radio shadowing analysis in this paper.

In case of the interference analysis, it was first necessary to calculate – on the basis of the turbines' parameters – the characteristic of the UFSR as a function of the angle between the receive direction and rotor's plane (see Fig. 4). The resulting far field characteristics for both the frequency of 160 MHz (Fig. 4a) and the frequency of 400 MHz (Fig. 4b) have been obtained for the worst case scenario where the rotor's plane is perpendicular to the transmit direction, which corresponds to the maximum signal reflection from the turbine's blades.

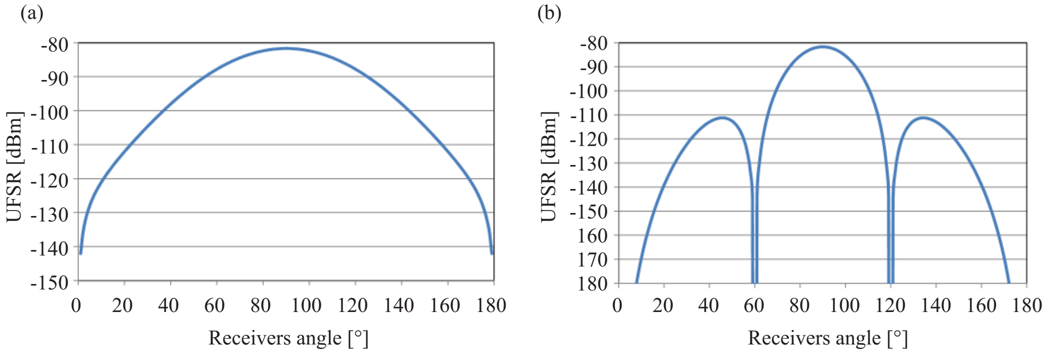

Fig. 4. *The UFSR vs. the angle between the receive direction and the wind turbine rotor plane for the frequency of: (a) 160 MHz, (b) 400 MHz*

On the basis of the information contained in Fig. 4, the parameters of the equivalent directional antenna for the frequencies of 160 MHz and 400 MHz have been defined and presented in Table 4.

Table 4. The parameters of the equivalent directional antennas

Frequency [MHz]	160	400
Antenna gain [dBi]	0	0
3 dB horizontal beamwidth [^{o}]	43	19
10 dB horizontal beamwidth [^{o}]	79	33

In the next step, the equivalent EIRP power values were calculated using the parameters of the base stations and the wind turbines indicated previously. The calculations were conducted under the assumption of the worst-case scenario analysis, i.e. for the case of the maximum reflection from the rotors. Additionally, taking the characteristics of the equivalent antennas into account, a configuration of the so-called dispersed interference source has been obtained. This dispersed source is comprised of multiple hypothetical "radio transmitters" (i.e. wind turbines), which radiate the signal towards each of the analyzed base stations. These stations are obviously a source of the wanted signal, but indirectly they also generate secondary interferences, which are caused by the reflections of the radio signal from the turbines' rotors. In Fig. 5, the notion of the equivalent sources of the secondary interfering signals has been explained. The arrows designate the azimuths of the main lobes of the equivalent directional antennas. During the simulations, it was assumed that the strongest interference only occurs for the rotors' azimuths that align with the direction between the base station and the wind farm. The above assumption means that in real conditions the actual interference level in most cases will be lower than the values resulting from the simulations. Furthermore, secondary interference levels higher than the simulated ones should never occur.

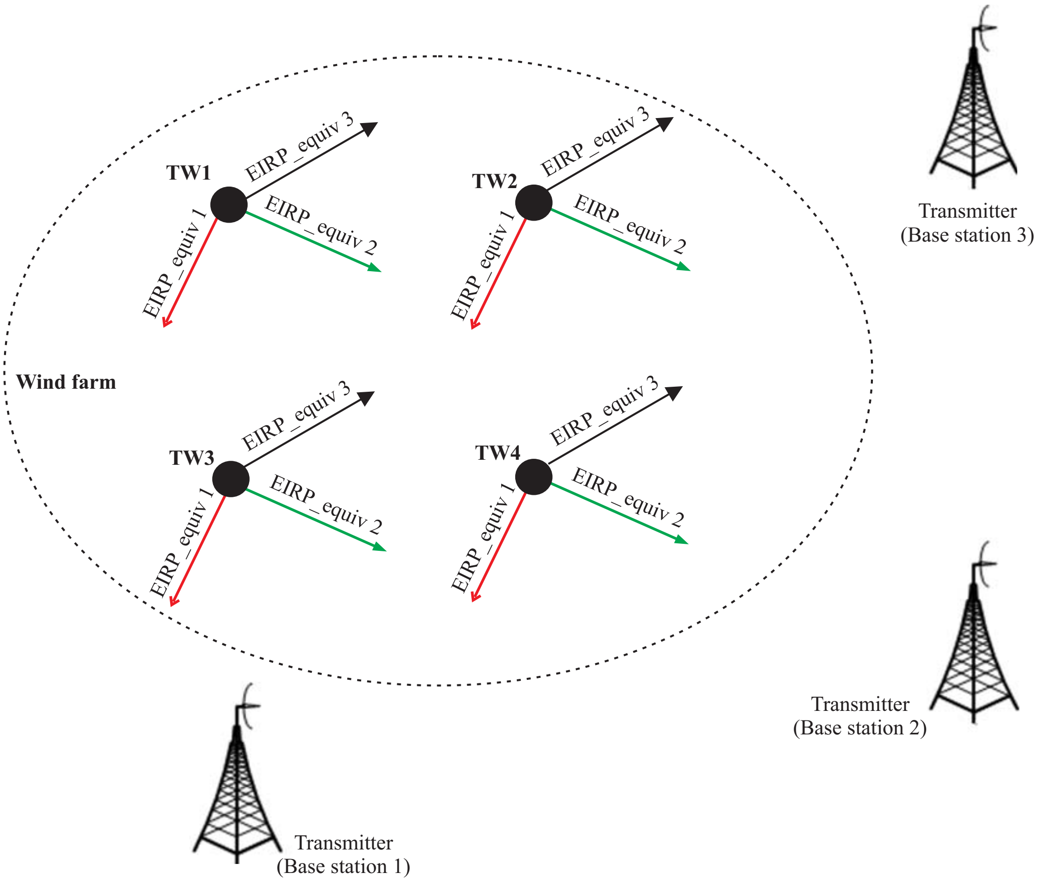

Fig. 5. *The concept of the equivalent EIRP power and the arrangement of the secondary interference sources for specific directions*

In Table 5, the equivalent EIRP power values, calculated for the analyzed base stations, have been gathered. It should be added that the EIRP power values of the base stations' transmitters assumed in these simulations have been adjusted in such a way that the signal strengths directly at the wind turbine location were equal for both analyzed frequencies. Such an approach was necessary to compare the wind farm's influence on the systems operating at 160 MHz and 400 MHz with good reliability.

Table 5. The equivalent EIRP power values calculated for the analyzed base stations

	BTS 1	BTS2	BTS 3
Distance to the middle of the wind farm [km]	32	44	41
Azimuth relative to the middle of the wind farm [°]	152	301	29
Equivalent EIRP power for 160 MHz [dBm]	-13	-15.8	-15.4
Equivalent EIRP power for 400 MHz [dBm]	3.2	0.4	0.9

Simulation Results

The simulation results for both analyzed frequencies are presented in Figs. 6-7. In Fig. 6, the levels of the received signal including the interference from the wind farm are shown, whereas the signal to interference ratio (SIR) is illustrated in Fig. 7.

The parameters of the simulations are the same as those presented in Table 2.

In the received power level simulations (Fig. 6), red color (pointed by R arrow) indicates the area where the interference criterion is not satisfied, i.e. the actual signal to interference ratio (SIR) is less than the required minimum value (which is 10 dB in this case). In the worst case, in those areas, there could be no coverage due to severe interferences and consequently, no radiocommunication could be maintained. The discussed places are marked in the SIR visualizations as well (Fig. 7).

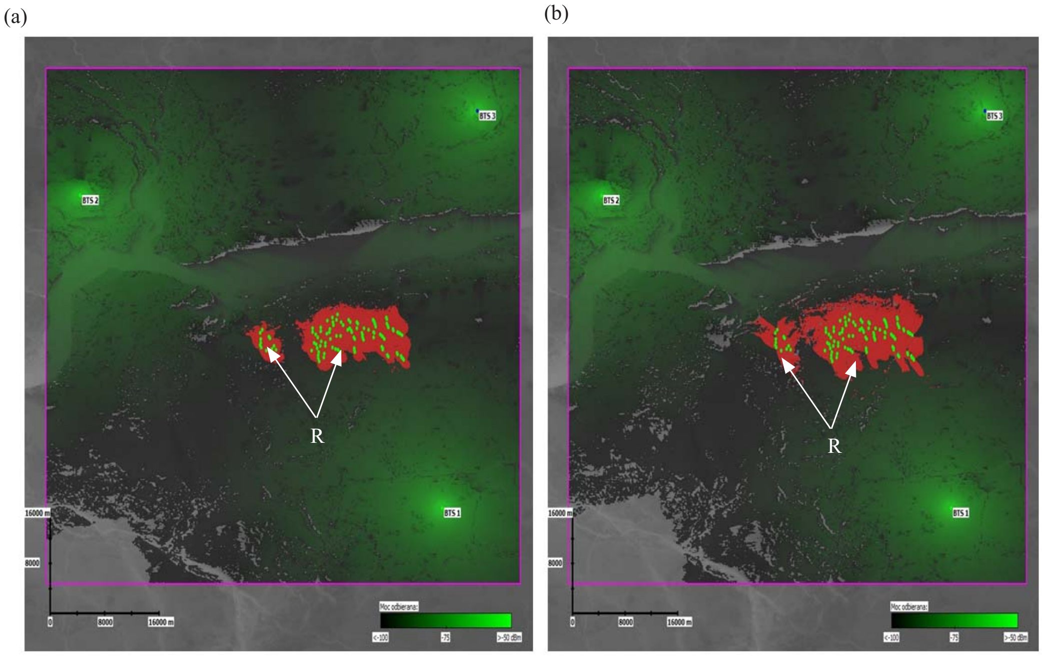

Fig. 6. *Received power level simulation for the frequency of: (a) 160 MHz, (b) 400 MHz*

The next observation regards the character of the interferences. In Fig. 4, the UFSR parameter has been drawn as a function of the reception angle for both analyzed frequencies. At 400 MHz, the resulting curve can be described as a “periodic” one, with a distinct set of “side lobes”, whereas the analogous characteristic for the 160 MHz is much more uniform and comprises only the “main lobe”. The above observation applies for the results presented in Figs. 6-7 as well. At 400 MHz, the area marked with grey color (which represents low values of SIR) is larger than at 160 MHz, but at the same time it is significantly shaped and its borders are much more distinct. The periodicity mentioned above is clearly visible in the figures: the areas of strong interference (dark grey color, DG arrow) are adjacent to the areas where the SIR is high (blue color, B arrow), while at 160 MHz the transitions between high and low SIR values are generally much more smoother.

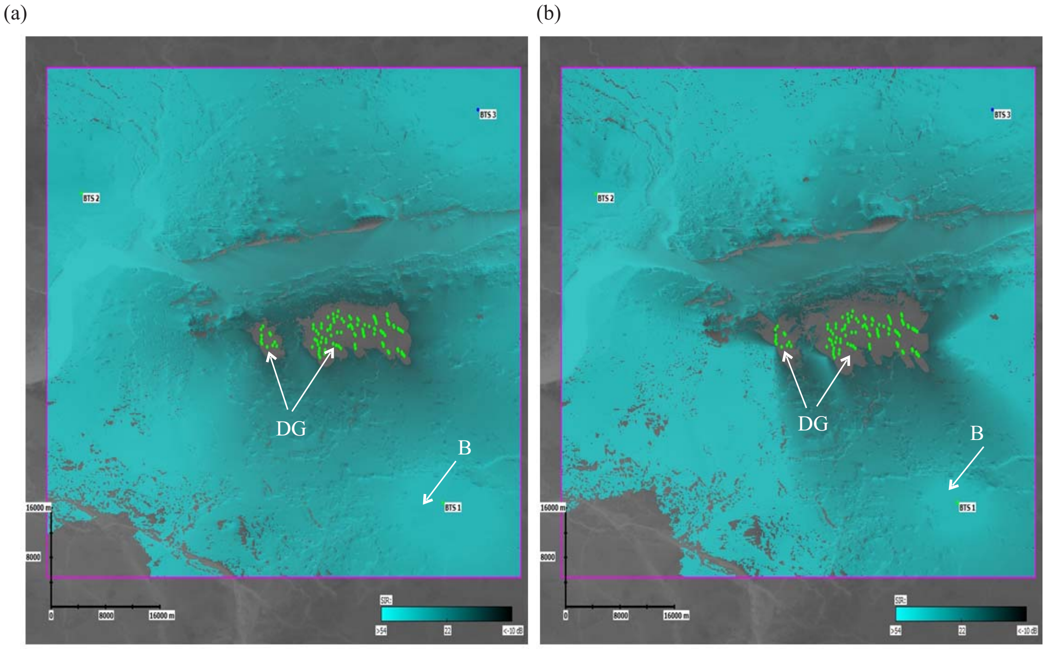

Fig. 7. *Signal to interference ratio (SIR) simulation for the frequency of: (a) 160 MHz, (b) 400 MHz*

It should also be underlined, the SIR value is affected not only by the frequency value or the turbines' and transmitters' parameters but also by the propagation phenomena which in turn depend on particular terrain features. By the definition, the SIR is a ratio of the wanted signal (the one that gets directly from the transmitter to the receiver) and the interference (in this case the signal that gets from the transmitter to the receiver through reflection from the turbine). The terrain features can potentially affect these both components, thus determining the resulting SIR value.

Conclusions

This article dealt with a topic of wind turbines' impact on a particular set of radio systems that operate in VHF and UHF bands (around 160 and 400 MHz, respectively). Given the constant – and global – growth of interest in renewable energy sources, such as wind, the importance of that issue will probably become more and more significant in the near future.

In the article, the authors confirmed – through on-site measurements – that, under some assumptions, the ITU-R BT.1893 model could be applied to both UHF and VHF bands. After that – utilizing this model – they carried out a simulation analysis of the interactions between wind turbines and systems working in those bands. As it turned out, at the UHF frequencies, the areas subjected to interferences caused by the signal reflecting from the wind turbines are larger than in the VHF band. Additionally, in the UHF, the reflected signal is much more periodic than in the VHF, so the areas of very strong interference are adjacent to the areas where the interference is very low. Consequently, in the higher of the analyzed bands, it is more difficult to predict, which areas will be adversely affected by the wind turbines.

On the other hand, it has to be stated that the level of interaction between the wind farms and radio systems strongly depends on specific conditions: the parameters of the turbines, terrain profile, etc.

As a result it would be hard (if not impossible) to formulate a universal and general set of rules describing the influence of the wind farm on radio communications. What is important is the development of methodology and tools facilitating the analysis of this issue – and this article was a small attempt to do that.

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Krzysztof Bronk, uzyskał stopień naukowy doktora nauk technicznych w dziedzinie telekomunikacji w 2010 roku. Obecnie jest adiunktem w Instytucie Łączności Państwowym Instytucie Badawczym. Jest autorem lub współautorem ponad 30 recenzowanych publikacji naukowych oraz około 20 prac i raportów technicznych. Jego zainteresowania naukowe związane są głównie z radiokomunikacją, a w szczególności z: planowaniem i projektowaniem systemów bezprzewodowych, radiem definiowanym programowo oraz radiem kognitywnym, technologią wieloantenową MIMO, kryptografią, zagadnieniami propagacyjnymi, technikami kodowania i transmisji jak i zagadnieniami związanymi z lokalizacją terminali oraz e-nawigacją. Do jego zainteresowań należą również: zorientowane obiektowo aplikacje wielowątkowe, algorytmy DSP oraz rozwiązania sterowania dla potrzeb pomiarów jakości w sieciach. Jest on ponadto obecnie zaangażowany w realizację kilku projektów naukowo-badawczych z partnerami zarówno akademickimi jak i przemysłowymi.

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