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# Wind Turbine Blade Deflection Sensing Using Blade-Mounted Ultrawideband Antennas

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***Abstract*—Wind turbine blade deflection sensing system using ultrawideband radio links propagating along the blade is presented. Special focus is given to the challenges related to the multipath propagation along the blade. Results of electromagnetic modeling of the wireless link budget for deflected blades are presented. Some aspects of the sensing system that are different from a typical wireless communication link are discussed.**

***Index Terms*—Ultrawideband antennas, Ultrawideband radiation, Microwave propagation, Dielectric bodies.**

## I. Introduction

The amount of energy obtainable from a single wind turbine is proportional to the diameter of its rotor. Therefore, new generations of wind turbines are equipped with even longer blades, currently exceeding the length of 100 m [1]. This allows for better economy as the cost of electricity from a single turbine decreases [2], but also brings more challenges related to the blade construction. Blades are built from light composite materials to avoid excessive loads on the tower and nacelle, which leads also to increased bending in strong winds and eventually to shutdown of the entire turbine to avoid collision of the blades with the tower. However, if the actual degree of bending of the blade is known, then the turbine can prevent the tower collision by pitching each of the blades out of the wind. This way, the turbine can be operated in stronger winds without shutdown and more energy can be harvested.

In our previous papers, we have presented a wind turbine blade deflection sensing system based on ultrawideband (UWB) technology [3]. In its most recent iteration, the system consists of two antennas at the blade root, and two antennas positioned near the blade tip. Bending of the blade is accompanied by shortening the distance between the tip and root antennas, which is detected by time of arrival of UWB pulse launched from the tip antenna. We have described the sensing system and its components and demonstrated its function and results [3]. One of the most challenging parts of the research was electromagnetic modeling of the propagation along the blade because the wireless link interacts with the dielectric material of the blade and multipath phenomena occur [4].

In this contribution to the special session *Recent Research on Wind Turbines: EM Modelling and Measurements* we will describe the wind turbine blade deflection sensing system and its challenges with emphasis on the ultrawideband antennas and their interaction with the blade. We point out that electromagnetic modeling of the antennas and the entire wireless link follows different priorities owing to the presence of the blade close to the antennas and along the entire propagation path. The aim of this contribution is thus to provide different view on modeling wind turbines from what is prevalent in terrestrial communication and radar.

## II. System Description

The system is composed of one or two transmitting (TX) antennas positioned near the tip of the blade and two receiving (RX) antennas near the blade root (see Fig. 1). As the blade bends, the distance between the TX and RX antennas changes, which is determined by finding the time of arrival of an UWB pulse launched from the TX antenna. The frequency range of the UWB pulse is 3.1–5.3 GHz.

The root RX antennas are positioned 40 cm above the surface of the root. This value was found as maximum with respect to limited space between the blade and the tower. One RX antenna is placed on the downwind side of the blade and one on the upwind side—this is to ensure that at least one RX antenna will have sufficient signal even when the blade is bending in both downwind and upwind direction.

The TX antennas near the blade tip are hidden inside the blade. This decision was necessary to prevent aerodynamic noise and decreased efficiency which would result from any protrusion on the blade surface. Also, antenna integrated inside the blade can be more easily protected from lightning strikes. Basic version of the sensing system works with a single TX antenna near the tip, however for better accuracy of determination of second order modes of blade a second antenna may be placed closer to the node point of the second order deflection of the blade. The tip TX antennas are fed by a transmission line attached to the inner webs of the blade and supplemented with lightning protection devices.

The time of arrival is determined by an improved correlator [5] and locks only on the leading edge of the received pulse. Therefore, late time multipath components are ignored, nevertheless early multipath components can still negatively affect the correlator.

## III. Antennas

Three types of antennas were considered for the sensing system. The first experiments were conducted with antenna consisting of a simple monopole on a ground plane and a

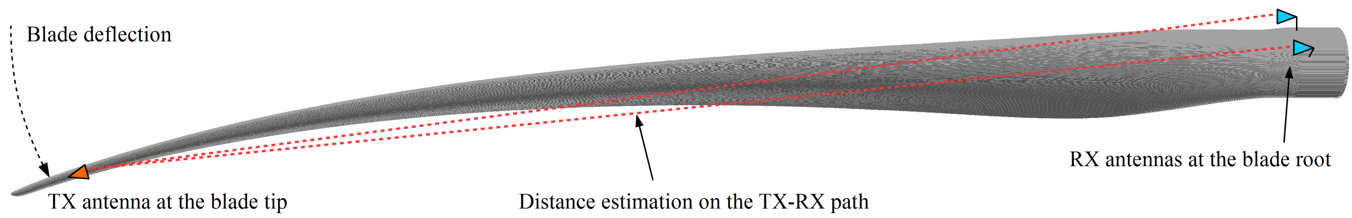


Fig. 1. Schematic of the wind turbine blade deflection sensing system using ultrawideband radio links between antennas at the tip and at the root of the blade.

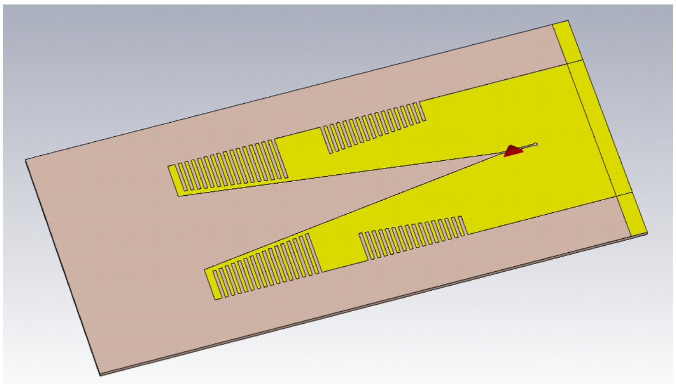

Fig. 2. Ultrawideband Vivaldi antenna with 10 dBi gain used as both TX and RX antenna.

corner reflector. The second type was antenna called "on-ground" which was a ground-mounted dielectric-enhanced aperture with three directors [4]. Main properties of this antenna were gain of 12 dBi and beam tilted approx. 20 degrees upwards, similarly as with the corner reflector antenna. We could see this as an advantage, because an antenna with tilted beam will produce less surface wave when mounted on the blade surface and less guided wave when mounted inside.

The most recent prototype is a corrugated Vivaldi antenna with 10 dBi gain, see Fig. 2. Despite lower gain and no beam tilt, the antenna is better suited for mass production thanks to its simple structure. In addition, it features superior stability of phase center [6], which is important for ultrawideband pulse operation such as the deflection sensing system, where precise determination of the pulse time of arrival is crucial. In the current testing configuration, the Vivaldi antennas are used at both TX and RX positions, equipped with a dielectric radome.

## IV. Multipath Effects

The very presence of the fiberglass wind turbine blade resulted in multiple forms of multipath propagation between TX and RX. Not only that the large part of the Fresnel zone was occupied by the blade body, but the blade also worked as a waveguide.

The wind turbine blades are hollow, and when an antenna is placed inside, it will create a guided wave along the entire length of the blade. This will not only "steal" energy from the direct path, but also create interference by leaking the signal through the fiberglass shell to outside, where the RX antennas are attached. The second interference channel is formed by the surface wave on the outside of the blade. This wave is created next to the TX antenna and propagates towards the root along the blade shell.

These wave guiding properties of the blade provided false communication channels for the wireless link between TX and RX. Why false? Why did we not use the natural waveguide inside the blade as the link medium? The reason is that the distance traveled by the wave guided along the body is approximately constant irrespective of its bending, and thus does not provide any information from which to determine the degree of bending.

Finally, the third source of interference comes from reflections of the wave from the outer shell of the blade. The result is more or less typical fading pattern seen in positioning the RX antennas and dependent on the deflection angle.

## V. Electromagnetic Modeling

During the design phase it was necessary to estimate the link budget and distortion of the received pulse. Unlike typical wireless links in this frequency band, it was not possible to model the propagation by asymptotic methods assuming far field conditions, due to multipath effects described in the previous section. Instead, the finite-difference time-domain (FDTD) method [7] was chosen to simulate the propagation along the entire length of the blade.

The choice of FDTD was based on the fact that it is a full wave method and thus capable of modeling near field effects near the antennas and surface waves along the blade. In addition, FDTD being a time domain method handles excitations with short pulses naturally without resorting to Fourier transforms.

However, the propagation simulations brought also several challenges. The frequency range of the pulse (3–5 GHz) and the physical lengths of the modeled blades (37.3 m and 58.7 m) meant that the computational domain would need to be electrically extremely large. With cell size of 5 mm the total number of mesh cells exceeded 10 billions and it became necessary to perform the calculations on a supercomputer running our in-house FDTD code. Another problem stemming from the large size of the domain was excessive numerical dispersion, an intrinsic error to the FDTD method [7]. This

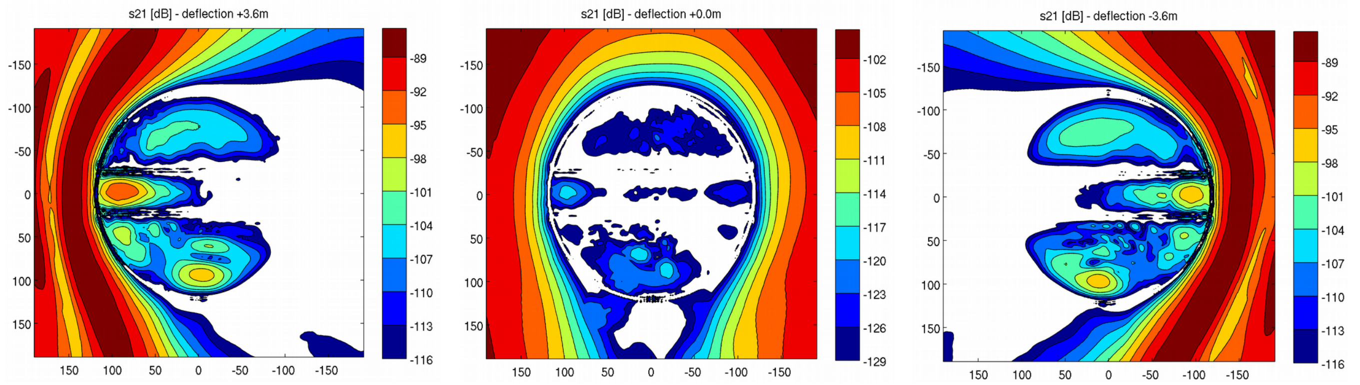


Fig. 3. Simulated link budget (in terms of $s_{21}$ parameter in dB) for arbitrary position of the root antennas. Left: downwind deflection +3.6 m; Center: no deflection; Right: upwind deflection -3.6 m. Distance of the RX antennas from the root is 2 m, with Vivaldi antennas at both ends.

problem was satisfactorily solved by employing dispersion compensation scheme as described in [8].

Figure 3 shows one of many outputs of the FDTD simulations—signal strength distribution in terms of the $s_{21}$ parameter at the root of the 58.7 m long blade. This calculation was important for the determination of the link budget and finding the optimal position of the RX antennas at the root, taking into account all possible deflections of the blade. In Fig 3, the wave propagating inside the blade can be seen, even when the blade is straight (center). The left and right subfigures show also the fading pattern due to reflection of the direct wave off the blade surface.

## VI. Measurements

Several measurements of the performance of the link on a real wind turbine blade were performed. One such setup is shown in Fig 4. The blade was pulled towards its downwind side and the signals received at the root were observed, although, unlike the FDTD simulations, only at a few selected positions. The TX antenna was placed in front of the pulling clamp to avoid interference.


Fig. 4. Measurement setup with the 37.3 m blade in the LM Wind Power test center. The pulling clamp for the deflection tests is visible on the blade.

## VII. Conclusion

Unlike most common wireless links where the medium is a free space (vacuum, air) with only a few and discontinuous obstacles, propagation along the wind turbine blade is more complex and its simulation (but also measurement) is challenging. Due to many multipath phenomena it is necessary to use a suitable simulation tool that will be able to correctly predict surface and interior guided waves. Using the simulation tool, such as FDTD in our case, may also require large computational resources. Special treatment of the results may also be needed, as the multipath signals travel large distances and errors small errors may be amplified. Despite the challenges, the simulation results show that valuable information about the propagation can be obtained, including the multipath effects.

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