Environmental Impacts on Antennas for Wireless Sensors on Outer Aircraft Surfaces

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***Abstract*—Wireless sensors on the outer surface of aircrafts are of interest for both research and control of modern aircrafts. However, the constraints are quite challenging for the antenna design: Since the surface may be conductive and the constructive height of the sensor must remain low, e.g. below one millimeter, the antenna gain and directivity can be quite unfavorable. Moreover, the reliability of the wireless link in particular under varying environmental conditions, e.g. due to rain or icing conditions, is also a critical aspect. In this paper we report simulations and experimental results obtained in an icing wind tunnel. We show that the additional path loss for flat antennas mounted on a wing model remains below 25dB due to icing and rain conditions.**

Keywords — antennas, RF performance; environmental influences; aircraft; wireless; ice, water

I. Introduction

Generally, for short range devices (SRD) there are three frequency bands of interest. These are frequencies which are useable worldwide and where the required antenna area is relatively small. The path losses increase with rising frequency. Depending on the used frequency the losses are in the range of 70dB under the condition of a direct line of sight and with an assumed distance of 20 meters. Provided that a suitable antenna concept is used, the losses such as the sum of the path losses of the channel and the additionally attenuation due to the environmental conditions are normally lower than 100dB. Modern wireless transmitter can reliably handle this low received signal strength. From this point of view wireless data communication could be a real alternative for various sensor systems for non-real time applications. A possible application of a wireless sensor system could be an ice detector which measures the formation and accretion of ice in a very early phase at neuralgic positions on an aircraft like the leading edge or the turbine inlet.

Sensor systems are important and absolutely necessary for reliable controlling of modern aircrafts. A lot of different sensors are available and integrated in the different applications especially in the area of aviation. Reliability is one of the important properties which a sensor system must have. The majority of the physical transmission takes place via wired connections. This has its absolutely entitlement for time critically procedures. For non-real time application where a terminated time scheduling is not required, wireless based data communication could be an adequate approach. The quality of a wireless communication is influenced by a lot of parameters, much more than the wired one. Some of this influences are more or less statically, e.g. the path losses for a fixed arrangement of transmit and receive antennas or the detuning of the antennas as a consequence of the material properties e.g. conductivity or permittivity in the surrounding of it. The losses are primarily depending on the local circumstances such as the reflection, diffraction and refraction as well as the possibility of a multipath propagation of the electromagnetic wave.

Impacts of environmental conditions are a more severe problem because these impacts can have diverse characteristics. Water and its different aggregate states for example has an enormous effect of the link quality. Our pretests have shown that especially at the ISM Bands of 2.45GHz and 5.8GHz a continuous coverage with a water film for example can lead to a total reflection at the antenna feed which means that there is no energy for radiation available because the entire quantity of energy will reflect back to the source. On the contrary water drops or a coverage of ice have a significant less degradation at the link.

In this work a special setup of radio communication was built up to explore the environmental impacts on the antennas within a wireless link how it could occur at the surface of an aircraft. Therefore, specially antennas for 868MHz, 2.45GHz and 5.8GHz were designed and fixed on a wing model which was placed inside an icing wind tunnel. For a period of a total of 10 hours of observation, the development of the path losses (transmission coefficient S21) between the receive (RX) antennas in the tunnel und the transmit (TX) antennas outside of it were recorded and explored. During this time, temperatures vary from -20 up to 5°C and wind speeds reach up to 20m/s. This means that various shapes of water drops up to some millimeters thick and ice coats were produced and their influence on the path losses were recorded.

For the current application a patch antenna structure with coaxial probe feed was chosen. There were some reasons for selecting this type of antenna. One important point is the planarity and the possibility to apply it on a curved surface with the big advantage of small back lobe radiation which means that most of the radiated energy is concentrated in one hemisphere. A further aspect - the low profile of the antenna structure - is important in matters of the requirements of the aerodynamics. Furthermore, due to the principle structure of a patch antenna with a ground layer on the bottom side of the patch, it's not really essential for the function of the antenna if there is a conducting or isolating material below the ground plane, this means that there is practically no big influence on the feed impedance respectively on the resonance frequency. In order to achieve an independency in the geometrical orientation of the antennas, a circular polarization radiation pattern can be implemented without any major effort. One disadvantage of this type of antennas is the narrow impedance bandwidth which is typically less than 5% for small antenna dimensions [1].

Furthermore, the efficiency of the antenna, defined as the effective radiated power regarding to the available power, gets poorer the thinner the substrate becomes. Usually the substrate thickness is in the range of 0.01 to 0.05 times the free-space wavelength of the chosen frequency [2]. That means the higher the frequency the thinner the substrate can be. The substrate thickness of the constructed antennas is in the range of 0.005 times the free-space wavelength; this is only one tenth of the optimal thickness for patch antennas. Under these circumstances the efficiency decreases. A reduction of the efficiency by half corresponds with 3dB more losses within the radio link.

The substrate material has a strong influence on the performance of the antenna too. For the first attempts an ordinary flame retardant, epoxy resin composite material (FR4) with relative permittivity $\varepsilon_r = 4.2$ and a dissipation factor $\tan\delta$ of 0.019 with a thickness of 1mm was selected. For the second step, a Teflon based Polytetrafluoroethylene (PTFE) material with $\varepsilon_r = 6$ and a dissipation factor $\tan\delta$ of 0.002 with a thickness of solely 640um was used. The PTFE material has a much higher temperature and permittivity stability and a much lower loss tangent than the FR4 material. With the higher dielectric factor, the size of the antenna shrinks however with the drawback of a further reduction of bandwidth and the efficiency[3].

Another important point is the choice of the transmission frequency. For the intended use of the sensor system a license free, worldwide available frequency band for short range devices is necessary. For this use case, there are only three bands disposable, at 868/915MHz, at 2.45GHz and at 5.8GHz. The lower the frequency the bigger the effective patch size becomes.

Fig. 1. Fixed RX antennas for 868MHz (right), 2.45GHz (middle) and 5.8GHz (left) on the top side of the wing model

The wing model and the mounted rectangle patch antennas for the three test frequencies are depicted in figure 1. The patch sizes, the optimal ground shapes as well as the position of the coplanar feeding point for a 50Ohm impedance were simulated and optimized for a 1mm FR4 substrate material.

Fig. 2. Dimension of the 2.45 GHz patch antenna with 50 Ohm coplanar semirigid feeding, mounted on a 2mm thick aluminum plate to simulate the influence of the conducting material below the patch

Below the ground plane of the antennas a 2mm thick rectangle aluminum plate was placed for shielding reasons and to reach a plane mounting surface (Fig.2).

II. TEST SETUP

To explore the environmental influence a test procedure was defined for measuring the transmission quality. Four parameters like temperature, wind speed, water content and setting angle of the wing were varied.

The adjustment for the temperature was in a range from minus 20°C up to 10°C, the wind speeds were adjusted up to 20m/s, the water content from 0 (dry air) up to 0.4 g/m³ water per cubic meter air flow. The setting angle was varied between 0° (Fig.3 right) und 20°.

Fig. 3. Icing condition, all three bottom antennas covered with ice (left) Build up of the wing model inside the icing wind tunnel (right)

Two sensor antennas per frequency were mounted with an adhesive tape at each side of a wing model (Fig.3. left), one at the top, the other at the bottom side of the wing. The top side was defined as the side which was looking to the TX antennas beside the tunnel. The TX antennas were placed in a distance of approximately 3 meters, for each center frequency an antenna, overall three TX antennas.

In total there were six RX-antennas mounted on the wing. The wing model was designed in order to fit exactly in the wind tunnel (Fig.3.right).

All six RX-antennas were connected per cable via an electronically controlled switch box to a network analyzer. The second port of the analyzer was connected via a second switch box with the three TX antennas (Fig. 4.)

In a switching interval from round about 5 seconds the path loss (transmission losses = S21) between the RX and the TX antennas were measured sequentially one by one. Additionally, to the path losses the influence at the resonance frequency was monitored (return loss = S22).

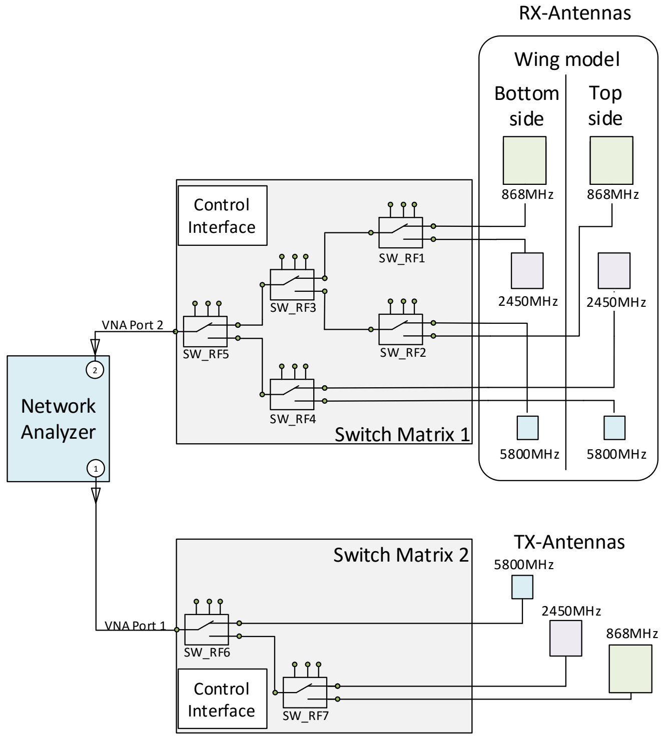

Fig. 4. Hardware test setup for path loss measurements with RX and TX antennas switch boxes and network analyzer

A control program periodically switched the antennas in the correct order, adjusted the frequency range of the VNA and stored the path- and return losses of the communication link for each frequency band. 201 points per frequency range.

The 868MHz band was recorded from 800MHz up to 1GHz with a step size of 1MHz. The 2.4GHz ISM band from 2.2GHz up to 2.8GHz with a step size of 3MHz and the 5.8GHz ISM band from 5.5GHz up to 6GHz with a step size of 2.5MHz. Consequentially the center frequencies were 860MHz (Index 61), 2449MHz (Index 84) and 5.8025GHz (Index 121). In total for each side of the wing three antennas that means six radio frequency links were monitored, two per frequency band. Every 5 seconds a measurement value was captured that means a cycle time of 30 seconds.

III. RESULTS

As mentioned before the prepared antennas were made from 1mm FR4 connected with a semi-rigid coaxial cable. The bottom side of the antenna was stuck on an 2mm thick aluminum carrier. Over the patch of the antenna a special protection tape was utilized, which was used for protecting the surfaces from damage and for fixing the antennas on the wing.

The impact on the return loss, that means the shift of the resonance frequency due to the mounting of the antenna at the aluminum carrier on the backside and the protection tape is depicted in Fig. 5. These measurements were done without applying water or ice at the antenna. The frequency shift is the same for all three frequencies, down to lower frequencies, therefore only the behavior of the 2.45GHz antenna was presented.

The starting point was the return loss of the antenna without an aluminum on the bottom and a protection tape at the top side of the antenna (light blue line, number 1). The second measurement was done with the aluminum on the bottom side and without the protection tape (blue line, number 2). The conducting material below the ground plane reduces the return loss of approximatively 20 percent, without a shift of the resonance frequency, which is unchanged in the middle of the 2.45GHz ISM band. Furthermore, there is no essential impact on the bandwidth apparent. This means for the impedance of the antenna, there is only a resistive shift from a higher feed impedance, in this case, from 36Ohm to 30Ohm but there is absolutely no change in the reactance locus curve.

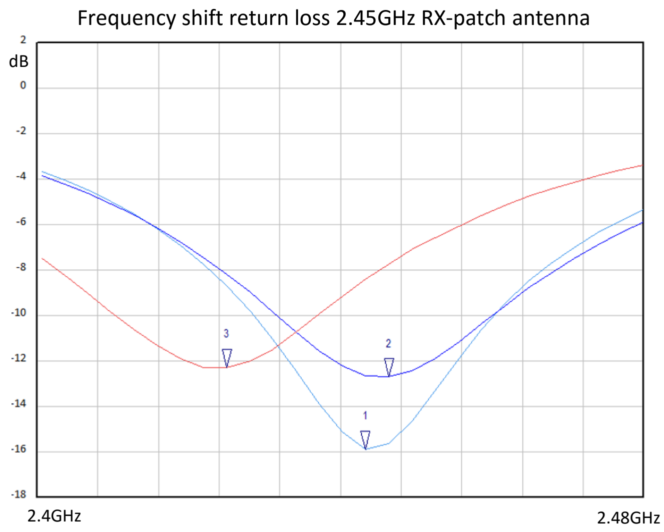

Fig. 5. Impact on the return loss of the 2.45GHz antenna. Light blue(1) the antenna without protection folie and aluminum carrier. Blue (2) antenna with aluminum carrier at the bottom side. Red curve (3) frequency shift due to the protection folie at the patch and aluminium carrier at the bottom side

The tape on the patch has much more influence on the resonance frequency. This circumstance leads to a parallel shift of the return loss curve in the range of 20MHz to lower frequencies within the 80MHz broad frequency band of the 2.45GHz antenna. The absolute value of the return loss from approximate -12.5dB and the bandwidth from approx. 40MHz are practically not affected, only a shift, no change of the curve shape. This means there is no change in the feed impedance, but a move of the locus curve in a more capacitive region. Therefore, it is necessary to retune the antenna including the tape back to the band center.

The measured gain of the used patch antenna shows a gain of round about 4.4dBi in the main radiation direction, which is in the z direction of the patch (Fig.6) defined as θ = 0°.

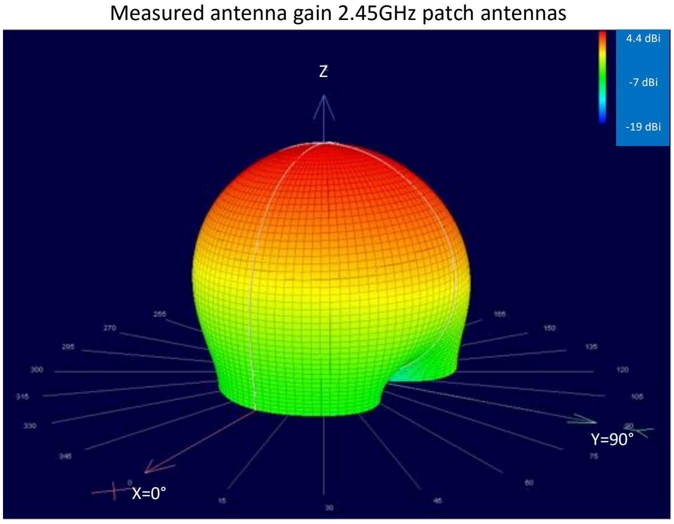

Fig. 6. Measured 3D radiation pattern of the used patch antennas

In addition, the measurement of the gain in X-direction, corresponds to the cutting plane 0° to 180° in the 3D plot, a minimum gain of approximate minus -6dBi.

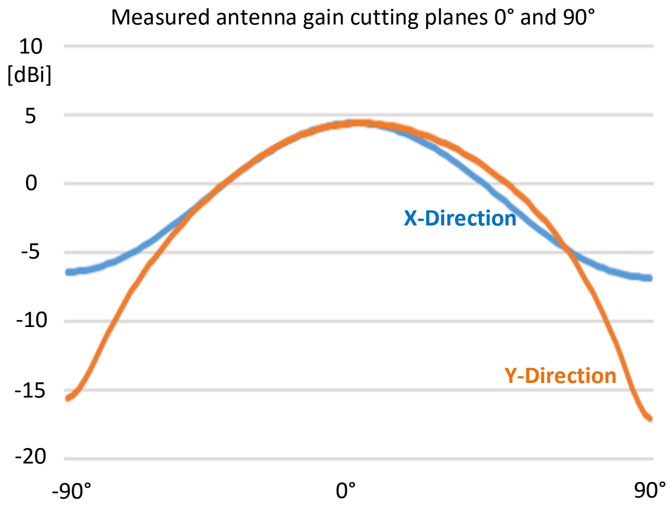

Fig. 7. Measured gain in X direction (cutting plane 0-180°) and Y direction (cutting planre 90-270°)

In Y-direction, at the cutting plane (90° to 270°), a minimum gain from -16dBi was measured (Fig. 7).

If the antennas are directed patch to patch with the same polarization, that means the antennas opposite each other, like in the wind tunnel for the top antenna and the transmit antenna outside of the tunnel, the total gain of the radio link is two times of the measured gain of one antenna, in sum approximately 8.8dBi.

For this configuration the calculated path attenuation at 2.45 GHz is the sum of all gains and attenuations within the radio link. These are: the output power of the network analyzer (10dBm), the antenna gains (8.8dBi), the cable attenuation of two coaxial cables with a length of 10m per item (11.6dB) as well as the free space path loss which is 49.8dB for the distance of 3 meters between RX and TX antenna. The calculated path loss is minus 54.2dB.

The measured path loss (figure 9 green curve) for the top antenna face to face with the TX antenna, without the impact of ice and water is in the range of -50dB which corresponds well with the theoretical calculation.

The reason for the peaks up to -41dB are caused by persons sometimes entering and working inside the room.

In the case that the antennas are placed in the same plane, depending on the orientation of the antennas the gain will be reduced to two times of minus 6dBi in X-direction or two times minus 16dBi in Y-direction. That means that the transmitted energy is in the worst case (same plane, orientation in Y-direction) less than a thousandth part of the energy in the main direction.

The calculated path loss for this configuration is -94.4dBm.

In the wind tunnel the RX-antennas on the bottom side of the wing face directly in the opposite direction of the TX-antennas outside of the tunnel. The antennas have no direct “line of sight” to the TX-antennas. The energy which is received from the RX antennas is much higher than expected due to the following facts:

- the multipath wave propagation as a result of the metallic environment
- the reflective properties of the objects in the surrounding room
- the diffraction of the electromagnetic wave.

The path losses over the frequency range from 2.2GHz up to 2.8GHz is shown in Fig.8. The maximum power is transmitted at the frequency at 2.45GHz which is exactly at the calculated frequency in the middle of the ISM Band.

In the figure 9 the path losses of the 2.45GHz top and the bottom antennas are depicted. The losses vary between minus 41.5dBm in the best case down to minus 63.5dBm in the worst case. Over the whole measurement period of eight hours the maximum change in the antenna gain was not more than 22dB. Within this time period a various amount of temperature – wind speed and water content combinations were adjusted.

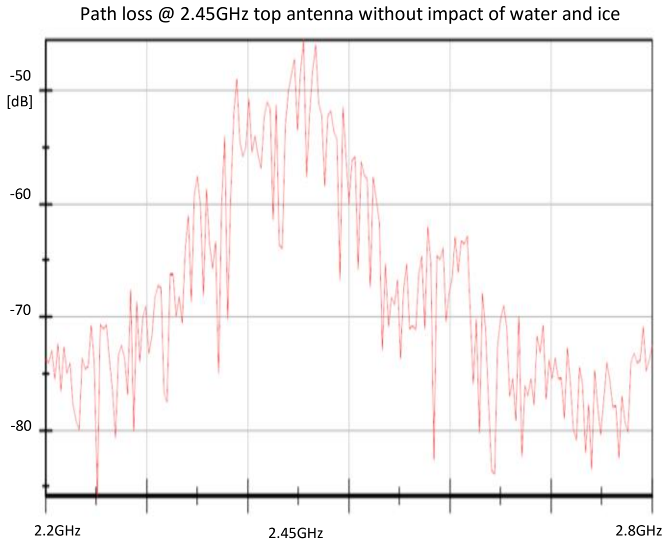

Fig. 8. Measured attenuation of the RF path between TX and RX top antenna at 2.45GHz at the beginning of the measurement in the ice tunnel after 200 seconds

The strong decrease of the path loss to minus 85dB (green curve, figure 9) at the beginning of the monitoring period results from a test where the antenna was disconnected. The measured losses are the noise level of the network analyzer.

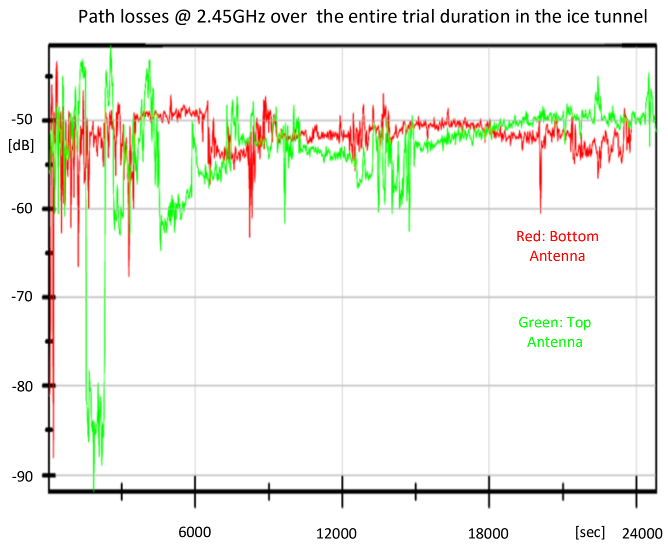

Fig. 9. Path losses from the 2.45GHz top and bottom antenna over eight hours inside the icing wind tunnel

The strong fluctuation in both curves up to approximately 3000 seconds at the beginning and partially the peaks during the total monitoring phase result from the staff which has to adjust the device during the test as well in the ice tunnel. For these tasks, it was necessary that persons were in the close proximity of the antennas.

It was observed that especially water leads to a strong influence of the losses. This behavior is more sensitive the higher the frequency is.

The dramatically jump from approximately minus 45dB down to minus 65dB at 4500 seconds after starting the monitoring (green curve, figure 9) was a consequence of turning the model wing to a radiation angle of 20° and of increasing the water content of the air to 0,4g/m³ at a wind speed of 10m/s. Under these conditions the quality of the communication between RX top and TX antenna decreases rapidly because of the relative position of the antennas and the circumstance that the higher amount of water degrades the antenna performance. After some time, the accession of the ice and the quality of the communication link increases.

At the same time the influence of the enhanced water content at the bottom antenna has less impact because of the better position to the TX antenna. Only a slight improvement in the radio link has been observed.

After 7000 seconds the wing model was turned back to 0° in the starting position. The losses of the bottom antenna increases rapidly in roughly the same range of the top antenna. The cause of this was the worse position to the TX antenna.

After 9000 seconds the heating was switched on and consequently the losses of the top antenna increase more than the ones at the bottom antenna obviously because of the higher amount of water at the top antenna.

At round about 13000 seconds, the heating process stopped and a further freezing cycle started. the communication quality increases at both links.

At 18000 seconds a dryer was used to reduce the ice at the bottom antenna only. In this test phase the increasing of the losses of the bottom antenna have been observed.

IV. CONCLUSION

Wireless sensors on the outer surface of aircrafts are of interest for both research and control of modern aircrafts. However, the constraints are quite challenging for the antenna design: Since the surface may be conductive and the constructive height of the sensor must remain low. Moreover, the reliability of the wireless link in particular under varying environmental conditions, e.g. due to rain or icing conditions, is also a critical aspect. In this paper we report simulations and experimental results obtained in an icing wind tunnel.

The transmission tests in the icing wind tunnel show a maximum deviation in the path losses of not more than 22dB between the best (dry conditions) and the worst case (wet conditions, water and ice at the antenna) at a 2.45GHz system under the test conditions described above.

A water film on the antenna has a strong influence on the path losses, especially at 2.45GHz. The thicker the water film the higher is the impact on the link quality. In the transition from the liquid to the solid phase the losses are decreasing almost up to the range of dry conditions depending on the thickness of the ice layer.

With the measured additional path losses of roughly 22dB plus the free space losses of approximately 66dB (calculated value, without multipath propagation) for a distance of 20m line of sight, a conventional 2.45GHz SRD transmitter should work under the condition of good antenna positions without performance restrictions.

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