

Wireless Propagation Analysis and Measurement in Enclosed Reflective Structures

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Abstract

Wireless propagation scenarios are generally classified as LOS (Line-of-sight) and NLOS (Non-line-of-sight). In LOS case, wireless signals usually experience Rician fading due to the existence of direct signal path between the transmitter and the receiver, while in the other case (NLOS), Rayleigh fading is expected most of the time [1]. In this paper, we explore the propagation characteristics in a special type of indoor environment—enclosed reflective structure, which refers to places where the wireless communication occurs in space enclosed by highly reflective materials such as metal walls. Examples of such application can be wireless communication inside an airplane, a train, or a space shuttle/module, and also in certain types of buildings such as certain industrial shops or barns. The strong signal reflection/resonance can significantly increase the number of arrival signals as well as excessive signal delay. To address this problem, we studied the reception statistics of two types of antennas (omni-directional and directional antennas). Through both Ray-tracing simulation and channel measurement, we found that the receive antennas experience Rayleigh fading even when the transmitter is only 3 meter away in direct line-of-sight with the receiver.

1. Introduction

The understanding of wireless propagation characteristics in various indoor and outdoor environments has become increasingly important because of the wide application of wireless communication nowadays. Extensive amount of work has been done to characterize the wireless signal propagation for typical indoor and outdoor scenarios [1]. In this paper, we study a special type of indoor environment that is enclosed by highly reflective materials such as metal walls. The motivation of this study is to gain a better understanding of wireless propagation inside a lunar module, an airplane, or other similar types of environment, which can be drastically different than normal expectation. We start with numerical modeling of a university clean room which is enclosed by metal walls (a representative of the environment of interest) and then ray-tracing simulation is performed to extract statistical characteristics of the wireless signal reception through both directional and omni-directional antennas. In confirmation of the findings in the numerical simulation, a channel measurement was done to compare the measured results with the simulation results.

2. Ray-tracing simulation

A commercial software (*EMTerrano*) was used to model and simulate the wireless propagation in the clean room environment. Fig. 1. demonstrates the detailed model of the clean room along with furniture and equipment inside. Since it is not feasible to model every geometrical details of each object in the test room, simplification is made to represent the objects in the room with 72 rectangular boxes including the surrounding metal walls and glass windows. Four different materials (wood, plastic, metal, glass) were used to represent different electrical properties of each object. The four side walls of the room were modeled as metal, while the ceiling and floor were modeled as glass and brick respectively. The total dimension of the room is 607 cm by 681 cm by 243 cm. The locations of the transmit antenna and the receiving area (200 cm by 100 cm) are indicated in Fig. 1. The transmitter and the receiver were separated by about 3 meter with a clear LOS path. The spatial resolution in the receiving area was 5 cm. Both the transmit and receive antennas were elevated 150 cm above the floor. The simulation frequency was 2.4 GHz (ISM band). Vertical polarization was assumed and the transmit power was 0 dBm.

Dipole antenna with omni-directional radiation was used as the transmit antenna. To compare the characteristics of signal reception with directional and omni-directional receive antennas, we considered three cases as described below:

1. Dipole antennas were used as receive antennas (Fig. 1). The antenna gain in the simulation is 2.1 dBi.
2. Patch antennas were used as receive antennas and positioned towards the transmitter (Fig. 1). The patch antenna used in the simulation had an antenna gain of 7.8 dBi and no back radiation (as in the theoretical patch antenna pattern). For patch antennas with finite ground plane, front to back ratio is about 15-20 dB.
3. Patch antennas were used as receive antennas and positioned away from the transmitter (Fig. 1).

In the second case, the reception of the direct path from the transmitter was maximized because of the alignment of antenna pattern with the direction of the transmitter. While in the third case, the receive antenna was completely

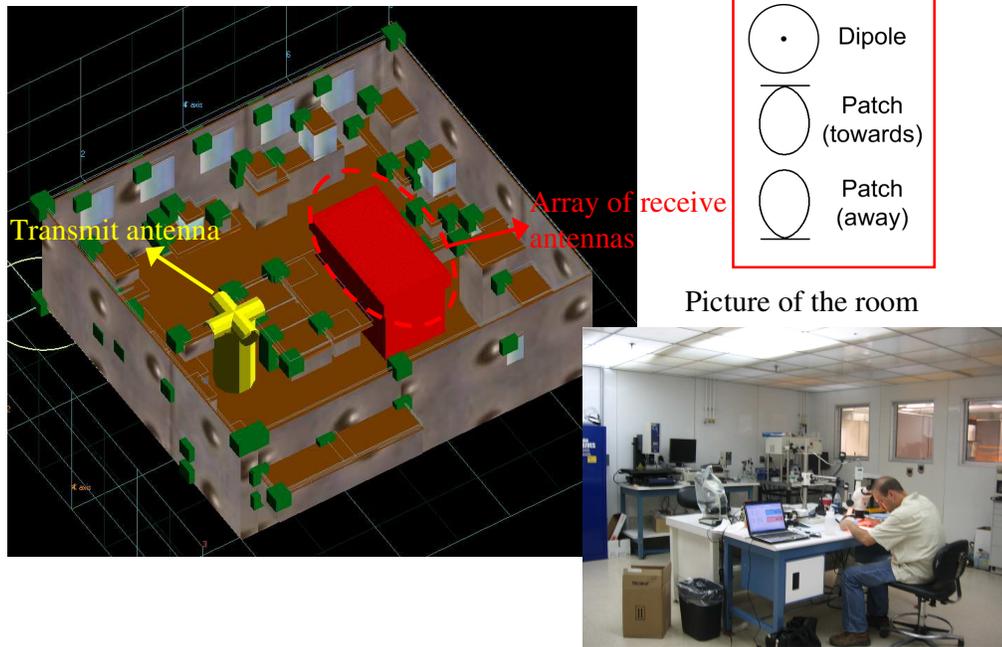


Fig. 1. Simulation model of the clean room in EMTerrano.

blind of the direct line-of-sight signal. This was intended to compare the best case scenario (second case) and the worst case scenario (third case).

Through 3D ray-tracing simulation, distributions of angle-of-arrival (AoA) for all receiving locations were obtained (data not included in the paper due to limited space). The direct LOS is found to be about 10 dB higher than other reflected/diffracted arriving signals. However, K factor, which is calculated from the ratio between the power of LOS component and the total power of other scattering components, ranges from -2 dB to -4 dB for different receive locations. This means that though there exists a LOS path between the transmitter and the receiver, the total power of indirect impinging signals is higher than the direct LOS signal and the wireless channel experiences Rayleigh fading instead of Rician fading. The above observation is quite contrary to common expectation of typical indoor environment because when a receiver is only 3 meter away from the transmitter with LOS path, the receiver usually has Rician fading. To explore the effect of the metallic walls surrounding the test room, we replaced the metallic walls with brick ones. The ray-tracing simulation results of the virtual room with brick walls are presented in Fig. 2 and Table I in comparison with the original test room.

In Fig. 2, the CDF curves of received signal power through different receive antennas are plotted for both the test room with metal walls and the virtual room with brick walls.

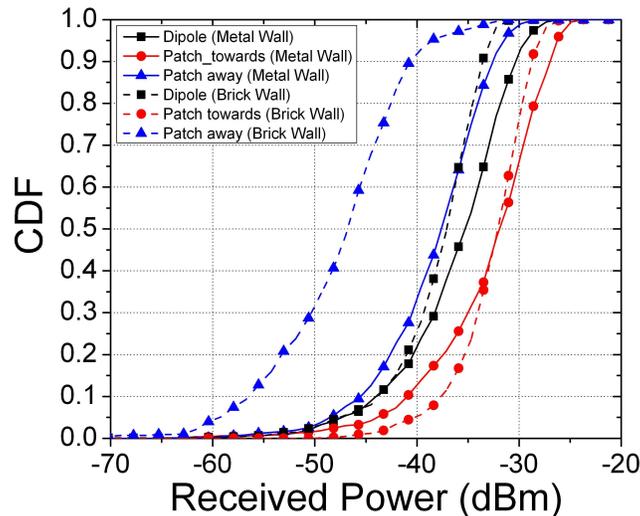


Fig. 2. CDF (cumulative distribution function) of received signal power through different receive antennas for comparison of a metallic wall surrounded room and a brick wall surrounded room.

For the test room with metal walls, the average receive power for the dipole antenna is -32.4 dBm, while the average receive power for the patch antenna is -28.7 dBm (towards transmitter) and -36.1 dBm (away from transmitter). The average receive power is very close for both types of receive antennas. In addition, the slope of each CDF curve fit well with that of a random Rayleigh fading signal with the same average power. This means both directional and omnidirectional antennas experience Rayleigh fading in the test indoor environment. This indicates that the average received power from the patch antenna varies mainly due to the variation in the angular distribution of the impinging waves in a local area rather than the signal reception of direct LOS signal.

For the virtual room with brick walls, because of weaker reflection from brick walls, the average received signal power for the patch antenna facing away from the transmitter is about 10 dB lower than from the same antenna in the test room with metal walls (blue curves in Fig. 2). While the total scattered signal power reduced significantly, the signal from the direct path remains the same. Therefore, both receive antennas (dipole antenna, patch antenna towards the transmitter) exhibit Rician fading, which is indicated by the steeper slope of the CDF curves as compared to that of Rayleigh fading signals (Fig. 2).

In Table I, we summarized the temporal and angular reception statistics for transmitter and receivers indicated in Fig. 1. Besides the difference of Rayleigh vs. Rician fading, there are other effects due to the metallic walls. For the test room with metal walls, the delay spreads for all situations reside in the same range. Therefore, the coherence bandwidth is approximately the same for all receive antennas. We also found that the angular spread in the azimuth plane for patch antennas is significantly lower than that of dipole antennas. This indicates a longer coherence distance for patch antennas as the wireless receiver moves around.

In comparison of the virtual room and the test room, the delay spread of the wireless signal increases from 7.7 ns to 47.6 ns due to the multiple resonance of the reflection on the surrounding metal walls. This means narrower coherent frequency bandwidth for wireless communication. The angular spread of the wireless reception is also narrower in the virtual room with brick walls since the LOS path becomes the dominant signal path. In summary, the strong multiple reflections from the surrounding metal walls are the major source of scattered signals and in this particular test room, the wireless receiver experiences Rayleigh fading even in LOS with the transmitter.

Based on the above observations, an antenna diversity system with two patch antennas facing opposite directions is expected to have a better performance than diversity systems with two dipole antennas with close proximity to each other for two reasons: first, the average receive power for dipole antennas and patch antennas are very close, which indicates similar signal statistics for individual branches of the diversity antenna array; second, much lower branch correlation between patch antennas employing pattern diversity is expected than closely-spaced dipole antennas in environments with rich multipath scattering as in the test room.

Table I Summary of reception statistics for different receive antennas

| Receive antenna | Metal wall | | | Brick wall |
|--|-------------|-----------------|--------------|-------------|
| | Dipole | Patch (towards) | Patch (away) | Dipole |
| Avg. rec. power (dBm) | -32.40 | -28.66 | -36.11 | -35.94 |
| Avg. delay spread (ns) | 47.56 | 40.50 | 48.02 | 7.67 |
| Delay spread range (ns) | 42.92-53.32 | 34.42-48.38 | 38.45-53.74 | 5.54-10.33 |
| Avg. angular spread in azimuth plane (degree) | 88.71 | 21.14 | 28.64 | 43.52 |
| Angular spread range in azimuth plane (degree) | 78.56-99.45 | 16.95-27.24 | 19.62-33.77 | 31.62-78.90 |

3. Channel Measurement

To confirm the findings in the ray-tracing simulation, we measured the received signal strength in the clean room using signal generator and spectrum analyzer. Dipole antenna was used as a transmit antenna, which is connected to an Agilent signal generator (model number: E8254A). On the receiver side, the received signal strength from either a dipole antenna or a patch antenna with different orientation was monitored by an Agilent spectrum analyzer (model number: E4408B). Continuous data sampling was collected as the mobile cart including receive antenna and other

instruments moving along straight parallel lines. Over 1600 data points were collected in a 1m by 2 m area. Both receive and transmit antennas were elevated to about 1.5 m above the floor. All experiments were carried out during weekend nights so that there were no other people interfering with the wireless channel over time. A fully fabric patch antenna was used in this measurement, which acts as normal patch antennas in terms of antenna gain and radiation pattern (see details in [2]).

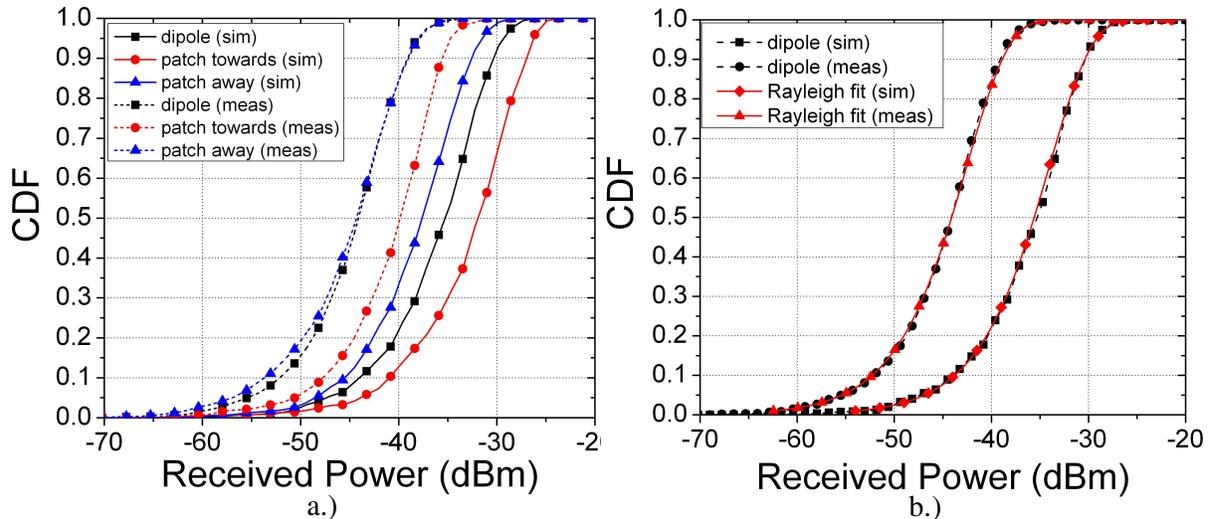


Fig. 3. a.) CDF (cumulative distribution function) of received signal power through different receive antennas; b.) CDF of received signal power from dipole antennas in comparison with Rayleigh fit curves.

To compare with the simulation results, we did three experiments (dipole-dipole, dipole-patch-towards, dipole-patch-away) for the transit and receive locations indicated in Fig. 1. The CDF curves of the receive signal power are plotted in Fig. 3 for both simulated and measured results. First of all, the relative trend between different receive antennas remains the same for both simulated and measured results. Patch antenna facing towards the transmit dipole antenna had the best signal reception. Dipole antenna had a slightly better reception than patch antenna facing away from the transmitter. Second, as shown in Fig. 3b, the received power statistics of dipole antenna fit very well with Rayleigh fading for both simulated and measured results. This confirms the observation in the Ray-tracing simulation that in this particular test room, multipath scattering is so strong that the receiver experience Rayleigh fading regardless of the fact that the receiver is in LOS of the transmitter. The difference in the absolute signal level for the simulated and measured results is mainly due to the extra energy loss in the coaxial cables and non-ideal antenna material loss.

4. Conclusion

In this study, we analyzed the wireless propagation statistics in an enclosed reflective environment. Due to the strong multiple reflections from the metal surrounding walls in the test room (similar to the environment in a space module), Rayleigh fading is predominant in the indoor wireless channel. Both results from simulations and measurements confirmed that the wireless channel undergoes Rayleigh fading even under the existence of direct line-of-sight between the transmitter and the receiver. Furthermore, based on the observations in this study, a diversity antenna array with two patch antennas facing opposite directions is expected to perform better than dipole antenna array with close element spacing. This needs to be confirmed by further analysis in the future work.

5. Acknowledgments

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6. References

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