Indoor propagation modeling using WIPL-D software – Part I

Introduction

Significant usage of various electronic devices (e.g., mobile phones, IoT devices, Bluetooth modules, smart house components…) requires computer modeling and simulating indoor telecommunication channels. In other words, typical telecommunication indoor channels, although physically small compared to most outdoor environments, require high quality propagation analysis.

In this paper the basic indoor scenarios, typically containing the room walls, transmitter (marked with Tx or T in following figures), receiver (marked with Rx or R) and various objects within the room are studied. One such example of the indoor scenario is shown in Fig. 1.

All information of interest can be obtained from electromagnetic field distribution calculated in frequency domain. From wideband frequency domain data time domain response can be calculated. For the examples considered here WIPL-D 3D EM Solver and WIPL-D 2D EM Solver were used for EM simulations in the frequency domain, while inverse Fast Fourier Transformation (iFFT) has been used to obtain the results in time domain.

The basic scenario represents a case of obtaining an electric field when the excitation is performed by using a single antenna. The specific topic arising here is the size of the problem. This means that significant computational resources are required at a single frequency. To make things worse, for the cases where the time domain solution is preferred, several dozens or even hundreds of frequency samples are required.

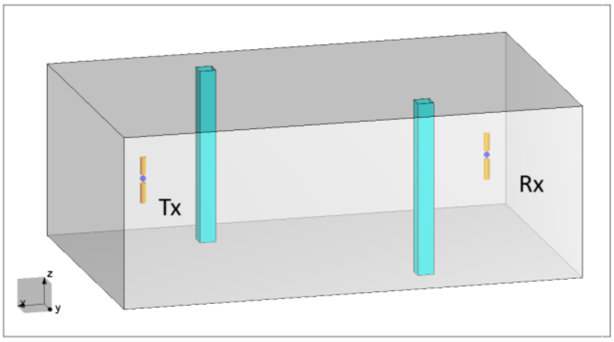


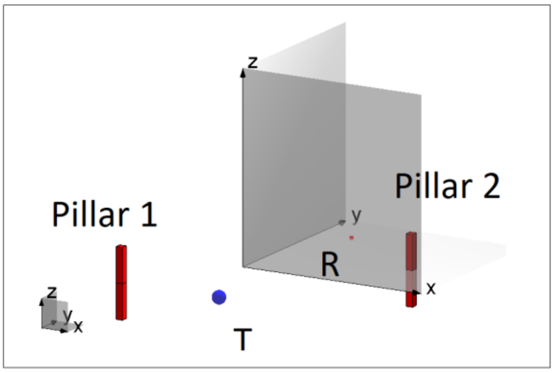
Fig. 1. Basic scenario containing the room, two pillars, a transmitter (Tx), and a receiver (Rx).

Computational resources analysis reveals that simulations using a typical 3D EM solver are limited to relatively low operating frequencies. For obtaining results at higher frequencies, it is necessary to apply advanced features capable of overcoming the limitations. This is the reason behind putting "Part I" in the title of the paper as it demonstrates usage of standard features available through less computationally intensive and approximative WIPL-D 2D EM Solver. Newly developed features overcoming 3D EM solver limitations will be demonstrated in the following "Part II" document.

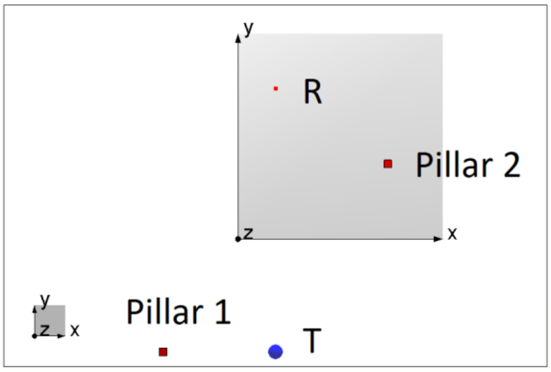
The paper is organized in the following way: the section following the Introduction specifies an EM problem definition. The next section deals with estimation of 2D and 3D resources. After that 2D and 3D scenarios will be compared. Finally, some practical issues with Dirac impulse and Gaussian Modulated Sine will be outlined.

Problem Definition

To demonstrate overall computational resources and to explain problems to be solved, let us consider concrete ($\varepsilon_{real}=4.5$, $\sigma=0.01$) room of length $a = 10$ m, width $b = 5$ m, and height $h = 3$ m. Inside the room there are one or two pillars of height h with square cross section of side d = 0.1 m (Fig. 2). Transmitter (T) and Receiver (R) are placed in arbitrary positions inside the room. The transmitter antenna emits a typical radar signal at central frequency $f = 3$ GHz, in a range of ±10% to ±30%. The task is to determine the time domain solution of the current/voltage/power induced at the port of receiver antenna. It is desirable to do this task by using full wave analysis, particularly a current version of WIPL-D software suite.



a) 3D view



b) 2D view

Fig. 2. Scenario consisted of a transmitter, a receiver, and two pillars: a) 3D view, and b) 2D view.

Current/voltage/power at the port of the receiver antenna is directly related to the near field at the port. Hence, in what follows we shall focus on the near field at the antenna port position.

Time domain solution in WIPL-D suite is based on simulations in frequency domain, performed in a frequency range that covers spectrum of time domain signal. By default, the lowest and the highest frequency in the spectrum are calculated so that the energy below the lowest and above the highest frequency are equal to 0.001%. In that sense, the largest scenario that can be simulated in the time domain is limited by resources needed for simulation in the frequency domain, at the highest frequency in the spectrum of time domain signal.

Resource limitations are dominantly related to the number of unknowns required for EM modeling and corresponding simulation time. Typical resource limitations for PC with 24 cores and 2 GPU cards are given in Table 1.

Table 1. Number of elements, number of unknowns and simulation times for seven typical projects.

Project	Number of elements	Number of unknowns	Total simulation time [min]
1	125,588	670,062	510
2	93,314	460,552	225
3	80,459	382,323	144
4	55,352	217,755	42
5	52,717	195,717	33
6	43,190	129,387	12
7	36,406	84,271	5

Estimation of resources for full wave 3D EM modeling

In WIPL-D, the number of unknowns for 3D EM modeling, N, is directly related to the surface area of objects to be modeled, S, the wavelength of the signal, λ, and number of unknowns needed per wavelength squared of the surface, N_0.

In the case of concrete material $N_0 = 60 / \lambda^2$. At frequency $f = 3$ GHz the wavelength is $\lambda = 0.1$ m, and the wavelength square is $\lambda^2 = 0.01\ \text{m}^2$. Surface area of the room is $S_{\text{room}} = 2(ab+ah+bh) = 190\ \text{m}^2 = 19{,}000\ \lambda^2$. Surface area of one pillar is $S_{\text{pillar}} = 2d^2 + 4dh = 1.22\ \text{m}^2 = 122\ \lambda^2$. The total number of unknowns needed for the room is $N_{\text{room}} = N_0\, S_{\text{room}} = 1{,}140{,}000$. The total number of unknowns needed for the pillar is $N_{\text{pillar}} = N_0\, S_{\text{pillar}} = 7{,}320$.

Estimated simulation time at one frequency for the room itself is 1.5 days. Estimated simulation time for a set of few pillars is a fraction of minute. For the sake of time analysis, the simulation needs to be performed in few tens of frequency points. Having this in mind it is concluded that it is not feasible to perform full wave 3D EM simulation for the full scenario (room + pillars). What is feasible is to perform the full wave simulation for set of pillars and ray tracing for the room walls, combining these two techniques into hybrid MoM/Ray Tracing method.

Another possibility is to solve the same problem using **2D EM modeling**.

Estimation of resources for full wave 2D EM modeling

The number of unknowns for 2D EM modeling, N, is directly related to the length of all contours of the 2D cross-section of 3D structure, the wavelength of the signal, λ, and number of unknowns needed per wavelength of the contour, N_0.

In the case of concrete material $N_0 = 12 / \lambda$. At frequency $f = 3$ GHz the wavelength is $\lambda = 0.1$ m. The length of the room contour is $L_{\text{room}} = 2(a+b) = 30\ \text{m} = 300\ \lambda$. The length of the pillar contour is $L_{\text{pillar}} = 4\text{d} = 0.4\ \text{m} = 4\ \lambda$. Total number of unknowns needed for the room is $N_{\text{room}} = N_0\, L_{\text{room}} = 3{,}600$. The total number of unknowns needed for the pillar is $N_{\text{pillar}} = N_0\, L_{\text{pillar}} = 48$.

Estimated simulation time at one frequency for the full scenario is a fraction of minute. For the sake of time domain analysis, the simulation needs to be performed in a few tens of frequencies. Having this in mind it is concluded that **it is feasible** to perform full wave 2D EM simulation of the full scenario (room + pillars).

The question of whether the full wave 3D EM simulation can be replaced by full wave 2D EM simulation should be considered next.

2D EM modeling vs 3D EM modeling of indoor scenarios

Let us consider the scenario consisting of a transmitter, a receiver and two pillars, as shown in Fig. 2a (3D view) and Fig. 2b (2D view). The transmitter is placed at $x_T = 0.5$ m and $y_T = -1.5$ m. The receiver is placed at $x_R = 0.5$ m and $y_R = 2$ m. The center of the 1st pillar is placed at $x_1 = -1$ m and $y_1 = -1.5$ m. The center of the 2nd pillar is placed at $x_2 = 2$ m and $y_2 = 1$ m. The transmitter antenna is a dipole antenna emitting omnidirectionally the vertically polarized Gaussian Modulated Sine wave. Having in mind all positions and distances it is seen that the signal first reaches the receiver antenna directly, then after reflecting from the 2nd pillar, then after reflecting from the 1st pillar, and then after reflecting from the room walls. To consider only the first three paths, the room walls can be omitted.

Fig. 3 shows *z*-component of electric field at the receiver location in time domain obtained by 3D and 2D simulation. The same results are shown in Fig. 4, scaled by factor 10. It is clearly shown that the signal arriving at the location of the receiver propagates along three paths.

It is also seen that waves have the same form in both 3D and 2D simulation. It can be concluded from this example that 2D simulation can be used instead of 3D simulation.

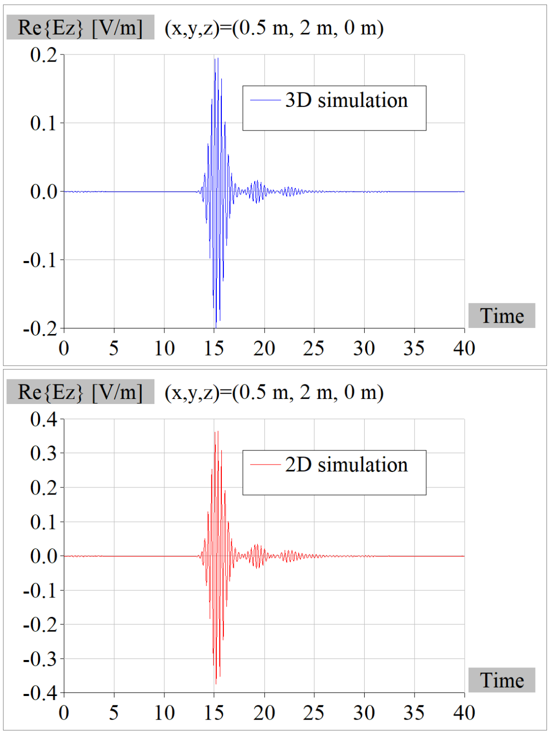


Fig. 3. Z-component of electric field at the location of the receiver in time domain for two-pillars scenario.

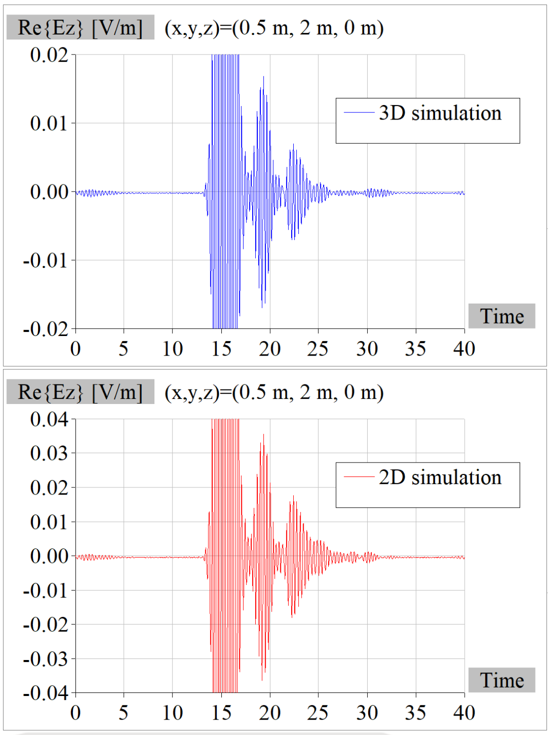


Fig. 4. The same results as in Fig. 3, scaled by factor 10.

It looks from Fig. 4 that the signal is distorted after reflections from the pillars. The same distortion is observed regardless of the simulation type (2D or 3D).

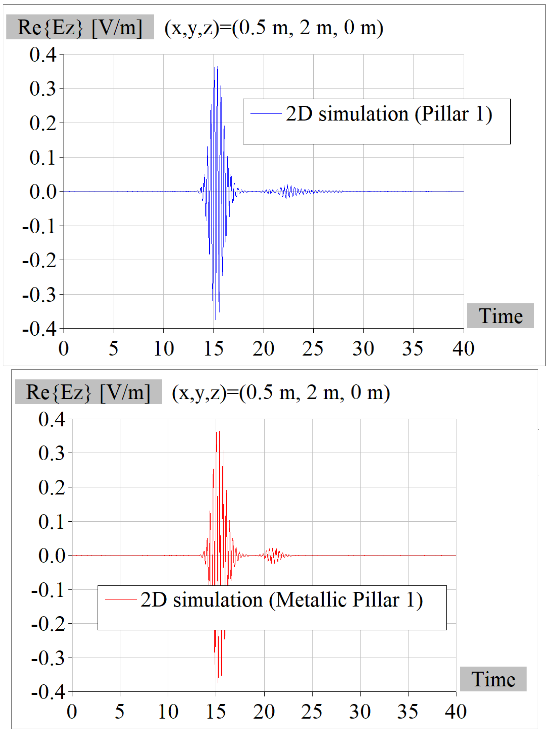


Fig. 5. Z-component of electric field at the location of the receiver in time domain for pillar 1 scenario.

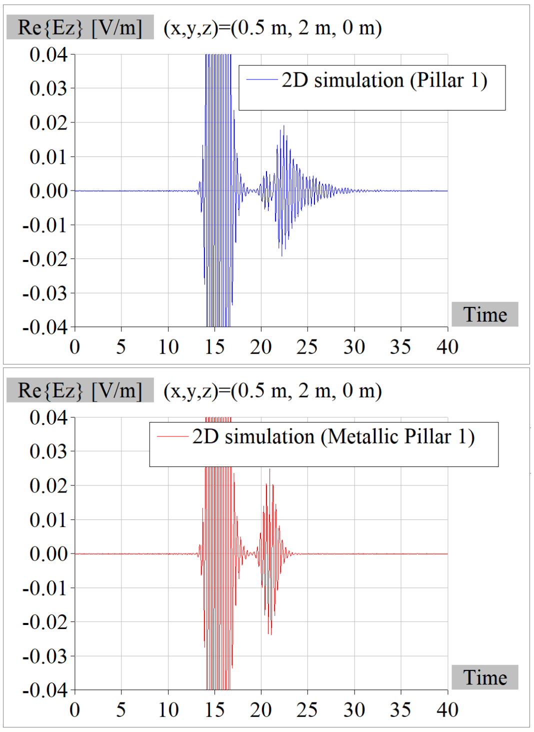


Fig. 6. The same results as in Fig. 5, scaled by factor 10.

To understand the reason for such behavior we performed the 2D simulation of the simpler scenario where the 2nd pillar has been removed. With 2nd pillar removed, two cases were considered. One includes a standard concrete pillar, while the second case deals with a metallic pillar. The results are shown in Fig. 5. and Fig. 6.

The signal is not distorted if reflected from the metal pillar but is distorted if it is reflected from the concrete pillar. This can be explained by the fact that a wave penetrates the concrete pilar and leaves it after a number of internal reflections.

Dirac delta impulse and pillars

Let us again consider the scenario consisting of a transmitter, a receiver, and two pillars, as shown in Fig. 7. This time, however, let us excite the structure using time domain signal represented with Dirac delta function.

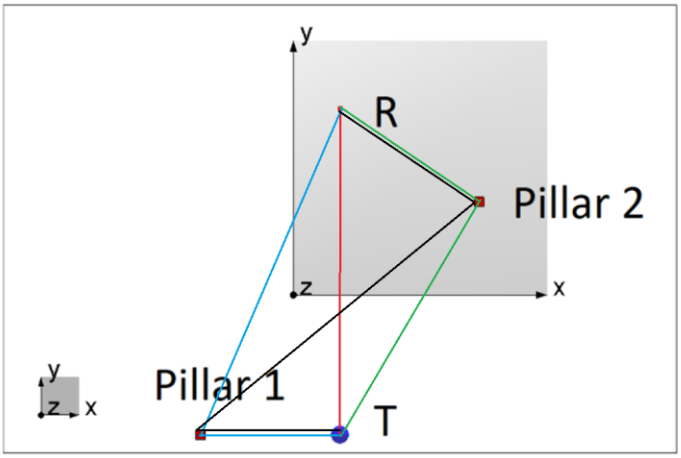


Fig. 7. Scenario consisted of a transmitter, a receiver and two pillars.

After reanalyzing the setup, we can conclude that there are four signal paths which should be considered. These paths are marked in Fig. 7. The red line marks a direct path between the transmitter and receiver, blue line includes reflection from the first pillar, green line reflection from the second pillar, while black line introduces reflections from both pillars.

The response to Dirac delta excitation is presented in Fig. 8. Beside the direct wave and the waves reflected separately from the first and the second pillar, the fourth delta impulse appears as well. Observing impulse time delay by comparing it with the ratio of distance marked as T-Pillar1-Pillar2-R and the speed of light, and taking into account the level of impulse, it is clear that the fourth impulse appears due to the reflection from both pillars.

Increasing the number of samples improves the clarity of the graph. However, it can also significantly increase the required computational resources. In that sense, a trade-off should be found. So, let us examine the scenario outlined in Fig. 7 in order to analyze the tradeoff.

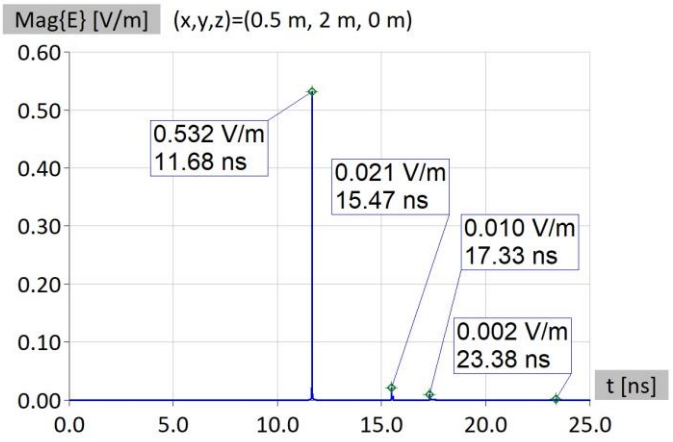


Fig. 8. Z-component of electric field at the location of the receiver in time domain for four paths considered.

The difference between time domain results when 5,001 and 1,251 time samples are used is shown in Fig. 9. Practically there is no difference in output results between the two settings. Of course, using 4 times lower number of samples significantly decreases computational resources.

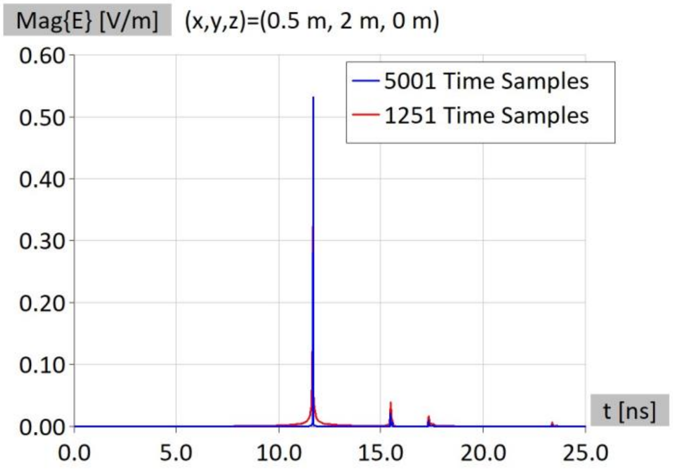


Fig. 9. Z-component of electric field at the location of the receiver in time domain for two different number of time samples.

Gaussian modulated pulse in room – various scenarios

To analyze receiving signal in a concrete room, a Gaussian modulated pulse (30% narrower than the pulses outlined in Figs. 3-6) is exploited. Carrier frequency is again set to 3 GHz.

The size of the room, the position of the pillars, and the locations of the transmitter and the receiver are changed. The transmitter operates as an omnidirectional antenna. All the simulations except the first simulation of the dipole antenna are performed using WIPL-D 2D Solver. The scenario is displayed in Fig. 10.

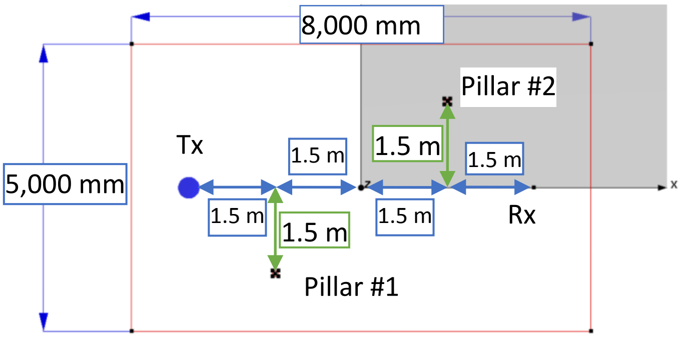


Fig. 10. Simulated scenario-transmitter, receiver, concrete room, and concrete pillars.

To verify 2D simulations, the same Gaussian modulated sines are exited in 2D and 3D environment. The time domain distribution of received signal is the same as it is shown in Fig. 11. The levels are different, which is expected due to the difference in the third dimension of the space.

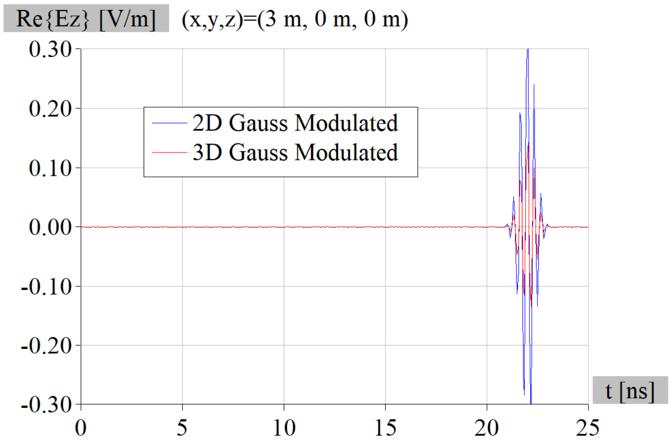


Fig. 11. Z-component of electric field at the receiver location in time domain for scenario in free space.

The next scenario to be investigated is scenario with two metallic pillars. The transmitter, the received position, and the pillars keep the position displayed in Fig. 10. The pillars are modeled as PEC metallic surfaces (in 2D space as PEC metallic strips). The room walls are omitted. The result is displayed in Fig. 12. The time domain received signal comprises three signals with different amplitudes. The first is directly received from the source, while the second and the third represent reflections from the first and the second pillar. Other multiple reflections cannot be observed when using this range.

The results presented in Fig. 13 were obtained with two concrete pillars replacing the metallic ones. The remainder of the scenario (the size of the pillars, positions…) remains the same.

As in the previous case, three signals can be observed. The signals are distorted compared to the case with purely metallic pillars. However, the conclusions regarding the reflections are similar.

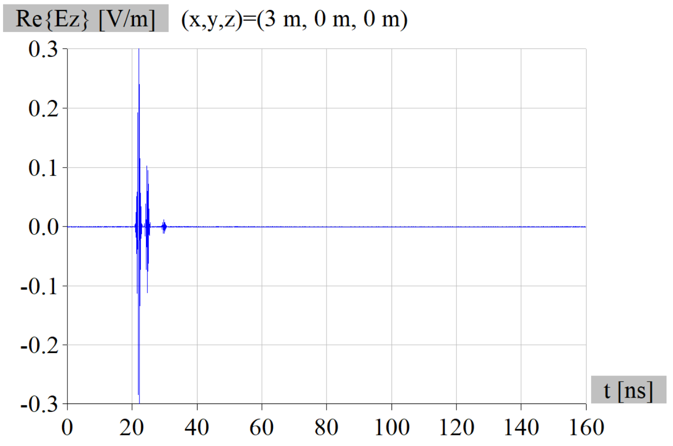


Fig. 12. Z-component of electric field at the position of the receiver in time domain for scenario with two metallic pillars in free space.

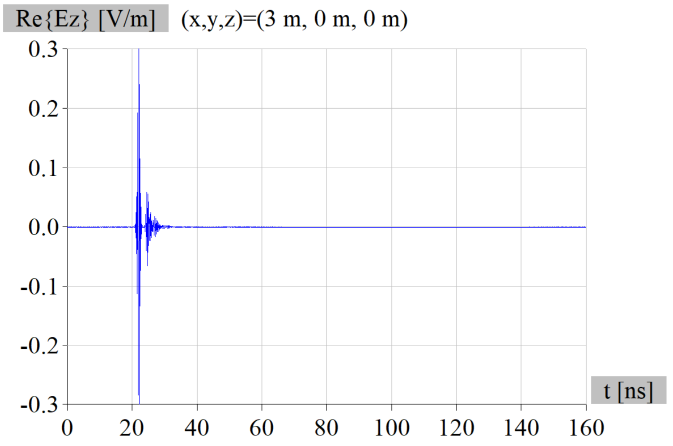


Fig. 13. Z-component of electric field at the position of the receiver in time domain for scenario with two concrete pillars in free space.

Fig. 14 displays a scenario with concrete pillars in concrete room. The result is expected – multiple received signals can be noticed. The direct signal is dominant and is the first to arrive at the receiver's position. Other large signals appear as reflections from the concrete walls. The small level signals are consequence of various multiple reflections.

The scenario which relates to Fig. 15 encompasses the transmitter, the receiver, and concrete walls without any pillar. When compared to Fig. 14, we can notice basic differences in response which are consequences of pillars' presence.

In Fig. 16, results for concrete room with walls with 200 mm finite thickness are displayed. All the reflections appearing in time domain are due to reflections from the inner and the outer side of the room walls.

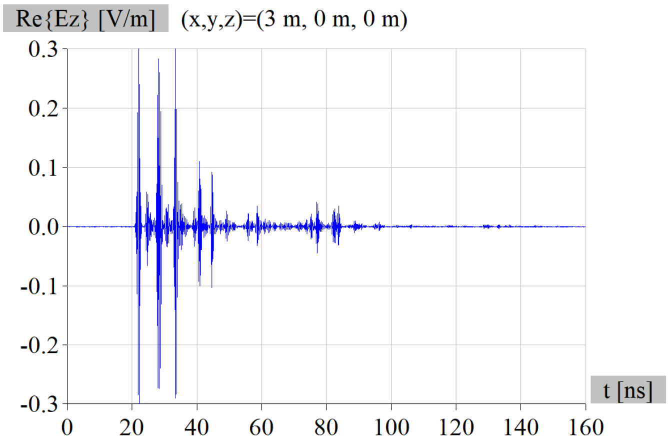


Fig. 14. Z-component of electric field at the position of the receiver in time domain for scenario with two pillars in concrete room.

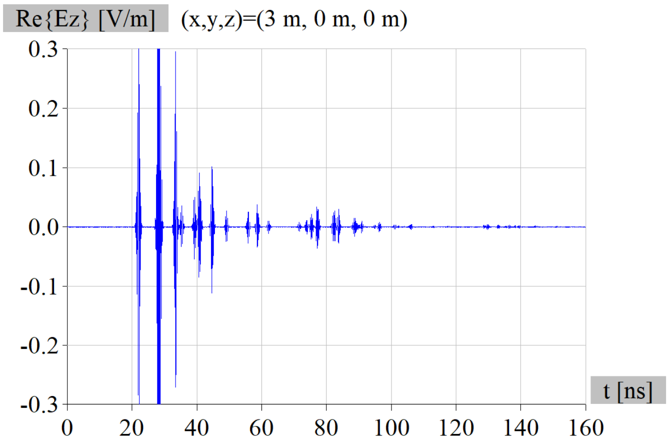


Fig. 15. Z-component of electric field at the position of the receiver in time domain for concrete room scenario without pillars.

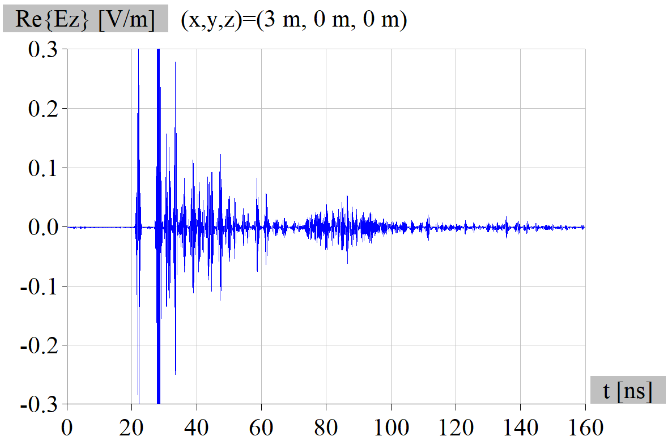


Fig. 16. Z-component of electric field at the position of the receiver in time domain for room with finite thickness walls.

Conclusion

The study demonstrates the significant computational challenges and methodologies for simulating indoor propagation channels using WIPL-D software. The paper compares the efficiency of 3D and 2D electromagnetic (EM) modeling to determine the most feasible approach for simulating complex indoor environments, particularly focusing on scenarios with obstacles like pillars. By employing WIPL-D's 2D EM Solver, which offers significant computational savings over 3D simulations, the study showcases how high-quality results can still be obtained for realistic indoor environments. The research illustrates that, for specific scenarios, 2D modeling can effectively replace 3D simulations, thus making it a more efficient alternative for analyzing time-domain propagation in smaller, resource-constrained computational environment. Moreover, the impact of material properties, such as the difference between concrete and metal pillars, on signal distortion is also highlighted, providing deeper insights into wave behavior in indoor settings.

New possibilities for more efficient features could be developed. These could help overcome existing 3D EM solver limitations and will be the subject of the “Part II” of this document.