

IoT Related EM Simulation Scenarios

Introduction

The most often, Internet of things (IoT) relates to interconnected network of sensors and mobile devices. In general, IoT is defined as set of interconnected physical objects or groups of physical objects embedded with sensors. The objects which are the part of IoT network usually have ability to process data and/or to interchange data with other systems over the internet or other communication networks. The field of IoT encompasses various technologies. However, this document will cover only electromagnetic (EM) aspects of selected IoT scenarios.

The application field of IoT is almost unlimited which is followed by the fact that the IoT market is versatile. For example, the consumer market involves IoT technologies in the concept of the smart home (e.g., remotely controlled vacuum cleaners, lighting, home heating systems, ...). Also, important IoT applications appear in the health systems, security systems, etc.

In this paper WIPL-D team presents suitability of WIPL-D software to analyze and design IoT systems. Several scenarios and IoT devices are described, related EM models are explained and simulation results are presented in the following sections. Short description of the document sections follows.

Section 1 - IoT devices within an aircraft apartment:

The operating environment of an Internet of Things (IoT) system is usually complex and includes the presence of some wave propagation obstacles, e.g., furniture for an indoor scenario. A typical example of such a scenario could be a modern traveling environment onboard a luxury aircraft which includes a passenger inside an aircraft apartment and several pieces of furniture (Figure 1).

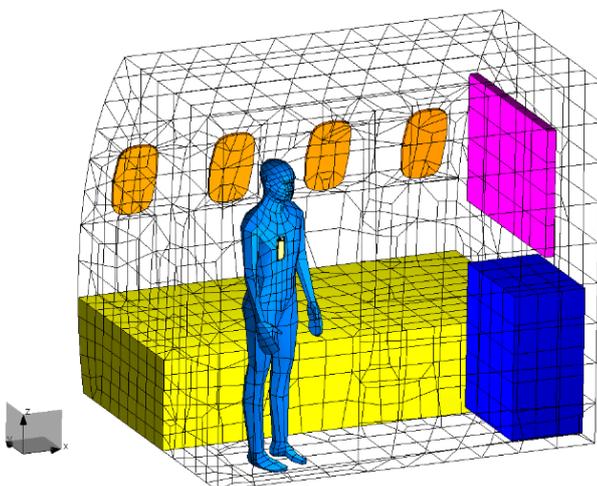


Figure 1. An IoT scenario: The model of the apartment with traveler phantom, a cellphone and a sensor (the sensor is not shown in this figure)

On the one side of the IoT link is a traveler with a cellphone, and on the other side is a warning sensor located in a locker compartment intended to warn the passenger if an object is forgotten inside a locker. The cellphone antenna is modeled as a printed dipole inside the phone housing, while the sensor hardware is simplified to an inverted-F antenna (IFA) [1].

Section 2 - IoT devices used for determining human position:

Beside typical data exchange, the EM radiation originating from Internet of Things (IoT) devices can be processed to provide a number of secondary information which could in turn be used for various purposes. One of the examples could be measurement and processing of signals occurring in an IoT system to realize movement detection or person tracking.

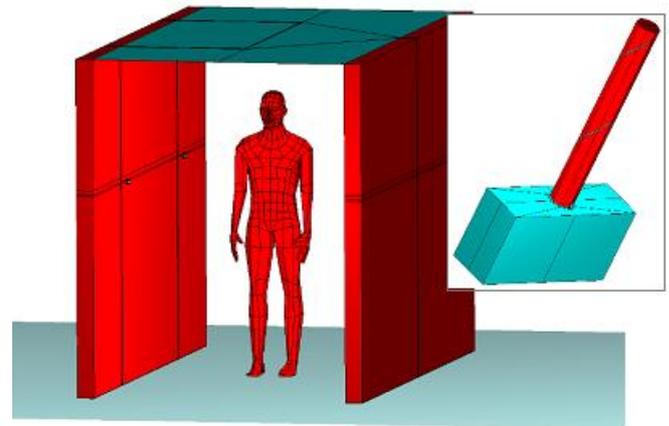


Figure 2. The corridor with ceil and floor, containing dielectric walls, human phantom, and three Wi-Fi routers

The indoor scenario presented encompasses the corridor with the ceiling and the floor modeled with metallic plates and infinite PEC plane, respectively, a person inside a corridor modeled with a human phantom and 3 Wi-Fi routers. From the perspective of a position-determination scenario, it is interesting to analyze situations where 1 of 3 routers transmits a signal, while the remaining 2 operate as receivers. It is expected that, as a person moves inside the corridor, the received signals will change. This property could provide a possibility to detect a presence or even determine a position of a human within a corridor.

Section 3 - Various RFID devices and scenarios:

Radio-frequency identification (RFID) devices as a part of IoT network are one of the many electromagnetic (EM) applications where WIPL-D software suite can be successfully used. RFID assumes the wireless usage transfer of data, mostly for the purposes of automatic identification and tracking of various tags attached to target objects

The range of industries in which the RFID technologies can be applied is huge (automotive, RFID-tagged pharmaceuticals, RFID

microchipping of pets, storage of goods, tracking, ...). In this section, we will briefly describe a part of possible applications of WIPL-D software for devices marked as RFID (tags and readers) assuming that all of them can be used as a part of an IoT network.

About WIPL-D Software

The simulations of all models and scenarios will be carried out using WIPL-D software suite, a cutting-edge full wave 3D electromagnetic Method-of-Moments based software which applies Surface Integral Equations (SIEs). The main WIPL-D software components are WIPL-D Pro and WIPL-D Pro CAD. WIPL-D Pro is a powerful solver and modeler of various EM structures. WIPL-D Pro CAD represents modeling and simulation environment where geometry modelling is simplified and based on various built-in solids and Boolean operations. Import of different CAD file formats is also supported.

Numerical kernel of WIPL-D software by default uses very sophisticated higher order basis functions (HOBFs) with quadrilateral meshing. This means that the mesh elements are quads, as opposed to commonly used triangles, and that the basis functions are higher order polynomials, not simple linear (rooftop) functions. Hence, for the case where a current distribution over a surface is approximated using HOBFs, the current distribution can have considerably higher dynamic than in the case where the same number of rooftops is used. Owing to this efficiency, significantly larger structures are quickly simulated on relatively inexpensive workstations. Application of HOBFs is entirely automatic, although the user can increase the accuracy of the approximation.

It will be shown that all calculations are very efficient providing high accuracy in reasonable simulation time. In addition, WIPL-D software is extremely efficient for simulation of coupling between very distant objects (no boundary box requirement). Furthermore, WIPL-D does not require meshing of the space between the coupled objects (e.g., two IoT sensors or the reader and the tag). Another advantage for simulating electrically large complex structures is *Smart reduction* feature. The *Smart reduction* is a feature which is very suitable for antenna placement problems. It is based on adaptive reduction of current expansion order over parts of the model which are distant from the antenna or in shadow, hence less relevant for EM simulation. Applying *Smart reduction*, the number of unknowns can be significantly reduced, while very good accuracy of calculated radiation pattern or coupling between multiple antennas is preserved.

1. IoT Scenarios Within an Aircraft Apartment

WIPL-D Models

A CAD file representing commercial airliner was imported to WIPL-D Pro CAD working environment and prepared for simulation. The imported model was modified to include the

luxury flight apartment, a passenger and pieces of furniture as presented in Figure 1 and Figure 3.

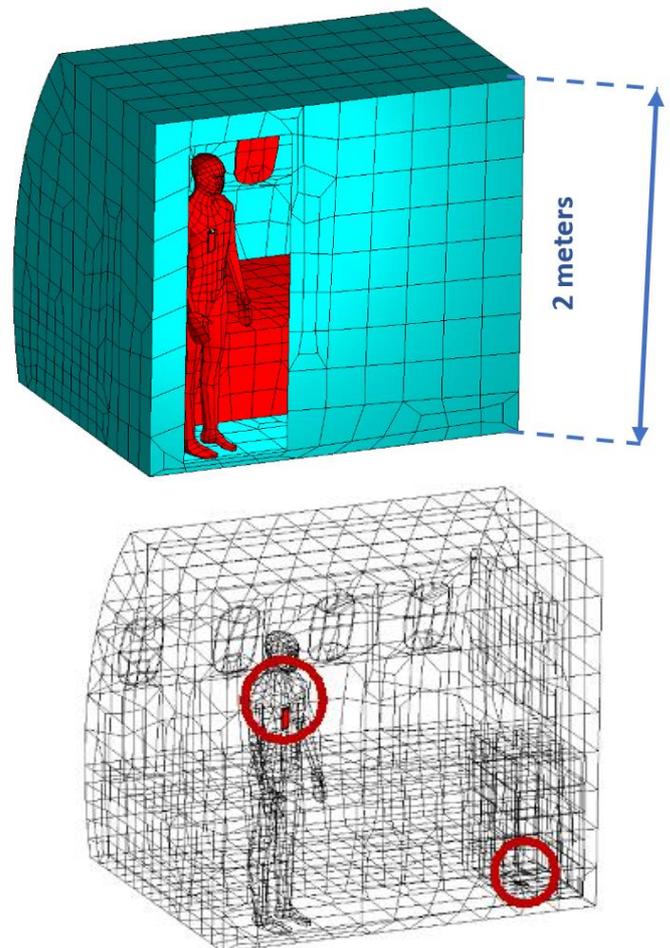


Figure 3. An IoT scenario within the aircraft apartment. Metallic walls and height of the apartment (top image). Communicating devices (bottom image)

As shown in Figures 1 and 3, the passenger is modeled using a human phantom with the cellphone located at the chest and presented as the yellow box in Figure 1. The model of the apartment includes metallic walls which are presented in transparent wire frame and dielectric windows in orange (Figure 1). A magenta box represents a monitor, yellow box stands for a bed, while a blue box models a locker (Figure 1). A sensor IFA is located inside the blue box (Figure 1). The apartment walls were modeled using PEC metallic surfaces (Figure 3). Finally, only the communicating devices are shown for clarity in the bottom of Figure 3.

The simplified cell-phone model is shown in Figure 4. On the top left-hand side, the exterior of the phone is presented – it has a form of a dielectric box. The interior is represented on the top right-hand side in the Figure 4. The printed circuit board (PCB) is approximated with a finite PEC plane. The dipole antenna is located adjacent to the PCB. The model of the IFA representing the sensor within the locker is shown in the Figure 4.

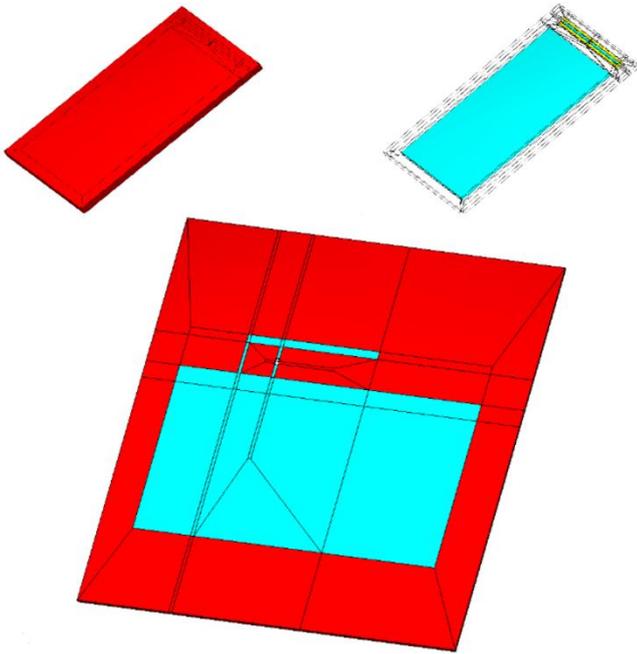


Figure 4. The model of the cellphone and its interior (top images) and IFA representing the sensor (bottom image)

This apartment scenario model contains several models of dielectric objects. A list of the objects and electrical properties of corresponding materials can be found in Table 1. The properties of the materials are selected for the illustration purposes only.

Table 1. Properties of applied materials

Object	Er	TgD
Human phantom	100	0 (Sigma = 3 [S/m])
Window glass	2	0.0025
Apartment walls		PEC
Bed	4	0.00025
Monitor		PEC
Locker	3	0.000667
Cellphone case	3	0

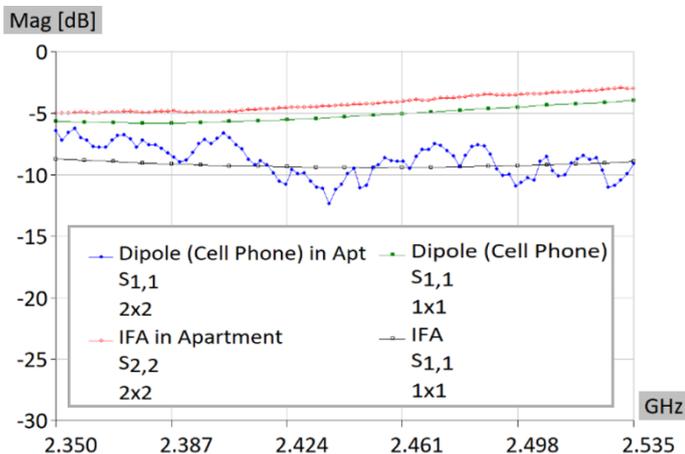


Figure 5. Comparison of S-parameters between IFA in free space, IFA in the apartment, dipole (in cell phone) in free space, and dipole (in cell phone) in the apartment

Simulations and Results

All the projects (Figures 5-6) were simulated in the frequency range from 2.350 GHz to 2.535 GHz. Dipole antenna (Figure 4, top) has been simulated as located in an isolated phone, while IFA (Figure 4) has been simulated as radiating in free space. Calculated S-parameters are shown in Figure 5. Both simulations are very fast as they take no more than a couple of minutes as the problems' sizes require around 2,000 unknowns.

After confirming that matching of both antennas is acceptable, the antennas are simulated as a part of the whole IoT aircraft apartment scenario. It is adopted that for frequency band from 2.350 GHz to 2.535 GHz, 94 frequency points are required. The apartment scenario simulations were performed with WIPL-D *Smart reduction* feature set to 50% and numerical kernel parameter *Integral accuracy* set to *Enhanced 2*. The results of simulation of two communicating devices inside the apartment onboard the aircraft were compared with S-parameters of IFA and the dipole (within the cell phone) in free space (Figure 5). It can be seen that the matching of the antennas is not affected significantly when they operate in this IoT scenario.

S-parameter representing transmission between two antennas located within the apartment is shown in Figure 6. The average coupling between the antenna in the frequency range is approximately -44 dB which can be used in a preliminary link budget calculation. S-parameters representing transmission between two antennas located within the apartment when IFA is moved along x axis with a space resolution of 6 mm are also presented in Figure 6. It can be concluded that the link budget remains almost unchanged for the specified movement of the sensor antenna.

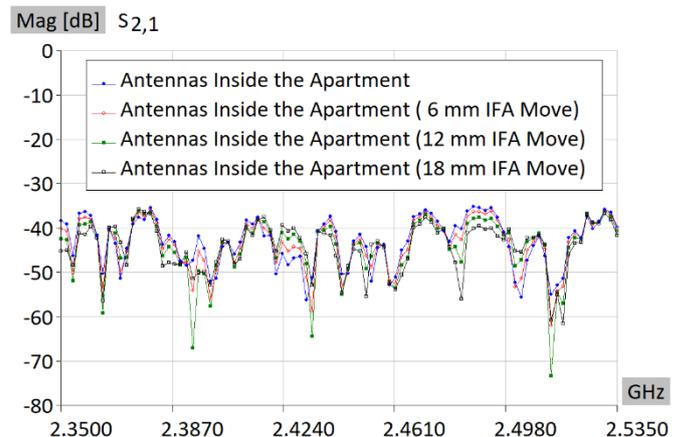


Figure 6. Transmission between two antennas within the apartment for several positions of the IFA

Specification of computer hardware used for simulations is presented in Table 2. Number of unknowns and simulation time per are presented in Table 3. Matrix fill was performed on CPU, while matrix solution was performed using GPU cards.

Table 2. Computer used in the aircraft apartment IoT scenario simulations.

Hardware	Description
CPU	Intel® Xeon® CPU E5-2650 v4 @ 2.20GHz 2.20 GHz (2 processors)
RAM	256 GB
GPU	4 cards: Nvidia GeForce GTX 1080 Ti

Table 3. Number of unknowns and simulation times for simulated aircraft apartment IoT scenario

Project	Number of Unknowns	Simulation Time per Frequency
Antennas within the apartment with obstacles	118,082	~19 minutes

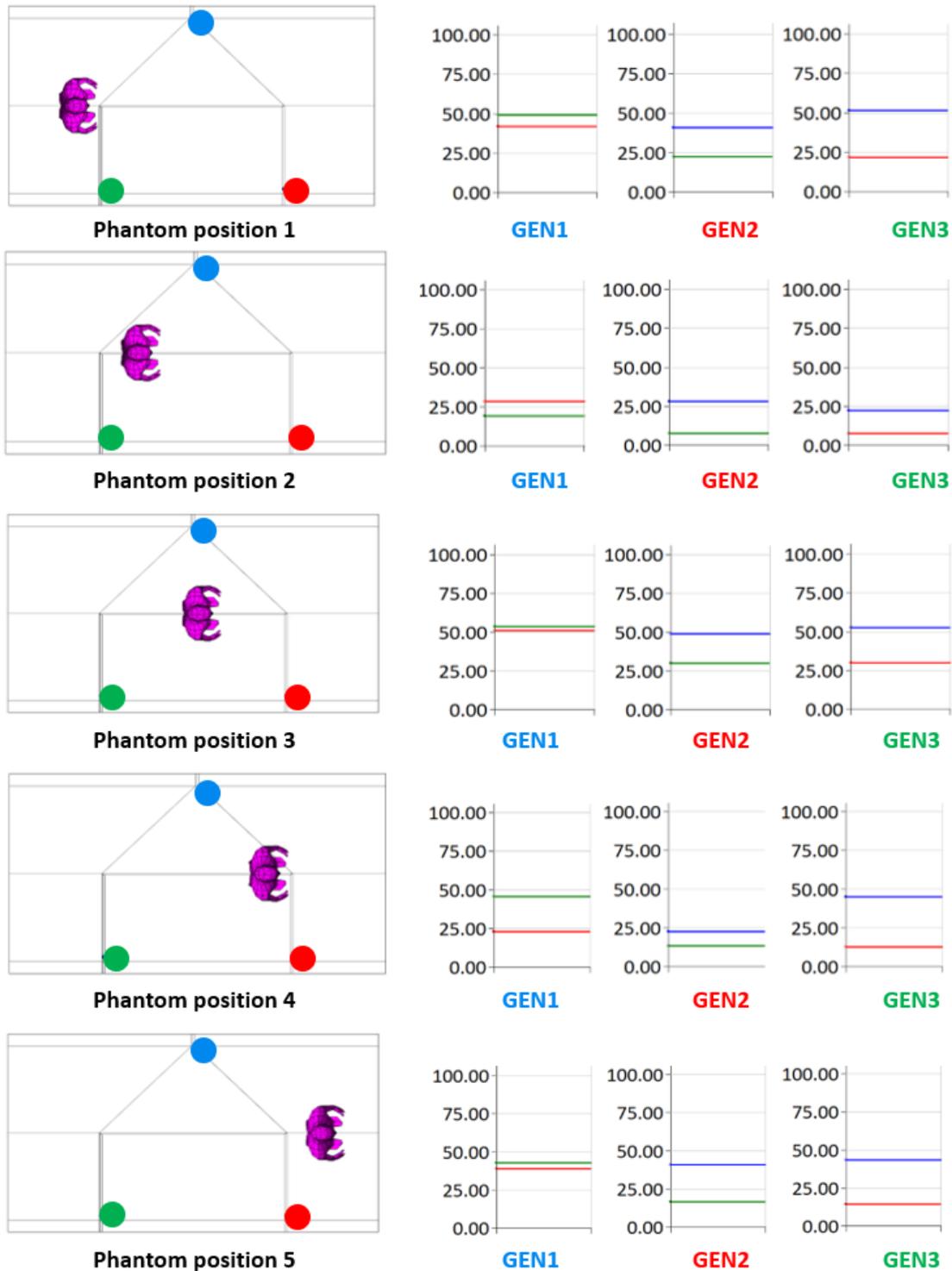


Figure 7. Phantom positions and levels of the currents

2. IoT Devices Used for Determining Human Position

WIPL-D Models

The complete model of the scenario considered here includes corridor with metallic floor and metallic ceiling, with walls modeled as dielectric bricks, human phantom, and 3 models of Wi-Fi router (shown in Figure 2 on page 1). The magnified view of Wi-Fi router model used in this particular scenario is also presented in the aforementioned Figure 1. The Wi-Fi routers are positioned at a height of $z=1.2$ meters so that they form an isosceles triangle (Figure 7). The list of the dielectric objects included in the scenario and corresponding electrical properties is listed in the Table 4.

Simulations and Results

Five simulations were performed, each with a different position of the phantom along the corridor to mimic the human movement. Simulations were carried out at 2.4 GHz. The signal levels related to all positions of the human phantom were recorded. The bird's-eye view of the corridor indicating five positions of the human body are presented on left part of Figure 7, while the corresponding received signal levels (antenna currents in particular) are shown on the right. The results presented in Figure 7 clearly show that a judicious processing of the received signals could provide, not only the information about the presence of a person inside the corridor, but the position of that person along the corridor as well.

Table 4. Specification of applied dielectric materials

Object	Er	TgD
Human phantom	100	0 (Sigma = 3 [S/m])
Helix mast	2	0
Corridor walls	3	0.0167

Computer hardware used for the simulations is presented in Table 5. Table 6 contains the info on the number of elements, the number of unknowns and the simulation time per one position of the human phantom. Matrix fill was performed on CPU, while matrix solution was performed using GPU cards.

Table 5. Computer used in the simulations.

Hardware	Description
CPU	Intel® Xeon® Gold 5118 CPU @ 2.30GHz 2.30 GHz (2 processors)
RAM	192 GB
GPU	4 cards: Nvidia GeForce GTX 1080 Ti

Table 6. Number of unknowns and simulation times for simulated scenario

Number of elements	Number of unknowns	Simulation time per phantom position
7,648	171,489	37 min

3. RFID Applications

Commercial RFID Tags

The typical RFID tag printed on a single layer dielectric substrate is shown in Figure 8. When the symmetry of the structure is introduced only a half of the model can be simulated which reduces simulation requirements. The model printed on the dielectric requires around 2,000 unknowns and a few seconds per frequency point for the case where the simulation is carried out using a regular desktop PC or a laptop. The comparison between results obtained with printed tag and the results obtained with pure metallic tag in free space are also shown in Figure 8.

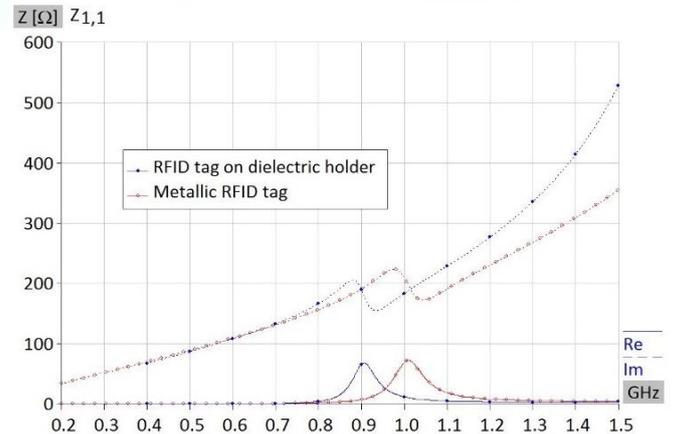
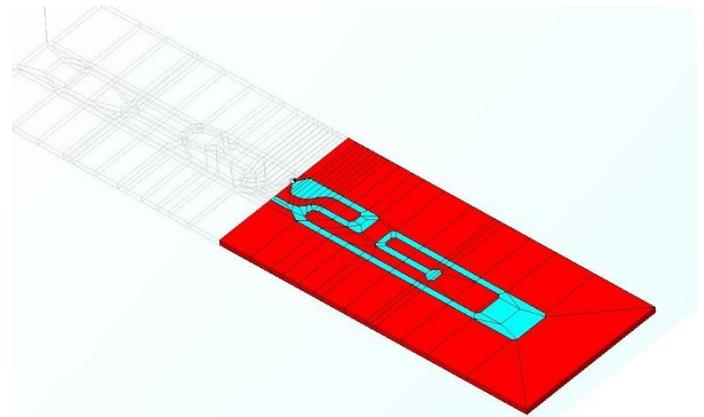


Figure 8. A RFID tag printed on dielectric substrate and impedances of tags in free space and printed on substrate

A tag on a flexible substrate has been also investigated. The effect of bending the presented tag is examined. This represents a situation that occurs with RFID systems in hospitals where similar tags are installed by wrapping them around patient's wrist. The simulation of a bent tag 3D EM model requires practically the same number of unknowns as for the straight one, and the simulation time is also almost identical. Tags with various bending shapes are shown in Figure 9. The obtained results for different bending shapes are shown in Figure 10.



Figure 9. Bent RFID tag emulating wrapping around wrist

Complex RFID Reader

RFID devices can operate in several frequency bands starting from LF (~130 kHz) over HF (~13.56 MHz) to ~900 MHz. For the bands with lower frequencies, RFID devices are mostly made as electrically small devices. In that sense, WIPL-D Pro has ability to simulate very precisely projects with electrically small details by using *double* precision. RFID readers at 13.56 MHz may have many turns in order to achieve electrical length needed to register low level tag signals. They are also usually immersed in plastic used for protection. Figures 11-12 show 13.56 MHz RFID reader implemented in 7 layers.

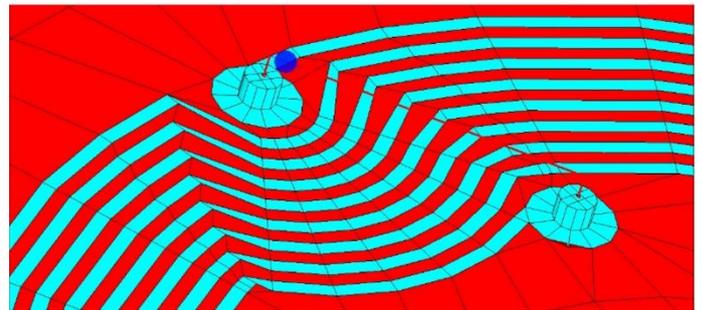
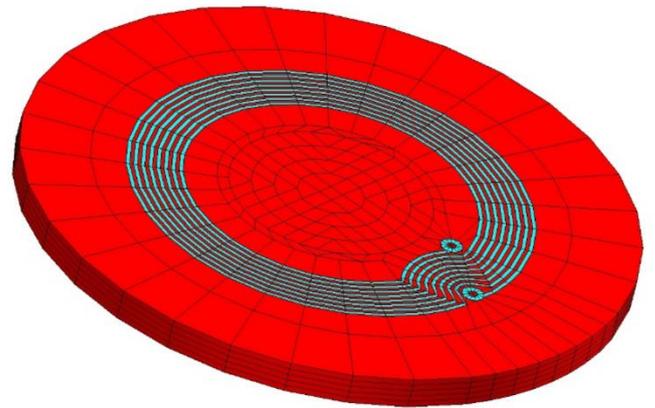


Figure 11. RFID reader and its feeding area

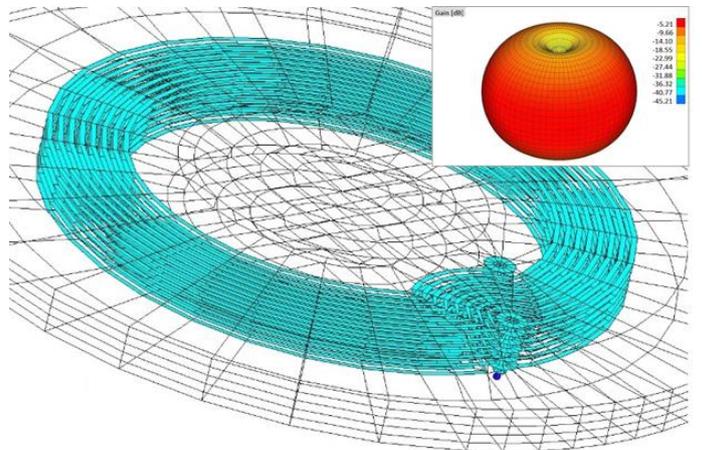


Figure 12. RFID reader interior with 7 metallic layers and its low gain performance

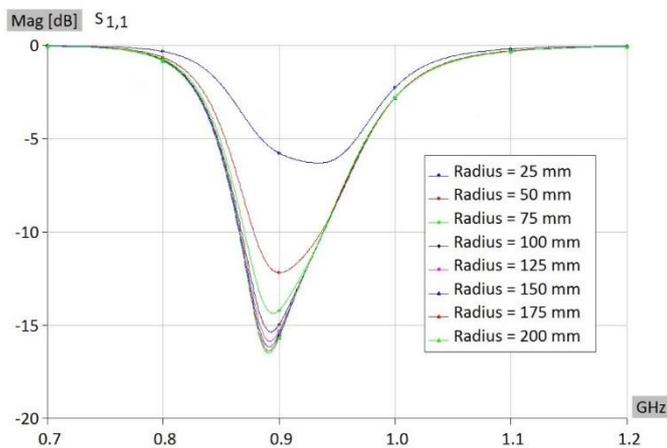


Figure 10. Return loss of the wrapped tag

Despite the significant complexity of the RFID reader, the problem requires less than 10,000 unknowns and simulations last under a minute. Simulations show great accuracy even when user deals with demanding performances such as calculation of the device radiation pattern (Figure 12).

Multiband RFID Device

Very often the devices made for RFID/IoT are general purpose, not application specific. An example can be cross spiral antenna (Figure 13). [2] The antenna exhibits good performances at 3 frequency bands so it is supposed to be used as combined RFID, mobile-phone (UMTS) and GPS band device (1.0 GHz, 1.8 GHz, and 1.67 GHz). In order to test the accuracy, feeding area of the structure was modeled in two completely different ways (Figure 13, bottom). The results originating from these two feedings are very stable and very similar (Figure 14).

The model with simple feed runs in a few seconds with ~2,000 unknowns required, while the complex feed model requires a few

more seconds with ~4,000 unknowns required. The excellent agreement with measured results is shown in Figure 14.

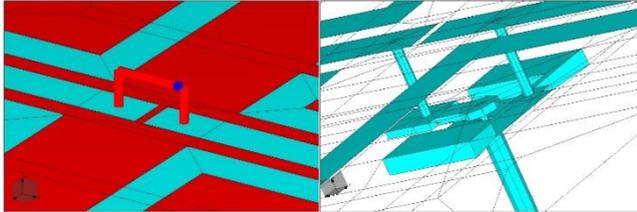
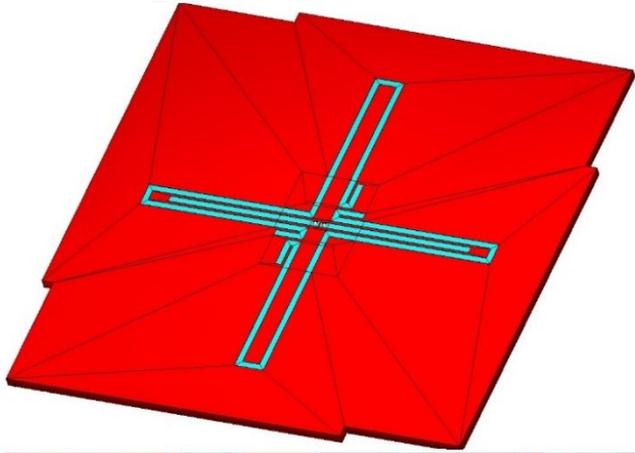


Figure 13. Three-band CSA simple feed and complex feed

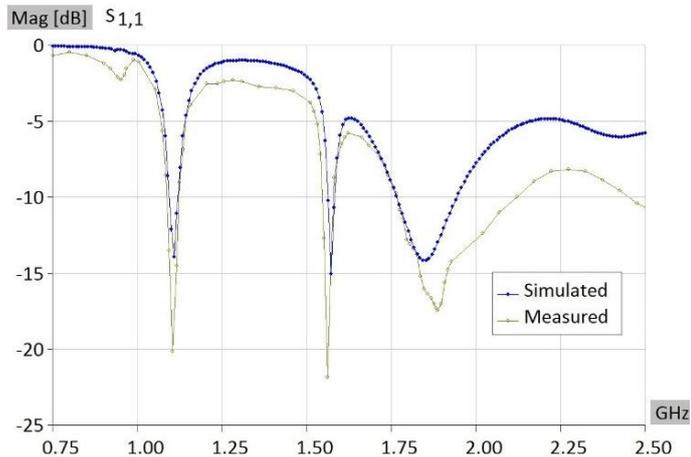
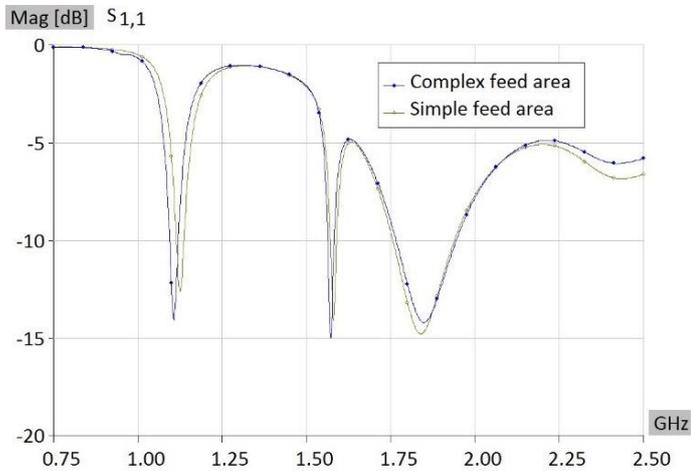


Figure 14. Two different feeding methods and comparison with measured results

Mobile RFID Reader

An example of mobile RFID device can be square quadrifilar spiral antenna (QSA, shown in Figure 15) with circular polarization for UHF mobile RFID reader. [3] In order to make a device with excellent performances but firm positioning, the separate dielectric substrates are used for power divider and feeding. Antenna exhibits extremely low axial ratio (Figure 16). Right-hand and left-hand circular polarizations are shown in Figure 17a.

One of many advantages of WIPL-D Pro is its ability to precisely calculate the coupling between the feeding ports. The same was exploited here and the result is shown in Figure 17b. For these simulations the project requires around 5,000 unknowns for the antenna, feeding network and finite ground. The simulation runs in just a couple of minutes.

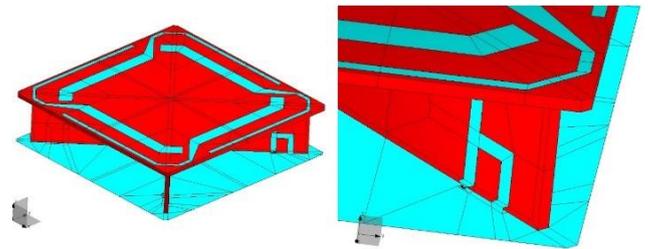


Figure 15. QSA antenna and feeding zone

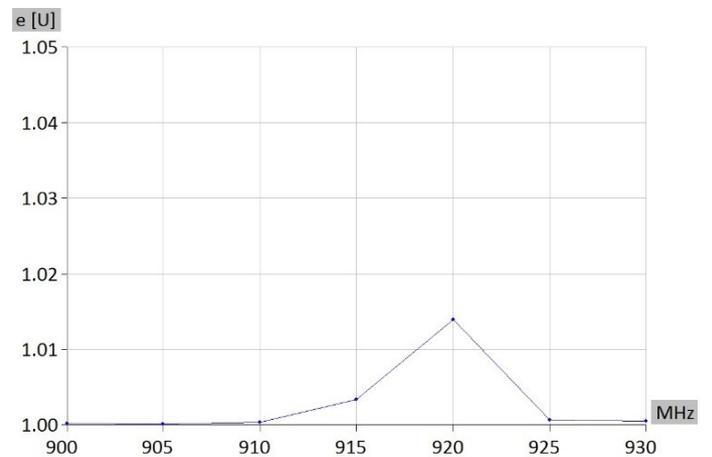


Figure 16. QSA axial ratio

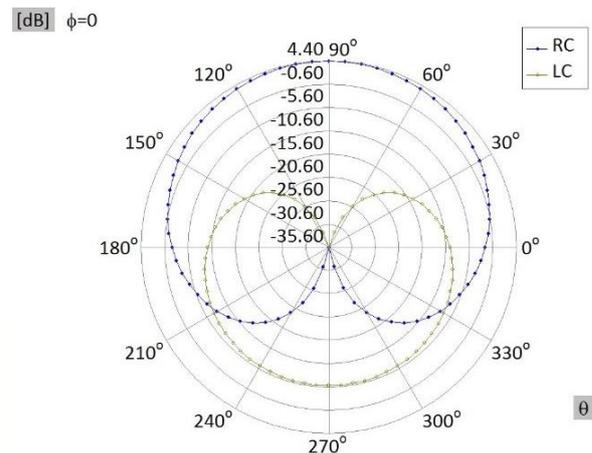


Figure 17a. RC and LC polarization (QSA)

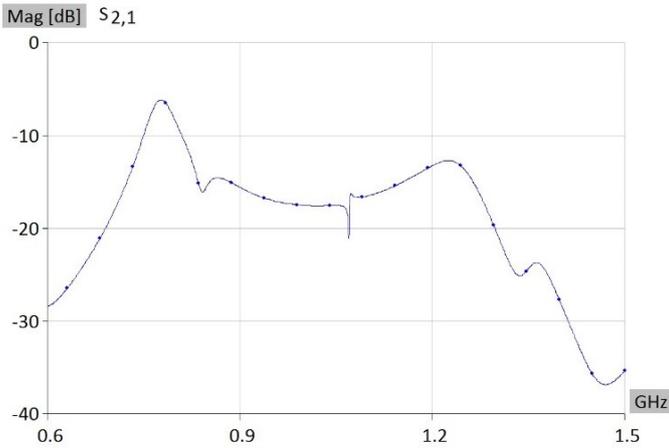


Figure 17b. Coupling between ports for QSA

A RFID Reader

This is a simple RFID reader, with a conductor pattern printed on both sides of a substrate and interconnections going through the dielectric (Figure 18). RFID reader model was created using WIPL-D Pro CAD. The model has been meshed automatically and simulated. The simulation requires around 1,000 unknowns and lasts ~ 30 seconds at regular desktop PC or laptop. The results of interest for the particular reader are: impedance and near field (Figure 18).

A more advanced design is based on rectangular spiral (see Figure 19); conductor pattern is double-sided, each side comprising several turns). The model represents a RFID operation scenario, i.e., coupling between two similar antennas with the different port impedances. The calculated return loss of a single antenna and coupling between two antennas is shown in Figure 20.

The simulation requirements do not depend on distance between antennas, as this is the basic property of WIPL-D kernel: no bounding box is required and the space between antennas is not meshed. Antennas can be placed arbitrarily (e.g., 10, 100 or 1000 λ apart) with a computational burden remaining unchanged. The coupling scenario requires under 10,000 HOBFs unknowns. Simulation time is a couple of minutes at any regular desktop PC or laptop.

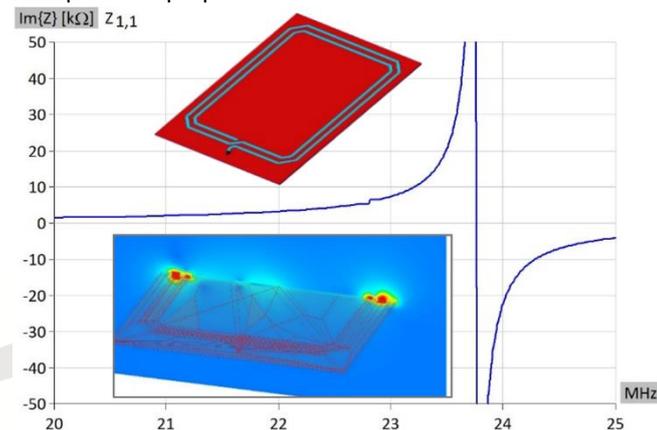


Figure 18. RFID reader and output results

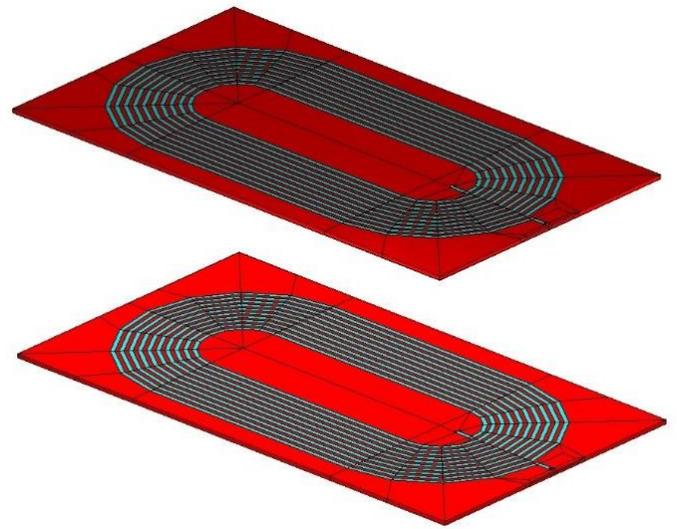


Figure 19. More complex RFID scenario

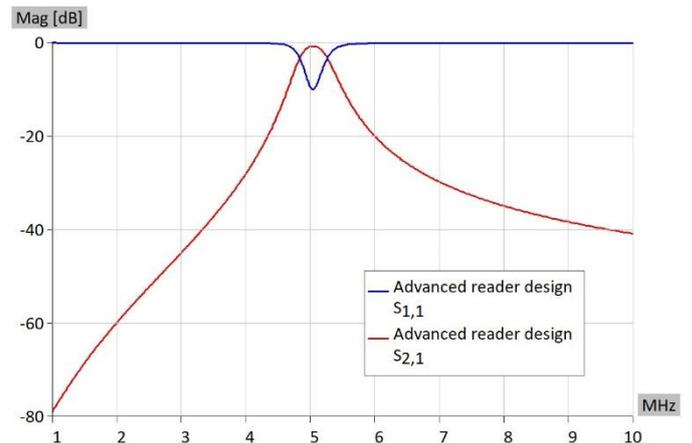


Figure 20. Return loss and coupling between RFID antennas

Realistic RFID Scenarios

Complex scenario which involves tags mounted on plastic containers and RFID reader located at some realistic distance are presented next (Figure 21).

The tag is placed on large plastic container (4 x 4 x 14 cm]. The container is made of plastic with dielectric constant $\epsilon_r=3$ and the thickness of 1 mm. The reader is placed at a distance of approximately 2 m.

The focus in this study is on the transmission between the reader and three tags (Figure 21). The excitation impulse is a simple trapezoidal modulated signal (Figure 22). The results of interest involve not only the coupling matrix in frequency domain (Figure 22), but also the received pulses in time domain.

The trapezoidal pulse is modulated with 1 GHz carrier, determining the frequency of the simulation. The entire scenario requires under 50,000 unknowns. Such simulation can be carried out in a couple of minutes per frequency point. The required hardware is a desktop PC equipped with moderate CUDA enabled GPU card.

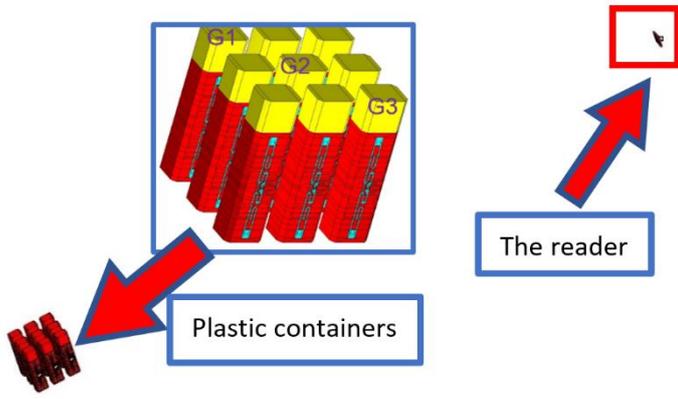


Figure 21. RFID tags on plastic containers away from the reader. Three tags are active: G1, G2, and G3

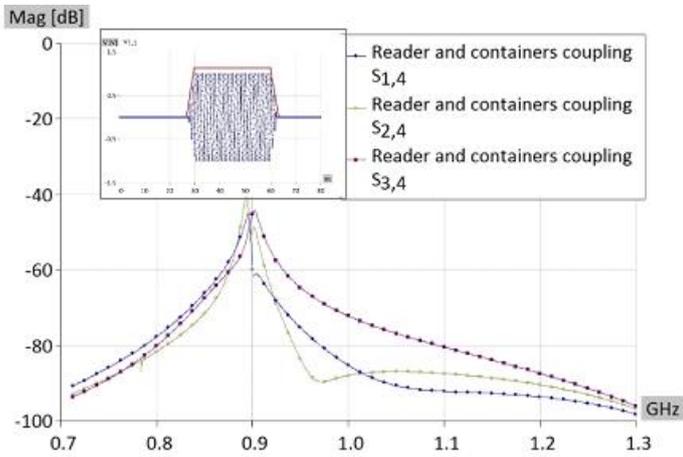


Figure 22. Excitation signal in time domain and coupling between the reader and the tags

The radiated impulse in the time domain is shown in Figure 23. This is basically the input current at the Tx port. Narrowband antenna yields long “tail” of the excitation impulse (Figure 23). Next, induced currents on Rx ports are shown in Figure 24. Current is in μA , while the Tx power is mA. Signal is delayed for ~ 6 ns, again with a long “tail” caused by narrowband antennas.

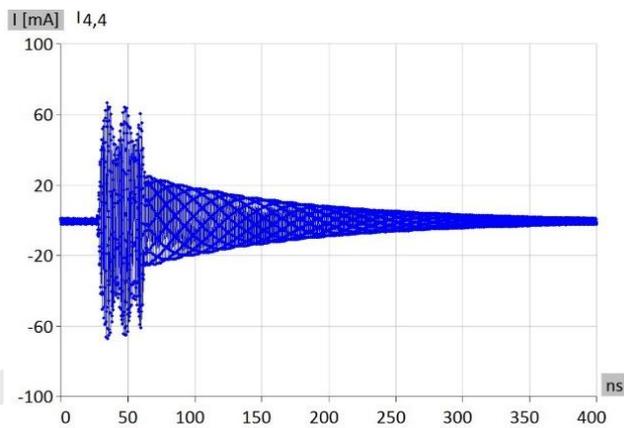


Figure 23. Radiated impulse

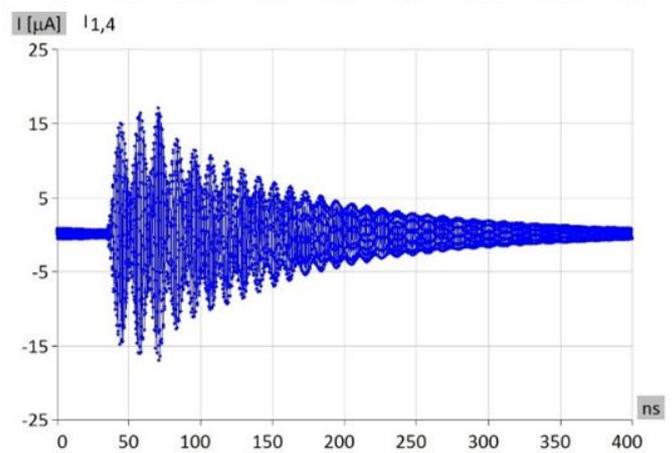
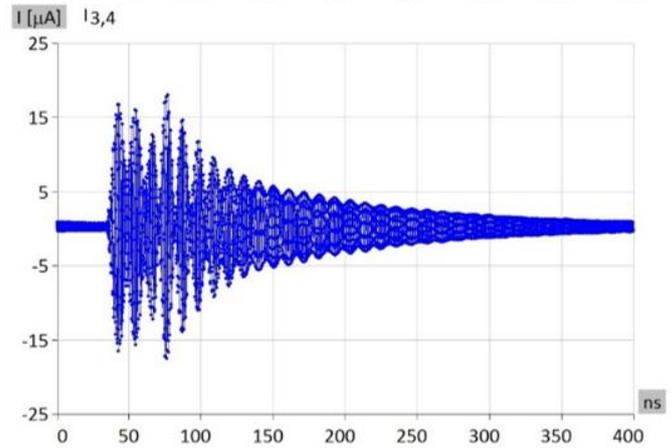
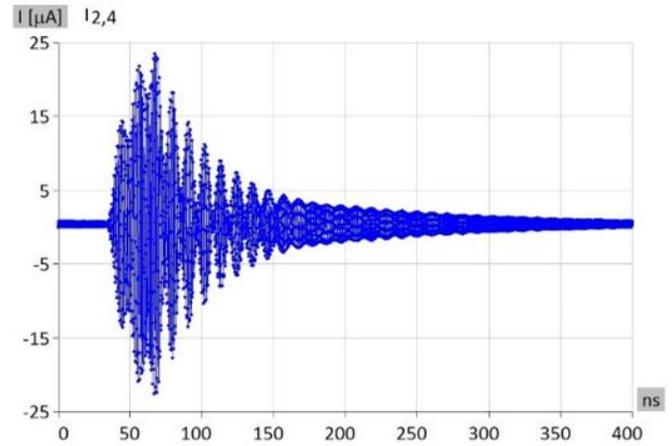


Figure 24. The received signals

4. Conclusion

Most prominent results for various IoT scenarios and devices in this paper are:

- IoT scenario inside aircraft containing two antennas, a traveler with cellphone, and the airplane apartment interior including the apartment walls and furniture.
- IoT environment where received antenna signals can be exploited for purpose of detection of human movement or even for determining exact human position within the corridor.
- Several RFID devices and an RFID scenario (reader/tag design, using flexible substrates and miniaturization).
- RFID reader devices are solved instantly with very low number of unknowns at regular desktop/laptop PC. Complex RFID simulation shows RFID tags mounted on plastic containers; RFID reader spaced 2 m apart.

It was shown that all presented simulations were successfully carried out using WIPL-D Software, a full wave 3D electromagnetic Method-of-Moments based software which applies Surface Integral Equations. Unlike common practice to simulate various models and scenarios applying various asymptotic solvers, WIPL-D full-wave MoM based solver, can be successfully used to simulate realistic scenarios and various devices in acceptable amount of time utilizing acceptable number of resources.

References

- [1] https://en.wikipedia.org/wiki/Inverted-F_antenna
- [2] "A multi-polarization multi-band cross spiral antenna for mobile communication devices", ISAP 2012 International Symposium.
- [3] "Compact Square Quadrifilar Spiral Antenna with circular polarization for UHF mobile RFID Reader", Microwave Conference Proceedings (APMC), 2010