Case Study

EM signal propagation and reception for communications systems and radar systems.

Developed and curated by the Ansys Academic Development Team

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Summary

This case study demonstrates some basic concepts in analyzing the power level estimation for the receiver end of a system, telecommunications and radars. This case study focuses on the explanation of the signal propagation, signal power analysis, deriving the Friis equation and the radar equation. The theoretical analysis is compared to simulation results using the Ansys HFSS™ high-frequency electromagnetic simulation software.

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1. Introduction

The main systems that utilize a receiver antenna are communication and radar systems. For a communication or radar system to operate, a minimum signal strength at the receiver antenna is required. The minimum signal strength needed is calculated considering the different parameters of the receiver system (system Noise Figure, system losses, system/antenna mismatches, etc). A receiver analysis can provide the minimum signal strength needed at the antenna end, which will be the focus of this case study.

As a receiver is a part of a system, it is important to understand the system composition and how the related equations evolve.

A basic system composition would identify three main components as:

a) the transmitter antenna that emits the EM signal into the air/atmosphere/propagation medium,

b) the propagation medium in which the EM signals propagate (while some power is transferred from signal into the medium as losses),

c) the receiver antenna that collects the EM signal and transfers it to the receiver system.

In order to estimate the power available at a distance from the transmitter, it is necessary to understand that a signal and the respective energy propagates as a wave. Since the antenna characteristics define the radiation method and directivity in respect to angle, the power density method needs to be used since the receiver antenna will intercept energy according to its effective area or aperture. The power density (S_t) at a distance R from the transmitter antenna is given by:

$$S_t = \frac{P_t}{4\pi R^2} G_t(\theta, \varphi) \quad [W/m^2] \tag{1}$$

where P_t is the power input to the antenna, $G_t\ (\theta, \varphi)$ is the total gain of the antenna (considering efficiency and directivity) in the direction (θ,φ). The same antenna can be used for transmission or reception of a signal. A graphical representation can be given below for the example of a horn antenna, the total gain (colored beam) and an example of effective area of a receiver antenna (red rectangle) that may intercept the radiated power is shown in the figure below:

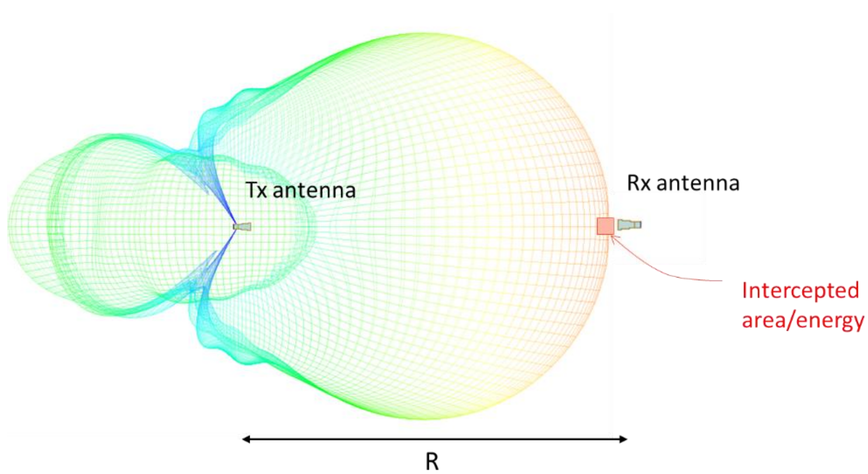

Figure 1: Energy transmission with a horn antenna and potential interception of a receiver antenna

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In the case of the antenna being used at the receiver end, the receiver antenna will intercept energy according to the receiver antenna effective area. The received power P_r at the receiver antenna can be represented as:

$$P_r = e_r \, A_r \, S_t \quad [W] \tag{2}$$

where A_r is the receiver antenna effective area, e_r is the radiation efficiency of the receiver antenna and S_t is the transmit signal power density at the position of the receiver antenna related to the transmitter.

There are mainly 2 setups that can be form using a transmitter and a receiver in everyday applications, and these are (a) the telecommunication setup and (b) the radar setup. In general, the transmitted signal will propagate and then will be received by the receiver. The transmitted signal may arrive at the receiver via different routes and a number of bounces/reflections. In the case of a telecommunications system, we are interested in the received signal with the highest power, and thus the signal that got reflected fewer times. In a radar system, the signals of interest are the signals that have bounced off objects and they are considered reflected signals, and by using signal processing we can estimate where the objects were.

2. Communication case

2.1 Friis equation

Let us analyze first a telecommunication setup. A high-level system view consists of the transmitter end, the propagation medium and the receiver end. The different propagation scenarios through the propagation medium will result in different signal power at the receiver end. The scenarios include different number of bounces, on different objects, different materials and the medium losses too. We can calculate all the previous using the appropriate equations for reflection and the effect of the material properties. However, in this analysis we will analyze the case of bounce-less propagation in air or vacuum (no losses). <u>This can be described as a line-of-sight setup in vacuum/air.</u> In the figure below we can see the above setup.

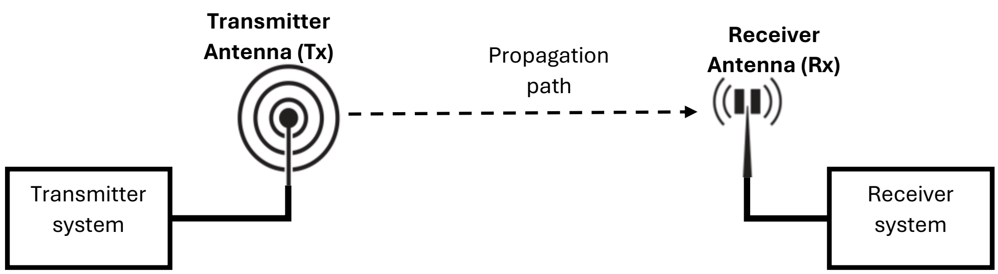

Figure 2: Telecommunications example

Lets try now to derive the detailed equation for the power received on receiver antenna via a direct path propagation method from a transmitter antenna that is placed at a distance. The power received by the receiver antenna including the radiation efficiency is given by the equation (2), where the components needed are the equation (1) and the below equations:

$$A_r = \frac{\lambda^2}{4\pi} \mathrm{D}_r(\theta_r, \varphi_r) \quad [m^2] \tag{3}$$

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$$G = e\,D \tag{4}$$

where λ is the wavelength of the carrier signal and D is the antenna directivity (the antenna radiation efficiency can be e_r or e_t for the receiver and transmitter antennas, respectively). Now, we can replace in the equation (2) the equations (1), (3) and (4), we get the below equation for the received power at the receiver:

$$P_r = e_r \cdot \frac{\lambda^2}{4\pi}\mathrm{D_r} \cdot \frac{1}{4\pi \mathrm{R}^2} P_t G_t \tag{5}$$

We can simplify by:

$$P_r = \left(\frac{\lambda}{4\pi R}\right)^2 \cdot e_r D_r \cdot P_t G_t \tag{6}$$

And:

$$P_r = \left(\frac{\lambda}{4\pi R}\right)^2 \cdot G_r \cdot P_t G_t \tag{7}$$

The equation (7) depends on the total gains of the transmit and receive antennas, that are direction dependent (θ, φ). The above equation is also known as the Friis equation and is usually written as:

$$P_r = \left(\frac{\lambda}{4\pi R}\right)^2 P_t\, G_t(\theta_t, \varphi_t)\, G_r(\theta_t, \varphi_t)\ \ [W] \tag{8}$$

To estimate the received power at the receiver end, there are mainly a few parameters that are required as shown above and they are the antenna gain parameters (transmitter and receiver antennas), the transmitter power and the distance between the transmitter and receiver antennas. Ansys HFSS software can simulate such scenario using the SBR+ solver. This example is a simple example to demonstrate the accuracy that can be achieved in a quick analysis. In the environment of the Ansys HFSS tool, we can design the antenna, estimate all the parameters and generate the telecommunication scenario.

2.2 Scenario setup and simulation

Below, we will compare a theoretical estimation of the above case against the results from an analysis in Ansys HFSS simulation using the SBR+ solver.

The parameters used are shown in the table below:

Table 1: Telecommunications case analysis parameters

Parameter	**Value**	**Units**
Carrier frequency ($\boldsymbol{f_c}$)	2.4	GHz
Transmitter excitation Power ($\boldsymbol{P_t}$)	1	Watt
*Antenna efficiency ($\boldsymbol{e_r}$)	1	
*Total Gain at boresight ($\boldsymbol{G}$)	13.2	dB
Tx-Rx Antenna orientation (boresight =0 deg)	0	deg
Tx-Rx Distance ($\boldsymbol{R}$) (variable)	5<R<300	m

*Applies for both Tx and Rx antennas

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The below figure shows the antenna setup that was used for the analysis.

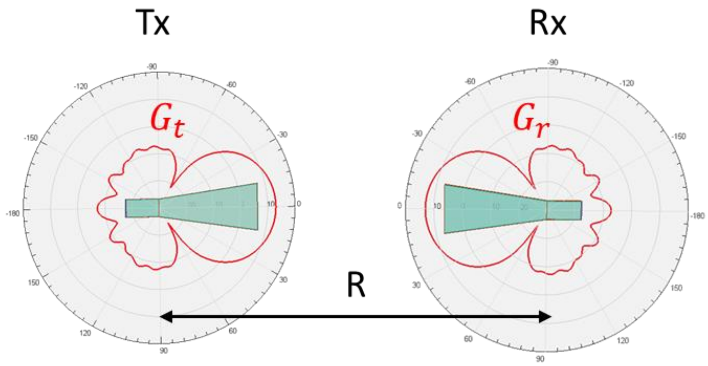

Figure 3: Antenna orientation for analysis

The gain of a horn antenna is given in the figure below for future ideas of scenarios that can be analyzed.

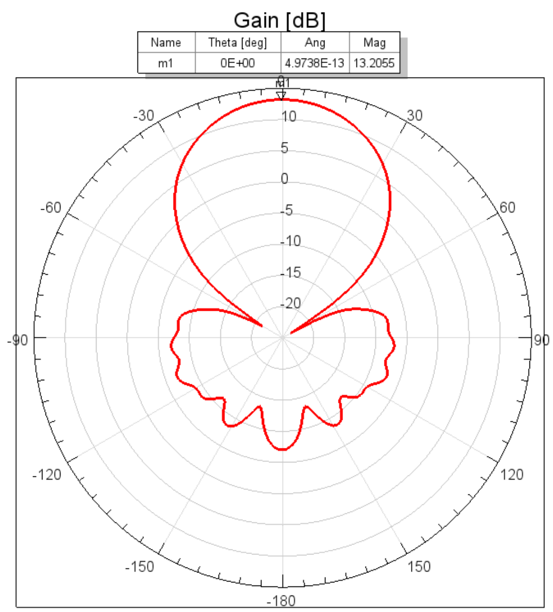

Figure 4: Antenna Gain section in dB

In the next figure, the theoretical calculation and the Ansys HFSS simulation results are presented.

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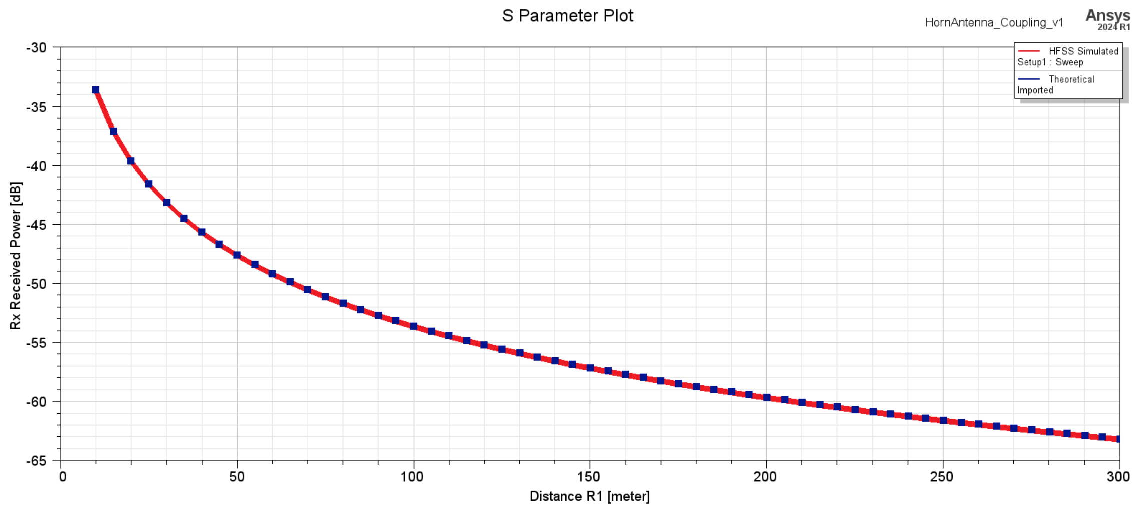

Figure 5: Received power at distance R from transmitter antenna

2.3 Conclusions

We can observe that the results for the two methods align perfectly with each other. The simulation time required for the Ansys HFSS setup is in the range of a few minutes including the parametric analysis for the range of the distances selected (5m to 300m with a step of 5m).

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3. Radar case

3.1 Radar equation

Radar and telecommunications can both be considered as antenna-to-antenna coupling phenomena in the presence of scatterers. In telecommunications, the transmitter and receiver are seldom co-located. Radar, on the other hand can exist as both monostatic and bistatic. The total electric field in any system with sources and scatterers is always composed of the incident electric field and the scattered electric field

$$E_{total} = E_{incident} + E_{scattered} \tag{9}$$

While telecommunication systems are concerned with the total electric field (with as small a scattered component as possible), radar systems operate by capturing and analyzing the scattered electric field from the environment on the receiver antenna.

In a similar way to the previous analysis, we can examine the radar scenario in detail. The difference between telecommunication cases and radar cases is that the propagation and reflection of the signal energy is the focus of the analysis. As explained previously, in a telecommunication case, the signal of interest is the direct signal from the transmitter to the receiver, ideally without any reflections. In the radar case, the signal of interest is the reflected signal. There are different radar systems with a variety of possible relative positions between the transmit and receive antennas, however, in this case we will analyze a monostatic radar. A monostatic radar is a radar in which the transmit and receive antennas are in very close proximity to each other and are pointing towards the same direction. Ideally, there is also no signal leakage from the transmit antenna to the receive antenna.

Here, the signals that are transmitted will hit objects in the field of view. The objects will intercept and re-emit energy towards the receive antenna. Thus, the propagation of the signal has a 2-way propagation. A high-level representation of such setup is shown in the figure below.

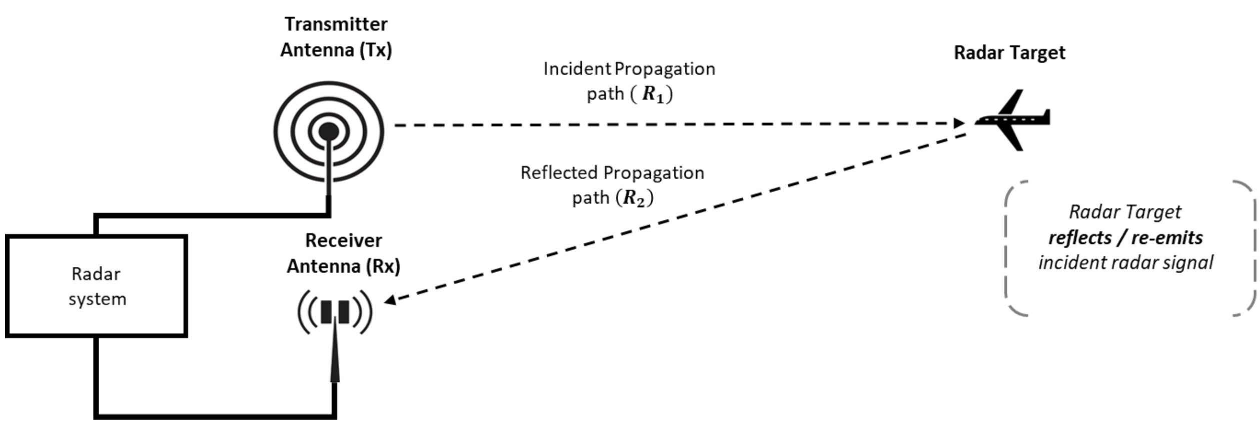

Figure 6: Radar example

The equations used to estimate the received power are the equations (3)-(6) with the modification that the power density that is intercepted by the receiver antenna will be the energy density as if the radar target generated by reflecting the incident signal energy. Let us estimate the power at the receiver end similarly as it was defined in equation (2):

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$$P_r = e_r\, A_r\, S_{refl} \quad [W] \tag{10}$$

where A_r is the receiver antenna effective area, e_r is the radiation efficiency of the receiving antenna and S_{refl} is the target-reflected signal power density at the position of the receiver antenna related to the target.

The target reflected signal power density can be estimated as any power density (that is power over sphere surface) and is show in the equation below:

$$S_{refl} = \frac{P_{refl}}{4\pi R_2^2} \quad [W/m^2] \tag{11}$$

where R_2 is the target-receiver distance.

The target reflects a part of the intercepted energy that is calculated with a factor called Radar Cross Section (RCS) and the shape of the target will define the reflected energy to different directions. In our case we consider the RCS only for the direction to the receiver antenna (σ). Thus, the reflected power can be estimated as:

$$P_{refl} = S_t\, \sigma \quad [W] \tag{12}$$

where S_t is the signal power density of the transmitted signal at the location of the target. Similar to the telecommunicationσ case, S_t is estimated as in the equation below:

$$S_t = \frac{P_t}{4\pi R_1^2} G_t(\theta, \varphi) \quad [W/m^2] \tag{13}$$

where P_t is the excitation power at the transmitter antenna, G_t is the total gain of the transmit antenna (direction dependent (θ, φ)) and R_1 is the transmitter-target distance.

The antenna effective area and the total gain can be estimated with the below expressions (for the receiver end as reference):

$$A_r = \frac{\lambda^2}{4\pi} D_r(\theta, \varphi) \quad [m^2] \tag{14}$$

$$G_r = e_r\, D_r \tag{15}$$

Where G_r is the (receive) total antenna gain that is direction dependent (θ, φ), λ is the wavelength of the carrier signal and D_r is the receiver antenna directivity.

Substituting the appropriate components in equation (10) we get:

$$P_r = S_{refl} \cdot A_r \cdot e_r \tag{16}$$

$$P_r = \frac{P_{refl}}{4\pi R_2^2} \cdot \frac{\lambda^2}{4\pi} D_r \cdot \frac{G_r}{D_r} \tag{17}$$

$$P_r = \frac{\frac{P_t}{4\pi R_1^2} G_t}{4\pi R_2^2} \frac{\lambda^2}{4\pi} G_r \tag{18}$$

According to the setup we considered for the radar case as monostatic radar, we need to clarify that in this case the distances transmitter-target (R_1) and target-receiver (R_2) are equal. Therefore:

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$$R_1 = R_2 \tag{19}$$

Using the additional condition above and the equation (18) can be written in the following form to estimate the received power for the radar case and for that reason is called also as the **Radar Equation**:

$$P_r = \frac{\lambda^2}{(4\pi)^3 R^4} P_t \, \sigma \, G_t(\theta_t, \varphi_t) \, G_r(\theta_r, \varphi_r) \qquad [W] \tag{20}$$

We can simulate the received power at the radar receiver using Ansys HFSS tool. A setup of a radar and a test target can be as simple as 2 antennas and a target that we can calculate the RCS. The radar will consist of identical antennas for the transmit and receive ends, set up in a monostatic radar configuration (transmit and receive antennas are at the same position), with a target being a sphere of given size. The RCS of a sphere can is uniform for all directions and the RCS is calculated using the radius as below:

$$\sigma = \pi r^2 \tag{21}$$

where r is the sphere radius.

3.2 Scenario setup and simulation

The distance between the radar antennas and the sphere will be variable, in order to estimate the received power using the equation (20). In detail, the complete set of parameters used is given in Table 2 and the schematic of the setup in Figure 6.

Table 2: Radar case analysis parameters

Parameter	**Value**	**Units**
Carrier frequency ($\boldsymbol{f_c}$)	2.4	GHz
Transmitter excitation Power ($\boldsymbol{P_t}$)	1	Watt
*Antenna efficiency ($\boldsymbol{e_r}$)	1	
*Total Gain at boresight ($\boldsymbol{G}$)	13.2	dB
*Tx-Rx Antenna orientation (boresight =0 deg)	0	deg
Target Distance from radar (variable) ($\boldsymbol{R}$)	5<R<300	m
Target Distance from Antennas ($\boldsymbol{R}$)	$R = R_1 = R_2$	m
Target sphere radius ($\boldsymbol{r}$)	0.5	m

*Applies for both Tx and Rx antennas

(a) (b)

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Figure 7: (a) Radar example setup , (b) example in Ansys HFSS design

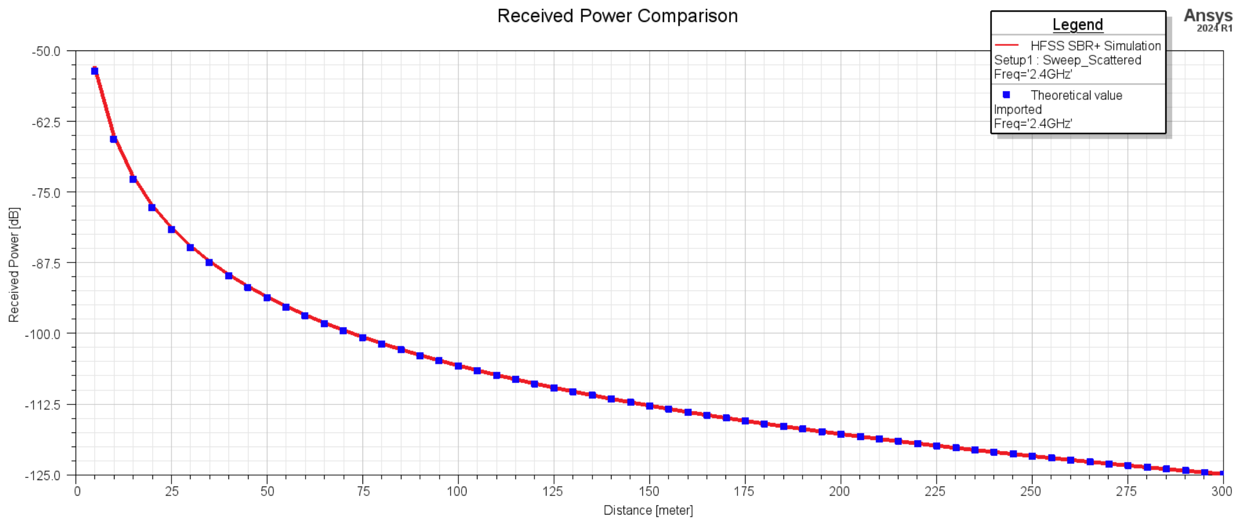

Figure 8: Radar example setup

3.3 Conclusions

In the above figure, we observe that the results align perfectly with each other. The simulation time required for the Ansys HFSS setup is in the range of a few minutes including the parametric analysis for the range of the Distances selected (5m to 300m with a step of 5m).

4. References

[1] C. Balanis, "Aperture Antennas: Analysis, Design, and Applications," in Modern Antenna Handbook, New York: Wiley, 2008

[2] M. Skolnik, Introduction to Radar Systems, 3rd Edition. New York: McGraw-Hill, 2001

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