Basics of a Two-Antenna System

Developed by Kathryn L. Smith, PhD

Sources

The material presented herein is from the following sources:

"Elements of Electromagnetics," by Matthew N.O Sadiku, 5th ed. (2010)
"Engineering Electromagnetics," by Nathan Ida, 3rd ed. (2015)
"Microwave Engineering," by David Pozar, 4th ed. (2012)
"Antenna Theory," by Constantine A. Balanis, 4th ed. (2016)

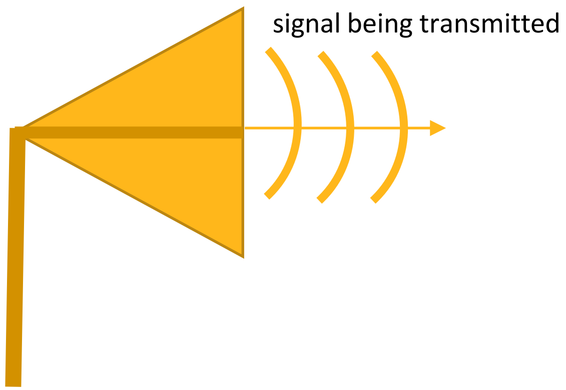
Agenda

Wireless communication systems transmit information between two antennas – a send antenna and a receive antenna. The power received by the second antenna is a product of the power sent by the first antenna, the geometry, composition, and positioning of the two antennas, the medium through which the signal travels, and the environment in which the system operates. In this module, we will focus on

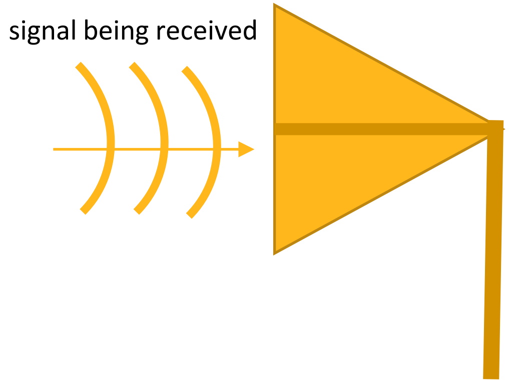
- The Basics of Antenna-to-Antenna Communication Systems
- Frii's Transmission Equation

The Basics of Antenna-to-Antenna Communication Systems

Antennas are engineered devices used to send and receive electromagnetic waves. A typical basic wireless communication system involves two antennas – one of which is used to send, or **transmit** a signal, and the other of which is used to **receive** it.



Antenna in transmit mode (Tx)



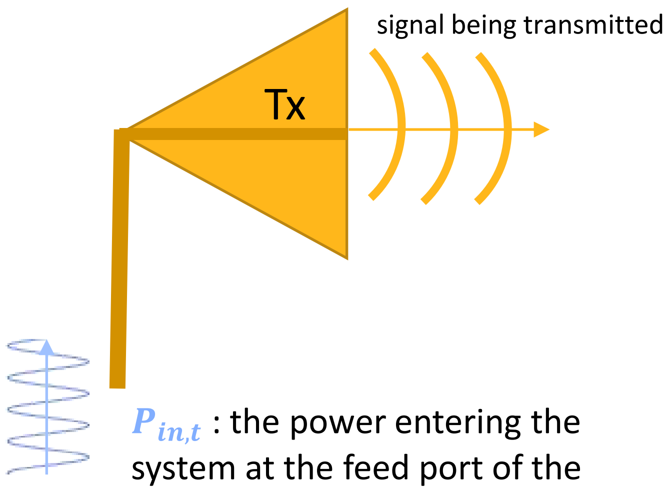
Antenna in receive mode (Rx)

The Basics of Antenna-to-Antenna Communication Systems

How successful the system is at communicating a signal is often judged in terms of a gain ratio – the ratio of power output at the output port of the receive antenna to power input at the feed port of the transmit antenna.

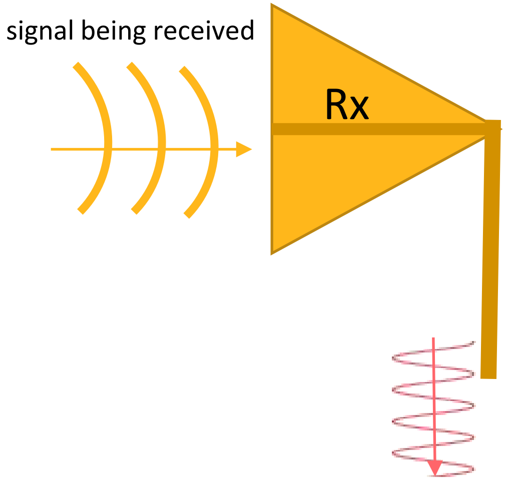
System Gain: $G_s = \frac{P_{out,r}}{P_{in,t}}$

*Note that this is **not** the same thing as antenna gain, which is a property of an individual antenna.



$P_{in,t}$: the power entering the system at the feed port of the transmit antenna

Antenna in transmit mode



$P_{out,r}$: the power exiting the system from the output port of the receive antenna

Antenna in receive mode

The Basics of Antenna-to-Antenna Communication Systems

The system gain is affected by several factors, generally falling under the categories of:

- Intrinsic properties of the individual antennas
- Properties of the system configuration
- Properties of the transmission medium/environment
- Compatibility of the two antennas

Let's look at each of these categories in turn.

Antenna in transmit mode

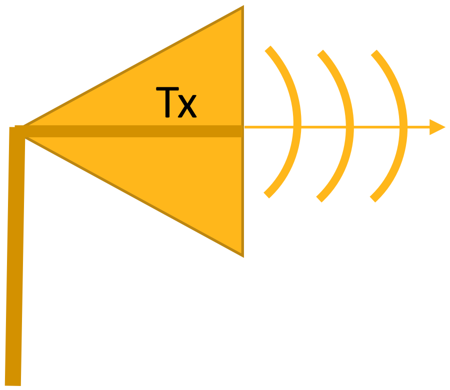
Antenna in receive mode

The Basics of Antenna-to-Antenna Communication Systems

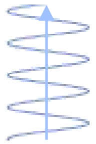
Intrinsic properties of the individual antennas

Antenna Gain of the Transmit Antenna

How well does the transmit antenna convert power that is input at its feed port into radiated electromagnetic power?



$P_{rad,t}$: the power radiated from the aperture of the transmit antenna



$P_{in,t}$: the power entering the transmit antenna at its feed terminal

$$G_t(\theta,\phi,\omega) = \frac{P_{rad,t}(\theta,\phi,\omega)}{P_{in,t}(\omega)}$$

Note that gain and radiated power are both directional (they depend on θ and ϕ), meaning that the antenna will likely radiate more strongly in some directions and less strongly in others.

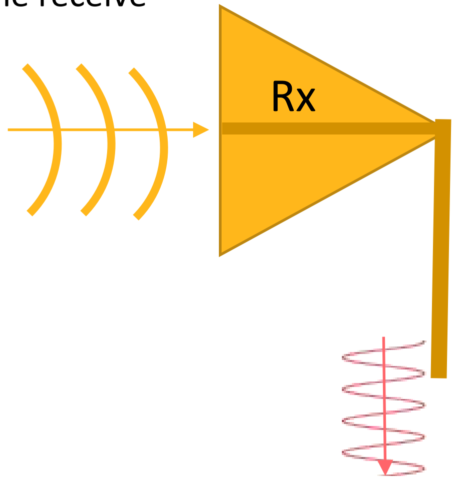
The Basics of Antenna-to-Antenna Communication Systems

Intrinsic properties of the individual antennas

Antenna Gain of the Receive Antenna

How well does the receive antenna convert electromagnetic power arriving at its radiating aperture into a guided signal exiting its output port?

$P_{rad,r}$: the electromagnetic power arriving at the aperture of the receive antenna



$P_{out,r}$: the power exiting the system from the output terminal of the receive antenna

$$G_r(\theta, \phi, \omega) = \frac{P_{rad,r}(\theta, \phi, \omega)}{P_{in,r}(\omega)}$$

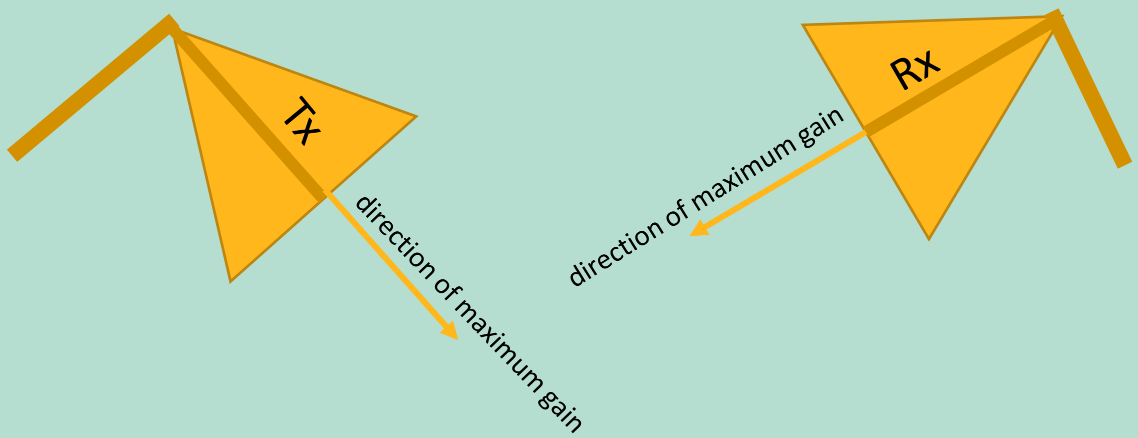
Note that gain and radiated power are both directional (they depend on θ and ϕ), meaning that the antenna will likely receive power more efficiently from some directions and less efficiently from others.

The Basics of Antenna-to-Antenna Communication Systems

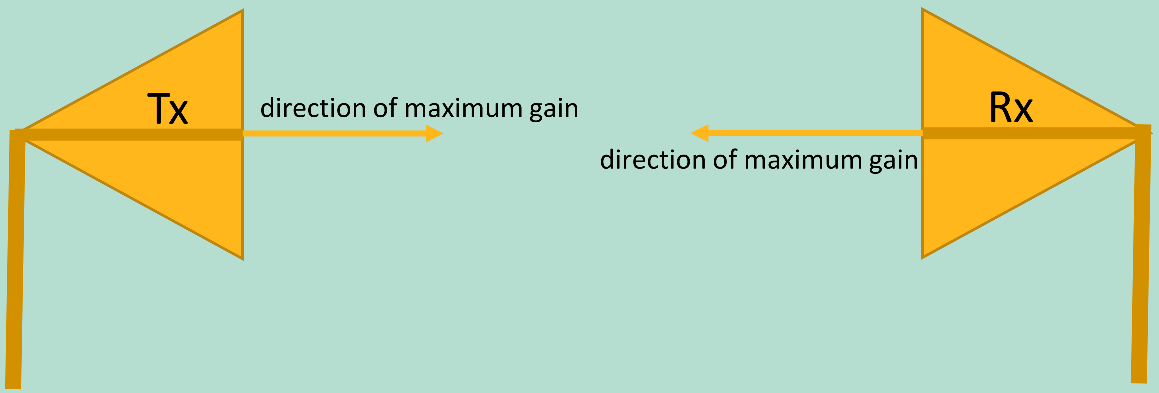
Properties of the system configuration

Antenna Alignment

Are the two antennas optimally aligned for communication? In other words, is the transmit antenna oriented so that its direction of maximum gain is pointed toward the receive antenna, and is the receive antenna oriented so that its direction of maximum gain is pointed toward the transmit antenna?



Example of poor alignment



Example of good alignment

The Basics of Antenna-to-Antenna Communication Systems

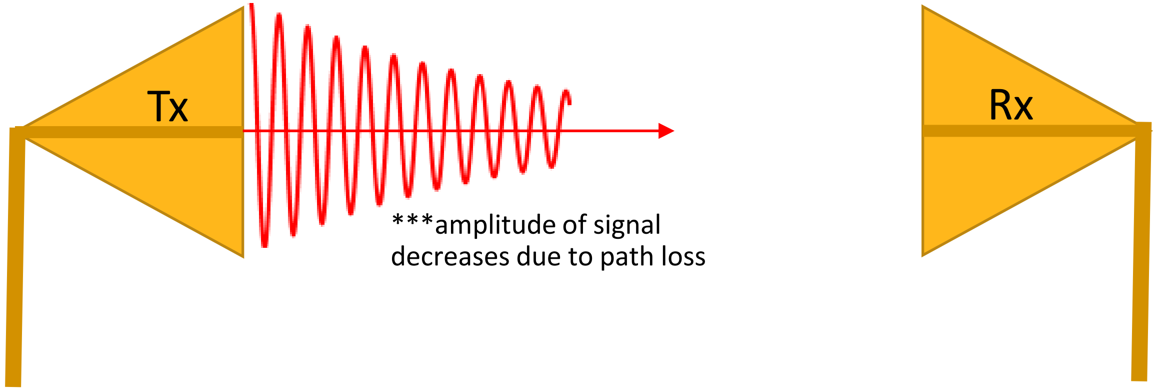
Properties of the system configuration

Path Loss

How far apart (specifically, how many wavelengths apart) are the antennas? The power of the transmitted signal is attenuated by path loss as it travels outward from the transmit antenna, according to

$$PL = \left(\frac{4\pi r}{\lambda}\right)^2$$

where *PL* is the path loss, *r* is the distance between the transmit and receive antennas, and λ is the wavelength of the transmitted signal. **Note that this loss occurs <u>even in a vacuum!</u>**



The Basics of Antenna-to-Antenna Communication Systems

Properties of the transmission medium/environment

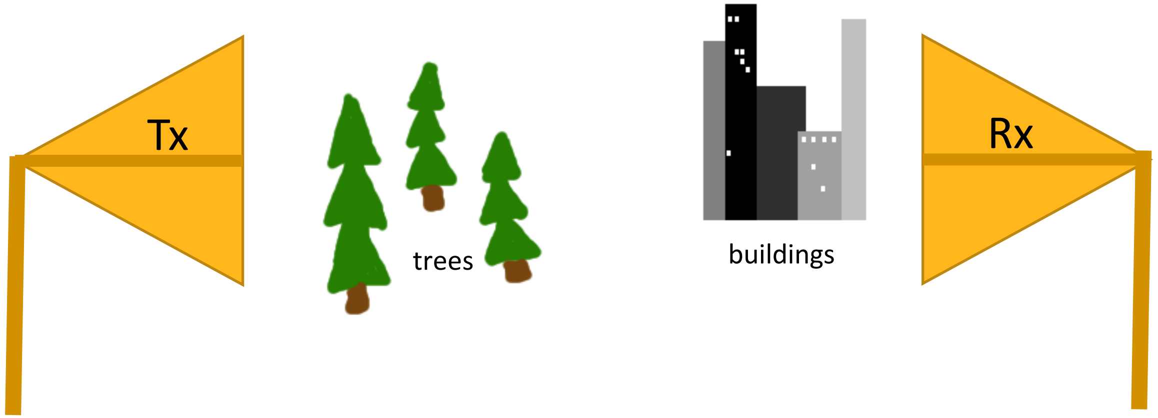
Material and Obstacle Losses

How lossy is the material in which the wave is propagating? A perfect vacuum is lossless, but materials with any amount of conductivity (such as air, especially if humid) will attenuate the wave. Remember, the propagation constant is given by:

$$\boxed{\gamma = \alpha + j\beta}$$

where α is the attenuation constant, inversely related to the material skin depth, and β is the lossless propagation constant.

Also, any inhomogeneity in the path (such as trees, clouds, or buildings) will result in reflection, reducing the amount of power successfully arriving at the receive antenna.



The Basics of Antenna-to-Antenna Communication Systems

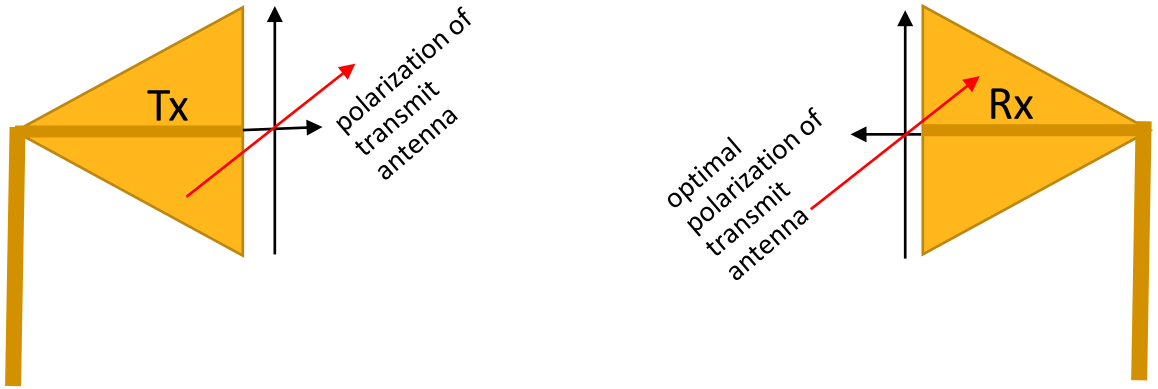
Compatibility of the two antennas

Polarization Losses

Each of the antennas involved is best suited to send/receive a particular polarization of electromagnetic signal. For maximum efficiency, the polarization of the two antennas needs to match. For instance, if the transmit antenna is linearly polarized in the vertical direction, the receive antenna must also be linearly polarized in the vertical direction. If there is an angular offset between two linearly polarized antennas, the **polarization loss factor** may be calculated as:

$$\boxed{\boldsymbol{PLF = cos^2(\phi)}}$$

where PLF is the polarization loss factor, and ϕ is the angle between the two linear polarizations. Note that a $90°$ angular offset will result in **total polarization loss** – no power transmitted between the two antennas.

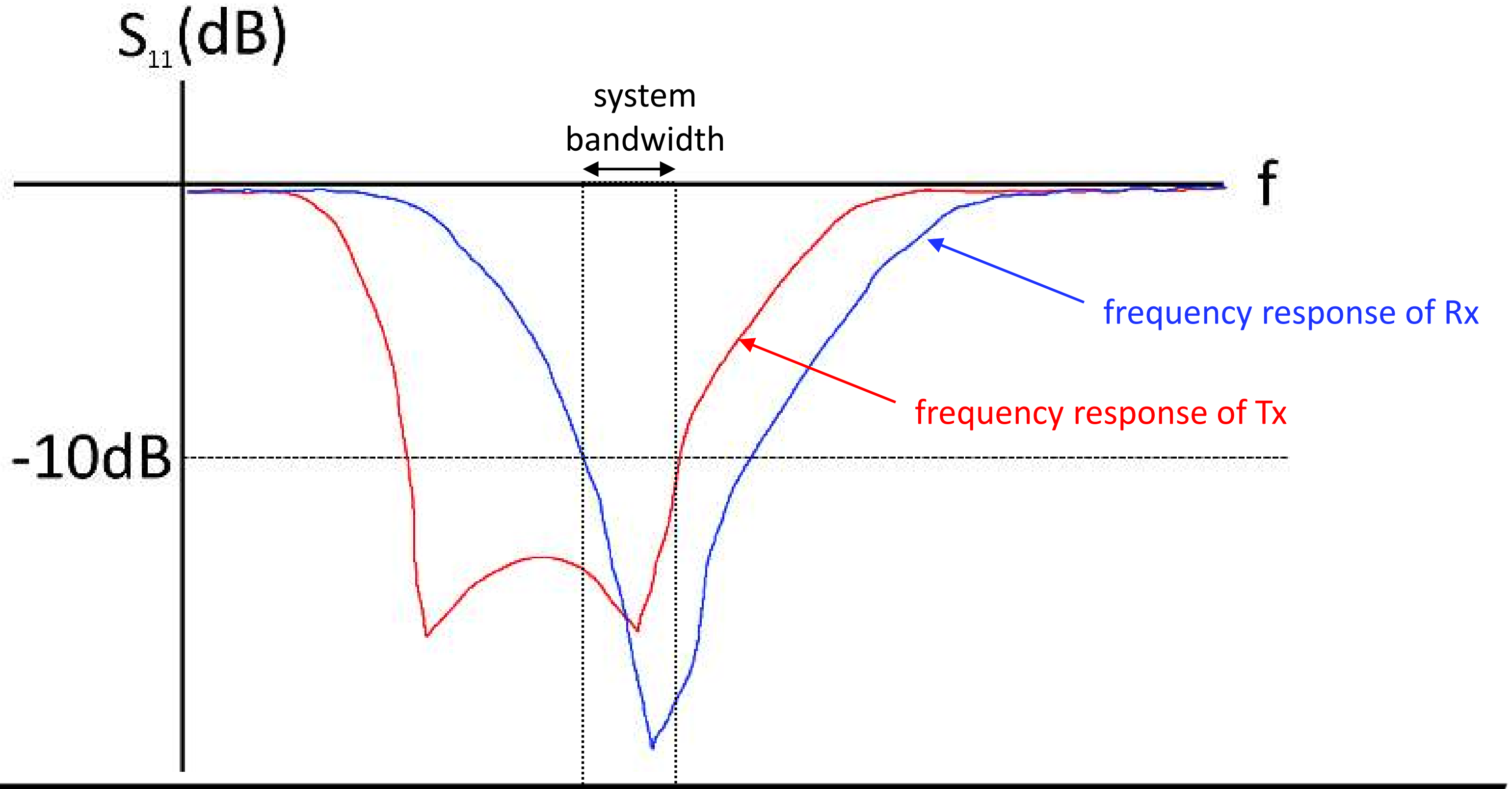


The Basics of Antenna-to-Antenna Communication Systems

Compatibility of the two antennas

<u>Frequency Response</u>

An antenna works best over a range of frequencies known as its “bandwidth”. For two antennas to be able to optimally communicate with one another, they must have overlapping bandwidth (they most both operate at the same frequencies.



Frii's Transmission Equation

Frii's Transmission Equation is a simple formula for calculating the ratio of power received to power transmitted, for a two-antenna system. This formula is stated as:

$$\frac{P_{out,r}}{P_{in,t}} = G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r) \left(\frac{\lambda}{4\pi r}\right)^2$$

where:

$P_{out,r}$ is the power exiting the port of the receive antenna, $P_{in,t}$ is the power input at the port of the transmit antenna,

$G_t(\theta_t, \phi_t)$ is the gain of the transmit antenna, and is a function of its orientation,

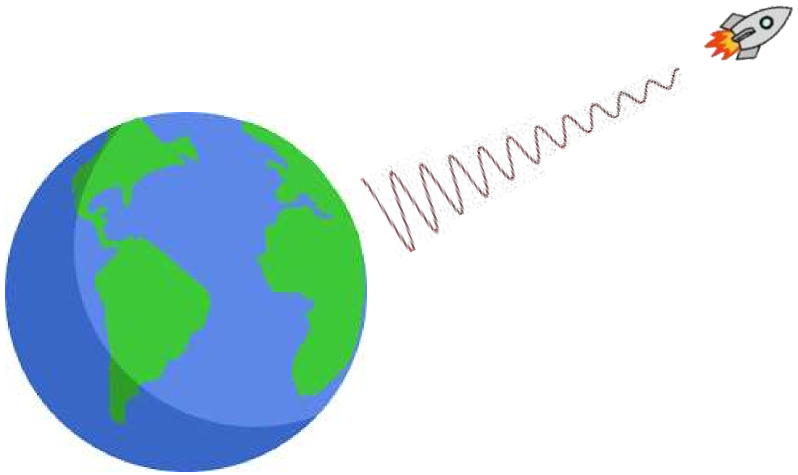
$G_r(\theta_r, \phi_r)$ is the gain of the receive antenna, and is a function of its orientation,

and $\left(\frac{\lambda}{4\pi r}\right)^2$ is the reciprocal of the path loss, calculated from λ, the signal wavelength, and *r*, the distance between the two antennas.

Frii's Transmission Equation

Frii's Transmission Equation allows calculation of the total power that is received at the destination antenna, given a particular input power.

So, if an engineer knows that a particular receiver is capable of decoding a signal as small as 10μW, for instance, they will be able to calculate the minimum power they need to send in order to receive a useful signal.



Frii's Transmission Equation

Frii's Transmission equation, as stated here, is a simplified link budget calculator. It does not account for every potential source of losses.

$$\frac{P_{out,r}}{P_{in,t}} = G_t(\theta_t, \phi_t)G_r(\theta_r, \phi_r)\left(\frac{\lambda}{4\pi r}\right)^2$$

It does not account for possible **polarization mismatch**, or in other words it assumes that the polarizations of the two antennas are perfectly matched.

It does not account for the possible **presence of obstructions**, or in other words it assumes that the antennas are in a perfectly homogeneous environment.

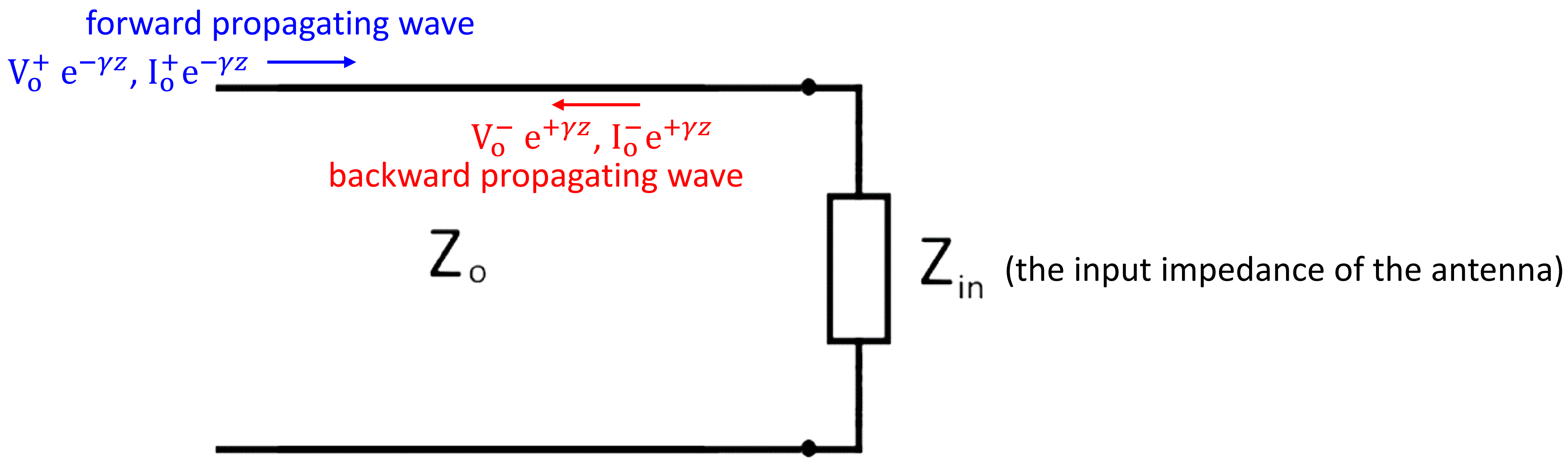
And it does not account for possible **wave attenuation by the material** $(\alpha \neq 0)$, or in other words it assumes that the medium through which the wave is traveling is perfectly lossless.

Frii's Transmission Equation

It should also be noted that Frii's Transmission Equation **does not address** the antenna feed efficiency.

In other words, if there is a mismatch between the impedance of the feed line and the input impedance to the antenna, resulting in voltage reflection at the antenna port, such loss <u>will not be captured</u> by Frii's Transmission Equation. The equation we have stated assumes **perfect impedance matching**.

For a refresher on impedance mismatch and voltage reflections, see the "Transmission Line Theory" module



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