WHITE PAPER:
ENHANCING POWER EFFICIENCY OF WIRELESS IoT DEVICES – FOCUS ON ANTENNA COMPONENTS

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Introduction

Billions of wireless IoT devices rely on battery power in a wide range of applications that include asset tracking, logistics, agricultural environment sensing, and smart utility monitoring, etc. In many of these applications, the devices are deployed in the fields for long periods of time without human intervention. These devices, operating on a single battery, are required to stay wirelessly connected to provide continuous service with a lifetime of 5 years to 10 years without replacing the battery. Therefore, power consumption of these IoT devicesbecomes critically important to the life expectancy of these devices and the uninterrupted service expected.

The power consumption of a wireless device depends on multiple factors:

- Amount of the data to be transmitted and received
- Duration of the device's airtime versus its sleep time
- Geographic coverage and range of its wireless network
- Wireless protocols which enable low power low data rate transmission
- And the most importantly, the RF performance of the antenna of the device

This white paper will provide a thorough discussion on how the RF performance of the antenna impacts the power efficiency of the wireless device. This in-depth discussion explains the insights of the antenna design and selection guideline during the product development phases of the devices.

The discussion of this paper starts from the introduction of one of the most fundamental equations in antenna theory, the Friis Transmission Formula, and how it links the RF performance of the antennas with the receive signal strength and the range of the wireless link. The guidelines on antenna design and selection are then provided, followed by explaining TE's streamline solutions to assist the customers as their RF technology partner and antenna product provider.

The Fundamental Friis Transmission Formula to Explain How the Antenna Performance Impacts the Power Consumption and Battery Life of the Device

Friis Transmission Formula [1] is the fundament equation to explain the relationship between the transmitted power (P_T), the received power (P_R) and the distance (D) between the two antennas in free space. This formula reveals how the antenna's performance impacts the power consumption and battery life of the device.

FIGURE 1: A WIRELESS COMMUNICATION LINK BETWEEN THE TRANSMIT AND RECEIVE ANTENNAS

$$\begin{aligned} P_R &= P_T G_T(\theta_T, \phi_T) G_R(\theta_R, \phi_R)(c/4\pi Df)^2 \eta_{pol} \\ &= P_T D_T(\theta_T, \phi_T)\eta_{matchT}\eta_{radT} D_R(\theta_R, \phi_R)\eta_{matchR}\eta_{radR}(c/4\pi Df)^2\eta_{pol} \end{aligned} \quad (1)$$

where,

$$G_T(\theta_T, \phi_T) = D_T(\theta_T, \phi_T)\eta_{totalT} = D_T(\theta_T, \phi_T)\eta_{matchT}\eta_{radT} \quad (2)$$

$$G_R(\theta_R, \phi_R) = D_T(\theta_R, \phi_R)\eta_{totalR} = D_R(\theta_R, \phi_R)\eta_{matchR}\eta_{radR} \quad (3)$$

c is the speed of light in free space

f is the frequency

D is the distance between the two antennas

η_{pol} is the polarization matching efficiency between the two antennas

$G_T(\theta_T,\phi_T)$ is the transmit antenna gain in the direction towards the receive antenna

$D_T(\theta_T,\phi_T)$ is the transmit antenna directivity in the direction towards the receive antenna

η_{matchT} is the transmit antenna impedance matching efficiency

η_{radT} is the transmit antenna radiation efficiency

$G_R(\theta_R,\phi_R)$ is the receive antenna gain in the direction towards the transmit antenna

$D_R(\theta_R,\phi_R)$ is the receive antenna directivity in the direction towards the transmit antenna

η_{matchR} is the receive antenna impedance matching efficiency

η_{radR} is the receive antenna radiation efficiency

The Friis Transmission Formula in equation (1) describes that, the transmitted power (P_T) from the transmitter is weighted by the gain of the transmit antenna in the direction towards the receive antenna $G_T(\theta_T,\phi_T)$, by the gain of the receive antenna towards the direction of the transmit antenna $G_R(\theta_R,\phi_R)$, by the path loss $(c/4\pi Df)^2$, and by the polarization matching efficiency between the two antennas η_{pol}, before the power is received by the receiver.

In equation (2), the gain of the transmit antenna in the direction towards the receive antenna, $G_T(\theta_T,\phi_T)$, is the product of the directivity of the transmit antenna in that direction, $D_T(\theta_T,\phi_T)$, and the efficiency of the transmit antenna, η_{totalT}, which is the combination of impedance matching efficiency, η_{matchT}, and the radiation efficiency of the transmit antenna, η_{radT}. Likewise, the same definition holds for the gain of the receive antenna in the direction towards the transmit antenna in equation (3).

Based on the Friis formula, in a wireless link with the required range *D*, the received power level from a given transmitted power is decided by both the transmit and receive antennas RF performance (gain, directivity, impedance matching efficiency, radiation efficiency) and the polarization matching efficiency between the two antennas. In other words, to meet a certain received power level, the required transmit power in the wireless link is decided by the performance of the antennas.

Through this discussion, the Friis formula is used to explain the insight of how the antenna's performance impacts the power consumption of the wireless devices. In the next section of this paper, the guideline on the antenna design and selection to meet the power consumption and communication link performance requirements is elaborated.

[1] Harald Friis, "A Note on a Simple Transmission Formula," Proc. IRE, 34, 1946, pp. 254-256

Antenna Design and Selection Guideline

The Friis Transmission formula explains how the antenna's RF performance impacts the received power for a given transmitted power at a certain distance away, or, how to determine the needed transmitted power to ensure the received power level meets the requirement. In this section, the antenna RF performance is further detailed to explain how to design or select an antenna based on these performance metrics.

Guideline 1: Choosing the antenna radiation pattern based on the propagation scenario

Antenna radiation pattern is a graphical description of the antenna's transmitted/received power strength in given directions. A full spatial description is typically given in the 3D spherical coordinate. An example of a 3D radiation pattern of a Bluetooth slot antenna at the edge of a PCB ground plane is given in Figure 2. The gain of the antenna in different direction is plotted in decibels (dBi), using the red to blue color scheme to indicate the antenna gain from high to low. Theta is the elevation angle measured off z-axis and Phi is the azimuth angle off x-axis and towards y-axis.

2D radiation pattern cuts are the "slices" of the 3D pattern to provide more details in the plane of interest. Figure 3 shows the 2D cuts in the three principal planes Phi=0° (x-z plane), Phi=90° (y-z plane), and Theta=90° (x-y plane) of the radiation pattern of the antenna in Figure 2.

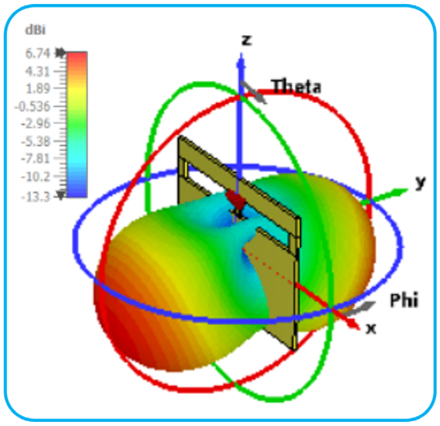


FIGURE 2: 3D GAIN RADIATION PATTERN AT 2.45 GHZ

In this Bluetooth slot antenna example, the gain in the x-z plane is low so there will be little power transmitted/received in the directions along this plane. The maximum gain of the antenna is towards the +y axis and –y axis directions. Therefore, when this Bluetooth antenna is used to transmit, we need to point the +y axis and –y axis of this antenna towards the receive antenna to enable maximizing the power delivered towards the receive antenna. We need to avoid placing the receive antenna in the directions along the x-z plane of this Bluetooth antenna where its transmitted power level is low. Vice versa, when the Bluetooth antenna is used to receive, we need to point the maximum gain radiation direction towards the direction of the incoming waves.

In different propagation scenarios, the waves come from different directions, so we need to choose the antennas which have the maximum radiation towards the incoming wave directions. For example, GPS signals come from the sky directions, so the GPS antennas need to have the maximum radiation towards the sky and minimum radiation towards the ground. Another example of a different propagation scenario is for vehicle-to-vehicle communications, in which the signals mostly come from the horizontal directions 360° circling around the vehicle. To have the equal opportunity to communicate with other vehicles, the antenna needs to have an omni-directional radiation pattern in the horizontal plane.

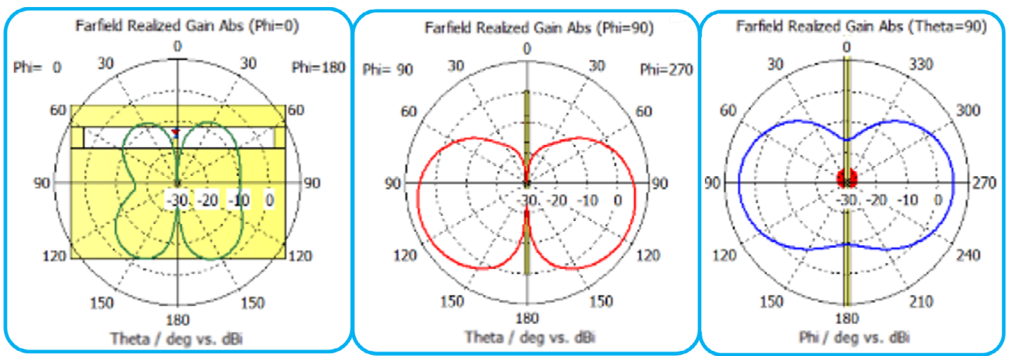


FIGURE 3: 2D GAIN RADIATION PATTERN CUTS IN THREE PRINCIPAL PLANES AT 2.45 GHZ

Guideline 2: Antenna total efficiency is the key

Antenna total efficiency (η_{total}) is used to quantify how much power is radiated compared to the amount of the power delivered to the antenna. Among the power which cannot be radiated, some is reflected at the port of the antenna due to impedance mismatch, and some is dissipated in the metallic materials which form the antenna and the dielectric material around the antenna. Impedance matching efficiency (η_{match}) is used to measure the impact of the reflected power. Radiation efficiency (η_{rad}) is used to reflect the power dissipated. ηtotal is the product of η_{match} and η_{rad}, as given in equation (3).

$$\eta_{total} = \eta_{match}\,\eta_{rad} \qquad (3)$$

$$\eta_{match} = 1-|\Gamma|^2 = 1-RL \qquad (4)$$

η_{match} can be calculated from $|\Gamma|^2$ – the power of the reflection coefficient (Γ) at the port of the antenna. $|\Gamma|^2$ is also known as the Return Loss (*RL*) of the antenna. η_{rad} is decided by the loss of the materials. It is important to choose low loss materials if possible. In the material property datasheets, electric conductivity and loss tangent are the parameters to measure the loss property of the materials.

Figure 4 shows the efficiencies of the Bluetooth slot antenna used as an example previously. This slot antenna is made in a low loss metallic plane and there is no dielectric material around it, so its radiation efficiency (red curve in Figure 4) is high – above 99% in the frequency band of interest. The antenna's total efficiency (green curve) is between 96% and 97% in this frequency band. The difference between the total efficiency and the radiation efficiency is the impedance matching efficiency, which is also high due to the good impedance matching (low *RL*) shown in Figure 5.

Guideline 3: Make sure the bandwidth of the antenna is wider than the band of interest

The bandwidth of an antenna is usually referred to as the frequency range in which the Return Loss is below a certain threshold, e.g., *RL* < -10dB, which indicates maximum 10% of the power is reflected and minimum 90% of the power is delivered to the antenna to transmit. As a result, η_{match} is at least 90% within the *RL* < -10dB bandwidth.

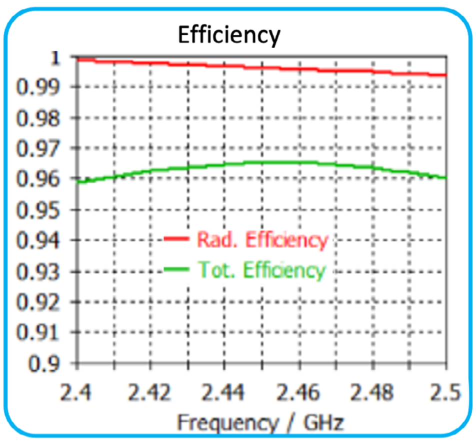


FIGURE 4: EFFICIENCIES OF THE BLUETOOTH SLOT ANTENNA

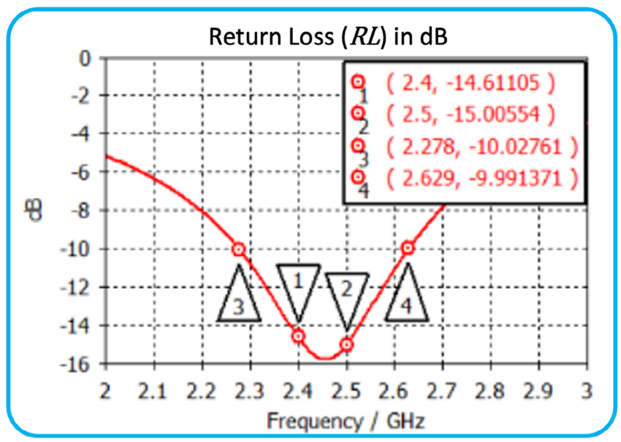


FIGURE 5: RETURN LOSS OF THE BLUETOOTH SLOT ANTENNA

Since an antenna's bandwidth is defined by its return loss performance, the plot in Figure 5 shows the Bluetooth slot antenna's *RL* < -10dB bandwidth is 351 MHz ranging from 2.278 GHz to 2.629 GHz, which is wider than the Bluetooth band of 2.4 GHz–2.4835 GHz.

When an antenna is selected for a device, it is important to verify if the bandwidth of the antenna is wider than the frequency band of interest. Typically, when an antenna is installed in a device, the structures surrounding the antenna, e.g., plastic cover, ground plane size, large SMT components in close proximity, etc., will contribute to change the antenna's impedance and shift the antenna's center frequency from what it is before the antenna is integrated into the device. If the antenna's bandwidth is wider than the frequency band of interest, the antenna will have higher tolerance to this shift and the Return Loss may still meet the performance requirement in the frequency band of interest.

However, if the antenna's bandwidth is too wide, the antenna can pick up out-of-band emission and interference, especially when multiple antennas for different transceivers are integrated in one device. Therefore, deciding the needed bandwidth for each antenna relies on the set up of the device and the application.

Guideline 4: Reduce power loss due to mutual coupling between antennas

When multiple antennas for different transceivers are integrated in one device, besides watching out for the antennas to pick out out-of-band interferences from each other, we also need to pay attention to the power loss from one antenna to the load of another antenna due to the mutual coupling between the antennas. Mutual coupling power loss can significantly reduce the antenna's power efficiency.

Mutual coupling happens when two antennas in close proximity are working in the same frequency bands. A portion of the power transmitted from one antenna is received by the other antenna thus this portion of the power is not radiated. Mutual coupling is therefore measured with the transmission coefficient between the two antennas. The power loss through mutual coupling reduces the antenna's total efficiency.

Figure 6 shows an example of how mutual coupling changes the total efficiencies of the antennas. In the first row, two slot antennas are placed orthogonally at the adjacent edges of the ground plane. The transmission coefficient between the two antennas remains below -20 dB in the Bluetooth frequency band which these antennas are designed for. The total efficiency of the antennas is above 94% in this band, close to the single slot antenna's efficiency in Figure 4. This means the mutual coupling between these two orthogonal antennas is low and there is little power lost through mutual coupling in this setting. (Note: because these two orthogonal slot antennas are identical, they have the same efficiencies. Therefore, only one antenna's efficiency is plotted in Figure 6).

However, in the second row, when the same slot antennas are placed in parallel on the opposite side of the ground plane, the transmission coefficient increase to above -10 dB, and the total efficiency drops to 82% – more than 10% of the power is lost due to the stronger mutual coupling between the parallel slot antennas.

Care must be taken to reduce the mutual coupling between the antennas as much as possible. Some commonly used approaches include increasing the distance between the antennas, placing the antennas orthogonally, and using differently polarized antennas. There are also many other methods to reduce mutual coupling which are not listed here.

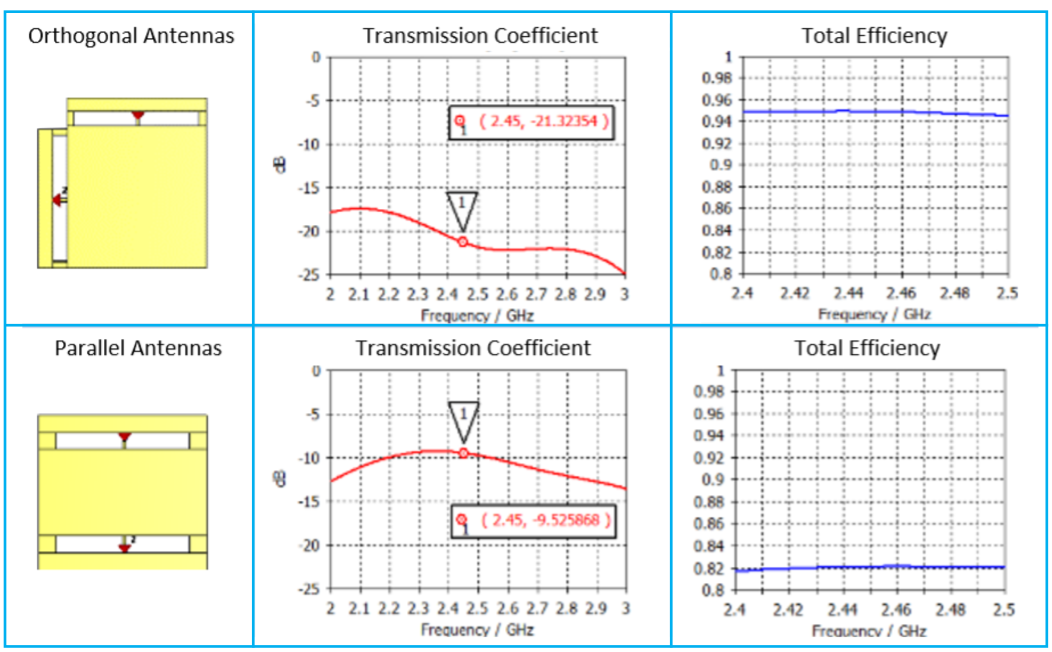


FIGURE 6: MUTUAL COUPLING LOSS REDUCES ANTENNA'S EFFICIENCY

Guideline 5: The choices of antenna type and antenna placement location

Antennas can be loosely classified as internal antennas and external antennas, based on if the antenna is installed inside the enclosure of the device or external to the enclosure.

External Antennas: There are two types of external antennas. The first type is terminal-mount antennas: directly attached to the enclosure of the device through a connector. There are two examples shown in Figure 7. The second type is remote antennas: placed at a remote location with a RF cable connected to the device, as an example shown in Figure 8.

Some of the terminal-mount antenna's are monopoles (Figure 7(a)), which is only a part of the radiating structure. The other part of the radiating structure is the PCB ground plane or the metallic enclosure of the device where the monopole is attached to. The monopole antenna's RF performance is therefore impacted by the size and shape of the PCB ground plane or the metallic enclosure.

Some of the terminal-mount antennas are dipoles (Figure 7(b)), which have the full antenna radiating structures built in, so their RF performances do not rely on the metallic enclosures nor the PCB ground plane of the devices.

Remote antennas (Figure 8) have the flexibility to be installed at the locations where the wireless signal is stronger than where the device is, e.g., on the rooftop of a vehicle or outside a building. However, there is always power lost in the RF cable. It is important to carefully choose the type of the cable and its length to minimize the cable power loss.

(a) monopole

(b) dipole

FIGURE 7: TERMINAL-MOUNT ANTENNAS

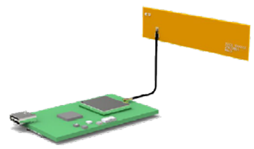
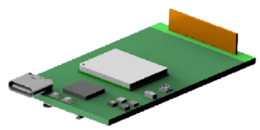
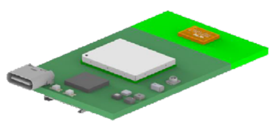
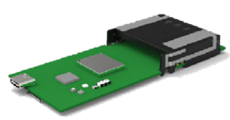
FIGURE 8: REMOTE ANTENNA

Internal Antennas: Industrial design is trending towards focusing on the user experience, and often requires the antennas to be invisible and integrated within the enclosure of the device. Compared with external antennas, internal antennas could have certain performance disadvantages:

1. The space inside the device available for the antenna is often limited, hence the antenna's efficiency and bandwidth are often negatively impacted
2. Internal antennas are closer to the RF lossy parts in the devices such as LCD display, batteries, SMT components, lossy plastic, etc., so internal antennas tend to have lower radiation efficiencies
3. Non-radiated active nearfield can be excited between the antenna and other metallic structures inside the device. This can significantly reduce the antenna's radiation efficiency
4. Internal antennas are closer to components such as the amplifier, microcontroller, mixer, etc. which could produce noise on the board. Therefore, internal antennas can pick up RF noises more easily than external antennas

With these disadvantages it is important to ensure the industrial designers and the antenna designers communicate early to ensure antenna disciplines are met to achieve optimized performing products.

Several types of internal antennas and their pros and cons comparison are listed in this table:

Antenna Type		Configuration	Tradeoff	
			Favorable	Challenge
1	FPC pigtail antenna		• Antenna is mounted in device's plastic housing • Ground plane independent • Device radio board size can be as small as needed	• Antenna mounting and cable routing impact antenna performance
2	PCB tab mount antenna		• Save some board space, compared to SMT antenna • Better radiation performance, compared to SMT antenna	• Antenna performance depends on ground plane size • Manual soldering is typically used
3	SMT antenna		• Reflow soldering is feasible	• Antenna performance depends on ground plane size • Occupy more board space, compared to tab mount antenna
4	Custom antenna		• Custom antenna design to achieve optimized RF performance • Possibility to utilize the 3D space. LDS antenna is an example	• Antenna performance depends on ground plane size

Guideline 7: The ground plane size is critically important

Often the ground plane of the PCB is essentially a part of the antenna. This is particularly true when a monopole, or its variations such as an inverted-F antenna (IFA) and planar IFA (PIFA), is used. This is because the monopole is one half of the radiating element and the PCB ground plane is the other half. When high antenna efficiency (e.g., > 50%) is required, the length of the ground plane needs to be minimum a quarter of the wavelength of the frequency of interest. This holds true for both external and internal monopole, IFA and PIFA types of antennas.

However, the trend of making the device smaller and smaller often requires the PCB ground plane to be smaller, thus the antenna's efficiency has to be sacrificed. Figure 10 depicts how the antenna efficiency drops more than 20% in the frequency band below 1 GHz, when the ground plane length is reduced from 120mm to 80mm.

Guideline 8: Mind the coaxial cable loss, cable radiation, and cable arrangement

RF coaxial cables bring the flexibility of placing the antenna off the board or in a remote location where the signal is stronger and the board RF noise level is lower. However, all cables have losses. It is important to minimize the cable length and use low loss cables when it is possible especially in high frequency applications. The two plots in Figure 11 compare the cable loss over frequency of some commonly used coaxial cables.

When the antenna is not balanced and when a balun or an RF choke is not used, there will be electric current flowing on the outside surface of the shield of the cable. This current becomes a source of radiation. This radiation is an unwanted emission and causes EMC problems. It also causes changes in the antenna's RF performance, including impedance, bandwidth, radiation pattern, total efficiency, and gain, in the frequency band of the antenna.

If a balun structure is not used at the port of the antenna, two common approaches can be taken to reduce the unwanted current on the cable and to minimize its impacts on the antenna's performance.

The first approach is to put ferrite beads on the cable near the antenna port. The ferrite beads can significantly suppress the unwanted current on the cable.

The second approach is to ground the shield of the cable onto the PCB or some nearby metallic structures. Figure 9 shows a SMT metallic clip which is used to secure the cable on the PCB as well as to ground the shield by providing a direct contact.

Cable arrangement can also impact the antenna's performance. Care needs to be taken on how to arrange the cable exiting from the antenna port, how to route the cable inside the device, and how to arrange the cable on the PCB before it is connected to the PCB. Lastly, the cable must be arranged in the repeated way for the same series of device.

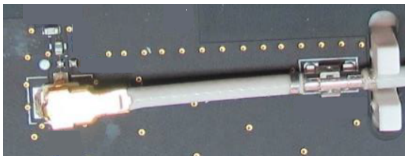


FIGURE 9: CABLE GROUNDING ON PCB

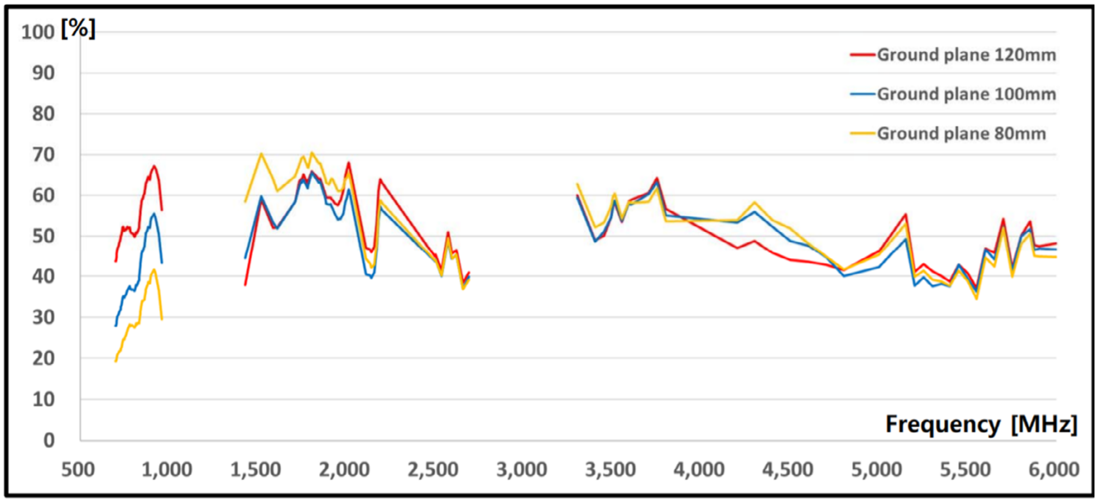
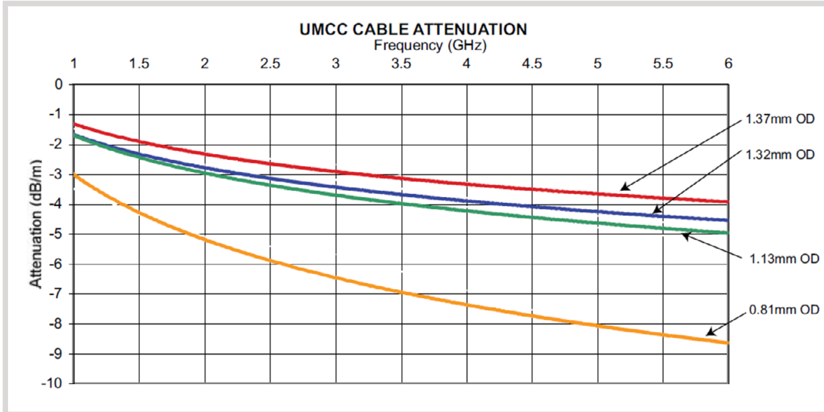


FIGURE 10: IMPACT OF GROUND PLANE SIZE ON THE ANTENNA EFFICIENCY



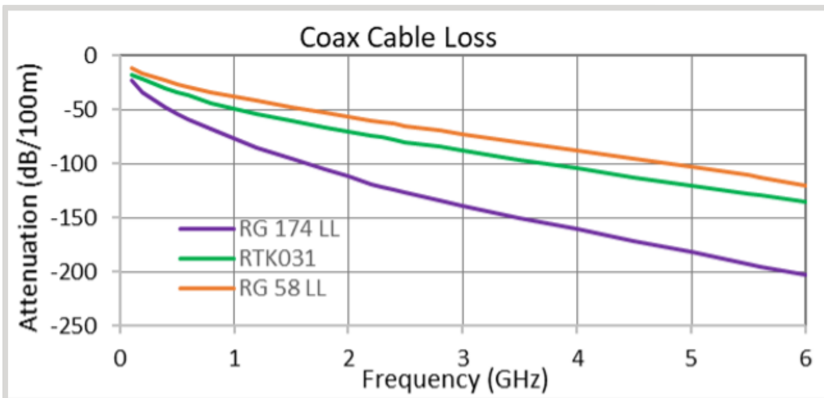


FIGURE 11: CABLE LOSS OVER FREQUENCY

How TE's Expertise Helps to Optimize Antenna Performance to Enhance IoT Device Power Efficiency

With decades of antenna product development and manufacturing experience, TE has provided numerous antennas to accelerate the success of our customers' products. In the majority of the time, the customers face several common challenges in finding the right antennas which can minimize the power consumption of the device while achieving the best possible wireless communication link. For each challenge, TE, as an RF technology partner, provides streamline solutions to serve the customers' needs:

Antenna challenges and solutions

Challenge 1

Unfamilar with RF requirements or expectations

Challenge 2

Quick time to market (TTM)

Challenge 3

Severe Industrial Design product constraints

Challenge 4

Inadequate power consumption

Challenge 5

Uninterrupted cellular signal for diagnostics performance

Solution 1

Consult an expert, choose appropriate technologies, partner early

Solution 2

Partner early, utilize platform products where applicable

Solution 3

Require varied manufacturing capabilities, including 3D antenna for most flexibility

Solution 4

Ensure highest efficiency solutions, prolonging battery life

Solution 5

Require robust radiation performance, confirmed through OTA testing

Consider antenna solutions early in product planning
Leverage antenna supplier's extensive experience to deliver optimized antenna performance

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