Signal propagation through the inside of robot leg for non-wired robot system

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Abstract

In nowadays, robots are made of many different components and connected with many cables. Such as general, audio, and video sensors, motor, gear, chains, and power cables. One of the important topics is to remove or reducing the cables, which can make the robot more flexible, lesser maintain, and easier to build up. Therefore, wireless communication would provide a solution that can replace these cables for the above issue. In this paper, we focus on one of the 5G communication key stone, Ultra-Reliable Low-Latency Communication (URLLC).

In Chapter 2, we propose a hybrid Medium Access Control (MAC) scheme for different wireless sensors communication based on our previous work, the Orthogonal Frequency subcarrier-based Multiple Access (OFSMA) access scheme, which combine the slot ALOHA and OFDMA. For general sensors, we use the OFSMA scheme to ensure URLLC standards. As for audio sensors and video sensors. There are many spaces inside the robot leg, arm, and body. We set a goal to transmit the signal directly through these small spaces as an internal waveguide to achieve wireless communication.

In Chapter 3, We design three different types of model which is interfere by internal structure. In the first part, we design rectangular based robot leg liked model. In the model, we set the material is iron, and some interfere structure. Finally, we Use High-Frequency Simulation Software (HFSS) to simulate in different frequency. In the second part, we change the material of the model in the first part into PVC plastic, and do the simulation. In the third part, we design a circular based robot leg liked model, with the material iron.

In Chapter 4, our goal is to find out the possibility for signal directly inside the robot body, arm, and leg. We design a realistic model which consider more interfere problem and add more structure based on the rectangular interfere model used in the last chapter to make a robot leg-liked model. And simulate by using HFSS with different frequency from 900MHz,1.5GHz, 2.4GHz, 5.5GHz, 15GHz, to 24GHz.

Chapter 1
Introduction

1.1 Background

The fifth-generation(5G) wireless systems have three keystones: enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine type communications (mMTC) [1]. Among these topics, URLLC is especially important for aiming to have ultra-reliably and very low latency. Including Internet of

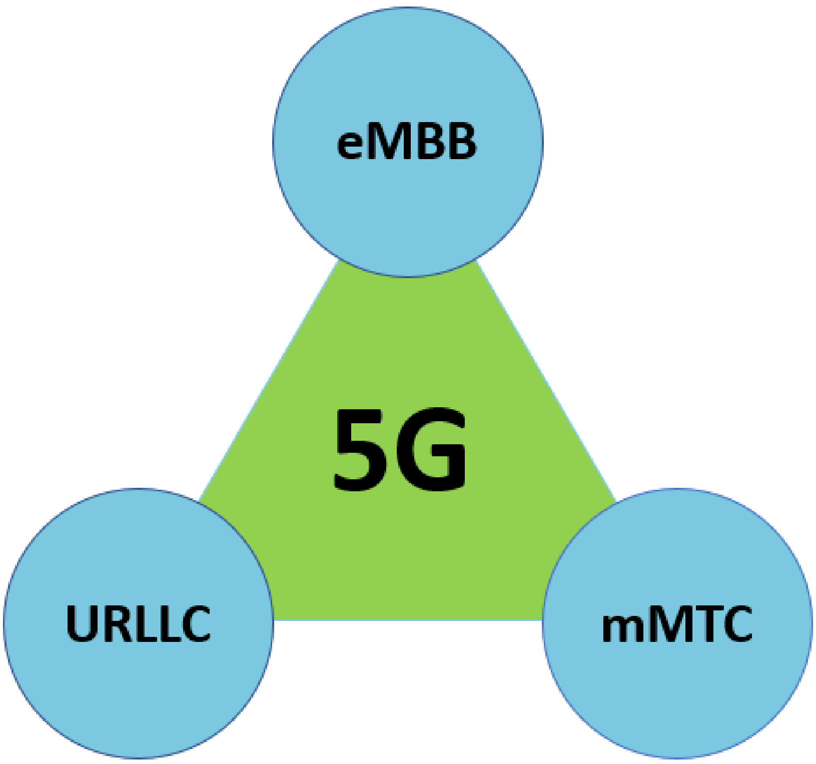


Figure 1.1.1: 5G services.

vehicles (IoV), Internet of Things (IoT), machine to machine (M2M) communication, and so on. URLLC is a kind of machine type communication (MTC) [2]. The 3rd Generation Partnership(3GPP) defines the URLLC standard. With 0.5ms for latency per link to users, 99.999% for reliability, and a 32byte packet with 1 ms for user plane latency [3].

1.2 Motivation

Nowadays, Robots are combined with many different components and connected with many cables [4]. One of the famous robotic topics is how to remove the wire inside

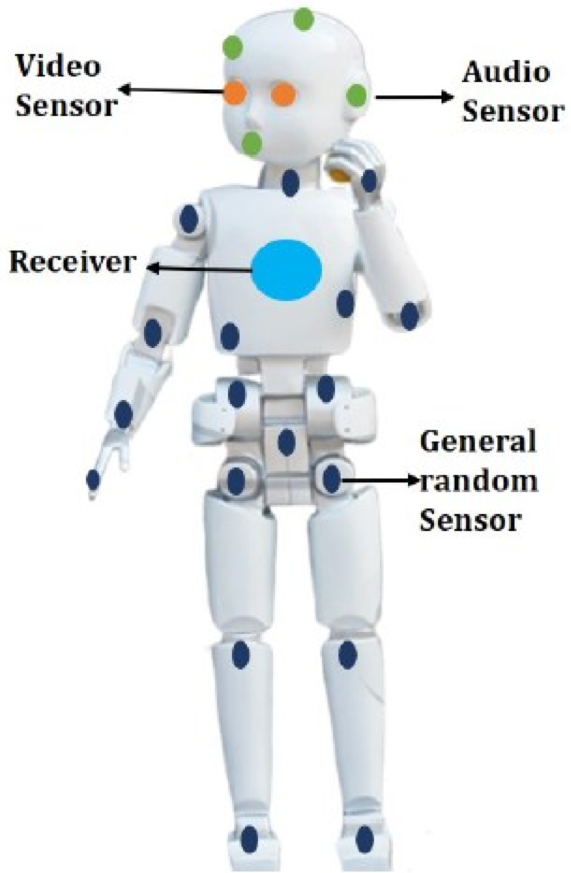


Figure 1.2.1: A typical humanoid robot with a large number of audio, video and general sensors [9].

robots. In order to make robots more flexible, lesser maintain and easier to build up. Especially for sensors. Numerous sensors with a large number of wires would cause an increase in weight and make the robot inflexible. To achieve this goal, wireless sensors become into focus. It is difficult to convert the wire system into wireless system, and challenges such as latency, safety, interference, and signal fading have to be overcome [5].

1.3 Relative Work

1.3.1 OFSMA

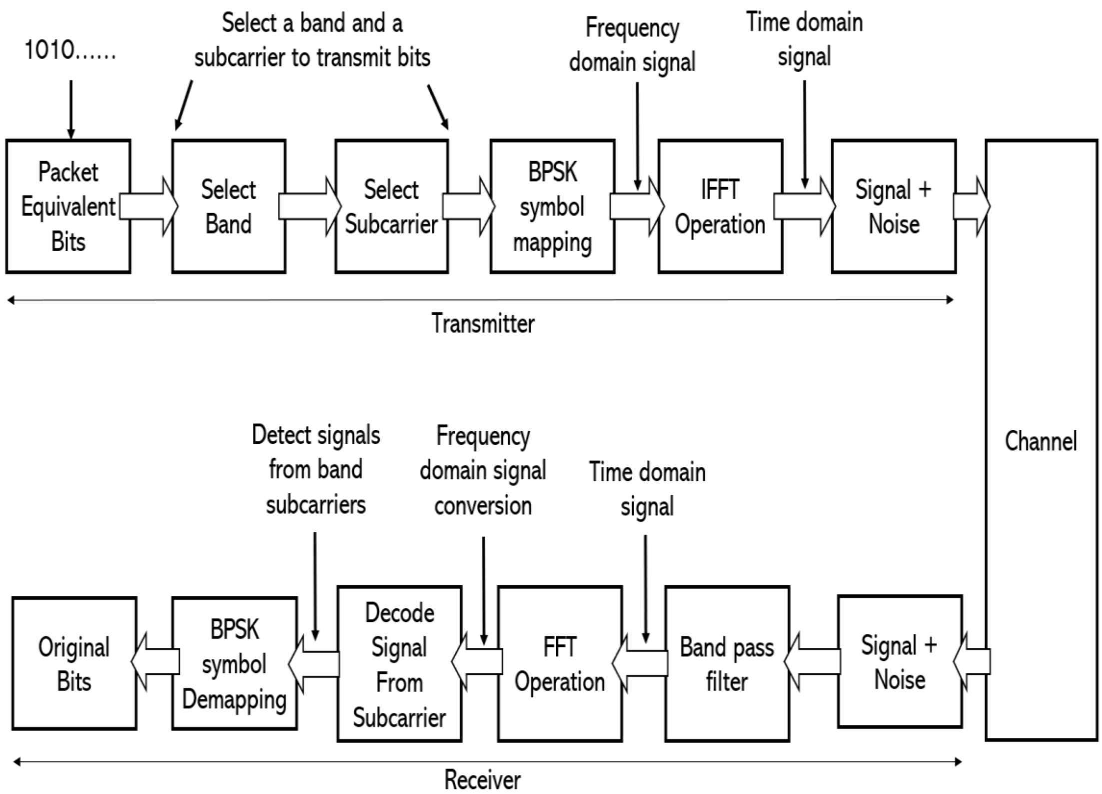


Figure 1.3.1.1: The progress cycle of OFSMA

“Medium Access Control (MAC)- Orthogonal Frequency subcarrier-based Multiple Access (OFSMA)” is a scheme that we had proposed in previous work. It combines with random access slot ALOHA [6] and OFDM [7] which unsure the URLLC standard, 99.999% reliability and short latency lower than 1ms with a packet transmission [8].

The single packet progressing cycle of OFSMA scheme is shown in Figure. 1.3.1.1. Before transmitting a packet, the transmitter will duplicate the packet, and choose a random frequency subcarrier to transmit the packet. Among the duplicate packet, if one packet is successfully received by the receiver, the transmission is regarded as successful transmission and the receiver discard the other replicated copies of the same packets [9].

1.3.2 Waveguide

Waveguides are used to transmit electromagnetic energy and power from one point in the space to another efficiently. The waveguide is now widely used in many internal signal propagation. One of the basic shapes of waveguides is rectangle shape waveguide. Usually, there are three transmission modes: TE, TM, TEM. But rectangular waveguides only supports TE and TM mode. The propagation would no success if the signal propagate below a certain frequency called cutoff frequency. For rectangular waveguides, TE10 mode has the lowest cutoff frequency[10].

Chapter 2

Method and Models

2.1 Design method - Hybrid Mac

In order to manage the transmission between different wireless sensors, the hybrid scheme is proposed which combines with OFSMA [11] and waveguide in Figure. 2.1.1.

Figure 2.1.1: OFSMA Hybrid mac access scheme

Basically, there are three kinds of sensors in a robot system: general sensors, video sensors, and audio sensors. We designed to transmit the signals through the different kinds of channels. In this hybrid scheme, the subcarrier channels are divided into two parts. The general sensors are designed to transmit the data packet by using OFSMA scheme, which randomly selects different frequency subcarriers and transmits the duplicate packet to ensure satisfied the URLLC standard. As for the video and audio sensors, we propose to make the data transmitted through the dedicated channel through the waveguide structures.

2.2 Design models

In every robot nowadays, there are many spaces between the inside structure of robot leg, arm, and body. We design to regard the robot structure as an internal waveguide and directly transmit the signal through these small spaces. Most of the research now consider the rectangular-based waveguide and designs an extra structure that can improve the transmission through the waveguide. Then, use the HFSS to do the simulations. However, those rectangular waveguide models cannot simulate realistic situations if we want to directly transmit the signal through the complex structure inside the robot. So, we decide to design some models which consider some realistic situations to increase the simulation accuracy.

The reason why we choose the leg as the model is that the structure of the leg is more simple than other parts of robot, such as arm and body. The degree of freedom of knee in leg model is only one. We only have to consider one direction while the model turning into different degrees.

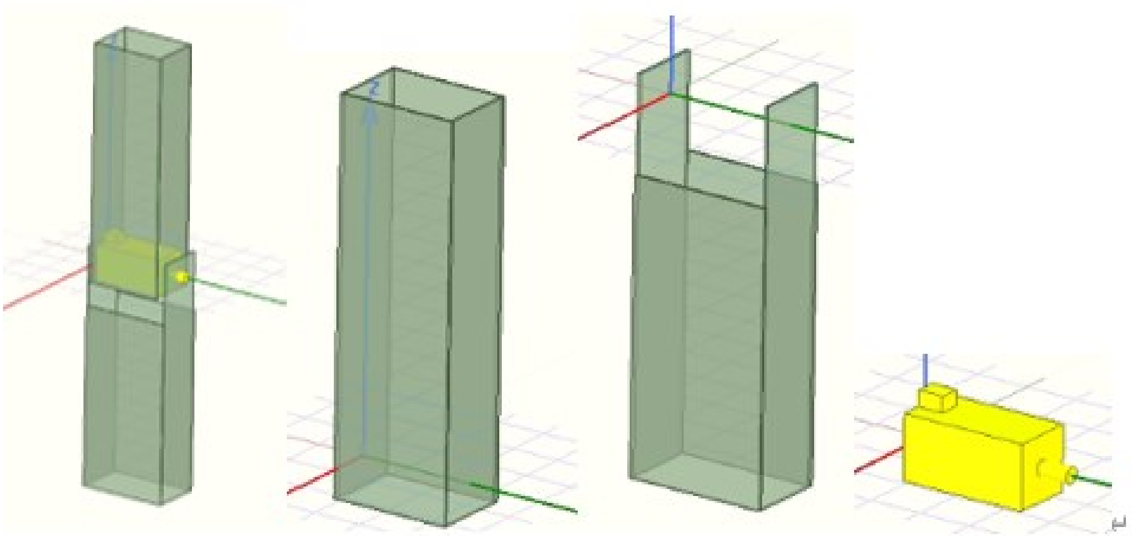
In this paper, we design four waveguide models based on the rectangular and circular structures of the robot leg. For the first three models, we add a motor inside the model and design the structure which considering the physical interfere problem with different shapes and materials. In the final model, we try to design a model with considering more realistic structure with adding more elements inside the model.

Chapter 3
Interfere model

3.1 Rectangular interfere model

A leg has divided into three parts. Thigh, knee, and calf. The overview of the rectangular waveguide model is in Figure. 3.1.1. In this model, the upper and downer part we design as the robot's thigh and calf. In the middle part we design to put a motor as a robot knee. Also, there is some space in the middle that consider the physical structure interference when motor turns into different degrees.

We first design the motor with the size of 60*60*120 (mm). And we set the length of



(A) (B) (C) (D)

Figure 3.1.1: Iron rectangular interfere model (A)overview, (B)upper leg, (C)downer leg, (D)motor

Table 3.1.1: Parameters of Rectangular Interfere Model (Iron)

Iron rectangular interfere model (mm)		
Overview	Model overall size	86*148*740
	Air propagation space	80*142*740
Motor	Material	Iron
	Body	60*60*120
	Shaft	Ø15*150
	Power interface	15*20*25
Upper leg	Material	Iron
	Left/right structure	3*80*400
	Front/back structure	3*126*400
Downer leg	Material	Iron
	Left/right structure	3*80*400
	Front/back structure	3*120*300

the upper and downer parts as 400 (mm). Then, we use this motor model as the design standard of the whole model to design other supporting structures. Finally, we set the material of this model as iron. The detailed parameters of this model are list in Table 3.1.1. And the simulation setting of the rectangular robot leg model in HFSS is list in Table 3.1.2.

We set the waveguide simulation mode TE01, and design the whole model structure using iron and simulate in 900MHz, 2.4GHz, 5.5GHz, 24GHz frequency. We choose these

Table 3.1.2: Simulation Parameters of Rectangular Interfere Model (Iron)

Rectangular robot leg simulation parameters (iron)	
Transmit power	20dBm
Delta S	0.02
Relative permittivity (air)	1.0006
Relative permittivity (iron)	1
Relative permeability (air)	1.0000004
Relative permeability (iron)	4000
Frequency	900MHz, 2.4GHz, 5.5GHz, 24GHz

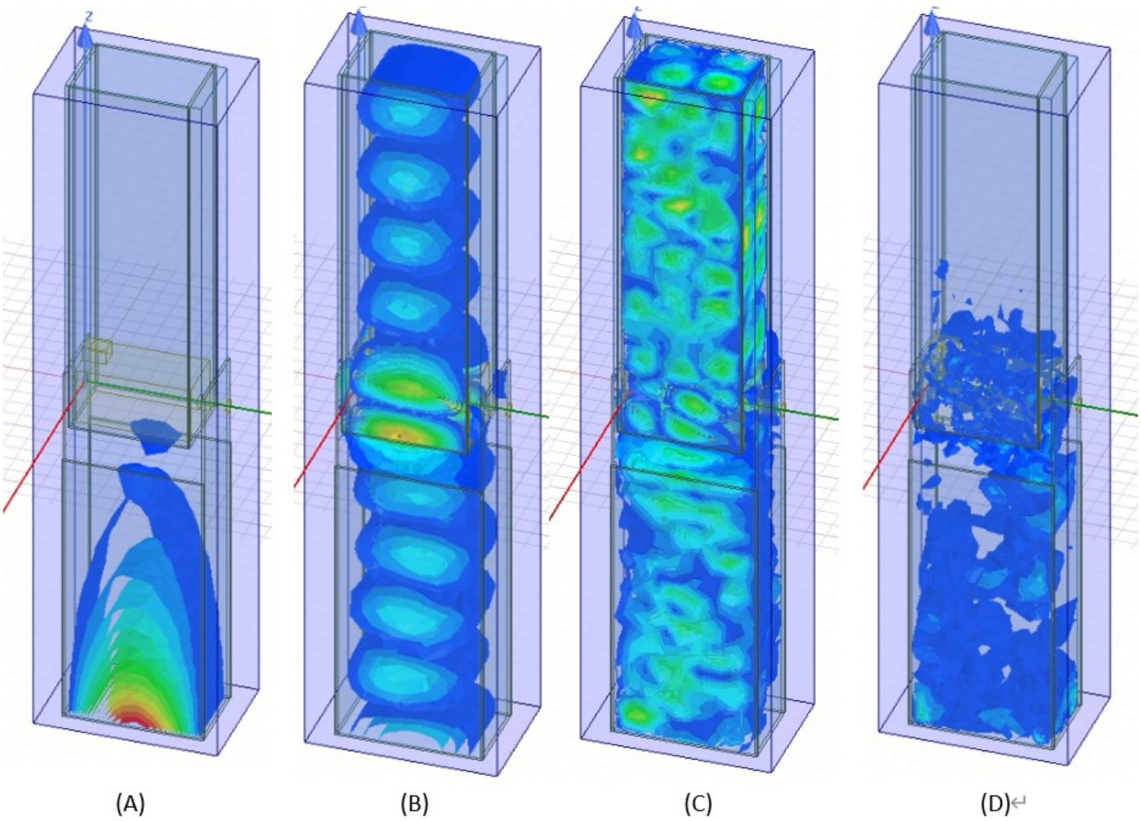


Figure 3.1.2: Signal propagation in iron rectangular interfere model with different frequency. (A)900MHz, (B)2.4GHz, (C)5.5GHz, (D)24GHz

Frequency is because they are now widely used in many fields. Then, we do the simulation and observe the signal propagation of the electric field. The result is shown in Figure. 3.1.2. In the result, we can observe that basically, the signal could only propagate at a certain frequency. And about the successfully propagate result, although there is some structures block inside the waveguide, the signal could still propagate through the small spaces inside the robot leg model. Also, we can observe the strength of successful propagated signal would significantly decrease. Those signals would block by the motor in the middle of the structure.

3.2 Rectangular interfere model with different material

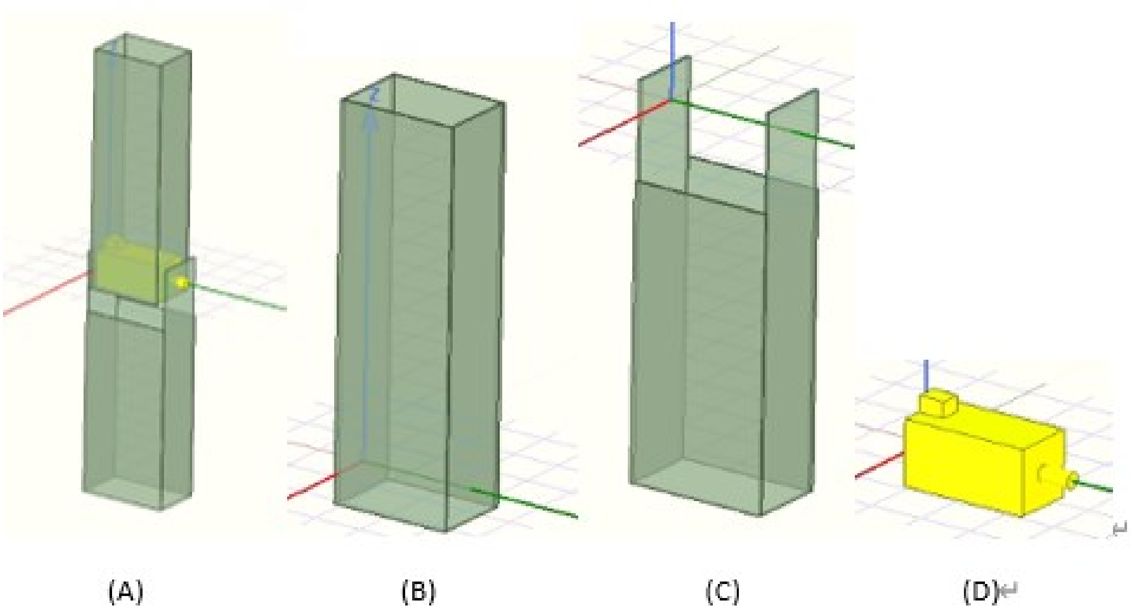


Figure 3.2.1: PVC plastic rectangular interfere model (A)overview, (B)upper leg, (C)downer leg, (D)motor

In this part, we want to find out the relationship between signal propagation and different materials structures of waveguide model. Therefore, we design using the model mentioned in the first part, and only change some parts of the model structure into PVC plastic to simulate the signal propagation. The overview of model is shown in Figure 3.2.1. And the structure parameters are list in Table 3.2.1. For the motor part, we keep the same material setting as the iron. And for the upper leg and downer leg structure, we change it into PVC plastic. Rest of the parameters such as sizes are not changed in the second robot leg model.

The simulation setting of different material rectangular robot leg model in HFSS is list in Table 3.2.2. In this model, we only change the structure except for motor into PVC

Table 3.2.1: Parameters of Rectangular Interfere Model (PVC plastic)

Rectangular robot leg (mm)		
Overview	Model overall size	86*148*740
	Air propagation space	80*142*740
Motor	Material	Iron
	Body	60*60*120
	Shaft	Ø15*150
	Power interface	15*20*25
Upper leg	Material	PVC plastic
	Left/right structure	3*80*400
	Front/back structure	3*126*400
Downer leg	Material	PVC plastic
	Left/right structure	3*80*400
	Front/back structure	3*120*300

plastic and simulate in 900MHz, 2.4GHz, 5.5GHz, 24GHz frequency. The result is shown in Figure. 3.2.2. We can observe that still, the signal would propagate at a certain frequency. But the performance of the propagation is weaker than using the iron because the signal cannot fully reflect inside the PVC plastic structure. The power efficiency would be very bad with using PVC plastic structure as the waveguide model.

Table 3.2.2: Simulation Parameters of Rectangular Interfere Model (PVC plastic)

Rectangular robot leg simulation parameters (PVC plastic)	
Transmit power	20dBm
Delta S	0.02
Relative permittivity (air)	1.0006
Relative permittivity (iron)	1
Relative permittivity (PVC plastic)	2.7
Relative permeability (air)	1.0000004
Relative permeability (iron)	4000
Relative permeability (PVC plastic)	1
Frequency	900MHz, 2.4GHz, 5.5GHz, 24GHz

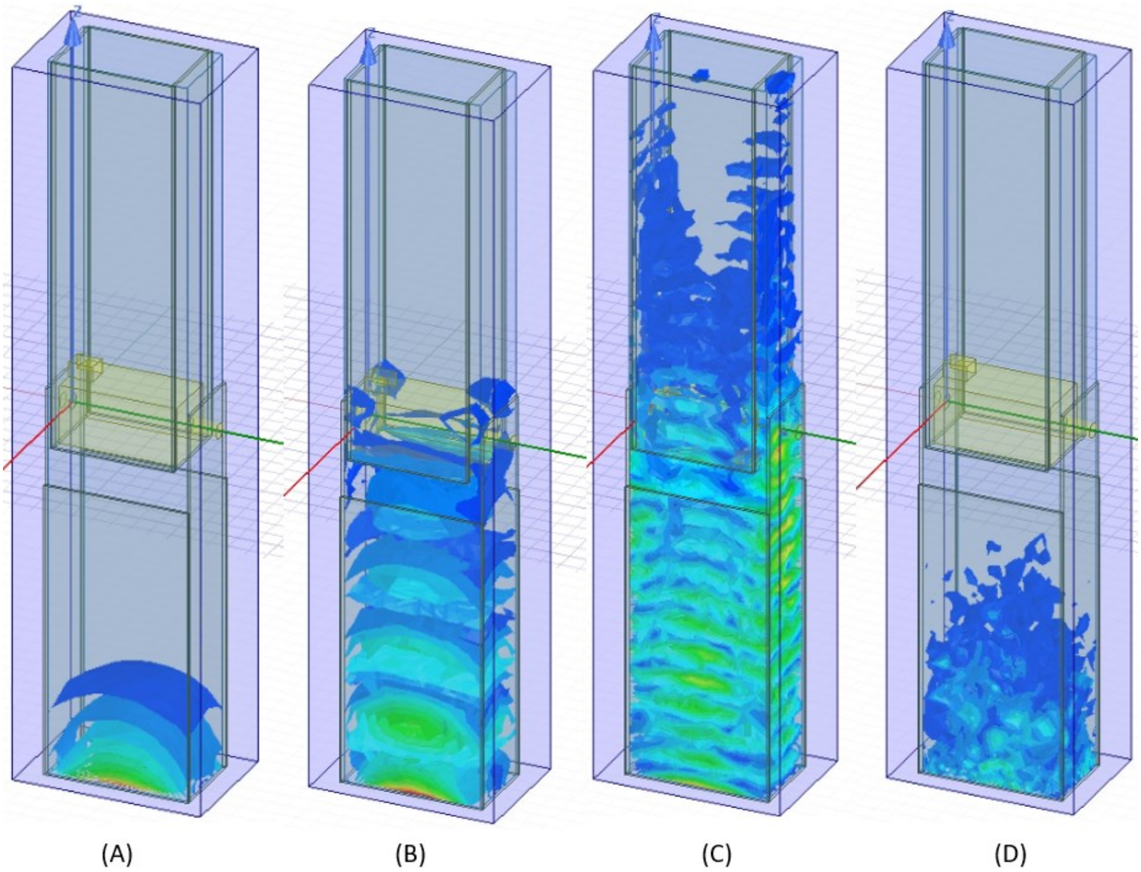


Figure 3.2.2: Signal propagation in iron rectangular interfere model with different frequency. (A)900MHz, (B)2.4GHz, (C)5.5GHz, (D)24GHz

3.3 Circular interfere model

The third model is using the circular-based waveguide model, shown in Figure. 3.3.1. And the parameters are list in Table 3.3.1. Some of the robot legs nowadays are designed as cylinders outward, with many supporting structures inside.

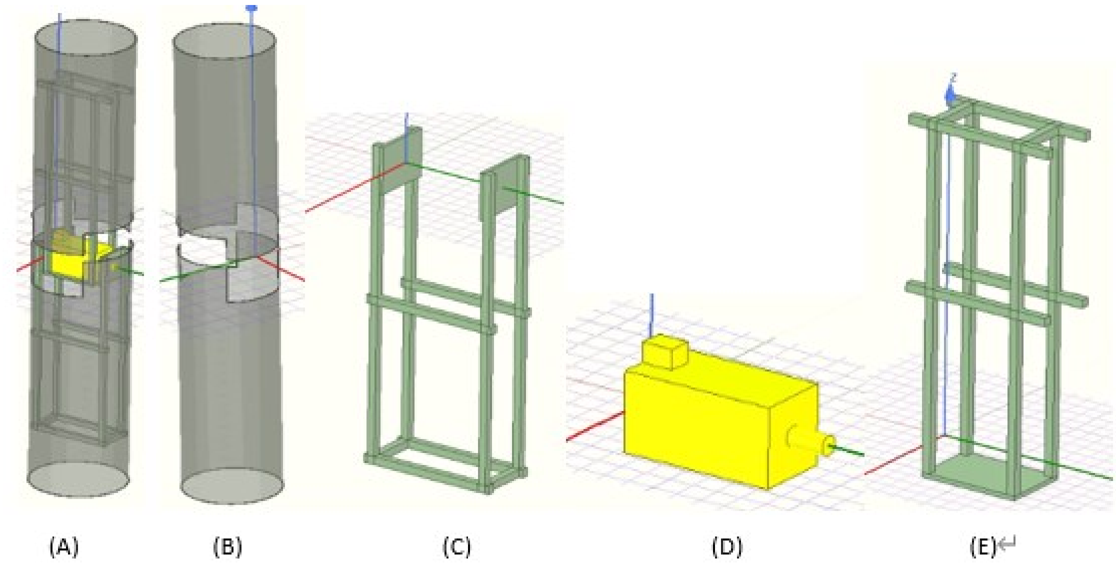


Figure 3.3.1: Circular Interfere model (A)overview, (B)outside shell, (C)downer leg, (D)motor, (E) upper leg

To simulate this situation, we design the inside structures assumes as the bones and an outside cylinder shell to cover the inside supporting structures. We set iron for the whole model material. First, we use the motor mentioned in the first part as the model standard. Then, we design many rectangular shape support structures as basic structure, with some

Table 3.3.1: Parameters of Circular Interfere Model Structure

<table>
<tr><th colspan="4">Circular robot leg (mm)</th></tr>
<tr><td rowspan="2">Overview</td><td>Model overall size</td><td colspan="2">Ø102*940</td></tr>
<tr><td>Air propagation space</td><td colspan="2">Ø100*940</td></tr>
<tr><td rowspan="5">cylindrical shell</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td rowspan="2">Upper shell</td><td>Inner</td><td>Ø100*425</td></tr>
<tr><td>Outer</td><td>Ø102*425</td></tr>
<tr><td rowspan="2">Downer shell</td><td>Inner</td><td>Ø100*500</td></tr>
<tr><td>Outer</td><td>Ø102*500</td></tr>
<tr><td rowspan="4">Motor</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Body</td><td colspan="2">60*60*120</td></tr>
<tr><td>Shaft</td><td colspan="2">Ø15*150</td></tr>
<tr><td>Power interface</td><td colspan="2">15*20*25</td></tr>
<tr><td rowspan="5">Upper leg</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Vertical support structure</td><td colspan="2">10*10*400</td></tr>
<tr><td>Horizon support structure (long)</td><td colspan="2">10*10*180</td></tr>
<tr><td>Horizon support structure (short)</td><td colspan="2">10*10*80</td></tr>
<tr><td>Bottom support structure</td><td colspan="2">5*80*120</td></tr>
<tr><td rowspan="5">Downer leg</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Vertical support structure</td><td colspan="2">10*10*400</td></tr>
<tr><td>Horizon support structure (long)</td><td colspan="2">10*10*180</td></tr>
<tr><td>Horizon support structure (short)</td><td colspan="2">10*10*80</td></tr>
<tr><td>Top support structure</td><td colspan="2">5*60*80</td></tr>
</table>

Table 3.3.2: Simulation Parameters of Circular Interfere Model

Circular robot leg simulation parameters	
Transmit power	20dBm
Delta S	0.02
Relative permittivity (air)	1.0006
Relative permittivity (iron)	1
Relative permeability (air)	1.0000004
Relative permeability (iron)	4000
Frequency	900MHz, 2.4GHz, 5.5GHz, 24GHz

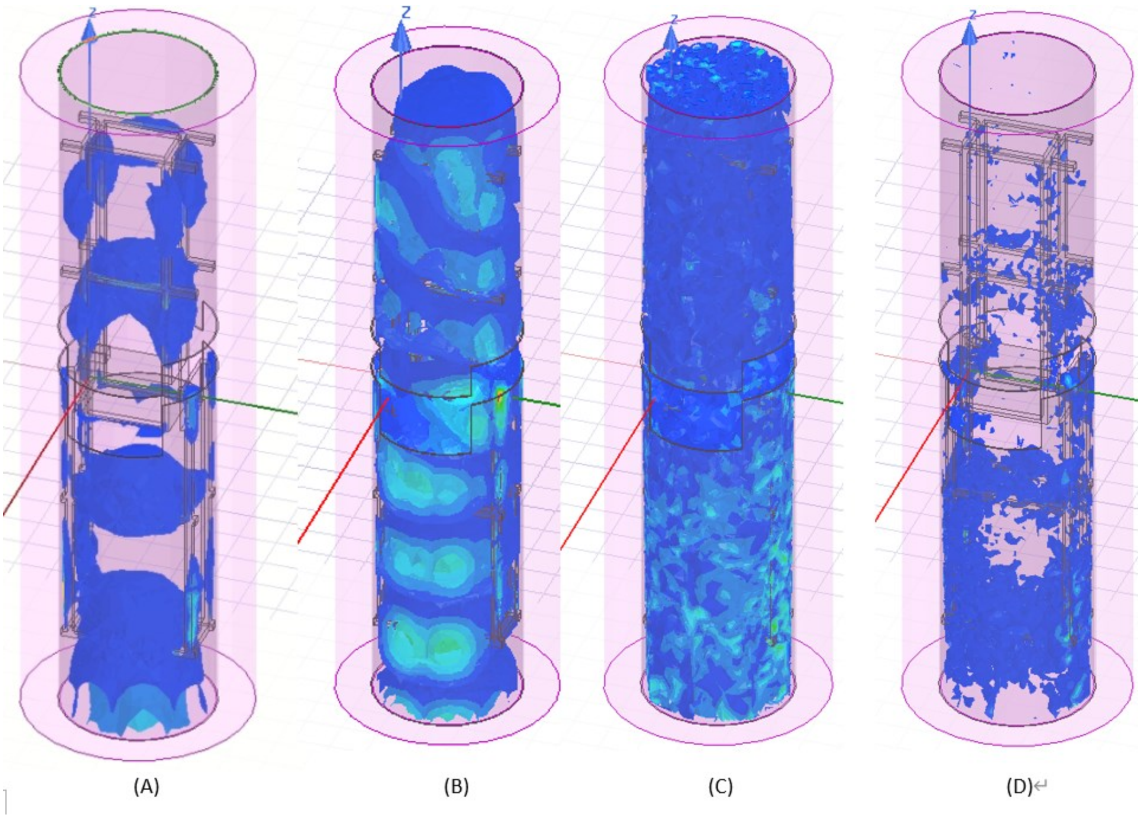


Figure 3.3.2: Signal propagation in circular robot leg model with different frequency. (A)900MHz, (B)2.4GHz, (C)5.5GHz, (D)24GHz

rectangular flakes which can sustain the motor in realistic situations. We also set the length of the upper and downer part as 400 (mm), and use these two supporting structures to design the air propagation space with the diameter Ø100 and height 940mm. Finally, use these parameters to design an outside cylindrical shell to cover the whole model. Also, there are spaces in the middle which consider the physical interfere problem.

The simulation setup of the circular robot leg model in HFSS is list in Table 3.3.2. We design the whole model structure with using iron and simulate in different frequencies of 900MHz, 2.4GHz, 5.5GHz, and 24GHz. In this model, we design the inside supporting structure and outside shell cover the whole model.

The simulation result is shown in Figure. 3.3.2. We can see that the propagation strength is very low due to the complex structure inside the model. These supporting structures inside the model would affect the reflection of signals propagate inside the waveguide model. Only at a certain frequency setting, the signal would propagate successfully, but the propagation strength is very weak.

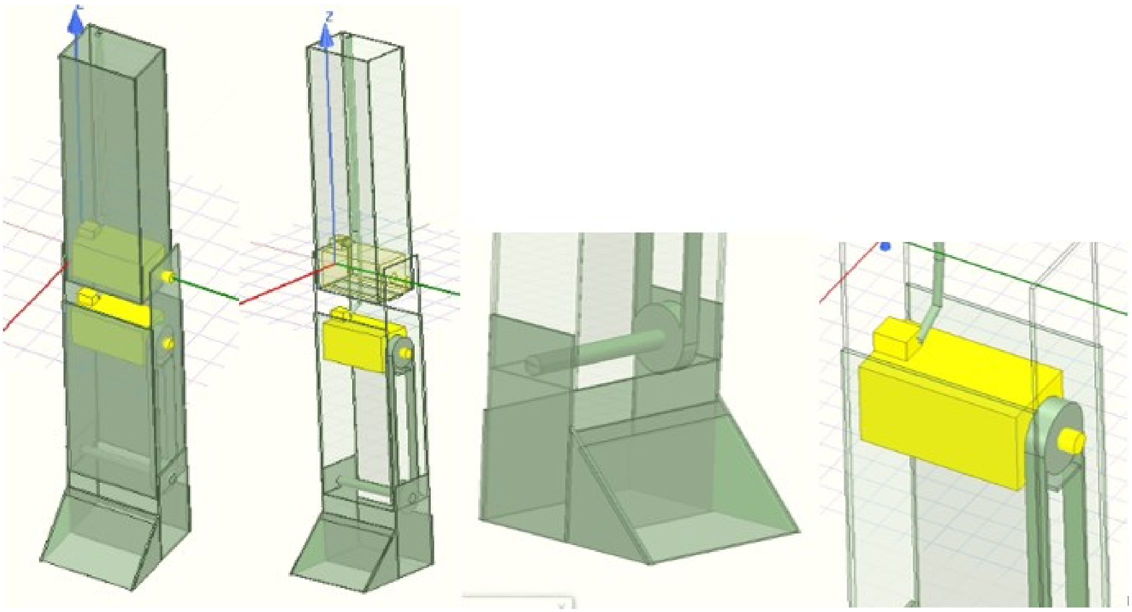
3.4 Summary

In this chapter, we design models to simulate the signal propagation inside the waveguides with some physical interfere. Thus, we design the Iron rectangular interfere model, PVC plastic rectangular interfere model, and iron circular interfere model. In the result shows, basically the signal can propagate through the models if there are spaces inside. And every model has different operation frequency range. Compare with these three models. We can see that the rectangular models has better performance. And the Iron models can have stronger signal propagation then the PVC plastic models.

Chapter 4
Realistic model

4.1 Realistic model

In this part, in order to simulate in realistic situation, we design the robot leg model based on the rectangular waveguide, and we add some elements inside this model, including adding the feet, gear, chain, and some power cables. The overview is shown in Figure 4.1.1. And the parameters are shown in Table 4.1.1. First, we first design the feet structure and which also consider the physical structure interfere with having some spaces. As for the inside of the feet structure, we design a rectangular board to keep the width and length of air propagation space are similar to the basic rectangular waveguide. Finally, we



(A) (B) (C) (D)

Figure 4.1.1: Realistic rectangular robot leg model (A)overview, (B)inside structure , (C)feet, (D)motor and feet control structure

Table 4.1.1: Parameters of realistic rectangular robot leg model

<table>
<tr><th colspan="4">Realistic rectangular robot leg (mm)</th></tr>
<tr><td rowspan="2">Overview</td><td>Model overall size</td><td colspan="2">153*256*850</td></tr>
<tr><td>Air propagation space</td><td colspan="2">80*148*850</td></tr>
<tr><td rowspan="5">Motor</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Body</td><td colspan="2">60*60*120</td></tr>
<tr><td>Support structure</td><td colspan="2">3*30*126</td></tr>
<tr><td>Shaft</td><td colspan="2">Ø15*150</td></tr>
<tr><td>Power interface</td><td colspan="2">15*20*25</td></tr>
<tr><td rowspan="3">Upper leg</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Left/right structure</td><td colspan="2">3*80*400</td></tr>
<tr><td>Front/back structure</td><td colspan="2">3*126*400</td></tr>
<tr><td rowspan="3">Downer leg</td><td>Material</td><td colspan="2">Iron</td></tr>
<tr><td>Left/right structure</td><td colspan="2">3*80*400</td></tr>
<tr><td>Front/back structure</td><td colspan="2">3*120*300</td></tr>
<tr><td rowspan="2">Power cable</td><td>First motor</td><td colspan="2">Ø7*355</td></tr>
<tr><td>Second motor</td><td colspan="2">Ø7*470</td></tr>
<tr><td rowspan="4">Feet control structure</td><td>Material</td><td colspan="2">iron</td></tr>
<tr><td>gear</td><td colspan="2">Ø50*15</td></tr>
<tr><td>chain</td><td colspan="2">3*15*240</td></tr>
<tr><td>drive shaft</td><td colspan="2">Ø15*150</td></tr>
<tr><td rowspan="5">Feet</td><td>Material</td><td colspan="2">iron</td></tr>
<tr><td>Front structure</td><td colspan="2">3*100*153</td></tr>
<tr><td>Back/middle structure</td><td colspan="2">3*80*154</td></tr>
<tr><td rowspan="2">Left/right structure</td><td>Rectangular</td><td>3*80*150</td></tr>
<tr><td>Right triangle</td><td>3*50*50</td></tr>
</table>

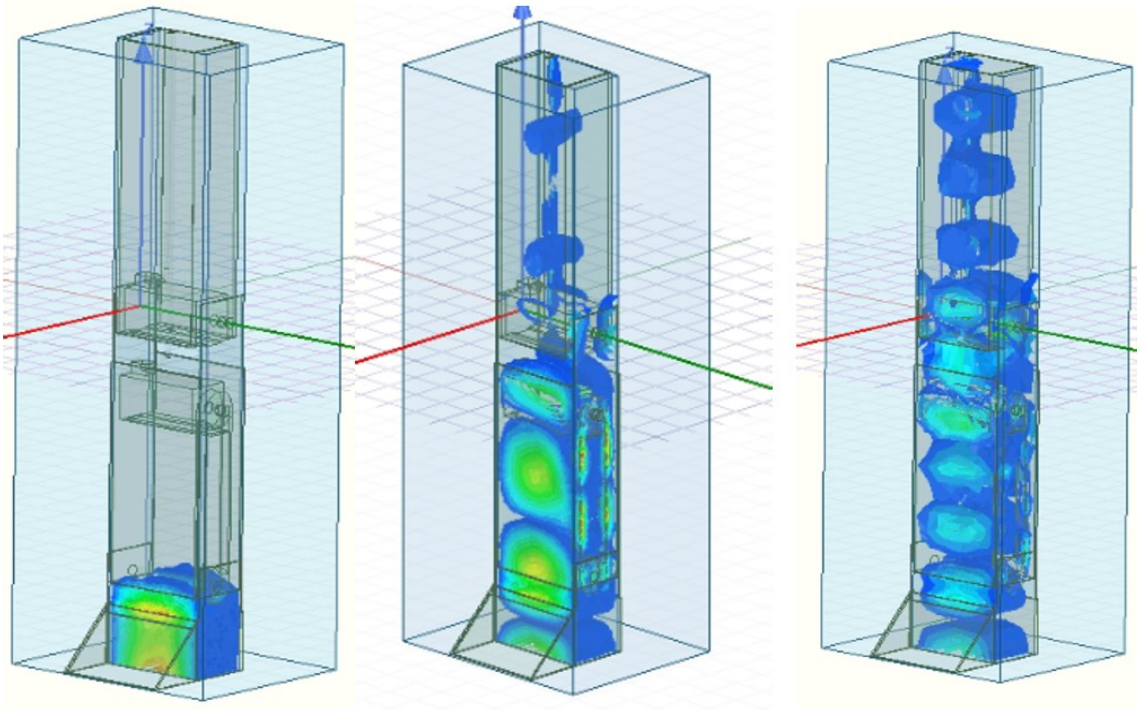
Table 4.1.2: Simulation Parameters of realistic rectangular robot leg model

Realistic rectangular robot leg simulation parameters	
Transmit power	20dBm
Delta S	0.02
Relative permittivity (air)	1.0006
Relative permittivity (iron)	1
Relative permeability (air)	1.0000004
Relative permeability (iron)	4000
Frequency	900MHz,1.5GHz, 2.4GHz, 5.5GHz, 15GHz, 24GHz

design to put the second motor under the knee part. This motor is designed to control the feet structure through the gear and chain. Then, we add two power cables for the two motors inside this model.

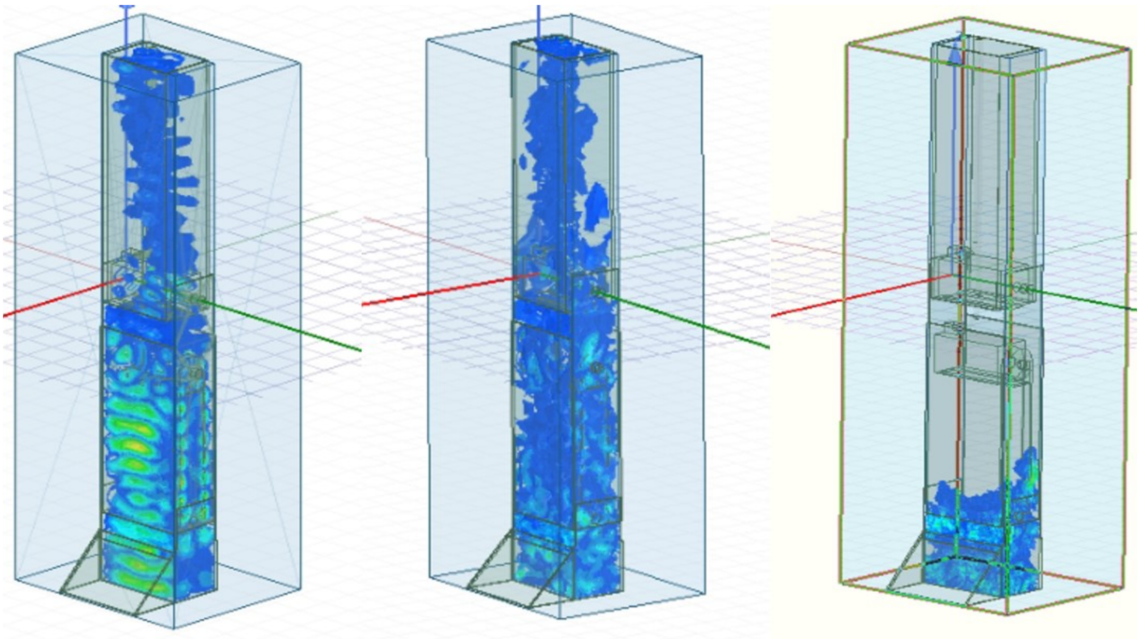
The simulation setting of the realistic rectangular robot leg model in HFSS is listed in Table 4.1.2. We set the waveguide simulation mode TE01, and design the whole model structure using iron and simulate in 900MHz, 1.5GHz, 2.4GHz, 5.5GHz, 15GHz, and 24GHz frequency. The simulation result is shown in Figure. 4.1.2 and Figure. 4.1.3.

In the theory, the cutoff frequency of this rectangular space size is around 1GHz, and the operating frequency range is from 1.3GHz to 1.9GHz. In the result, first, we can observe that the frequency of 900MHz and 24GHz in this model cannot let the signal propagate due to the width of the waveguide. About the 1.5GHz frequency result, we can see that under the operation frequency, the signal could propagate successfully in the below part of the model. However, when signals try to propagate through the motor part, most of the signals are blocked. In the endpoint, only some very weak signal can propagate through the whole model. As for the other frequencies' situation. Although these frequencies are much higher than the operating frequency, it still can propagate some parts of the signal.



(A) (B) (C)

Figure 4.1.2: Signal propagation in realistic rectangular robot leg model with different frequency. (A)900MHz, (B)1.5GHz, (C)2.4GHz



(D) (E) (F)

Figure 4.1.3: Signal propagation in realistic rectangular robot leg model with different frequency. (D)5.5GHz, (E)15GHz, (F)24GHz

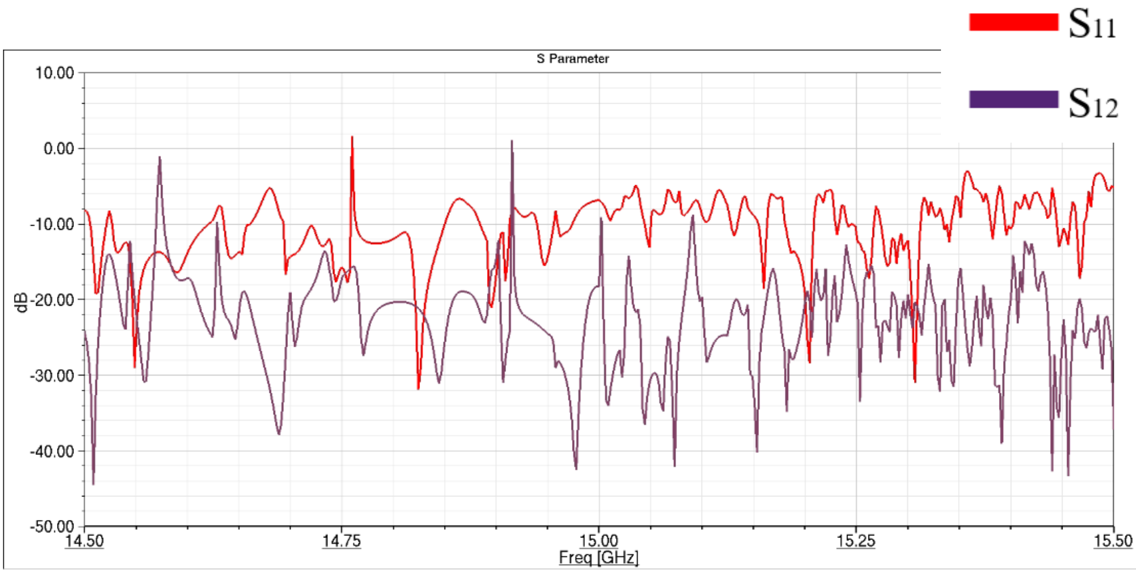


Figure 4.1.4: The S11 and S12 parameters of the signal propagation result in 15 GHz

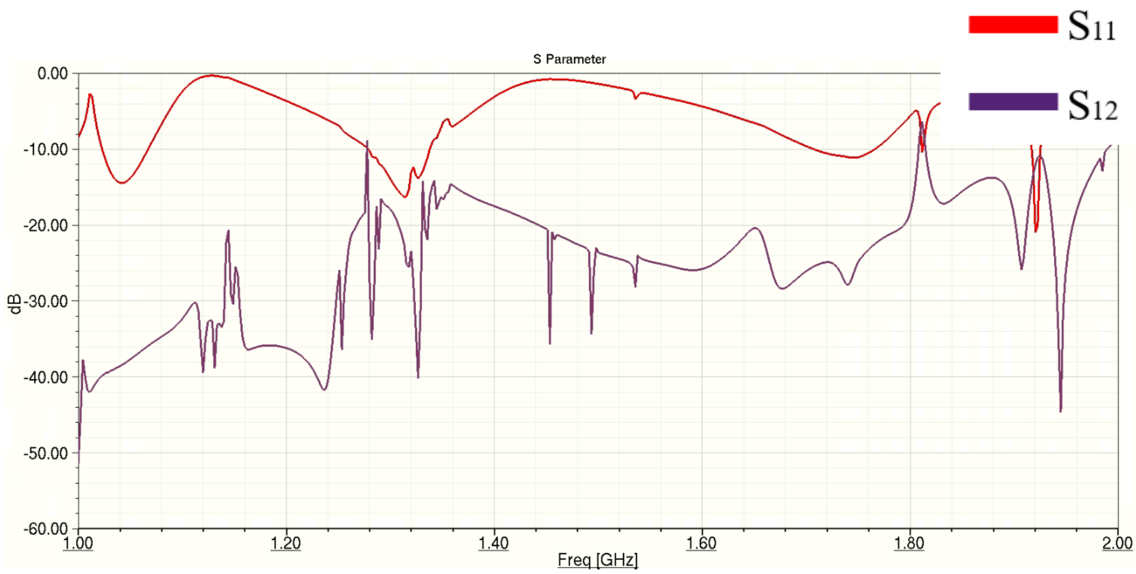


Figure 4.1.5: The S11 and S12 parameters of the signal propagation result in 1.5 GHz

we can also observe that when a signal transmits through motors, the strength becomes lower. But still, the endpoint of the realistic rectangular robot leg model can receive a little poor signal.

In Figure.4.1.4 and Figure.4.1.5, the red line is s_{11} and the purple is s_{12}. We can also observe that at the operation frequency around 1.5GHz, the signal is hardly transmitted through the model. But the 15GHz result, despite that the efficiency is not very good, it still can achieve propagate directly through the robot leg model.

4.2 Summary

In this chapter, we design a realistic rectangular robot leg which added some elements inside to have a more realistic simulation environment. Including adding motor, gear, chain, and feet control structure. Then, we simulate in different frequency from 900MHz, 1.5GHz, 2.4GHz, 5.5GHz, 15GHz, to 24GHz. As the result shown, we can observe that although the theory operation frequency is around 1.5 GHz, this model would have better performance in 15 GHz.

Chapter 5
Conclusion and Future Works

5.1 Conclusion

In this paper, we mention our previous work, OFSMA scheme. Which satisfied the URLLC standard. Then, we designed to combine the OFSMA scheme and internal waveguide into a new hybrid scheme to propagate the signal from different source, normal sensors, video and audio sensors. For the dedicate channel of internal waveguide propagation, we set a goal to transmit the signal directly through small spaces inside the robot arm, leg, and body. Therefore, We design four different robot leg models with different sizes, shapes, and materials to make the simulation become more realistic. Then, we simulate these models with different frequencies.

As the result showed, We can observe that the more complicated structure inside the waveguide, the weaker signal can propagate. And if the waveguide structure has small spaces, the signal could propagate through the model with a range of frequency for every size of waveguide model. In the conclusion, we believe that nonmatter the how the structure is inside the waveguide model, it exits a best frequency to propagate the signal with strongest strength, and a range of frequency which can also transmit the signal successfully with weaker signal propagation strength. Also, in the simulation we can find out that the signal propagation performance of rectangular waveguide is better than using the circular shape waveguide.

These results proved that there is the possibility to propagate the signals directly through the complex structures inside the robot.

5.2 Future works

As for the extension of this paper, we would first bend the knee part into different degrees and do the simulation to test the strength of signal propagation. Then, we would also design other models which have more complicated structures inside to increase the simulation accuracy and find out the signal propagation relationship between different shapes, materials, inside structures, bending degrees, and other interfere.

In the future, this model could be the concept of signal propagation of a non-wired robot systems which can efficiently decrease the cables and make the robot decrease the weight, easier to maintain, and more flexible.

Research Achievements

Chihyeh Chen, Megumi Saito, and Shigeru Shimamoto, “Signal propagation through the inside of robot leg for non-wired robot system”
Accepted as the poster by 2022 IEEE Consumer Communications & Networking Conference, online virtual conference, January 8-11, 2022.

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