The Optimal Design of 26 Ghz 5G-R Micro-strip MIMO Outdoor Antennas for Future Railway Mobile Communication System

Selvi Lukman, Yul Yunazwin Nazaruddin, Bo Ai, and Endra Joelianto

Abstract—**The 5G technology for Future Railway Mobile Communication System (FRMCS) must satisfy the ever-increasing seamless connection requirements of millimeter-wave and massive Multiple Input Multiple Output (MIMO) technologies. This study constructs an optimal design of 26 Ghz outdoor antenna micro-strip for the Future Railway Mobile Communication System (FRMCS) in 5G communication system. The designated structure of 2 x 2 antenna patch with 112 radiations is fed by the micro-strip feeding technique. The simulation of the constructed design is conducted by utilizing CST Microwave Studio software. Satisfactory results are achieved by the return loss value -11.113 dB, VSWR value 1.7712 and a high antenna gain at 14.89 dBi. Therefore, this optimal MIMO antenna design and simulation is sufficient to accommodate the challenging demands of the overcoming atmospheric attenuations from FRMCS's high mobility and frequency.**

Index Terms—**Antenna design, 5G-R, micro-strip, FRMCS**

I. Introduction

As the era of 5G has arrived, rail operators now have a game-changing opportunity to modernize the aging railway infrastructures. The global standard for railway communication will soon be replaced by the Future Railway Mobile Communication System (FRMCS). The broadband-ready technology of FRMCS will ensure the acceleration of safety improvements, digital transformation and operational efficiency. The collaboration of 5G communication technology for railway (5G-R) and FRMCS provides high throughputs especially with the supported combination of Internet of Things (IoT) and Machine Type Communications (MTC). A platform for innovative applications such as group video callings and automated train control requires an ultra-reliable, mission critical and low-latency communication to ensure satisfactory predictive maintenances. Both will enhance passenger experiences and bring down operating costs.

An increasingly saturated radio frequency spectrum in today's cellular base stations is one of the series of pressing challenges for the insatiable demand of FRMCS. The acceleration ability to a seamless data transmission is under threat especially in many dense areas. The deployment of a dedicated High Speed Rail (HSR) base stations will simultaneously connect the uninterrupted communications from large numbers of antennas with multiple spatially separated user terminals over the same frequency resources.

Accordingly, the massive MIMO technology is broadly accepted to unlock the collaboration of 5G-R and FRMCS experiences. The beamforming characteristic from the massive number of antennas will focus some substantial energies to improve the throughputs.

The Federal Communications Commission of the United States delegated the recent frequency bands from 27.5 to 28.35 GHz in July 2016 for 5G spectrum allocation [1]. The implementation of a MIMO complex design must be well-coordinated to fulfil the 5G requirements. Previous study has addressed a meaningful conclusion of an antenna design integration to support 4G and 5G wireless communication standards for mobile application. The design and simulation of 28 GHz MIMO antenna with four elements of 16 x 14 mm antenna dimension was printed on RT Duroid 5880 [2]. A meaning conclusion was achieved that the integrated antenna design should at least provide 12 dBi antenna gain with more than 1 GHz bandwidth.

Another attempt of antenna simulation investigated an unaccustomed band of 28.38 Ghz MIMO application for 5G cellular technology by utilizing a wide band planar patch antenna. It was also reported that a designated of 28 Ghz MIMO antenna for 5G cellular network by utilizing C shaped dielectric lens meta-material has successfully increased the antenna gain [3] [4]. Some wider choices of the 5G modified antenna configuration for mobile phones achieved more than 10 dB gain antenna acquisition [5]. Previous mentioned studies have almost exclusively focused on 5G cellular networks. However, it is obligated for 5G-R to be operated on a dedicated spectrum with separated

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infrastructures for a safe own related services [6]. Accordingly, the compensation of massive MIMO must address the severe path loss issues of HSR propagation since this technology is the key bone for the emerging 5G digital railways. To overcome the susceptibility of rapid signal degradations, the deployment of smaller antennas to be integrated in the antenna arrays must be conducted separately from the occupation of cellular networks since the critical mission of 5G-R is strictly required [7] .

Although satisfactory results appear to be consistent for 5G cellular networks, they appear to be inapplicable for 5G-R. Therefore, this paper addresses a specific design and characterization for 26 GHz MIMO configuration for 5G-R which is so far insufficiently explored in the scientific literature, since more than adequate results are required to support a safe transmission of HSR.

In this special contribution, the design of a micro-strip rectangular 26 Ghz MIMO antenna as referred to the World Radio Communications Conferences (WRC) 2019 is conducted to meet the requirement of 5G-R wireless broadband [8]. The antenna design is simulated by utilizing Computer Simulation Technology (CST) Microwave Studio software. It is also excited with the micro-strip line feeding technique to obtain the most optimal performance.

The paper is organized as follows. Section II discusses the design of rectangular antenna patch and a basic knowledge of the massive MIMO for 5G-R. Research and methodology are summarized in section III. Section IV contains results and discussion. Finally, some meaningful conclusions and future insights are addressed in Section V.

II. The Design of Rectangular Antenna Patch

The micro-strip patch antenna is the most customary type of antenna. It is structured as a non-planar or planar geometry of dielectric substrate component with a ground plane. The specific width and length of the rectangular patch is easy to analyze by exciting it with transmission lines [9]. The below formula calculates the width of radiating rectangular patch.

$$W = \frac{c}{2 f_0 \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{1}$$

c is denoted as the wave propagation through different materials at light speed which value is $3\times10^8\ m/s$ in a vacuum condition. The antenna working frequency is allocated in 26 Ghz for 5G-R communication system. The parameter ε_r defines a relative permittivity of dielectric constant from the substrates. The rectangular patch length is calculated from Δl as the fringing effect which is introduced at the air gaps. The fringing effect occurs because of the magnetic flux lines bulging. When the density of magnetic flux is decreased, the air gap in the effective are is increased. Consequently, the fringing effects make the antenna size wider after the excitation [10] as formulated.

$$\Delta L = 0.412h \frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{2}$$

Parameter h denotes the substrate height while ε_{reff} defines the constructive dielectric constant which is given by.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\left(\frac{h}{W}\right)}}\right) \tag{3}$$

Accordingly, Δl can be expressed as:

$$L = L_{eff} - 2\Delta L \tag{4}$$

Hence, L_{eff} is the most effective patch length which is formulated as below.

$$L_{eff} = \frac{c}{2 f_0 \sqrt{\varepsilon_{reff}}} \tag{5}$$

The impedances and antenna characteristics are greatly influenced by the feeding technique. The contacting technique is conducted by attaching the radio frequency power directly to a connecting element radiating patch in order to transfer the power of electromagnetic field [11]. Therefore, the width of micro-strip line can be expressed by.

$$W = \frac{2h}{\pi}\left\{B - 1 - \text{In}(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\text{In}(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right]\right\} \tag{6}$$

where relative dielectric constant ε_r is calculated as given.

$$B = \frac{60\varepsilon_r^2}{Z_0\sqrt{\varepsilon_r}} \tag{7}$$

One of the key enabling technology for 5G railway wireless communication broadband is the massive MIMO antenna configuration technology. Group of antennas are located at the transceiver to provide a relatively energy efficiency and high spectral utilization with a simple processing [12]. Since, the MIMO technology exploits multipath effects as opposed to eradicating and compensating signal, multiple antenna receivers and transmitters are utilized for a more uniformly distributed energy in the structure [13] .

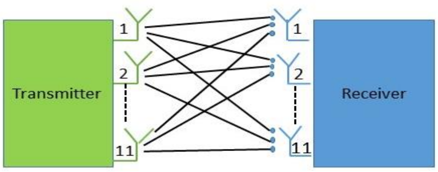

Fig. 1. The basic principle of MIMO system.

A better signal strength with a clearer line of site can be easily achieved by utilizing these bounced and reflected radio frequency transmission from the MIMO technology as depicted in Fig 1. The signals are transmitted through multiple antennas over the same path in the similar bandwidth. The other receiving antennas accept the signals through the different paths which result a more reliable data transmission. The increasing data rates are resulted from groups of transmitter and receiver antennas configuration. The receiver antenna is designated by considering some negligible time differences between the receptions of each signal. The configuration of arrays active antennas configurations has been acknowledged to be employed in many wireless communication systems [14], [15] . The antenna configuration is structured by deploying a group of radiating elements. The adjustment is performed through digital beamforming where its enhancement is emerged from the directivity, side-lobe level, polarization purity and bandwidth parameters. These mentioned properties make the array active antennas technologies become very challenging for a new range of applications.

III. Research Methodology

A. Figures Flowchart Design and Antenna Characteristic

The proposed optimal design for 26 micro-strip MIMO outdoor antennas of 5G-R steps and decisions are visually represented in Fig.2.

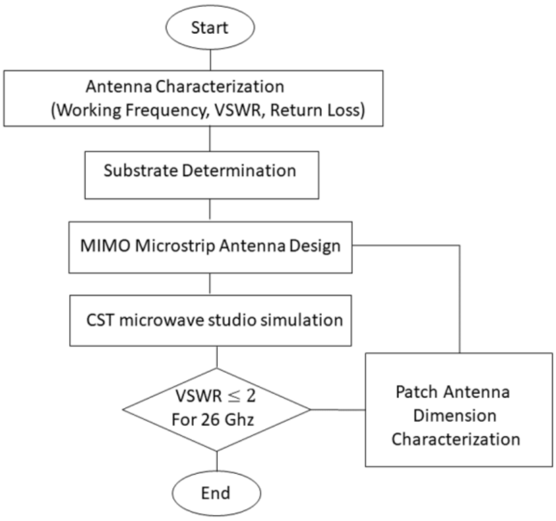

Fig. 2. The flowchart system design of 5G-R.

Table I shows the utilized basic properties to describe the desirable characterization of 26 *Ghz* of 5G-R micro-strip MIMO outdoor antennas for FRMCS.

TABLE I
ANTENNA CHARACTERIZATION

No	Parameter	Antenna Characterization
1	Working Frequency	26 *Ghz*
2	Return Loss	15 *dBi*
3	Bandwidth	> 500 *Mhz*
4	VSWR	< 2
5	Gain	>12 *dBi*

In the frequency domain, dielectric constant describes a relative permittivity in the form of complex number of frequency domain by calculating the permittivity of a certain medium relative to that of the vacuum permittivity. Additionally, the loss tangent isolates the information of the losses from the fundamental parameters. Dielectric substrates provide a reliable mechanical support to the antennas in term of the cost, application, size and moreover the resonant frequency.

Dielectrics are utilized not only for improving the mechanical and electrical stability but also they are capable to produce the displacement currents that lead to time varying magnetic field in accordance with the Ampere's Law [16]. In this work, a high frequency laminated substrate PTFE of Rogers RT/Duroid 5880 composites which was reinforced with glass microfibers is utilized to provide a low dielectric constant and losses and so therefore making them well suitable for the broadband applications and high frequency utilization [17] .

B. The 5G-Railway Communication MIMO Antenna Design

The MIMO antenna design is one of the most extensive technology of 5G wireless communication system. It has attracted a lot of attention because of its inherent characteristic in varies scenarios. In this section, a designated micro-strip antenna is simulated to achieve the most optimal design to be applied in the future 5G system of HSR. The manual design comprises patch rectangular antenna dimensions that are excited by utilizing a micro-strip feeding technique.

The micro-strip feeding dimension is structured as T-junction form with the impedance feed lines of 50Ω and 100Ω. The manual design was carried out firstly by calculating the antenna patch W as given.

$$W = \frac{3\times10^{8}}{2\times26\times10^{9}\times\sqrt{\frac{2.2+1}{2}}} = 4.80 \tag{8}$$

Meanwhile the length (l) can be calculated as follows.

$$\varepsilon_{reff} = \frac{2.2+1}{2} + \frac{2.2+1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{1.575}{4.80}\right)}}\right) = 2.628 \tag{9}$$

$$\Delta L = 0.412\times1.575\times\frac{(2.628+0.3)\left(\frac{4.24}{1.575}+0.264\right)}{(2.628-0.258)\left(\frac{4.24}{1.575}+0.8\right)} = 0.679\text{mm} \tag{10}$$

$$L_{eff} = \frac{3\times10^{8}}{2\times26\times10^{9}\times\sqrt{2.628}} = 3.5 \tag{11}$$

$$L = 3.5-(2\times0.679) = 2.14 \tag{12}$$

Finally, the given calculation of rectangular antenna patch dimension is $W \times L =$ 4.80 mm × 2.14 mm. The impedance of rectangular path antenna will vary greatly depending on the measuring points. A connection with 50Ω and 100Ω impedance is utilized not only to achieve an equilibrium of the coil induction and capacitor but it is also intended for dividing the power in order to couple electromagnetic power of a transmission line. Accordingly, the width of feeding for a connection with 50Ω is given.

$$B = \frac{60 \times 3.14^2}{50 \times \sqrt{2.2}} = 7.98$$

$$W = \frac{2 \times 1.575}{3.14} \times \left\{ \begin{array}{l} 7.98 - 1 - \text{In}\left(\left(2 \times 7.98\right) - 1\right) + \frac{2.2 - 1}{2 \times 2.2} \times \\ \left[\text{In}\left(7.98 - 1\right) + 0.39 - \frac{0.61}{2.2} \right] \end{array} \right\} = 4.82 \quad (13)$$

Equation (13) shows 4.82 mm for 50Ω feeding dimension width which differs from the previous feeding length (L_{eff} = 5 mm).Therefore, in order to ease the elements positions, the distance between elements is calculated as given.

$$d = \frac{c}{2f} = \frac{3 \times 10^8}{52 \times 10^9} = 5.7 \quad (14)$$

Subsequently, a 100Ω T-Junction form is also utilized for the optimal design of a single patch antenna micro-strip with 56 radiation elements. Therefore, the width of 100Ω feeding is calculated as given.

$$B = \frac{60 \times 3.14^2}{100 \times \sqrt{2.2}} = 3.99 \quad (15)$$

$$W = \frac{2 \times 1.575}{3.14} \times \left\{ \begin{array}{l} 3.99 - 1 - \text{In}\left(\left(2 \times 3.99\right) - 1\right) + \frac{2.2 - 1}{2 \times 2.2} \times \\ \left[\text{In}\left(3.99 - 1\right) + 0.39 - \frac{0.61}{2.2} \right] \end{array} \right\} = 1.38 \quad (16)$$

Equation (16) shows a different width of 100Ω micro-strip from the previous feeding length. (L_{eff} = 5 mm). Nevertheless, this diverse value is required to facilitate the additional substrates for bandwidth replenishment. After the manual antenna design is accomplished, CST Microwave Studio is utilized to simulate the design. The simulation of 26 *Ghz* of 5G-R MIMO micro-strip antenna is conducted by adjusting the antenna dimensions to the desirable parameters for the most optimal characterization. In this study, the Defected Ground Structure (DGS) is purposefully utilized to enhance the bandwidth. The utilized DGS ensures a higher mode of harmonic suppression with additional mutual coupling between adjacent elements when cross polarization is radiated. [18] [19] .

When the planar transmission line is integrated with the DGS on its ground plane, the current distribution is disturbed by the ground plane's defects. Consequently, some corresponded parameter characteristics such as slot resistances, inductances and capacitances of the transmission line will also be interrupted. To minimize these effects, this work attempts the DGS model to be designated in a form of a dumbbell shaped defect which was installed on the micro-strip's ground plane as shown in Fig.3.

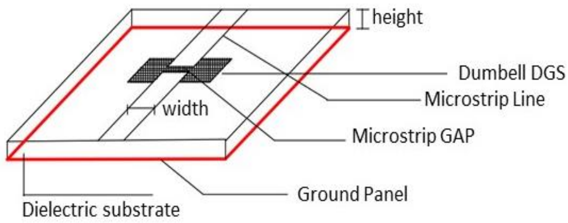

Fig. 3. A dumbbell shaped type of DGS

IV. Results and Discussion

In this section, the final design geometry of antenna rectangular 2 x 2 patch with 112 radiation elements is presented. Fig.4 displays a single antenna element which was resulted from the manual calculation and antenna array configuration.

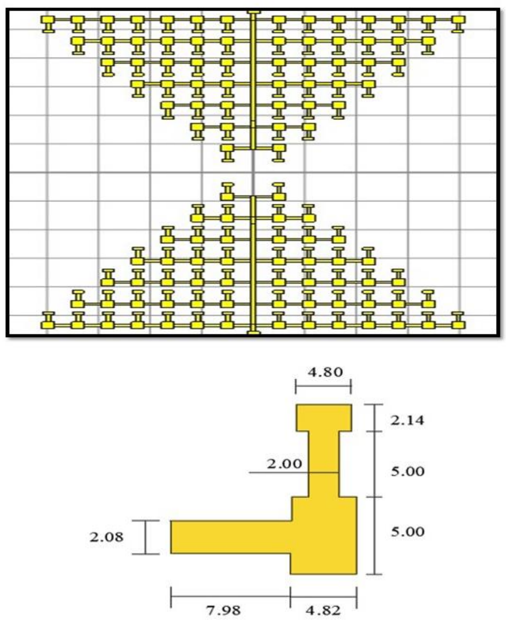

Fig. 4. The final geometry of MIMO antenna with 112 radiation elements

The configuration of antenna will create a new wave of electromagnetic characteristic. The final dimension of the rectangular micro-strip antenna patch is given as Table II:

TABLE II
Final Design Specification

Parameter	Unit (mm)
L	2.14
Lm, Lp	5
W	4.80
Wm	1.48
Wp	4.82

Zm	6.78
H	1.575
Ws	196.88
Ls	232.44

This section also discusses the measure of Voltage Standing Wave Ratio (VSWR) as the indication of radio frequency power effectivity to be transmitted into the loads through the power source. A perfect power transmission requires a well-matched impedance with the transmission line, radio and antenna's impedance [20] . In conclusion, VSWR describes a reflection coefficient function of the antenna's power reflection. This coefficient is denoted by Γ and defined by the following formula.

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{17}$$

The reflection coefficient ratio or a return loss describes a ratio of reflected waves amplitude to the wave incidents at the junction. For a desirable antenna application, VSWR value is preferable to be under 2. Fig. 5 has shown a well-match performance between the source impedances and load impedances where the overall AC's voltages are similar from end-to-end without any interferences.

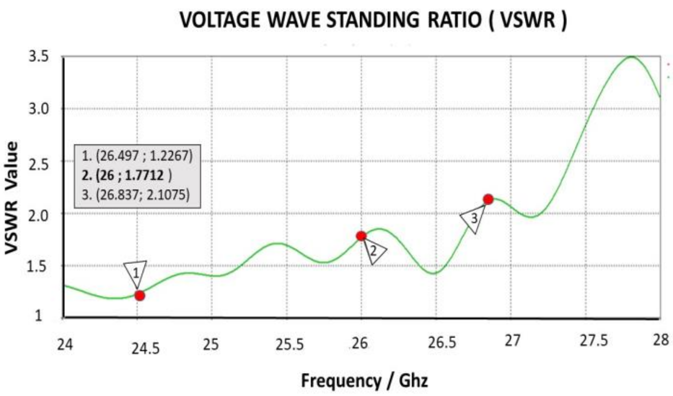

Fig. 5. The VSWR of 26 Ghz of 5G-R MIMO micro-strip antenna

The return loss or S-parameter is taken into account in the simulation as a high return loss is always a favorable parameter achievement. This parameter of return loss is usually expressed in decibels (dB) and it was correlated to low insertion losses [21]. Another parameter of reflection is namely as the reflectance. It may be concluded when S-parameters = 0, the power is fully reflected [22]. The value of reflectance is a negative number and if it is excessive then it is not a favorable parameter result.

In this study, the result of the return loss is -11.113 *dBi* This result is very advantageous since it indicates that almost 90% of the power is transmitted to the antennas [23]. Fig. 6 shows how well the signal power loss is returned by a discontinuity phenomenon in the transmission lines when impedance mismatch arises from the device which is inserted in the terminating loads.

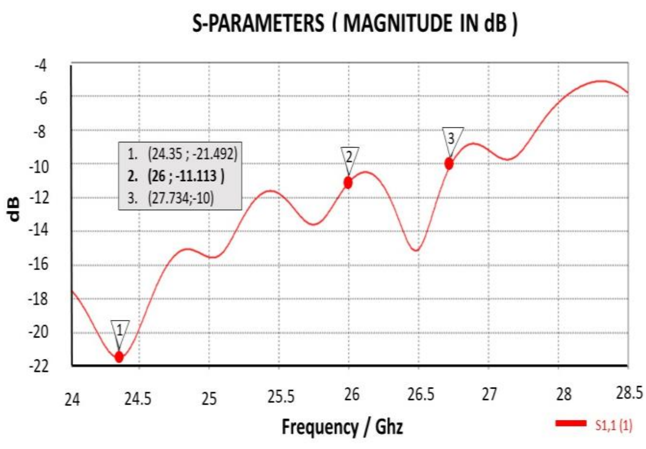

Fig. 6. Return loss of 26 *Ghz* in 5G-R-MIMO micro-strip antenna

Finally, the optimal design of 26 *Ghz* G-R MIMO outdoor antennas for FRMCS has fulfilled the specified characterization as shown in Table I. Ultimately, the optimized antenna array configuration is 14.89 *dB* at peak as displayed in Fig. 7.

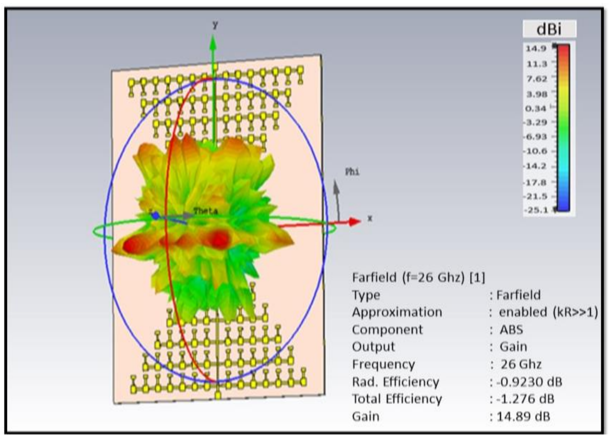

Fig. 7. The gain of 26 Ghz 5G-R-MIMO micro-strip antenna simulation

The result is more satisfying than the existed design and simulation of antenna configuration for 5G mm-wave which was obtained in the previous research since the gain antenna was resulted only at maximum 10.29 *dB* with the similar specification of DGS [24].

A satisfying MIMO metrics performance demonstrates excellent antenna characterizations and field correlation in the corresponded frequency band. Hence, the high antenna gain from the simulation is more than capable to overcome the raised atmospheric attenuations, fading, shadowing and absorption at mm-wave frequencies to mitigate the challenges of HSR scenarios so accordingly this optimal design is a potential contender for the application of the forthcoming 5G-R in FRMSC application.

V. Conclusions

In this paper, an optimal design of an outdoor 5G micro-strip MIMO antenna design for HSR is constructed for 26 *Ghz* frequency band. The structure of 2×2 micro strip antenna with 112 radiation elements is fed by the micro-strip line feeding technique. The satisfactory results are indicated with return loss value -11.113 , VSWR value 1.7712 and a desirable peak gain at 14.89 dB. The achievement of the optimal design is applicable to fulfil the requirement of seamless connection for the FRMCS implementation. The high antenna gain from the simulation is sufficient to accommodate the challenging tasks from the overcoming atmospheric attenuations of the higher mobility and frequencies. In the future works, larger number of individual antenna elements with different kind of materials and feeding techniques can be applied for high speed scenarios because the higher the gain the narrower the beam will be.

APPENDIX

ABBREVIATIONS AND ACRONYMS

c	speed of light $3\times10^{8} m/s$
dB	decibels
dBi	decibels relative to isotropic
Ghz	Giga Hertz
ε_r	dielectric constant
h	substrate height (mm)
ε_{reff}	most effective dielectric constant
L_{eff}	most effective patch length
Γ	reflected coefficient
w	width of antenna (mm)
l	length (mm)
L	patch's length (mm)
Lm	feed's length (mm)
Lp	feed's length (mm)
W	patch's width (mm)
W_m	feed's width for 100Ω (mm)
W_p	feed's width for 50Ω (mm)
Zm	distance between feed (mm)
H	substrate thickness RT 5880 (mm)
W_s	width of substrate
MIMO	multiple input multiple output
mm-WAVE	millimeter wave
5G-HSR	Fifth Generation for high speed rail
FRMCS	Future Railway Mobile Communication System
IoT	Internet of Things
MTC	Machine Type Communications
CST	Computer Simulation Technology
DGS	Defected Ground Structure
PTFE	Polytetrafluoroethylene
VSWR	Voltage Wave Standing Ratio
Wi-Fi	Wireless Fidelity

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