A Broadband Millimeter Wave Microstrip Antenna For 5G Communication Systems

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***Abstract*— Every day, more and more people throughout the globe own portable wireless gadgets. Larger data transfers and faster data speeds have been necessitated by this growth. In recent years, millimeter wave frequencies have been used for 5th Generation (5G) communication networks throughout the globe because of this demand. Studies have made use of the millimeter wave frequency, which has lately garnered the attention of microstrip antenna designers. Broad frequency coverage and fast data transmission rates are two of millimeter wave microstrip antennas' most significant advantages. High data transmission speeds will be possible because to this advantage, which will allow a large number of users to connect at once.**

***Keywords*— broadband, millimeter wave, microstrip antenna, 5G, communication systems**

I. INTRODUCTION

Today, wireless communication tools have become an indispensable daily necessity for people. People can choose and use different types of mobile services according to their needs. In parallel with developing technology and needs, expectations from wireless systems are increasing. While the number of users on the previously developed wireless networks was limited to a certain number, the user and usage area increased over time. Over time, automatic aircraft, machines, autonomous transportation vehicles, smart networks, smart homes, cities, mobile services are desired to be turned into remotely controllable systems. In addition, low cost, high data capacity and high data transfer rate are expected from these wireless systems.

The foundations of wireless communication systems date back to the 1980s. The 1st generation communication system was named AMPS (Advanced Mobile Phone Service) in 1983. With the 2nd Generation (2G) communication system, the transition from the Analog system to the Digital system was achieved in 1997. After 1999, 3rd Generation (3G) standards were announced by ITU (International Telecommunication Union). With the 3rd Generation communication system using 5 MHz bandwidth, the transition from a voice-centered system to a data-centered system has been achieved. As of 2013, WIMAX (Worldwide Inoperability For Microwave) and LTE (Long Term Evolution) systems have been developed. These systems include high speed data and voice transfer feature. These systems, which are similar to each other, offer a bandwidth of 20 MHz. LTE and WIMAX standards, which are two different 4G technologies developed, were completed in 2011 and are used by networks [1].

Today, the interest of portable wireless system developers has turned towards the wireless communication technology called 5G technology. The expectations that 5G systems must meet are much higher speed, greater multi-data transfer. More bandwidth is needed for this. Before 5G systems, bandwidths below 6 GHz were used [2]. Due to the limited bandwidth here, frequency bands above 6 GHz have been defined by ITU (International Telecommunication Union). With the bandwidth it provides within these bands, the millimeter wave (mm wave) bandwidth is very attractive. A millimeter wave bandwidth of 24 GHz and above has been deemed suitable for 5G systems [3].

II. 5TH GENERATION (5G) SYSTEMS

5G technology is not just an advanced version of broadband networks. This technology comes with possibilities that can serve in many branches. Thanks to this newly developed technology, it will be possible for users to stay connected to networks with high reliability and low latency in public transportation vehicles such as high-speed trains in areas with high mobility. In addition, 5G technology comes with many advantages such as more data capacity, lower data latency, more mobility and data reliability [4]. The reduction in energy consumption offered by 5G technology to telecom technology will be one of the most important contributions of 5G technology. In addition, for the use of increasingly widespread software-based network services, 5G technology will provide very important services in this sector thanks to data security and speed [5].

5G can be named as a new type of network designed to connect almost all devices. We can give examples of machines, transportation vehicles, generations and many vehicles.

Fig. 1. Frequency ranges allocated by country and targeted for operation: dark lines are licensed light lines unlicensed bands [9].

In addition, 5G communication technology aims to provide ultra-low latency, much higher data rates, security, network capacity width and the experience of connecting a much larger number of users to the network at the same time [6].

With the development of 5G technology, the coverage areas will expand, and the waiting times for users will be shortened thanks to the increased data transfer rate. In this way, increasing internet demands will be met much more quickly. 5G will help to provide innovative usage services in many areas such as remote control in the industrial field, healthcare, agricultural technologies [7].

It is recommended that WRC-19 (agenda item 1.13) support the work in the 24.5–27.5 GHz and 37.0–43.5 GHz bands and that the technical conditions for 5G be made suitable. In Figure 1, the frequency ranges allocated by countries and targeted to work as of December 2020 are shown. Generally speaking, countries work in the 24-30 GHz band for 5G technology. Considering that the investments will increase at these frequencies, the studies to be carried out in these intervals are gaining value day by day [8].

III. Millimeter Wave Technology

Requirements such as very high data transfer rates, low bit error rate, fast video and audio streaming, and much less interference from sound are expected from wireless systems that have grown with great momentum in recent years. The carrier spectrum frequency, which varies in the 700 MHz and 2.6 GHz bands, is insufficient for high quality data transfer and low delay times, which are the requirements of today's communication systems [10]. With the increase in the number of users around the world and the increasing number of mobile phones, with the transition to smart phones and tablets, the average data transfer rates and the need for new spectrums have led to new searches to increase system capacities [11]. With the 5G vision that has been developing since 2018, targets such as data rate at multigigabit per second, reduction of delay times below 1 ms, capacity increase in the amount of devices falling into a certain area have been the source of interest for many researches in this field [12]. Interest in carrier frequencies above 6 GHz is increasing day by day. Although not all of these needs can be met at the same time, some of the needs should be met to a certain extent and a systematic development should be allowed. Research and development activities have started to make 5G millimeter wave frequencies ready for use by 2020. Along with IMT-2020, the requirements for 5G networks, devices and services have been published by the ITU [2].

Looking at recent history, mobile communication is one of the best technology innovations. Mobile communication has become indispensable thanks to the development of technological tools and the relationship between them. Together with portable mobile data provider devices such as smart phones, e-books, netbooks, it has become an important part of life for five billion people and continues to grow with an unprecedented development [13].

The bandwidth needed to meet the requirements of 5G systems is higher. Since the spectrum width below 6 GHz is not sufficient for 5G systems, frequencies above 6Ghz are shown as candidate frequency bands for 5G systems by ITU. Millimeter waveband has been one of the most attractive candidates with the unlicensed broadband range it provides. The wavelength of the millimeter wave frequency is approximately between 1 mm and 10 mm. Millimeter-wave rays have wavelengths that are smaller than microwave rays and larger than x-rays and infrared rays.

The spectrum region of millimeter waves corresponds to the frequency range of 30 to 300 GHz. The high frequency and propagation patterns of millimeter waves have made them attractive for radar and communication systems [4].

One of the factors to be considered in the millimeter wave frequency band is atmospheric factors. Effects such as fog, rain, oxygen absorption and water vapor can cause weakening of the signals. It can also affect polarization in signals and cause depolarization or multidirectional propagation. The variation of millimeter wave signals between 1 and 1000 GHz according to moist air and dry air is seen in Figure 2 depending on the frequency. At distances up to 1 km, the atmosphere effect can be neglected as it is below 0.5 dB up to 50 GHz. While the effect of oxygen absorption increases between 50 and 70 GHz, it increases at 60 GHz and reaches a maximum value of 15dB. Adverse weather conditions and oxygen absorption have little effect on millimeter wave couplings at distances up to about 100 m [14].

IV. Microstrip Antennas

The foundations of microstrip antennas date back to the 1950s. The first microstrip antenna was designed by Deschamps in 1953. Guttom and Bassiniot produced a patented flat microstrip antenna in 1955. Munson worked on microstrip antennas in 1974 and designed the first ratic Microstrip antenna. Howell worked on basic rectangular and circular microstrip antennas in 1975 and the first circular and rectangular microstrip antennas were designed by Howell in 1975. Microstrip patch antennas are basically placed on a dielectric base. It consists of a radiant metal patch on one surface and an earthen ground on the other. The radiating surface can be in strip, rectangular, triangular, circular and other geometric forms. Microstrip antennas are inexpensive components with their simple physical geometry. The metal patch can be made of conductive material, usually silver, copper or gold. Microstrip antennas were initially used in applications such as airplanes, space shuttles, satellites and missiles. Following this, the need for smaller profile microstrip antennas in commercial and institutional applications such as wireless communication has increased day by day. Especially the need for commercial areas has increased the interest in microstrip antennas. This need has brought with it many scientific studies on microstrip antennas. When their small structures are integrated into planar and non-planar surfaces, their robust structure is one of the most important advantages. They are easy to manufacture thanks to their simple structure. It is possible to obtain a versatile structure in terms of polarization, radiation pattern and impedance when the ideal mode radiant structure is designed with various geometric combinations on the dielectric material.

In recent years, with the increasing interest and need for the 5G system, millimeter wave frequencies have been focused on. With these studies, the tendency towards thin substrates and lower dielectric coefficients in substrate selection has increased. The production and design of microstrip antennas, which are getting smaller and smaller, becomes more difficult in terms of cost and production due to sensitive substrate material and very small designs.

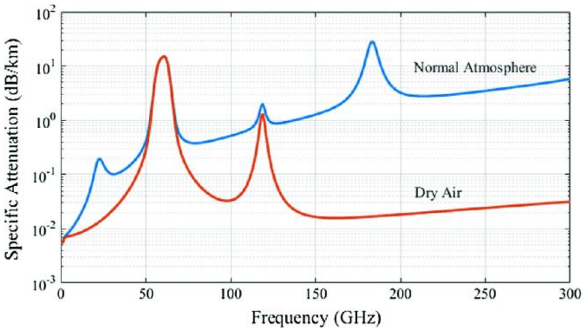

Fig. 2. Attenuation graph of millimeter wave signals compared to dry and humid air in standard conditions.

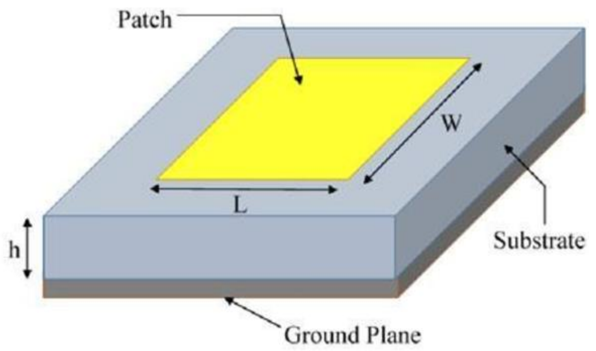

Fig. 3. Microstrip antenna structure.

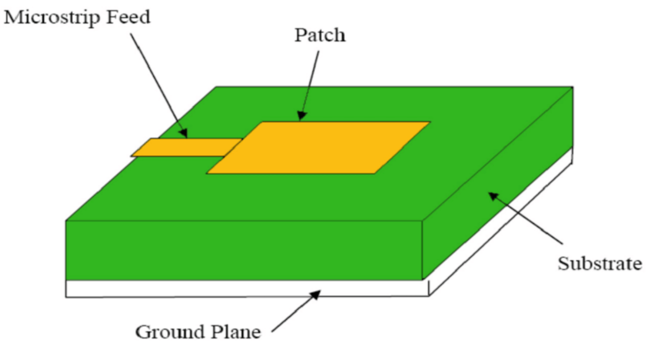

Fig. 4. Microstrip planar line-shaped feeding.

As seen in Figure 3, microstrip antennas are composed of a thin substrate material with a low dielectric coefficient, a conductive patch radiating on one surface of this material, and a ground plane on the other surface of the material.

Basically, antenna size criteria,

- Metal patch thickness t <<λ_o
- Substrate thickness, patch-soil length h<< λ_o , 0.003 $\lambda_o \leq h \leq 0.05\ \lambda_o$
- L patch length $\lambda_o/3<L<\lambda_o/2$
- The dielectric material constant is expressed as Ɛr 2.2 ⩽ Ɛr⩽12.

In microstrip antennas, radiation is generally provided by electric fields called fringing from the ground plane and patch edges. For this reason, the designed patch and ground plane greatly affect the antenna performance. In addition, the dielectric coefficient and quality of the selected substrate material are also important. As the dielectric constant approaches 2,2, the losses in the electric fields will decrease and the performance will increase [15].

Microstrip antennas have several advantages. Their low weight and volume expands their usage areas. In addition, thanks to their thin profile, they provide ease of integration in vehicles in the automotive and defense sectors. It is advantageous in terms of production cost and can be produced easily. They can be easily integrated into microwave circuits. Such advantages have made the field of microstrip antennas attractive to scientists in terms of study area [16].

A. Microstrip Antenna Feed Types

While designing a microstrip antenna, the most suitable feeding technique and circuit for the designed antenna should be designed accordingly. The feeding mechanism has an important value on the working conditions of the antenna. Microstrip antennas are commonly fed by four different feeding techniques. These are microstrip planar line feed, coaxial feed, aperture coupled feed, and proximity coupled feed.

1) Microstrip planar line-shaped feeding: As seen in Figure 4, the most preferred feeding method of microstrip antennas is the microstrip planar line shaped feeding type. The patch line and the supply line are positioned on the same plane. This provides convenience in terms of production. In microstrip feed, it consists of a sliver line whose width adjacent to the patch is much smaller than the patch width. The microstrip line is very easy to manufacture, adjust and design the strip according to the antenna. As the substrate thickness increases, the surface thickness and unwanted radiation may increase, which can reduce the bandwidth by approximately 5% [17].

2) Coaxial supply: As can be seen in Figure 5, a coaxial line is used in coaxial feed, unlike the microstrip planar line feed. This line consists of inner and outer conductors. While the outer conductor is connected to the antenna ground, the inner conductor passing through the coaxial line is connected to the radiating plane with a hole drilled in the substrate material. The feeding point can be connected to the radiation plane from a desired point. This point can be determined with the simulations to be made in such a way as to achieve the best impedance match. It is a frequently used method due to its ease of use and high efficiency. One of its most important disadvantages is its narrow bandwidth. As the substrate thickness increases, since the inner line length will increase in coaxial feeding, it may have a reducing effect on the bandwidth and difficulties may occur in coaxial feeding [17].

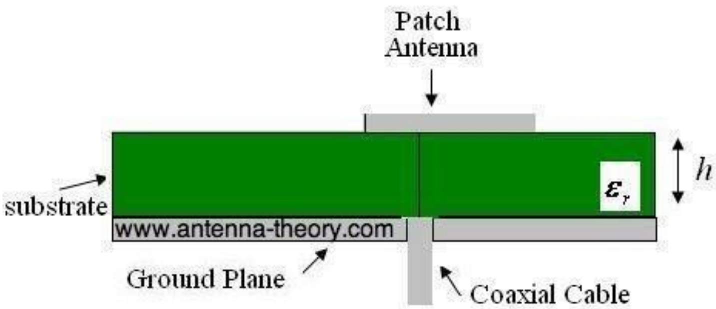

Fig. 5. Coaxial feed.

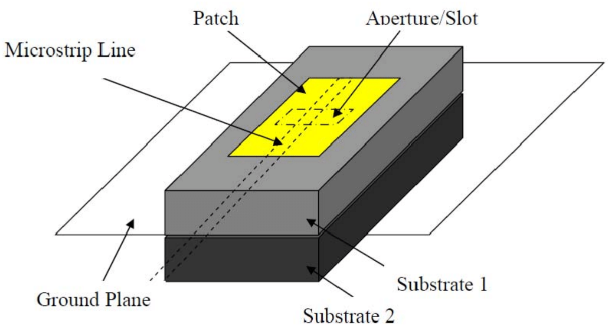

Fig. 6. Aperture coupled feed.

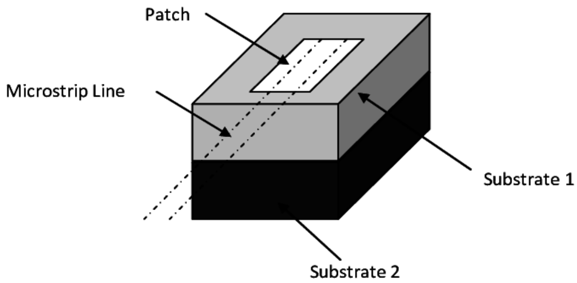

Fig. 7. Proximity coupled feed.

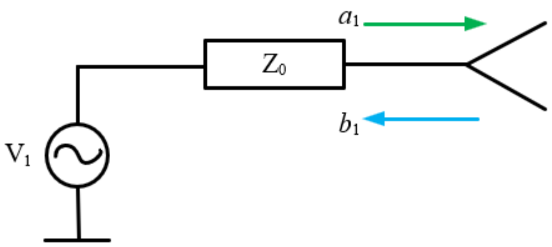

Fig. 8. System consisting of a single antenna.

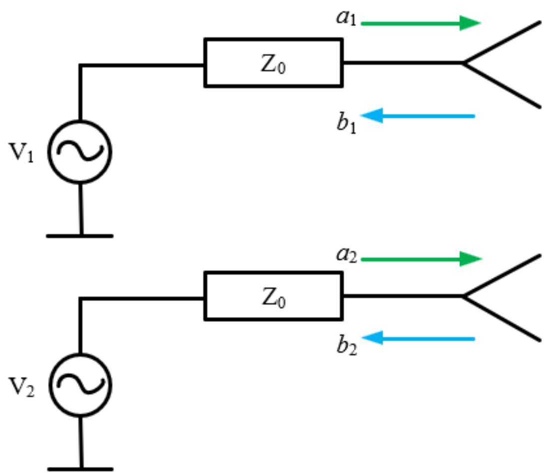

Fig. 9. System consisting of two antennas.

3) Aperture coupled feed: As seen in Figure 6, the aperture coupled feed has two substrates separated by the ground plane. At the bottom of the underlying substrate is the microstrip line, which transmits its energy to the radiant patch through the gap above the ground plane. This structure ensures that the radiant patch and the supply element are independent, protecting the radiant patch and the radiation leaking from the supply line. Material with high dielectric constant is used in the substrate in the lower part, and material with low dielectric constant is used in the substrate in the upper part [17].

4) Proximity coupled feed: In the proximity-coupled feed, as in the aperture-coupled feed, substrate material with two different dielectric coefficients added on top of each other is used. In this type of feeding, patch and soil planes are located on the outer parts of the substrate materials. The feeding line is positioned to be between these two sub-stones. In proximity-coupled feeding, the substrate thicknesses must be set at appropriate thicknesses to achieve impedance matching. The dimensions of the microstrip patch are important parameters that need to be optimized for impedance matching, such as the length of the transmission line. The most important challenge of proximity and aperture coupled feeds is the production difficulties in their position relative to each other due to the use of different substrates.

V. Antenna Performance Parameters

A. S-Parameters

S-Parameters are one of the most important parameters that allow us to obtain information about the radiation performance of antennas and impedance matching. The S-parameters show the relationships between the input and output signals provided by the ports in an electrical system in terms of supplied electricity. The S-parameter we need to examine in a single port antenna system is S11. S11 is expressed as the reflection coefficient. When we look at this value, we can see how much energy is reflected to the antenna through the port. In an ideal antenna, it is desired that all power is transmitted from the antenna and no reflected signals are formed. However, it is inevitable that there will be some reflected signals in the antennas, even if it is undesirable. The reference S11 value in antennas is -10 dB and below. At a value of -10 dB, the power of the signal given to the antenna radiates at the rate of 90%, so it is reflected back at the rate of 10%.

$$S11 = b1 / a1 \quad (1)$$

As seen in the figure, the S11 value in a single-element antenna system is the ratio of the signal value reflected back from the antenna to the signal going to the antenna.

In antennas with two antennas or more multiple ports, there is a common interaction between the antennas. A two-antenna system is shown in Figure 9. When we look at the parameters of this antenna, the parameter S11 represents the return loss of the first antenna. Likewise, the parameter S22 expresses the return loss of the second antenna. Other S-parameters are those that evaluate the mutual interaction between antenna pairs S12 and S21. S12 examines the effect of radiation from the second antenna on the first antenna. S12 is the ratio of the signal returning from the first antenna to the signal going to the second antenna. S21, on the other hand, examines the effect of radiation from the first antenna on the second antenna. S21 is the ratio of the signal returning from the second antenna to the signal going to the first antenna. Interaction between antennas is inevitable. The aim is to make the necessary adjustments and reduce the interaction below the -10dB level. Its parameters are generally specified in dB (decibels) and are calculated using the equation below.

$$|Sxy|dB=20log10|Sxy| \quad (2)$$

$$S11 = b1 / a1 \quad (3)$$

$$S12 = b1 / a2 \quad (4)$$

$$S21 = b2 / a1 \quad (5)$$

$$S22 = b2 / a2 \quad (6)$$

B. Impedance Bandwidth

The impedance bandwidth can be found by examining the graph depending on the S11 and frequency values of that antenna. The acceptable S11 parameter in an antenna is below -10dB. As seen in Figure 10, the first frequency point where S11 value falls below -10dB on the graph is defined as the lower frequency value (f_{low}), and the first frequency point where it exceeds 10dB after the lower frequency value is defined as the upper frequency value (f_{up}). As given in Equation 7, the bandwidth (BW) consists of the difference between the upper and lower frequency values. Percentage bandwidth is given in Equation 8. If the percent bandwidth is over 20%, these antennas are referred to as ultra-wideband antennas.

$$BW = f\text{up} - f\text{low} \quad (7)$$

$$BW(\%) = BW \,/\, f\text{center} \times 100 \quad (8)$$

C. Directionality

The directivity of an antenna is calculated as the ratio of the radiation intensity of the antenna to the radiation intensity of the isotropic antenna. The directionality is also the ratio of the radiant intensity to the total radiant power (P_{rad})(W) multiplied by 4π [15].

$$\text{Directionality } (D_0) = U_{max} \,/\, U_{\text{isotropic}} = 4\pi U \,/\, P_{rad} \quad (9)$$

D. Yield

As given in the equation, the efficiency of the antenna is obtained by dividing the radiant power (radiant) converted into electromagnetic wave by the power entering the antenna (input).

$$\text{Yield } (E) = P_{\text{radiant}} \,/\, P_{\text{input}} \quad (10)$$

E. Gain

The gain of the antenna is defined as the ratio of the radiation intensity in a specified direction to the radiant power emanating from an omnidirectional (isotropic) source and is denoted by G. The gain value, like directivity and efficiency, is unitless. As given in Equation 11, the gain of the antenna is equal to the product of the directivity and the efficiency.

$$\text{The gain value } (G) = E \times D_0 \quad (11)$$

F. Radiation Pattern

The radiation pattern is the graph showing the change of the electromagnetic field strength emitted by the antenna according to the angle values at a certain distance, formed by the antenna at a specified distance.

VI. Millimeter Wave Antenna Designs Proposed in the Literature

In recent years, the excessive increase in the number of wireless devices has brought demands for data size and data transfer speed. With this need, the orientation towards 5G technology in wireless communication tools has increased to a great extent and it is aimed to use millimeter wave frequencies in these devices. 5G technology, which includes millimeter wave frequencies, promises that many devices will be connected to each other at high speed with much larger data. With this need, the interest in antennas operating at millimeter wave frequency has increased intensely. As the operating frequency increases, antennas naturally become smaller. For this reason, designing very small-sized antennas suitable for targeted millimeter wave frequencies by using antenna modification methods has become a very important research topic. Some millimeter wave antennas proposed in the literature are presented below. In the study presented by Ahmad et al. [18] in Figure 11, a millimeter wave antenna was designed for 5G communication systems. The dimensions of the antenna with resonant frequencies of 29.5 and 30.5 GHz are 4.8x5x0.508 $mm3$. Although it has a relatively small antenna structure, it is quite low in terms of the bandwidth it provides. The proposed antenna and S-parameters are shown in Figure 11.

In the study presented by Shahjehan et al. [19] in Figure 12, a millimeter wave antenna was designed for 5G communication requests. The antenna maximum bandwidth is 5.5 GHz and 8.67 GHz at these points, with resonant frequencies of 37 and 54 GHz. The antenna dimensions are 7.2x5x.0.787 $mm3$. Although it has a relatively small antenna structure, it is low in terms of the bandwidth it provides. The proposed antenna and S-parameters are shown in Figure 12.

In the study presented by Qayyum et al. [20] in Figure 13, a microstrip antenna operating in the 28 GHz (27.6–28.55 GHz, 3.10%) resonant frequency range was designed for 5G communication systems. It has been observed that the resonance frequency range of the antenna designed with the dimensions of 7.23x7.23 $mm2$ is quite low. Antenna structure is given in Figure 13.

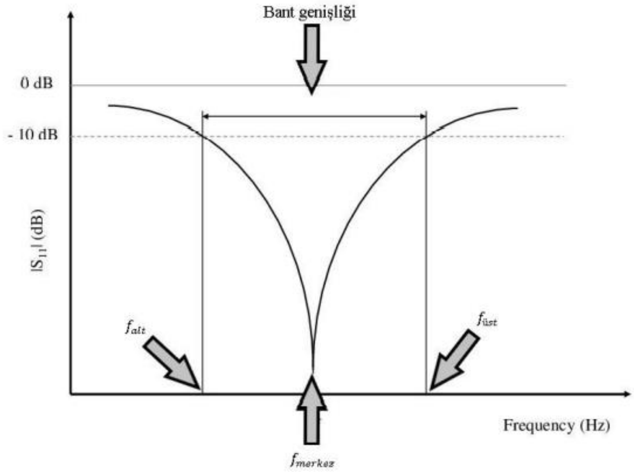

Fig. 10. Display of impedance bandwidth of an antenna.

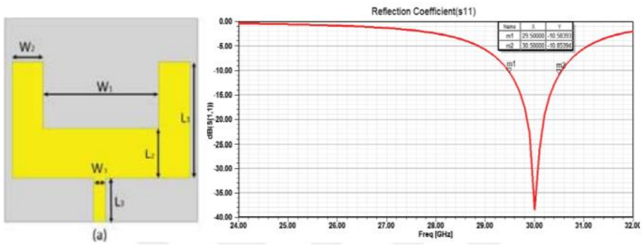

Fig. 11. Millimeter wave antenna geometry and S11 parameter (Ahmad et al., 2020).

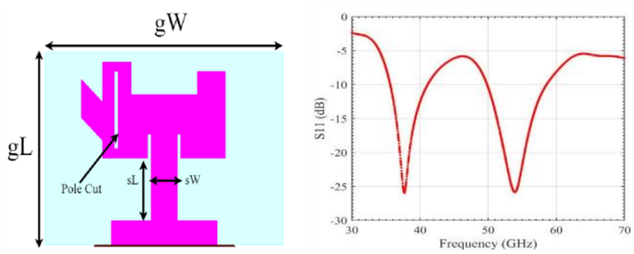

Fig. 12. Millimeter wave antenna geometry and S11 parameters (Zeeshan et al., 2019)..

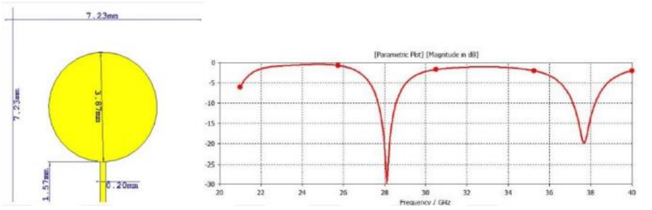

Fig. 13. Millimeter wave antenna geometry and S11 parameters (Qayyum et al., 2020).

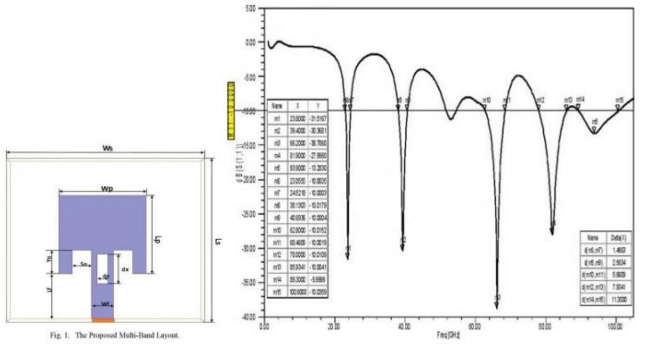

Fig. 14. Millimeter wave antenna geometry and S11 parameters (Saeed et al., 2021).

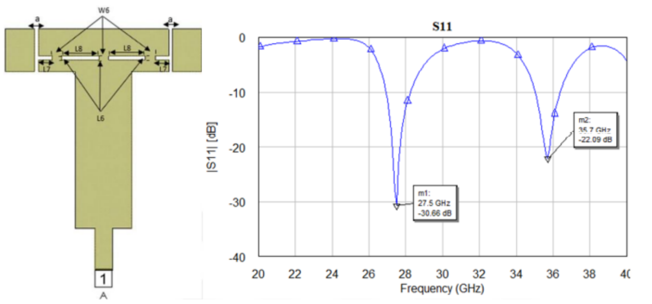

Fig. 15. Millimeter wave antenna geometry and S11 parameters (Apoorova et al., 2019).

Saeed et al. [21] presented in Figure 14; a millimeter-wave antenna is proposed for low-profile 5G systems with the dimensions of 8.6x9.2x0.6 $mm3$. The antenna whose resonance frequencies are shown in the figure is multiband. The resonance frequency ranges of the microstrip antenna, whose antenna geometry is shown in the figure, are low.

A millimeter-wave antenna has been developed for dual band 5G systems, presented in Figure 15 by Apoorva et al. [22]. This antenna, which has a center frequency of 27.5 and 35.7 GHz, has the dimensions of 12.5x10.1 $mm2$. The antenna geometry shown in the figure has low resonance frequency ranges.

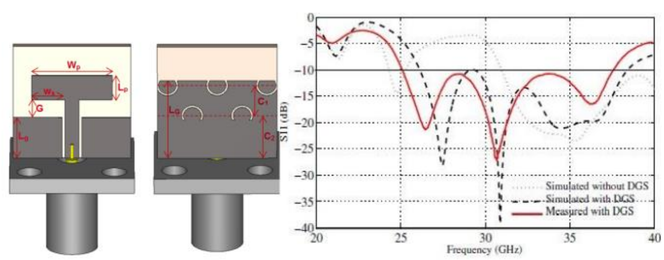

Fig. 16. Millimeter wave antenna geometry and S11 parameters (Jilani et al., 2017).

Jilani et al. [23] presented in Figure 16, a millimeter wave antenna designed for 5G wireless systems and applications is given. The measurement results of the antenna offer a bandwidth in the range of 25.1–37.5 GHz. The maximum gain of the antenna is 9.86 dB at 36.8 GHz. The antenna designed in a T-shape offers over 80% efficiency in the operating range.

Contrubition of the Authors

The contributions of the authors to the article are equal.

Conflict of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were observed in this study

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