Chapter 23
Highly Isolated Self-Multiplexing 5G Antenna for IoT Applications

Sandeep Sharma, Padmini Nigam, Arjuna Muduli, and Amrindra Pal

1 Introduction

The advanced automation in manufacturing is now a reality, so are the advances in health monitoring, fleet management, system maintenance tracking all this and many more thanks to Internet of Things (IoT) [1]. The IoT systems play an essential role in enhancing people's daily lives and establishing the connection between smart home equipment and a smart atmosphere. IoT systems build the concept of smart home, smart cities, smart hospitals and smart building also [2]. The industrial sector is also facing the challenges in the development of the industrial IoT (IIoT) systems for their use, also facing difficulty to establish business model. The major industrial structure, like machines, traffic and components etc., the IIoT is facing many operational and technical difficulties, like trustworthiness, timeless and security of the connection [3]. Nowadays, 3GPP and LTE are the most widely used technologies for communication with IoT systems [4], because these techniques offer wide area cover, low operation cost, more secure, allocated spectrum, and easiness in the management. But the recently available cellular infrastructure is not in the position

S. Sharma
Center for Reliability Sciences & Technologies, Chang Gung University, Taoyuan City, Taiwan

OMKARR Tech, New Delhi, India
e-mail: D000016086@cgu.edu.tw

P. Nigam · A. Pal (✉)
DIT University, Dehradun, India
e-mail: padmini.nigam@dituniversity.edu.in; amrindra.pal@dituniversity.edu.in

A. Muduli
KL Education Foundation, Guntur, Andhra Pradesh, India
e-mail: arjuna@kluniversity.in

S. Tanwar (ed.), *Blockchain for 5G-Enabled IoT*,
https://doi.org/10.1007/978-3-030-67490-8_23

to support the machine-type communications (MTC), which is the heart of the IoT system [5, 6].

The 5G offers the path to the billions of smart devices to automatically interact and share the data. Nowadays, diversified applications of the various instruments are found and create trouble for the IoT systems to identify that devices are capable or not to fulfil the need of the application [7]. Present IoT systems use the Bluetooth Low Energy (BLE), ZigBee, etc. technologies for specific applications. As well as some other data transfer or communication medium like Wi-Fi, low-power wide-area (LP-WA) networks, cellular communications (e.g. MTC using 3GPP, 4G (LTE)), etc. [3]. The IoT systems are changing continuously at a higher rate with the new concepts and technologies and expanding in the new application areas also.

The evolving 5G infrastructure are capable enough to resolve the above-mentioned issues. It offers the high data with low latency and large area of coverage for MTC communication as compared to 4G. In fact, the machine-to-machine (M2M) communication can establish the communication between a large number of smart devices. Figure 23.1 shows the 5G-based IoT application infrastructure [3].

The success of IoT is based not only on wired but equally on wireless communication capabilities. The wireless communication systems have enabled multifold faster development and the implementation of IoT systems as the systems are/now can be mobile. An IoT system essentially requires the data is transmitted in small packets at low transmission rate(s), reducing the bandwidth requirements. Typically, the bandwidth requirement for IoT applications is less than 1 MHz. Due to their reliable propagation characteristics, sub-GHz bands (Europe utilizes 868 MHz band and the USA uses the 915 MHz band) are often preferred. Although these frequency bands see less traffic with respect to other bands in the spectrum (like

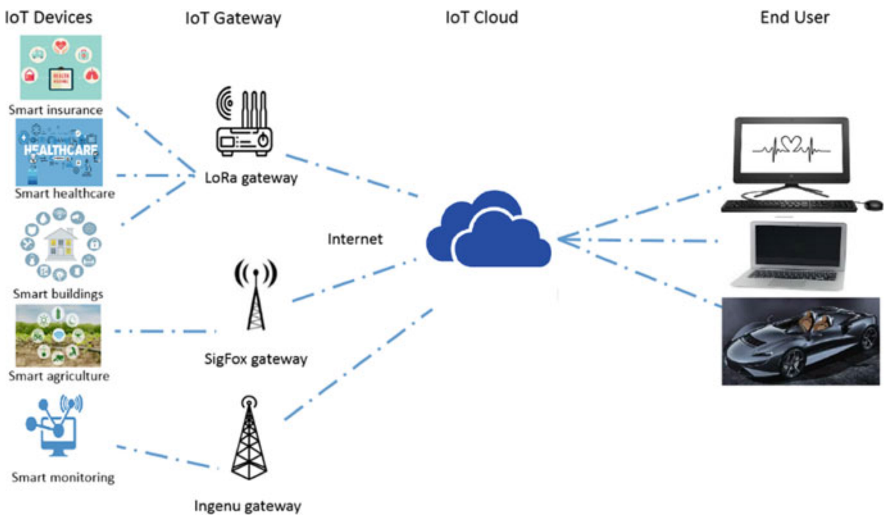

Fig. 23.1 A typical network infrastructure for 5G IoT applications [8]

2.4 GHz band), there is always a possibility of interference issues arising from other standards. The 5G communication networks provide faster, better and reliable communication networks for communicating systems. 5G network constitutes two parts, the Long-Term Evolution technology (FR1 – lower-frequency range, up to 6 GHz) and the millimetre wave (FR2 – higher-frequency range, from 24 to 52 GHz) [9]. The 5G antenna module for the IoT-based system is designed based on one or more of data rate, frequency of operation, range of communication and power consumption. The designer has several limitations to work with, namely, small footprint, minimum fading (interference) or negligible noise, higher gain and maximum radiation efficiency, and an enhanced version of multiplexing order is also required. The substrate integrated waveguide (SIW)-based antenna design provides a viable solution offering advantages like lightweight, high gain, maximum radiation efficiency, low fabrication and maintenance cost, high quality factor (Q) as well as improved power handling capacity than its counterparts μ-strip and CPW technology [10].

There are a large number of applications where we have a multiuser system environment requiring a reliable communication link (military applications) or a system having numerous antenna elements connected to a base station (medical or IoT applications) and the like(s). For a multiuser system environment connected with the base station consisting of large number of antenna elements, the SIW-based MIMO (multiple-input multiple-output) antenna for the 5G band application functional over the frequency range of 3.4–3.6 GHz is used. The MIMO system offers zero or negligible amount of mutual coupling over a single element. This is achieved by deploying an additional diplexer and triplexer decoupling network. A diplexer, triplexer, quadplexer or multiplexer is defined as a device that utilizes a single antenna for multiple transmitters operating at different frequencies. This decoupling network will consist of a diplexer, triplexer, quadplexer or multiplexer element, depending upon the number of input ports (feed points, di for two, tri for three, quad for four and multi for more than four transmitters), generally incorporated with antenna modules. These increase not only the antenna space, size and cost but the complexity of the proposed system as well, thus making these systems not suitable for portable IoT application or 5G communication systems.

This chapter provides a design to overcome the above problems. The SIW-based self-multiplexed antenna integrated with decoupling network working over 5G is proposed. This technique offers small footprint and compact size and is easily realized with highly demanding IoT systems. The isolation between two antennas having gain stability as well as unidirectional radiation pattern is more than -20 dB.

2 Evolution of Technology from 1G to 5G

In the era of advancement in the wireless communication system, 5G communication technology takes the outstanding part because of its prominent features. Previously, a decade ago from 1980 to 1990, the 1G-based communications was used, in which the basic voice service is used by the consumer with analog-based protocols. At this time only voice service was under consideration with PSTN (public switched telephone network) and PDMA (packet division multiple access) techniques. 1G technology is operated over the frequency of 150 MHz/900 MHz with the narrower bandwidth of 30 KHz and lower speed of 2.4 kbps. It has the several of disadvantages like bad voice quality, large size and poor battery life of cell phones. At this time, it is better than nothing; at least it's wireless and mobile. After that from 1991 to 2000, 2G communication had discovered using the new digital technique of GSM and CDMA. It is the first digital standard era of wireless communication with improved coverage area and capacity of no. of users than 1G technology. It is operated at the frequency of 1.8 GHz/900 MHz with the moderate bandwidth of 25 MHz and data rate of 64 kbps. It allows the text messaging service also, and the signals are also stronger than 1G. In this range, 2.5G comes with the GPRS cellular technique. It has the additional features of web browsing and e-mail services. At this time, the cell phones are combined with camera also. After the evolution takes place from 2.5G to 3G wireless system from 2000 to 2010, it has the frequency range of 1.6–2.0 GHz with bandwidth of 100 MHz. It is designed by CDMA, UMTS and EDGE techniques to provide the digital broadband and increased speed. It is the first mobile with broadband data services [11, 12]. At this time, the cell phones/mobile become the smart mobile with the extra features of fast communication, video call and broadcasting, mobile TV, etc. It also has the excellent value of data rates of 144 kbps to 2 Mbps with increased no. user capacity. These 3G mobiles are rather expensive than 2G. After that a new era has introduced with 4G communication from 2010 to 2020 with advent features of 3G. It is designed primarily for increased data rate from 100 Mbps to 1 Gbps. It is working at the frequency range of 2–8 GHz with the bandwidth of 100 MHz. It depends upon Wi-Fi and LTE technology and has the IP-based protocols and high speed and connectivity. It is the true mobile broadband service with MAGIC. The MAGIC term is defined as follows: M stands for mobile multimedia, A stands for anytime anywhere, G stands for global mobile support, I stands for integrated wireless solution, and C stands for customized personal service. 4G is a kind of multifunctional and flexible technology which depends upon OFDM (orthogonal frequency-division multiplexing) and OFDMA (orthogonal frequency-division multiple access) techniques. Nowadays, due to the 4G communication technique, we can easily and rapidly upload and download the high-definition (HD) video, movies, songs and other information. 4G system produces the high quality of services, super security and bigger battery life also. Then after 4G, the advanced and versatile features of 5G communication are presented with extreme high data rate of 1–100 Gbps, which is 100 times higher than 4G communication. The 5G communication has introduced from 2020 to 2030 with high capacity and speedy data rates. It also supports voice streaming, buckle up, high Internet, and interactive multimedia applications. It supports WWWW (World Wide Wireless Web) technology and defines the next version of mobile communication. After 5G, a novel version of communication technology is also taking place as 6G and 7G. 6G will integrate 5G with satellite global coverage with ultra-fast Internet access along with smart home and cities applications, while

7G relates world completely wireless with space roaming and artificial intelligence techniques. It's a fully wireless network which depends over artificial intelligence methodology [13].

2.1 5G Communication

Wireless networks have made an extraordinary development in the past few years. The demand of more bandwidth and lower latency has been a motivation to develop efficient systems. 5G is the fifth-generation mobile network, and this is the wireless communication technology which enhances user experience with the help of its features to personalize mobile communication experience. 5G is intended to offer higher data speeds (multi-Gbps), better reliability, increased availability, enormous network capacity, ultra-low latency and a better than before uniform user experience. Improved performance and enhanced efficiency allow new as well as better user experiences. 5G provides the infrastructure which will increase the performance and capabilities of the communication network. 5G includes high carrier frequencies, unprecedented number of antennas, massive bandwidths and device density. 5G emerged from orthogonal frequency-division multiplexing (OFDM). OFDM is the method of modulating a digital signal across numerous different channels to reduce interference. Sub-6 GHz and mm-wave which have wider bandwidth are used in 5G technology. The same mobile networking principles like 4G LTE are used in 5G OFDM. In addition to it, 5G air interface further increases OFDM to give a better scalability and flexibility. As a result, more people can have access to 5G technology [14].

5G provides a seamless compatibility with dense heterogeneous network. This satisfies the high demand of traffic and efficient connectivity to the users. 5G works smoothly even when the number of users connected to the Internet goes over billions in number. Basically, 5G uses the unused part of 3–300 GHz high-frequency mm-wave. This sub-spectrum of mm-wave spectrum can support improved data rate over present wireless system to over hundreds of times to satisfy end user needs. 5G is designed to efficiently use every bit of spectrum across a wide array of available bands and spectrum. 5G is invented to emerge into service areas say, for example, connecting the Internet of Things, artificial intelligence, virtual reality and critical communication systems. This is achieved by 5G NR air interface design techniques, like self-contained TDD sub-frame design. 5G is designed to be energy efficient; it consumes less energy as compared to prior communication devices. This helps in reduction in environmental issues as well as network maintenance issues. Current mobile network consumes about 15–20% of total power consumption on actual data traffic, and the rest of the energy is wasted [15].

5G will have a massive impact on businesses; it will provide high data speeds with higher network reliability. Businesses could use 5G to connect their devices to the same network. By doing this, we can make machines work with the help of mobile device. This can be applied where higher degree of precision is needed.

This will help in increasing the efficiency of businesses and giving users faster access to information. 5G technology can also help in intelligent movement and communication among vehicles. Traffic management can be achieved by designing a network of interconnected vehicles. Real-time data of traffic can be provided to the drivers so that vehicles on the road can choose less congested road to arrive at destination.

2.2 5G-Enabled IoT Applications

The upcoming years of 5G communication will totally improve the insight of lifestyle on society, industry and business field also. It is a radical technology with unique and massive research areas like in healthcare, smart city, robotics and virtual reality-based systems. The IoT technology is incorporated with 5G communication network to attain the tremendous outcomes in every perception of human life. IoT defines as the Internet of Things, in which the things are integrated with various new technologies, software and sensors for the result to obtain the exchange of data and information over the network. 5G with IoT applications defines as a new opening generation for integration of intelligence with comfort and security [16–18].

1. Transition from normal to smart communication
2. Excellence of services
3. Internet of Things to everything
4. Artificial intelligence and edge intelligence
5. Vehicular technology in 5G and beyond
   (a) Intelligent aerial vehicles
   (b) Intelligent car without man
   (c) Intelligent transportation
   (d) Intelligent robotics system

2.3 Blockchain

A system or policy for recording information in a secure and robust manner that it is very difficult, if not impossible, to hack, maliciously change, or cheat a system. Could this be true? Yes, through a system called blockchain. It is a digital ledger or an indefinitely growing list of cryptographically linked blocks (records) [19–23]. These blocks individually are constituted by a collection essentially of a cryptographic hash of the previous block, a timestamp and transaction data (generally represented as a Merkle tree). These are distributed as well as duplicated across the entire network of computer systems on the blockchain. It has supported the transition to a much required cryptographically secured and decentralized network from the existing centralized client-server systems (Internet). It facilitates the users to have a distributed P2P network, where information can be exchanged without the need of any trusted intermediary [24] among non-trusting members.

2.4 *Usage of Blockchain in 5G-Enabled IoT*

The fast-paced evolution of smart applications focused at improving the quality of life for us; Internet of Things is the forerunner in the digitization of services. As IoT infrastructure grows, there is an increase in the access points that need to access and share information. Cloud computing has played an important role in aiding these fast-paced developments related to the IoT domain. However, centralized structure like these as described in detail in [25] may lead to failure in maintaining data transparency. Blockchain provides loads of improved features in terms of security, decentralization and scalability, identity, autonomy, security, reliability [25–27] as well as privacy [28]; Fig. 23.2 depicts the advantages of blockchain deployment in industrial automation based on 5G-enabled IoT systems.

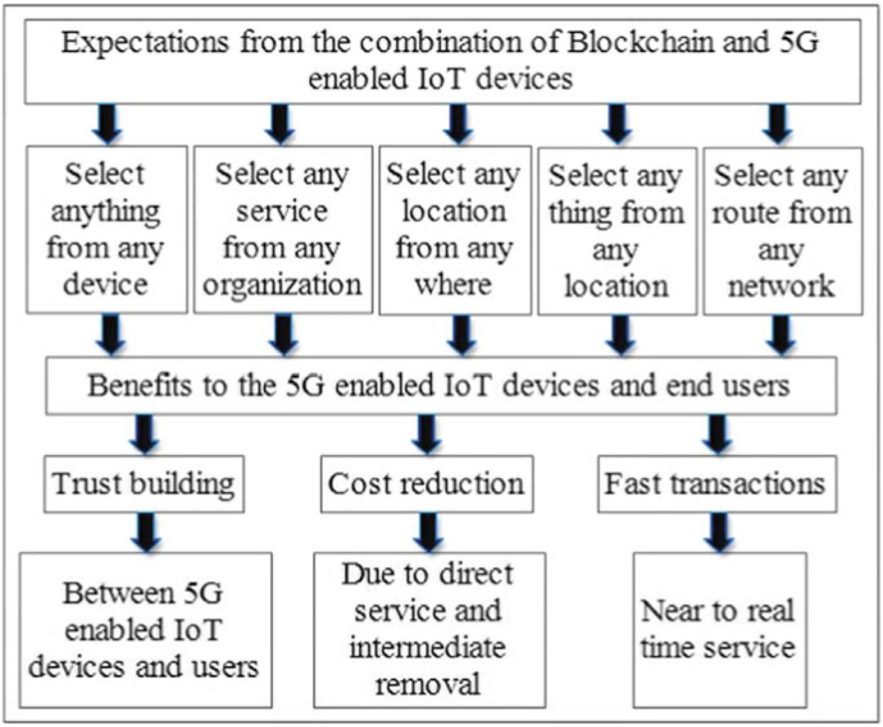

Fig. 23.2 Key benefits of using blockchain with 5G-enabled IoT for industrial automation [23]

2.5 *Role of an Antenna Design for 5G-Enabled IoT*

Antenna is an interface between the IoT device and the rest of the network or system. It is apparent that without a reliable antenna, none of the advantages as have been portrayed above are possible. A good antenna contributes to the success of the system by:

- Improving gains without increasing the cost of additional battery consumption
- Providing consistent signal propagation to facilitate on-the-go communication during IoT device movement
- Improving the signal level while simultaneously reducing noise reception (elimination of noise if possible) through optimum isolation (particularly from other antennas or components in a product having multiple elements, that is, antennas or components)

In a typical communication system, there is a requirement of two antennas – one that transmits and the other that receives. Thus, slight improvement in the antenna involved and the performance receives a twofold improvement in received signal-to-noise ratio, leading to improvement in the data rates, enhanced range and increased security. It can be concluded that there is an overall improvement in the user experience, thus resulting in the improved customer satisfaction.

3 Antenna

The antenna is the interface between the transmission line and space. The IEEE standard defines an antenna as “the antenna or aerial as a means for radiating or receiving the radio waves”. Antennas are passive devices; the power radiated cannot be greater than the power entering from the transmitter side. The antennas are reciprocal in nature, i.e. one design works as both a receiver and a transmitter [29].

- Some techniques to implement the antenna:

  (a) Microstrip-based antenna
  (b) Waveguide-based antenna
  (c) Meta-material-based antenna

Figure 23.3 shows the category wise available in different antennas. Some of the antennas are suitable for IoT system applications.

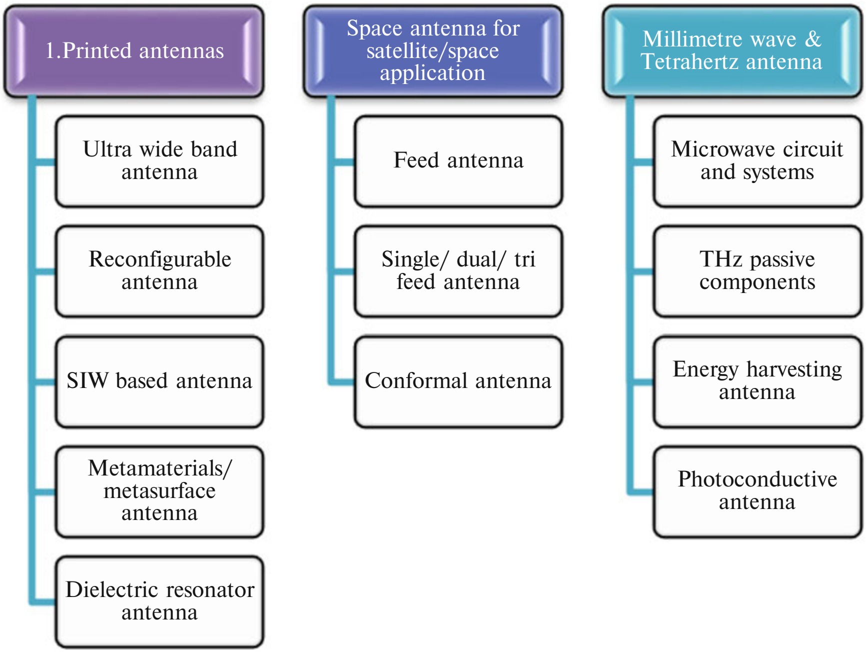

Fig. 23.3 Typical available antennas

3.1 Yearly Configuration of Radio Engineering

Radio engineering utilizing the waveguide, transmission line and antenna as a key element and concept of the electromagnetic field to produce signals within the radio band (frequency range – 20 kHz up to 300 GHz). Figure 23.4 shows the yearly evolution of the radio engineering field.

3.2 Applications of Radio Engineering and Antennas

There are a wide range of applications of antennas in radio engineering; some are listed below for ready reference.

1. The Commercial Application
   (a) 802.11x markets: (i). WLAN and (ii). WPAN
   (b) Automotive RADAR at 77/79 GHz
   (c) Telecommunications backhaul
   (d) Wireless last-mile connectivity

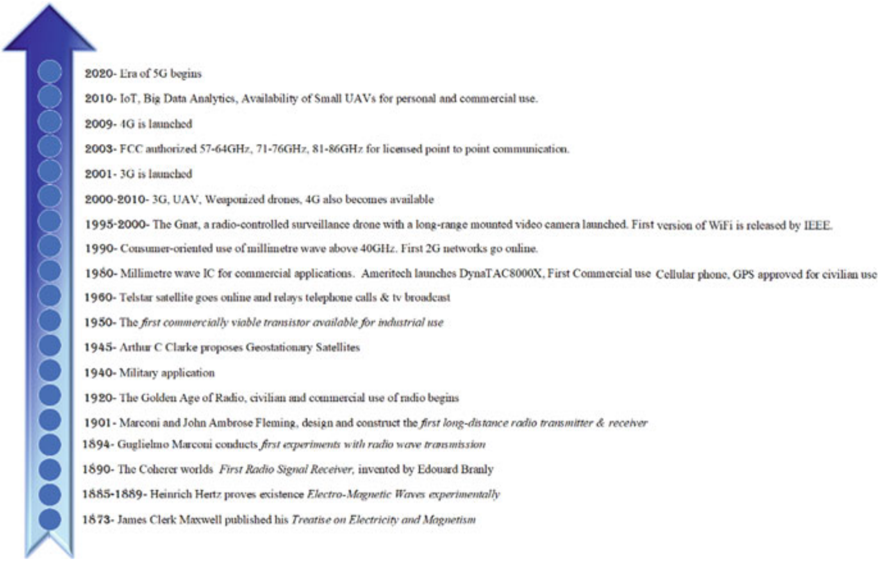

Fig. 23.4 Evolution of the radio engineering field

2. Military Markets (38, 60, 94 GHz)
   (a) Future combat systems
   (b) Secure communications
   (c) Satellite communications
   (d) Military phased array
   (e) Reconfigurable, software definable systems

To implement any kind of antenna, the transmission line takes the most critical role in designing it. So, several transmission lines with their properties and disadvantages are displayed in Table 23.1 [30–36].

4 Substrate Integrated Circuits (SICs)

The basic principle of SICs is to convert non-planar structures into their corresponding planar form and enable the planar fabrication processing of the non-planar and 3D design [37, 38].

- SIC Structures:
  1. SIW (SIW)
  2. Substrate integrated non-radiated dielectric guide (SINRD)
  3. Substrate integrated image guide (SIIG)

  In all of the above, SIW is the most popular structure.

Table 23.1 Planar transmission line properties

Transmission line	Microstrip line	Strip line	Suspended	Fin line	Slot line	Inverted microstrip line	Coplanar waveguide
Operating frequency (GHz)	≤110	≤60	≤220	≤220	≤110	≤220	≤110
Characteristics impedance range	10–100	20–150	20–150	20–400	60–200	25–130	40–150
Dimension	Small	Moderate	Moderate	Moderate	Small	Small	Small
Loss	High	Low	Low	Moderate	High	Moderate	High
Power handling	Low	Low	Low	Low	Low	Low	Low
Solid-state device mounting	Fair	Moderate	Moderate	Easy	Easy	Moderate	Very easy
Low-cost production	Good	Good	Fair	Fair	Good	Fair	Good

4.1 Substrate Integrated Waveguide (SIW) Technology

Recently, the microwave-based wireless components perform a significant role in the field of communication modules. It includes the microwave- and RF-based components for the development of different systems. However, previously, several techniques are combined with microstrip, metallic and coplanar waveguides to achieve the high Q-factor for active as well as passive components. As the microwave system is the emerging topic for the RF researchers to implement the device with high data rates for 5G/6G application and excellent sensing and power handling capabilities. These all are the basic requirement of wireless communication system, so to cover all above advantages, SIW plays the crucial role in the microwave system with easy fabrication topology. The upcoming wireless communication module with SIW technology provides the advancement towards the high reliability, increased performance, good stability and enhanced integration with systems [39].

SIW is the planar form of the rectangular waveguide. A dielectric is filled between two parallel metal plates. These two rows of the conducting vias/holes connect the two parallel plates through the substrate. To implement the millimetre wave integrate circuit, the SIW technology is mostly used. It offers advantages like cost-effectiveness and high-density integration and is most suitable for the mass production of the wireless system. It has widespread solution for millimetre wave applications. SIW was first proposed by **K. Wu and Deslandes**.

Definition *“The waveguide like structure fabricated by using two periodic rows of metallic holes or vias or slots connecting the top and bottom ground planes of dielectric substrate”.*

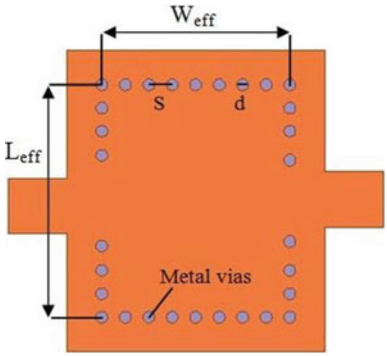

Fig. 23.5 Substrate integrated waveguide structure

It also combines the advantages of microstrip (low cost, easy fabrication, compact size, low weight) and metallic waveguide (low loss, complete shielding and high power handling capability) [40]. Figure 23.5 depicts a typical SIW structure.

- The effective width of the SIW is given as:

$$w_{\text{eff}} = w - \frac{d^2}{0.95s} \text{ or } w_{\text{eff}} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \tag{23.1}$$

- To maintain loss-free radiation, choose and guided wavelength:

$$s \geq 2d \tag{23.2}$$

$$d \leq \lambda_g/5 \tag{23.3}$$

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r(2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}} \tag{23.4}$$

where w is the width of the rectangular waveguide, s is the pitch, d is the diameter of vias and λ_g is the guided wavelength of SIW.

4.2 Substrate Dimensions

- Height (h) $\leq W_{\text{eff}}/2$.
- Thickness of copper (t) = 5* skin depth.
- Skin depth $= \frac{1}{\sqrt{\pi * f * \mu * \sigma}} = 0.0105$.
- Substrate height is 0.508 mm and thickness is 0.035 mm.

Table 23.2 Previous reported work for the SIW-based antenna

Techniques	Advantages	Disadvantages
Array type	Less bandwidth and large gain	Complex design and large sizes
SIW feed	Less bandwidth and large gain	Large size
SIW cavity	More bandwidth and size miniaturization	Average gain
HMSIW cavity	More bandwidth and size miniaturization	Average gain
QMSIW cavity	More bandwidth and size miniaturization	Average gain
Super state	More bandwidth and moderate gain	Complex design and large size

Table 23.3 Comparative analysis of the SIW technique with other available techniques

Features	Loss	Power handling capability	Compactness	Cost	Self-shielded	Self-packaged
Waveguide	Less	High	Low	High	Yes	Yes
Planar transmission line	High	Low	Good	Less	No	No
SIW	Moderate	Moderate	Good	Less	Yes	Yes

4.3 Advantages of SIW Technology

1. Complete circuit in a planar form (including passive component, active component and antennas)
2. Low-cost and well-developed manufacturing process
3. High-density integration of millimetre wave components and systems
4. Complete shielding (no interference)
5. Low losses (energy saving)
6. High Q-factor
7. High power handling
8. High performance

A brief comparison among the different techniques and antenna technology available in literature is shown in Tables 23.2 and 23.3, respectively [41, 42].

In the last decades, SIW technology has reached incredible popularity

4.4 SIW-Based Components

SIW is fabricated by using planar circuitry as given below, and the comparison among different types of SIW-based antenna is described in Table 23.4.

1. Active component

   (a) Feedback oscillator

Table 23.4 Comparison of different types of SIW antenna

Features	Horn	Patch	Slot	Leaky-wave antenna
Frequency	<1 THz	<0.1 THz	<0.5 THz	<0.5 THz
Cost	Average+	Low	Low	High+
Gain	Average	Low	High	Moderate
Size	Large+	Average	Small	Large++
Bandwidth	Wide	Narrow	Wide	Narrow
Fabrication	Difficult	Easy	Average	Difficult

   (b) Mixer
   (c) Frequency selector
   (d) Power amplifier

2. Passive component

   (a) Filter
   (b) Directional coupler
   (c) Magic tee

3. Antennas

   (a) SIW horn antenna
   (b) SIW slot antenna
   (c) SIW leaky-wave antenna

4.5 Future Scope of SIW Technology

1. The SIW array-based slot antenna as the best solution for improving the gain as well as radiation efficiency
2. The meta-material-based slot loaded antenna also as improvement of gain and bandwidth
3. Extended to implement some or other unlicensed frequency applications:

   (a) 70 GHz band (E-band)
   (b) 79 GHz (automotive RADAR systems)
   (c) 80 GHz (E-band)
   (d) 94 GHz (millimetre wave imaging)

4. Extended to dual- and tri-band unlicensed frequency applications
5. Extended to implement high-frequency applications, i.e. THz applications [38–41]

5 Diplexer/Triplexer as Frequency-Selective Element

In the last few years, wireless communication systems have been mostly developed in diplexing and triplexing, maintaining additional and extraordinary functionality and compactness. The major part of conventional diplexing- or triplexing-based communication system is diplexer/triplexer as shown in Fig. 23.6, in which the uplink and downlink channels of transmitter and receiver signal are in neighbouring frequency bands. To enhance the isolation between the uplink and downlink bands, transmission noise rejection and low power transmission for the transceiver, we will propose planar SIW-based self-diplexed/triplexed antennas.

The function of this device is to combine and/or split RF transmitters to facilitate the use of single device by multiple transmitters or receivers on different frequencies reducing cost, space and requirement of addition circuit components. This device may either facilitate transmission from more than one transmitter over a single RF antenna, or it may be used to work as a transceiver for transmitting over one frequency band while receiving is done on another band of frequency [24].

The antenna diplexer has multiple applications. The most common application is to be used as a transceiver at a cellular base station for simultaneous inflow and outflow of signals. This device (self-duplexing antenna) provides high isolation between the used receiving and transmitting feeds, thus allowing the same device to operate for transmission/reception simultaneously blocking the signal. An alternate application for the device could be at a broadcast station, where signal is simultaneously transmitted with many a different frequencies with one antenna element. The device's operation prevents the output of any of the transmitters being fed back into the other's input, thus enabling the use of a single antenna.

In domestic environment, these devices may be used to couple the TV feed coming from terrestrial feeds as well as satellite transmissions into a common feed multiplexed over frequency passed down through the same lead. Figure 23.7 shows the mode of operation of the diplexer.

A diplexer/triplexer designer must keep the following in mind while designing the device and the overall system:

- To function in the adjacent frequency band used for reception and transmission
- To efficiently handle the output power (at the transmitter end)
- To provide adequate rejection of transmitter noise occurring at the reception frequency

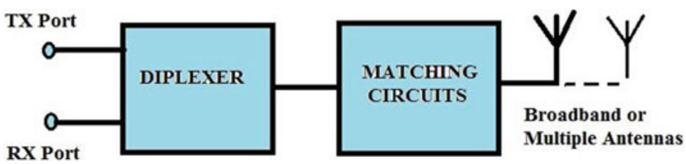

Fig. 23.6 Block diagrams of a traditional diplexer antenna system [27]

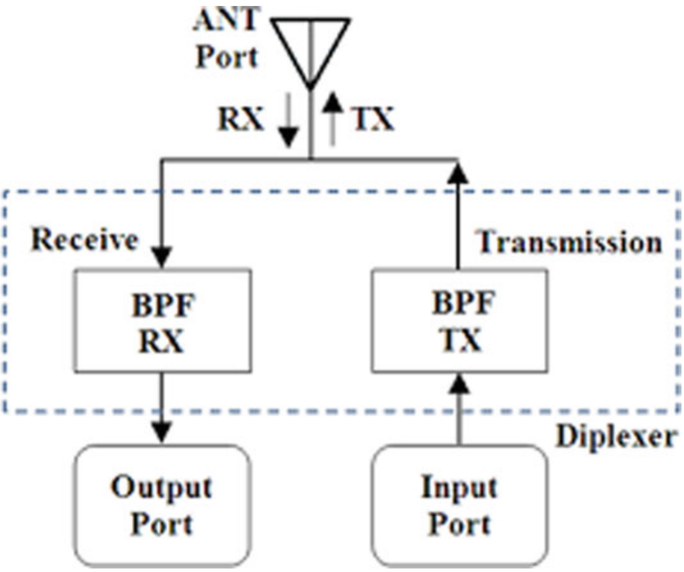

Fig. 23.7 Diplexer working for transmission and receiving antenna [24]

- To operate at, or less than, the frequency separation between the transmitter and receiver
- Sufficient isolation to be ensured to eliminate receiver desensitization [43]

5.1 Motivation

1. *Self-Diplexing Technique*

   In this technique, the antenna has two ports of different frequencies as uplink and downlink. With the help of self-diplexed antenna, we can reduce the complexity of high-order diplexer network, which leads to minimum cost and small size of overall RF (radio-frequency) front-end system. From the last few years, the state of the art of SIW technology becomes a very promising candidate to the implementation and realization of conventional waveguide and other non-planar circuits into their planar counterparts.
2. *Self-Triplexing Technique*

   In the field of communication, the higher-order diplexer and triplexer come under the types of frequency-selective elements, which provide ease of connectivity to multi-band antenna from multiple transmitter/receiver with the help of better isolation between them. Generally this type of circuit increases the complexity of system and limits its application also.
3. *Self-Quadplexing Technique*

In the RF front-end system, quad band antenna is connected to the external element as quadplexer to provide the isolation or low mutual coupling among the input ports, but it requires additional circuitry and in turn extra space for this circuitry in order to keep things compact by eliminating the external quadplexer from RF system, a new technique is proposed called a self-quadplexing technique used to implement the four-port single antenna with high isolation values.

5.2 Different Techniques to Achieve the Objectives

1. *Defected Ground Structure (DGS)*

   Recently, DGS plays a significant role in wireless as well as electromagnetic field. DGS can be found by etching off any shape over the ground plane, as its name describes itself. DGS depends upon the dimension and shape of the defect. Due to DGS method, the shielded current distribution is also disturbed, which results in the propagation of electromagnetic wave through the substrate layer. For getting the better performance of the system, the shape of defect may be altered from simple to complex. With the help of DGS, the isolation between the ports can be increased, and mutual coupling can be reduced also, e.g. dumbbell and bowtie-shaped, etc. [26, 44, 45].
2. *Electromagnetic Band Gap Structure (EBG)*

   EBG structures are used for improving the performances of many RF and microwave devices utilizing the surface wave suppression. They are inserted between the arrays of antenna to reduce the mutual coupling and increase the isolation between the input ports. It prevents some undesired operating mode and control harmonics, e.g. 3-D, 2-D and 1-D EBG, mushroom and uni-polar EBG, etc. [46, 47].
3. *Meander Lines*

   Meander lines are added between two input ports, and this feature supplies an extra input to the port to cancel the signal due to mutual coupling, by which mutual coupling can be reduced and isolation increased [48].
4. *Grounding Vias*

   It is the kind of efficient approach for implementing self-diplexing and self-triplexing antenna system. This approach is recently proposed in microstrip patch antenna for better polarization and controlling the resonant frequency of antenna, so this methodology can be proposed for SIW-based antennas also, where the loaded grounding vias are considered as shunt inductors and produce the inductive effect. This method can also enhance the isolation between ports and gives the better tuning of frequency response [37, 38].
5. *Shunt Component Between Transmission Lines*

   It provides the good isolation level between transmitter and receiver antenna but has the complex structure to fulfil the desire.

5.3 *Flowchart for Simulating the Electromagnetic Structure*

To simulate any kind of active or passive electromagnetic components, the proposed flowchart is used (shown in Fig. 23.8). To analyse the simulation of any microwave or terahertz components, different electromagnetic software are used based on their applications as defined in Table 23.5.

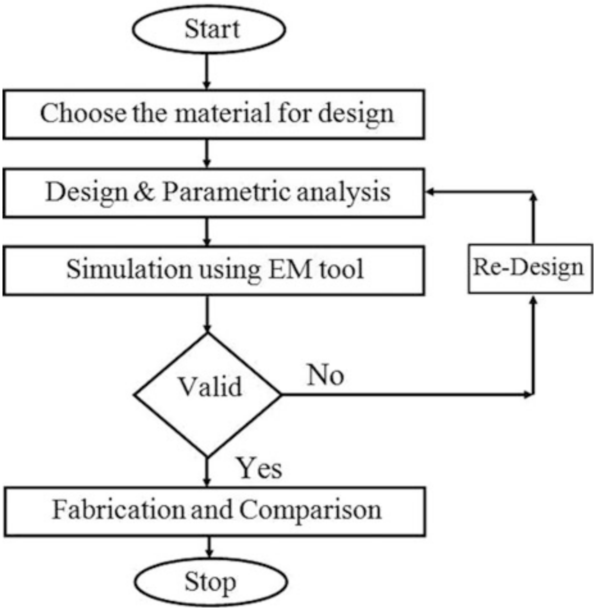

Fig. 23.8 Flowchart of simulating the electromagnetic structure

Table 23.5 Software for antenna design and simulation

Software	Numerical techniques used	Applications (microwave structures)
HFSS	FEM	EM simulation of passive 3-D µwave structures
CST	FIT/FEM/TLM	EM simulation of passive 3-D µwave structures
MW STUDIO	FDTD	EM simulation of passive 3-D µwave structures
ENSEMBLE	MOM	EM simulation of passive 2-D µwave structures
IE3D	MOM	EM simulation of passive 2-D µwave structures
TICRA	GO/GTD/PO/PTD	Reflector antenna analysis, shaping, optimization
MW WIZARD	MOM	Synthesis, analysis of 3-D passive µwave filter
WASPNET	MOM/FEM/FDTD	EM analysis tool for 3-D passive µwave filter
WIPL-D	MOM	EM simulation/analysis of EM structures
EMPIRE	FDTD	EM simulation of passive 3-D µwave structures
ADS	Equations	Microwave passive circuit simulation (feed networks)

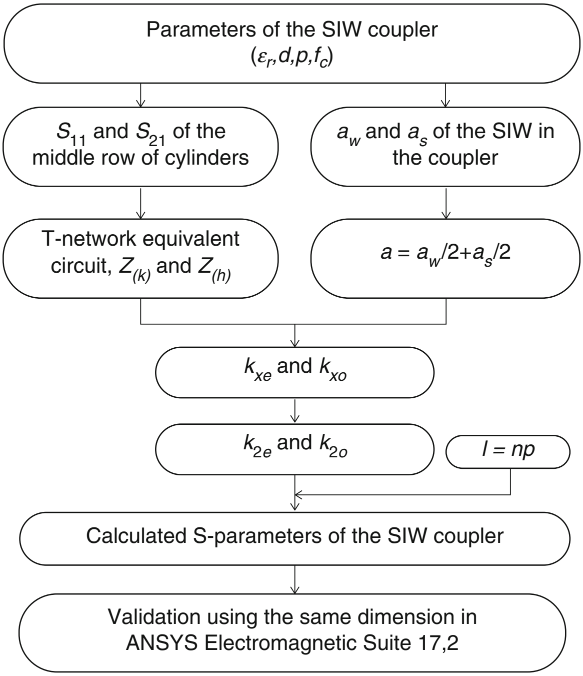

Fig. 23.9 SIW coupling analysis flowchart

5.4 SIW Coupling Analysis Method

The SIW coupling is based on the different features of antenna as its relative permittivity (ε_r), vias gapping (d), resonating/centre frequency (f_c) and pitch (p) values of SIW design. The row of the cylinder or conducting vias proposed the electromagnetic boundary conditions, and with the help of ADS software, "T"-network can be found out. By this even and odd impedance can be retrieved and at last |S|-parameters are calculated by HFSS software. The overall working is defined in the flowchart as shown in Fig. 23.9. The coupling analysis is done by S_{21} parameter for the two-port device.

6 IoT-Based Antennas

IoT-based communication mostly depends upon the sensors and artificial intelligence techniques. Data Communication Systems use a device called IoT antenna for data transmission and reception. These antennas are compact and flexible in nature to operate within 5G bands as in lower and upper both bands. These bands are defined in Table 23.6. An antenna is a passive electromagnetic device used to transfer the information from one place to another. For this transmitting

Table 23.6 5G communication bands for IoT applications

Frequency band	Frequency range of operation	Objective
Sub-1 GHz band	600 MHz band 700 MHz band	Wide area coverage
Sub-6 GHz	3.3–3.8 GHz (mostly allocated) 3.8–4.2 GHz, 4.5–5 GHz 2.3–2.5 GHz, 5.9–7.1 GHz	Good mixture of coverage and speed requirements
Millimetre wave band	28 GHz, 38 GHz bands May be 60 GHz band	Higher speed requirements

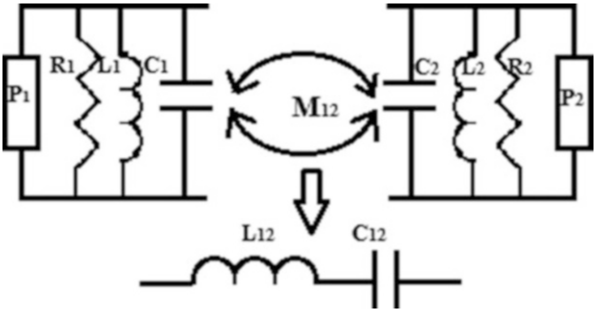

Fig. 23.10 The equivalent circuit model of self-diplexing antenna

as well as receiving, both antennas are used generally in communication and RF front-end systems. Previously, the antenna systems were combined with the diplexer and triplexer elements. These elements are kind of frequency selective or filter element and used to recognize the particular frequency. The self-diplexing, self-triplexing and self-quadplexing antenna, are mostly implemented by SIW technology, these antennas find applications for satellite/RADAR communication, and can be integrated with IoT applications best use. These are defined in sub-sections as below [49].

6.1 *Equivalent Circuit Model of Self-Diplexing Circuit Modules*

The equivalent circuit model for the self-diplexing antenna is shown in Fig. 23.10. The proposed equivalent circuit model is realized with the help of ADS (Advanced Design System) software. Here each parallel combination of RLC components produces the resonant frequencies. Likewise, parallel combination of R_1, L_1 and C_1 produces the first resonant frequency, while another parallel combination of R_2, L_2 and C_2 produces the second resonant frequency. The mutual coupling (M_{12}) between two frequencies is defined by series combination of *LC* network. Here L_{12} and C_{12} present the minimum isolation value for the proposed self-diplexing antenna.

The resonating frequency can be defined by:

$$f_0 = {}^{1}\Big/_{2\pi\sqrt{LC}} \tag{23.5}$$

6.2 *Self-Triplexing Antenna for IoT Applications*

The self-triplexing antenna and triplexers are working at three distinct resonant frequencies. Previously the triplexers are used in RF front-end systems for selecting and filtering the required three frequencies used for further communication. This triplexer is used to provide the required isolation value among three ports; however, this geometry contains more space in overall system. So, the self-triplexing antennas are introduced in RF field to remove the extra circuitry as triplexer from communication system [50–56]. These proposed antennas are more in demand, and RF researchers are mostly working in this field to integrate it with other technology like artificial intelligence, sensors, etc. The comparison among self-triplexing antennas and triplexer is displayed in Table 23.7.

6.2.1 Equivalent Circuit Model of Self-Triplexing Circuit Modules

The equivalent circuit model for self-triplexing antenna is shown in Fig. 23.11. The triplexing antenna works at three resonating frequencies, and each resonating frequency is defined by the parallel section of RLC network connected with the port

Table 23.7 Comparison among triplexer and self-triplexing circuit modules

Features/ref.	[54]	[52]	[50]	[51]	[56]
Resonating frequencies (GHz)	7.8, 9.4, 9.8	11, 12.2, 13.1	4.14, 6.1, 8.32	8.5, 9.7, 12.0	0.85, 1.65, 2.45
Min. isolation	22.5	26.45	30.8	23	22.7
Permittivity (ε_r)	2.2	2.2	2.2	2.2	NA
Gain (dBi)	7.2, 7.2, 7.0	5.1, 5.54, 6.12	4.26, 4.41, 6.27	3.5, 4.7, 5.2	0.85, 4.0, 4.23
Frequency tunability	Yes	Yes	Yes	NA	Yes
Size (mm^2)	32 × 23	26 × 27.5	22 × 22	20.5 × 20.5	115 × 77
FTBR	>17.3	>15	>15	>19.5	NA
Multiplexing circuit	Not required	Not required	Not required	Not required	Required

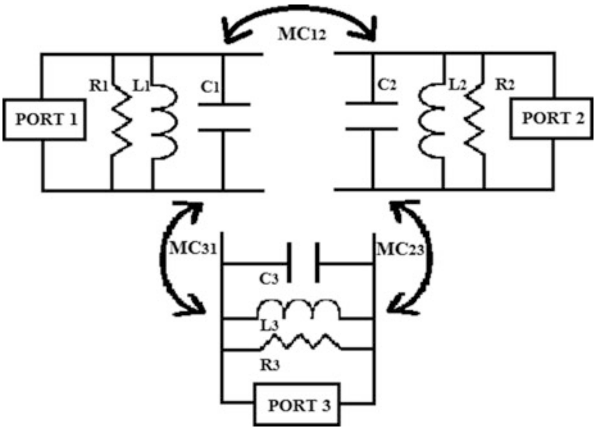

Fig. 23.11 The equivalent circuit model of the self-triplexing antenna

of 50 ohm line. At that time, only single port is ON and produces the corresponding resonating frequency. The first RLC network as R_1, L_1 and C_1 produces the first resonant frequency; likewise, the second and third parallel RLC sections give the second and third operating frequencies. The isolation is the main parameter of the proposed antenna, so the mutual coupling is defined by the M_{12}, M_{23} and M_{31} components, where M_{12} shows the mutual coupling between port 1 and port 2. Similarly, the M_{23} and M_{31} define the minimum mutual coupling between port 2 and port 3 and port 3 and port 1. The proposed equivalent model can be easily realized by ADS software and justified by HFSS also. The value of each resonating frequency can be obtained by Eq. (23.5).

6.3 Self-Quadplexing Antenna for IoT Applications

The frequency-selective element or filters are used to refine the frequency of interest and blocked the others, so quadplexer is also the same element used to find out the four required frequencies with the help of each port. This is mostly used in satellite-, RADAR- and RF-based systems to eliminate the noise and unwanted frequencies; only the desired range of frequency can be passed by the four ports of the quadplexer element. It requires the extra space in any of RF communication systems to provide the isolation or low coupling among the input ports, so the latest technology named as self-quadplexing antenna is introduced by RF researches. It is the most prominent technique used in RF front-end system with light weight, compact space and low losses [57–60]. Here several features of self-quadplexing antenna are explained in Table 23.8. Nowadays, this proposed quadplexing technique is implemented with the help SIW methodology, to get extreme better results than others.

Table 23.8 Comparison among multiplexer and self-quadplexing circuit modules

Features/ref.	[61]	[60]	[59]	[58]	[57]
Resonating frequencies (GHz)	3.5, 5.2, 5.5, 5.8	8.1, 8.78, 9.7, 11.0	5.14, 5.78, 6.74, 7.74	2.4, 3.5, 5.2, 5.8	1.2, 2.4, 3.5, 5.2
Min. isolation	23.6	22.6	28	NA	NA
Permittivity (ε_r)	2.2	2.2	2.33	NA	NA ($\mu_r = 1$)
Gain (dBi)	5.43, 4.1, 3.56, 3.6	5.5, 6.9, 7.47, 7.45	4.1, 4.96, 6.2, 6.1	2.8, 2.1, 3.5, 3.2	5.47, 5.88, 1.97, 3.56
Frequency tunability	Yes	Yes	Yes	No	No
Size (mm^2)	38.8 × 25.6	29 × 29	22 × 22	25 × 20	90 × 60
FTBR	NA	>17	>17.5	NA	NA
Multiplexing circuit	Not required	Not required	Not required	Required	Required

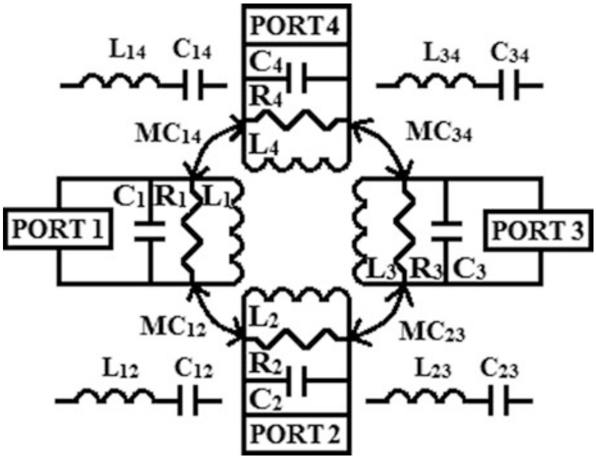

Fig. 23.12 The equivalent circuit model of the self-quadplexing antenna

6.3.1 Equivalent Circuit Model of Self-Quadplexing Circuit Modules

The equivalent circuit model for the self-quadplexing antenna is displayed in Fig. 23.12. The quadplexing antenna module contains the four input ports, and the isolation is defined among all ports in terms of mutual coupling. Here all four resonating frequencies are determined by the parallel combination of RLC network, and mutual coupling is attained by series combination of LC networks. One port is ON simultaneously and produces the particular resonant frequency. The mutual coupling is known in the form of interference, so the minimum mutual coupling is reciprocal to high isolation value and it is proportional to low interference among input ports. The mutual coupling among four ports is defined by M_{12}, M_{23}, M_{34}

and M_{41}. This model can be implemented by ADS software with the help of no. of equations, and electromagnetic structure can be executed by HFSS or CST software.

7 Conclusion

With the substantial development of the latest mobile and satellite communication, the multiple frequency antennas with high isolation and low mutual coupling are one of the particular interests. The SIW (SIW)-based single-layered self-diplexing, self-triplexing and self-quadplexing antenna has been proposed for mobile and satellite communication, the design techniques help to achieve high isolation and low mutual coupling between transmitting and receiving antenna. Additionally, low cross-polarization, high gain and maximum front-to-back ratio are obtained. These proposed antennas are used in RF front-end system without the need of extra circuitry like diplexer and triplexer. These antennas have low manufacturing cost, light weight and low losses; by virtue of this, it can be easily incorporated with 5G-enabled applications and IoT-based applications also. As the upcoming era will become fully 5G and IoT-enabled communication, then proposed antennas as self-diplexing, self-triplexing and self-quadplexing antennas are of great and fit choice for RF researchers and engineers.

References

1. I. Budhiraja, S. Tyagi, S. Tanwar, N. Kumar, J.J.P.C. Rodrigues, Tactile internet for smart communities in 5G: An insight for NOMA-based solutions. IEEE Trans. Ind. Inform. **15**(5), 3104–3112 (2019)
2. R. Gupta, A. Shukla, S. Tanwar, AaYusH: A smart contract-based telesurgery system for healthcare 4.0, in *2020 IEEE Int. Conf. Commun. Work. ICC Work. 2020 – Proc.*, (2020), pp. 1–6
3. S. Li, L. Da Xu, S. Zhao, 5G Internet of Things: A survey. J. Ind. Inf. Integr. **10**(February), 1–9 (2018)
4. D. Astely, E. Dahlman, G. Fodor, S. Parkvall, J. Sachs, LTE release 12 and beyond. IEEE Commun. Mag. **51**(7), 154–160 (2013)
5. D. Vukobratovic et al., CONDENSE: A reconfigurable knowledge acquisition architecture for future 5G IoT. IEEE Access **4**, 3360–3378 (2016)
6. Q. Wang, D. Chen, N. Zhang, Z. Qin, Z. Qin, LACS: A lightweight label-based access control scheme in IoT-based 5G caching context. IEEE Access **5**(c), 4018–4027 (2017)
7. I.F. Akyildiz, S. Nie, S.C. Lin, M. Chandrasekaran, 5G roadmap: 10 key enabling technologies. Comput. Netw. **106**, 17–48 (2016)
8. M. Marchese, A. Moheddine, F. Patrone, IoT and UAV integration in 5G hybrid terrestrial-satellite networks. Sensors (Switzerland) **19**(17), 3704 (2019)
9. R. Gupta, S. Tanwar, S. Tyagi, N. Kumar, Tactile internet and its applications in 5G era: A comprehensive review. Int. J. Commun. Syst. **32**(14), 1–49 (2019)
10. J. Vora, S. Kaneriya, S. Tanwar, S. Tyagi, N. Kumar, M.S. Obaidat, TILAA: Tactile internet-based ambient assistant living in fog environment. Futur. Gener. Comput. Syst. **98**, 635–649 (2019)

11. I. Syrytsin, S. Zhang, G.F. Pedersen, A.S. Morris, Compact quad-mode planar phased array with wideband for 5G mobile terminals. IEEE Trans. Antennas Propag. **66**(9), 4648–4657 (2018)
12. Y. Zhang, J.Y. Deng, M.J. Li, D. Sun, L.X. Guo, A MIMO dielectric resonator antenna with improved isolation for 5G mm-wave applications. IEEE Antennas Wirel. Propag. Lett. **18**(4), 747–751 (2019)
13. M. Ciydem, E.A. Miran, Dual-polarization wideband Sub-6 GHz suspended patch antenna for 5G base station. IEEE Antennas Wirel. Propag. Lett. **19**(7), 1142–1146 (2020)
14. M.M. Samadi Taheri, A. Abdipour, S. Zhang, G.F. Pedersen, Integrated millimeter-wave wideband end-fire 5G beam steerable array and low-frequency 4G LTE antenna in mobile terminals. IEEE Trans. Veh. Technol. **68**(4), 4042–4046 (2019)
15. Z. Ren, A. Zhao, S. Wu, MIMO antenna with compact decoupled antenna pairs for 5G mobile terminals. IEEE Antennas Wirel. Propag. Lett. **18**(7), 1367–1371 (2019)
16. N. Wang, P. Wang, A. Alipour-Fanid, L. Jiao, K. Zeng, Physical-layer security of 5G wireless networks for IoT: Challenges and opportunities. IEEE Internet Things J. **6**(5), 8169–8181 (2019)
17. A. Ijaz et al., Enabling massive IoT in 5G and beyond Systems: PHY radio frame design considerations. IEEE Access **4**(ii), 3322–3339 (2016)
18. L. Chettri, R. Bera, A comprehensive survey on Internet of Things (IoT) toward 5G wireless systems. IEEE Internet Things J. **7**(1), 16–32 (2020)
19. W.Z. Khan, M.H. Rehman, H.M. Zangoti, M.K. Afzal, N. Armi, K. Salah, Industrial internet of things: Recent advances, enabling technologies and open challenges. Comput. Electr. Eng. **81**, 106522 (2020)
20. R. Gupta, S. Tanwar, S. Tyagi, N. Kumar, Tactile-internet-based telesurgery system for healthcare 4.0: An architecture, research challenges, and future directions. IEEE Netw. **33**(6), 22–29 (2019)
21. R. Gupta, A. Kumari, S. Tanwar, N. Kumar, Blockchain-envisioned softwarized multi-swarming UAVs to tackle COVID-I9 situations. IEEE Netw., 1–8 (2020)
22. S. Tanwar, J. Vora, S. Tyagi, N. Kumar, M.S. Obaidat, A systematic review on security issues in vehicular ad hoc network. Secur. Priv. **1**(5), e39 (2018)
23. I. Mistry, S. Tanwar, S. Tyagi, N. Kumar, Blockchain for 5G-enabled IoT for industrial automation: A systematic review, solutions, and challenges. Mech. Syst. Signal Process. **135**, 106382 (2020)
24. H. Chu, L. Peng, C. Jin, J.X. Chen, An unbalanced-to-balanced diplexer based on substrate integrated waveguide cavity. Int. J. RF Microw. Comput. Eng. **25**(2), 173–177 (2015)
25. A. Kumar, D. Chaturvedi, S. Raghavan, Design of a self-diplexing antenna using SIW technique with high isolation. AEU – Int. J. Electron. Commun. **94**, 386–391 (2018)
26. N.C. Karmakar, S.M. Roy, I. Balbin, Quasi-static modeling of defected ground structure. IEEE Trans. Microw. Theory Tech. **54**(5), 2160–2168 (2006)
27. D. Silveira et al., Improvements and analysis of nonlinear parallel behavioral models. Int. J. RF Microw. Comput. Eng. **19**(5), 615–626 (2009)
28. S. Nandi, A. Mohan, SIW-based cavity-backed self-diplexing antenna with plus-shaped slot. Microw. Opt. Technol. Lett. **60**(4), 827–834 (2018)
29. C.A. Balanis, *Antenna Theory Analysis and Design* (Wiley, Hoboken, 2005), p. 811
30. C.Y.D. Sim, C.C. Chang, J.S. Row, Dual-feed dual-polarized patch antenna with low cross polarization and high isolation. IEEE Trans. Antennas Propag. **57**(10 PART 2), 3321–3324 (2009)
31. D.H. Schaubert, F.G. Farrar, A. Sindoris, S.T. Hayes, Microstrip antennas with frequency agility and polarization diversity. IEEE Trans. Antennas Propag. **29**(1), 118–123 (1981)
32. Y.M. Pan, P.F. Hu, X.Y. Zhang, S.Y. Zheng, A low-profile high-gain and wideband filtering antenna with metasurface. IEEE Trans. Antennas Propag. **64**(5), 2010–2016 (2016)
33. J. Ouyang, F. Yang, Z.M. Wang, Reducing mutual coupling of closely spaced microstrip MIMO antennas for WLAN application. IEEE Antennas Wirel. Propag. Lett. **10**, 310–313 (2011)

34. D. Deslandes, K. Wu, Integrated microstrip and rectangular waveguide in planar form. IEEE Microw. Wirel. Compon. Lett. **11**(2), 68–70 (2001)
35. D. Deslandes, Design equations for tapered microstrip-to-substrate integrated waveguide transitions. IEEE MTT-S Int. Microw. Symp. Dig., 704–707 (2010)
36. M. Bozzi, A. Georgiadis, K. Wu, Review of substrate-integrated waveguide circuits and antennas. IET Microw. Antennas Propag. **5**(8), 909–920 (2011)
37. H. Uchimura, T. Takenoshita, M. Fujii, Development of a 'laminated waveguide. IEEE Trans. Microw. Theory Tech. **46**(12 PART 2), 2438–2443 (1998)
38. G.L. Huang et al., Lightweight perforated waveguide structure realized by 3-D printing for RF applications. IEEE Trans. Antennas Propag. **46**(8), 3897–3904 (2017)
39. N. Ranjkesh, M. Shahabadi, Loss mechanisms in SIW and MSIW. Prog. Electromagn. Res. B **4**, 299–309 (2008)
40. L. Yan, W. Hong, G. Hua, J. Chen, K. Wu, T.J. Cui, Simulation and experiment on SIW slot array antennas. IEEE Microw. Wirel. Compon. Lett. **14**(9), 446–448 (2004)
41. F. Kuroki, R.J. Tamaru, Low-loss and low-cost solution for printed transmission lines at millimeter-wavelengths by using bilaterally metal-loaded tri-plate transmission line. IEEE MTT-S Int. Microw. Symp. Dig., 301–304 (2009)
42. J. Hirokawa, M. Ando, Single-layer feed waveguide consisting of posts for plane tem wave excitation in parallel plates. IEEE Trans. Antennas Propag. **46**(5), 625–630 (1998)
43. C.H. Liang, C.Y. Chang, Novel microstrip stepped-impedance resonator for compact wideband bandpass filters, in *APMC 2009 – Asia Pacific Microw. Conf. 2009*, (2009), pp. 941–944
44. R. Sharma, T. Chakravarty, S. Bhooshan, A.B. Bhattacharyya, Design of a novel 3 DB microstrip backward wave coupler using defected ground structure. Prog. Electromagn. Res. **65**, 261–273 (2006)
45. N.C. Karmakar, S.M. Roy, I. Balbin, Quasi-static modeling of defected ground structure in IEEE Trans. Microw. Theory Tech. **54**(5), 2160–2168 (2006)
46. H.H. Xie, Y.C. Jiao, L.N. Chen, F.S. Zhang, An effective analysis method for EBG reducing patch antenna coupling. Prog. Electromagn. Res. Lett. **21**(March), 187–193 (2011)
47. B. Mohajer-Iravani, S. Shahparnia, O.M. Ramahi, Coupling reduction in enclosures and cavities using electromagnetic band gap structures. IEEE Trans. Electromagn. Compat. **48**(2), 292–303 (2006)
48. J. Ghosh, S. Ghosal, D. Mitra, S.R.B. Chaudhuri, Mutual coupling reduction between closely placed microstrip patch antenna using meander line resonator. Prog. Electromagn. Res. Lett. **59**(April), 115–122 (2016)
49. G.A. Akpakwu, B.J. Silva, G.P. Hancke, A.M. Abu-Mahfouz, A survey on 5G networks for the internet of things: Communication technologies and challenges. IEEE Access **6**(c), 3619–3647 (2017)
50. S.K.K. Dash, Q.S. Cheng, R.K. Barik, N.C. Pradhan, K.S. Subramanian, A compact triple-fed high-isolation SIW-based self-triplexing antenna. IEEE Antennas Wirel. Propag. Lett. **19**(5), 766–770 (2020)
51. P. Nigam, The substrate integrated waveguide based self (2019), pp. 241–246
52. P. Nigam, R. Agarwal, A. Muduli, S. Sharma, A. Pal, Substrate integrated waveguide based cavity-backed self-triplexing slot antenna for X-Ku band applications. Int. J. RF Microw. Comput. Eng. **30**(4), 1–11 (2020)
53. A. Kumar, D. Chaturvedi, S. Raghavan, Low-profile substrate integrated waveguide (SIW) cavity-backed self-triplexed slot antenna. Int. J. RF Microw. Comput. Eng. **29**(3), 1–7 (2019)
54. K. Kumar, S. Dwar, Substrate integrated waveguide cavity-backed self-Triplexing slot antenna. IEEE Antennas Wirel. Propag. Lett. **16**(c), 3249–3252 (2017)
55. A. Kumar, S. Raghavan, A self-triplexing SIW cavity-backed slot antenna. IEEE Antennas Wirel. Propag. Lett. **17**(5), 772–775 (2018)
56. P. Cheong, K.F. Chang, W.W. Choi, K.W. Tam, A highly integrated antenna-triplexer with simultaneous three-port isolations based on multi-mode excitation. IEEE Trans. Antennas Propag. **63**(1), 363–368 (2015)

57. H. Liu, P. Wen, S. Zhu, B. Ren, X. Guan, H. Yu, Quad-band CPW-fed monopole antenna based on flexible pentangle-loop radiator. IEEE Antennas Wirel. Propag. Lett. **14**(c), 1373–1377 (2015)
58. X. Sun, G. Zeng, H.C. Yang, Y. Li, A compact quadband CPW-fed slot antenna for M-WiMAX/WLAN applications. IEEE Antennas Wirel. Propag. Lett. **11**, 395–398 (2012)
59. S.K.K. Dash, Q.S. Cheng, R.K. Barik, A compact substrate integrated waveguide backed self-quadruplexing antenna for C-band communication. Int. J. RF Microw. Comput. Eng. **30**(10), 1–9 (2020)
60. S. Priya, S. Dwari, K. Kumar, M.K. Mandal, Compact self-quadruplexing SIW cavity-backed slot antenna. IEEE Trans. Antennas Propag. **67**(10), 6656–6660 (2019)
61. A. Kumar, Design of self-quadruplexing antenna using substrate-integrated waveguide technique. Microw. Opt. Technol. Lett. **61**(12), 2687–2689 (2019)