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A review of the development and application of RF technology and its sub-technologies

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Abstract. With the acceleration of industry reform, new communication technologies are required to have larger bandwidth, faster transmission speed and more comprehensive applications. As a mature and effective high-frequency technology, RF band technology can meet many communication requirements in practical applications and plays an irreplaceable role in current production and life. At the same time, RF technology is also an important part of modern communication system, which has a good development prospect and has been widely used in many fields. In order to let more people understand the importance of radio frequency technology and promote the further development of radio frequency technology, this paper will introduce the important applications of radio frequency technology in practice from four aspects: the application of radio frequency in satellite, radio frequency identification, radio frequency ablation technology and radio frequency integrated circuit, and treat the application of radio frequency technology in practice from different angles, and illustrate the significance and development prospects of radio frequency technology.

Keywords: Radio frequency, Radiofrequency integrated circuit, Radiofrequency Identification, Radiofrequency ablation, "Starlink" system.

1. Introduction

With the advancement of the digital age, people's demand for high-speed and high-capacity communications has prompted more and more in-depth research on the high-frequency band. The valuable resources contained in the radio frequency band have gradually been effectively utilized by people, and various new technologies based on the radio frequency band have gradually developed as well. Radio frequency refers to the electromagnetic frequency that can radiate into space, and the frequency range is between 300kHz and 30ghz. It is the abbreviation of high frequency AC variable

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electromagnetic wave. Alternating current that changes less than 1000 times per second is called low-frequency current, and alternating current that changes more than 10000 times per second is called high-frequency current. RF is such a high-frequency current.

As an important technology in high frequency technology, radio frequency technology has been widely used in many fields, such as television, radio, mobile phone, radar, automatic identification system, medical treatment, agriculture and so on. In order to let more people interested in RF technology have a rough understanding of RF technology, this article will introduce the important applications of RF technology in circuit devices, Internet of things, medical treatment and long-distance wireless communication from four different aspects. In this article, we aim to introduce the application of RF technology in these four aspects, and analyze the application scenarios, advantages and limitations of the technology, so that people can understand RF technology from a more comprehensive perspective.

2. Radiofrequency Integrated Circuit (RFIC)

RFIC is a type of RF transceiver semiconductor, also known as a transceiver, consisting of one logic region and one analog circuit region. It can convert digital signals from the modem chip into analog signals and convert them into radio frequencies that people can use. At the same time, it can convert external signals into digital signals and transmit them to the modem.

With the arrival of the 5G era, 5G communication has become a topic of great concern and concern for people. However, in the past, people's attention to mobile phones often focused on CPU, GPU, baseband, screen, and camera. In recent years, with the emergence of 5G technology and the rise of domestic RF chips, 5G RF chips have gradually entered the public eye. We know that the reason why mobile phones can communicate with base stations is by transmitting and receiving wireless electromagnetic waves from each other. A series of circuits, chips, components, etc. specifically responsible for transmitting and receiving wireless electromagnetic waves in mobile phones are collectively referred to as RFIC. Radio frequency and baseband are the cornerstones for mobile phones to achieve communication functions.

2.1. The Importance of RFIC

Compared to 4G, 5G has significantly improved its performance indicators. The eMBB (Enhanced Mobile Broadband) scenario of 5G has increased the mobile phone speed to gigabit or even tens of thousands of megabits, which is nearly 100 times higher than the early LTE speed (100Mbps). However, while achieving a leap in transmission speed, 2G/3G/4G, combined with 5G, MIMO (Multi Antenna Technology), and dual card dual standby technology have doubled the number of antennas and supported frequency bands in mobile phones. In the early days of 4G, there were only less than 20 frequency band combinations. In contrast, 5G has over 10000 frequency band combinations, making its complexity terrifying. At the same time, because the thickness and weight of 5G mobile phones cannot be increased, and power consumption cannot be increased, RF chips play a crucial role in 5G communication.

2.2. Development of RFIC

Early RFIC mainly relied on silicon based bipolar transistor discrete devices, interconnecting passive components such as diodes, inductors, capacitors, and integrating them onto PCBs(printed circuit board) to form radio frequency hybrid integrated circuits.

Since the 1990s, with the advancement of IC process technology, RFIC have achieved interconnection and integration of various transistor chips and passive components (or chips) such as diodes, inductors, capacitors, etc. on ceramic substrates. Then, they have been miniaturized or microencapsulated, greatly reducing the size of RF circuits and quickly replacing the old hybrid circuits using discrete devices, resulting in significant progress and development of RFIC, and it has promoted the rapid development of miniaturization packaging and wireless communication technology [1].

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2.3. Challenges Encountered in the Development of RFIC

In 2015, RFIC encountered the most severe challenge in its development. From a technical point of view, under the framework of hardware technology at that time, RFIC can be regarded as the earliest integrated circuit submodule to get rid of Moore's Law, because the influence of device size on RF is too great. Roughly speaking, the main design technology of RFIC at that time had been solidified in the 65nm era, that is, almost 2010, and there were few breakthroughs. From 2005 to 2015, the communication side, especially the mobile phone communication end, was the main driving force for the advancement of RFIC technology, and many people said at the time that the research and development of this technology has basically come to an end in 2015 [2]. With the popularization of mobile phone NFC(Near Field Communication) technology, the market that can be expected to be expected by RFIC in the future is shrinking, and the possible growth points in the future will return to the earliest expected RF tag field of RFIC (application scenarios are mainly concentrated in the Internet of Things perception segment, such as unmanned supermarkets, unmanned warehousing, unmanned driving, etc.) The profitability rate of these fields is currently uncertain, but the product technical requirements will basically not exceed the technical requirements at that time, and the technical implementation restrictions are much better. That is to say, in the past (mainly before 2015) due to the high profit of the product brought by the technical expansion of RFIC brought by communication technology has passed, and after 2015, the RFIC industry will enter the era of low profit, the possibility of technological breakthrough is low, in the absence of IC industry before no major technological revolution (material upgrade or process improvement), RFIC's technology tree is basically climbed, mainly back-end application layer product integration innovation, in short, market expansion things, Not something that RFIC designed.

2.4. Technological Breakthroughs in RFIC in Recent Years

Samsung began its RF OEM(Original Entrusted Manufacture) service with a 28nm process in 2015 and expanded to a 14nm process in 2017. Since 2017, it has launched over 500 million mobile RF chips, mainly used in high-end smartphones.

The RFIC converts the received RF signal into a digital signal for digital processing, and converts the processed digital signal into an RF signal for transmission. In RF process technology, both analog/RF device performance and digital device performance are very important.

With the miniaturization of semiconductor process nodes, digital circuits have significantly improved in performance, power consumption, and area. However, analog/RF modules are difficult to miniaturize due to parasitic characteristics. Due to the narrow linewidth, the resistance increases, RF signal amplification performance weakens, power consumption increases, and the overall performance of the RF chip decreases.

It is understood that in order to overcome the technical challenges of analog/RF circuits in process miniaturization, Samsung has developed a unique RF device structure called "RFeFET (RF extremeFET)". The new structure is only available on the 8nm RF platform, and the new RF device can improve RF performance with low power.

Compared to the previous 14nm process, Samsung's "RFeFET" helps achieve miniaturization of digital circuits while improving analog/RF performance, providing a high-performance 5G technology platform. Due to the improved performance of RFeFET, the total number of transistors and the area of analog circuits in the RFIC can be reduced.

Samsung stated that compared to its previous 14nm process, its 8nm RF process can reduce the RFIC area by about 35% and improve energy efficiency by about 35% using the "RFeFET" technology [3].

At the TSMC 2021 Technology Forum held on June 2, 2021, TSMC President Wei Zhejia announced the launch of the 6nm RF (N6RF) process.

TSMC announced the launch of the 6nm Radio Frequency (N6RF) process, which improves the performance of N6RF transistors by over 16% compared to the previous generation of 16nm RF technology. In addition, N6RF supports 5G RF transceivers in the Sub 6GHz and millimeter wave frequency bands, significantly reducing power and area without affecting the performance, functionality,

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and battery life provided to consumers. N6RF will also enhance WiFi 6/6e performance and power efficiency.

TSMC stated that compared to 4G, 5G smartphones require more silicon area and consume more electricity to provide higher wireless data rates. Chips that support 5G integrate more functions and components, and their sizes are getting larger and larger, competing with batteries for limited internal space in smartphones. TSMC stated that N6RF is an advanced RF technology that incorporates the power consumption, efficiency, and area advantages of advanced N6 logic processes into 5G RF and WiFi 6/6e solutions, and is a response to the 5G era [4].

2.5. Future Market Development of RFIC

According to Yole's prediction, the mobile RFIC front-end market will grow from $15 billion in 2017 to $35 billion in 2023, ushering in a 14% rapid growth rate. In the global sales distribution of RFIC front-end, filters account for the largest share, increasing from $8 billion in 2017 to $22.5 billion in 2023, with an annualized growth rate of 19%; The second largest market share is PA, which will grow from $5 billion in 2017 to $7 billion in 2023, with an annualized growth rate of 7%. The above data fully indicates that filters and PA are the key players in RFIC devices [5].

3. Radiofrequency Identification (RFID)

3.1. Principle

Radiofrequency identification (RFID) is an automatic identification technology that enables remote, non-contact communication. It typically consists of three components: a radio frequency tag, a reader, and an antenna, as shown in Fig. 1. When the electronic tag enters the radio frequency magnetic field generated by the reader, the antenna within the tag generates an induced current, activating the tag. The A/D conversion circuit in the tag then encodes and transmits the information stored in the tag's chip. The RFID transmission generally adopts load modulation: according to the binary coding beat transmitted by the electronic tag to the reader, the load resistance or capacitor is controlled to access or disconnect, so that the amplitude of the tag carrier wave is changed regularly, and is transmitted to the reader through electromagnetic space coupling. Subsequently, after the reader antenna receives the change, it is restored to binary code by demodulation to realize the communication between the RFID tag and the reader.

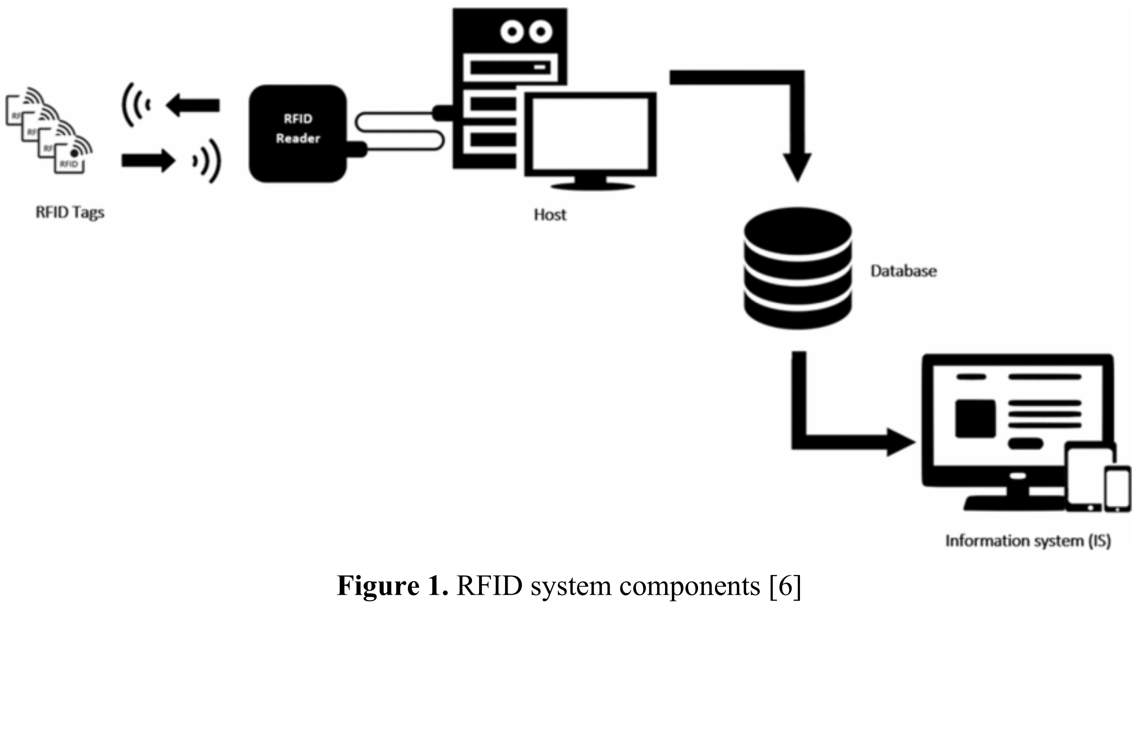

Figure 1. RFID system components [6]

3.2. Classification

RFID can be classified according to different standards, with the most common classification based on the energy supply into three types: active tags, passive tags, and semi-passive tags. The active tag is powered by its battery, which has high reliability and long transmission distance, but the material cost is high. Passive tags convert part of RF energy into the direct current power supply, so the cost is low, but the transmission distance and signal reception are limited. The semi-passive tag is equipped with a battery inside, which is dormant when it is not working and is working when it receives the signal, so it can save power. RFID can also be classified according to working in different frequency bands or frequency points, internal memory of electronic tags, etc.

3.3. Development

RFID technology can be traced back to the 1940s when it was based on the improvement and application of radar technology, which was still limited to the military field. The British Air Force was the first to use this technology on combat aircraft, mainly for distinguishing enemy aircraft from self-defeating aircraft. In 1948, Harry Stockman published "Communication with Reflected Power" in the Proceedings of the Institute of Radio Engineers (IRE), which laid the theoretical foundation for RFID technology. In 1973, Mario W. Cardullo patented an active RFID tag with rewritable memory, the first RFID tag in the world. In the mid-1990s, the first ultra-high frequency (UHF) reader came out, and RFID technology was gradually adopted by enterprises [7]. In 1999, the Massachusetts Institute of Technology first put forward the concept of the "Internet of Things", to provide all items with their unique code, so as to realize the identification of items, RFID electronic tags gradually appear in the major brands of goods. After entering the 21st century, RFID technology is no longer limited to the enterprise, began to gradually enter the public's daily life.

3.4. Application

With the rapid progress of RFID technology, it is now used in many important fields, such as logistics management, biometrics, anti-counterfeiting, aviation, and so on. In terms of logistics, enterprises can attach RFID tags to objects, collect data through readers and upload it to the cloud to realize real-time tracking and positioning of items and determine the number of items. Figure 2 shows the specific process of tracking goods. In recent years, RFID technology combined with infinite Internet of Things communication has built a multi-card identification system to further reduce the signal interference in the process of electronic tag identification, and reduce power consumption and cost by optimizing the circuit, to improve the identification accuracy and efficiency. In terms of biometrics, the chip is implanted into the animal body to realize product tracking and traceability, and other functions.

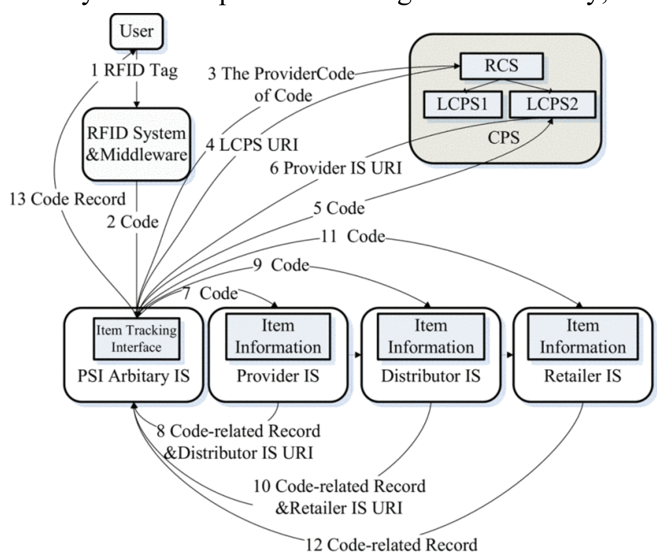

Figure 2. Distributed Item Logistics Record Tracking [8]

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3.5. Challenges and Prospects

With the increasing social demand for remote interaction, more industries have an urgent demand for RFID technology. However, there are few types of research on large equipment such as substations, although the electromagnetic field generated by the current of electrical equipment in operation is the source of electromagnetic interference, which will affect the performance of RFID. However, in future construction, enterprises can study special technologies and transmission power reduction, so that these devices can also apply Internet of Things technology to select RFID tags for devices, form correlation practice remote supervision and inspection, and improve work efficiency and product safety.

4. Radiofrequency Ablation (RFA)

In the past three decades, radiofrequency ablation (RFA) technology has been increasingly used in the treatment of cardiac arrhythmia, cervical and lumbar disc herniation, and tumor resection under its advantages of being minimally invasive, having fewer complications, and having good therapeutic effects on small tumors. However, the traditional RFA technique still has limitations such as limited ablation zone, high local tumor progression (LTP) rate, and risk of thermal injury. The purpose of this article is to provide an overview of the principle of action, historical progress, and challenges of expanding the indications for radiofrequency ablation.

4.1. Principle

Radiofrequency ablation (RFA) is a class of minimally invasive techniques in which high-frequency alternating current (HFAC) emitted from electrodes heats tumor tissue to cause coagulative necrosis. It can be performed by placing an electrode with an uninsulated tip inside the tumor tissue under the guidance of ultrasound equipment, CT, X-ray machine, etc. [9]. Since the electrode tip is not insulated, the high-frequency electromagnetic field can directly enter the tissue around the electrode. The ions in the tissue are subjected to the electric field force and oscillate with the electromagnetic field at high speed, generating heat by mutual friction and increasing the temperature of the tissue. When the temperature reaches a certain value, the proteins in the tissue are denatured, the intracellular water is lost, and the tumor tissue undergoes coagulative necrosis, to achieve the purpose of killing the tumor [10].

4.2. Challenges and Solutions Encountered in the Development of RFA

4.2.1. Conflict between Electrode Power and Charring

The effective killing range caused by RF ablation when used to treat tumors is related to the power of RF ablation. However, when the temperature of the electrode-tissue interface exceeds 100°C [11, 12], it can cause charring of the tissue around the electrode, forming an insulating band that significantly reduces the current density and affects the ablation effect.

To improve the relationship between energy and tissue interaction, avoid tissue charring, and improve ablation efficiency, internal cooling electrodes, and perfusion electrodes have been developed [13]. The internal cooling electrode cools the tip of the needle by adding cold circulating fluid inside the tip, reducing the probability of charring of nearby tissues and maintaining a low impedance for more efficient energy transfer to the periphery. The perfusion electrode is surrounded by multiple holes through which saline is passed directly into the tumor. The saline can cool the tip of the needle and the tissue directly while lowering the impedance of the tissue to avoid charring [11]. In addition, the hot saline will be transferred to the surrounding tissues, and the effect of expanding the ablation zone can also be achieved [9].

4.2.2. High Local Tumor Progression (LTP) Rate

The limited extent of coagulative necrosis in conventional tumor-puncture RFA, coupled with the complexity of localizing the center of the tumor to the electrodes from three dimensions, makes it

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difficult to create a sufficient 0.5-1.0 cm ablation margin to completely kill the tumor [14]. There is also the theoretical possibility of tumor propagation through the electrode pathway due to the tumor-penetrating nature of the procedure. At the same time, the increased intratumorally pressure due to tissue vaporization also has the potential for tumor spread through the drainage vessels, leading to frequent tumor recurrence. Therefore, local tumor progression (LTP) has been one of the limitations of conventional RFA. A study by Kim YS et al. in 2013 showed that the 3-year LTP rate after RFA was as high as 21.4% [15].

To expand the ablation zone of the electrodes, the non-contact RFA technique has emerged in recent years. This technique places multiple electrodes on the outside of the tumor and performs RF ablation centripetally [14]. The advantage of this technique is that it provides a sufficient ablation margin to facilitate tumor control. In addition, non-contact RFA eliminates peripheral vascularity of the tumor and reduces the possibility of tumor spread. Therefore, the RFA technique can significantly reduce LTP [16].

4.2.3. Risk of Neurological Damage

In 2004, Nakatsuka et al. performed radiofrequency ablation in 17 patients (totaling 23 bone metastases) [9, 17]. After treatment, four patients experienced thermal injury to the spinal cord during radiofrequency ablation. The researchers concluded that there is a risk of spinal cord thermal injury with the application of radiofrequency ablation for tumors adjacent to the spinal cord. And in 2009, Nakatsuka et al. did another experiment on cases of spinal metastases adjacent to the spinal cord [9, 18]. The researchers monitored the patients' intraspinal temperature in real-time during radiofrequency ablation. The results were that 9 out of 10 patients did not exceed 45 degrees Celsius, and one patient reached 48 degrees Celsius, which resulted in transient neurologic injury. Without real-time temperature monitoring, there is a risk of permanent nerve damage [9].

Currently, internal cooling electrodes and perfusion electrodes are mainly used to cool down the electrodes and their surrounding tissues to reduce the possibility of thermal injury to the nerves near the tumor.

4.3. Challenges and Prospects

RFA technology has made great progress in the past 20 years of research, with its stable performance, increased electrode types, and increasing indications. It is widely used in oncology treatment and recognized by clinicians. However, it is still considered imperfect and needs further improvement. How to expand the ablation range as much as possible under the condition of avoiding "steam burst" and tissue charring, and reasonable deployment of needles are the main research directions of RF ablation precision therapy.

5. Satellite Communication in RF Band

Satellites are widely used in radio frequency band, covering many fields such as communication, navigation, remote sensing and so on. The most important application of satellite in radio frequency band is wireless communication in communication field. According to the orbit altitude of the satellite, the satellite communication system can be divided into three types: high, medium and low orbit. Among them, low earth orbit (LEO) satellites are very attractive to the satellite communication industry due to their relatively low time delay, path loss and development cost [19]. The Starlink project is naturally the most popular satellite network communication project at present.

5.1. Starlink Plan

With the advent of the digital age, human demand for network connectivity is growing. Traditional network infrastructure is difficult to provide stable services in some regions or environments, so Satellite Internet services came into being. Elon Musk, CEO of SpaceX, announced in 2015 that SpaceX would launch about 12000 satellite chains into low earth orbit to form a huge low earth orbit satellite constellation. The distribution composition of star chain constellation is shown in Table 1.

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The satellites of the Starlink have two working modes: transparent forwarding and routing switching within the constellation. The earlier versions of the Starlink were not equipped with a laser communication link. Before the satellite v1.5 version realizes inter satellite networking, satellite link satellites can only use transparent forwarding mode for communication. In the transparent forwarding mode, the ground user terminal can only provide network access services through the ground station. If there is no ground station nearby, the communication function cannot be realized. Therefore, the operators of the Starlink plan need to build a large number of ground stations around the world to be able to communicate normally. After the v1.5 satellite is deployed, the Starlink can realize the constellation intranet, and satellites in space can transmit information to each other. Through the on-board routing switching mode of the Starlink satellite, the ground user terminal can access the network worldwide without establishing a ground gateway station in a specific area, with faster transmission rate and shorter time delay [19].

Table 1. The Development History of the Starlink Program [20]

Track type	Development	Quantity	altitude of orbit	Working frequency band	Main purpose
LEO	Phase 1	1584	550km	Ku/Ka	Covering most areas except for the North and South Poles
	Phase 2	2825	1100km	Ku/Ka	Global coverage
VLEO	Phase 3	7518	340km	V	Increase capacity and reduce latency

5.2. Advantages of the Starlink Program

5.2.1. Low Cost

The low launch cost of the Starlink program is one of the most significant advantages. SpaceX's Falcon 9 rocket is a reusable rocket that can be recycled and reused. In addition, SpaceX also uses the launch strategy of one rocket and multiple satellites, that is, launching multiple satellites at the same time in a launch mission, which can further reduce the cost. For example, in a launch mission on March 14, 2021, SpaceX used a Falcon 9 rocket to launch a total of 60 satellite of Starlink. This reduces the launch cost of each satellite to less than 500000 US dollars [21]. And compared with 5g communication, the power consumption of Starlink communication is also significantly lower than 5g communication, which is also a low-cost advantage of the Starlink plan.

5.2.2. Global Coverage

The global coverage communication of Starlink is one of the most unique advantages. Although the terrestrial base stations have significant advantages in bandwidth and speed, due to the limitations of terrain, landform and human activities on the earth's surface, only about 20% of the world's land area and 5% of the ocean area are covered by terrestrial communication base stations, and many remote areas with sparse population such as mountains, forests and deserts cannot access the Internet [22]. Through the deployment of large-scale satellites, the Starlink plan can achieve seamless coverage in any corner of the earth.

5.2.3. Fast Communication Speed

Compared with traditional terrestrial optical fiber communication, laser communication in satellite constellation has higher bandwidth and smaller time delay. With the advantage of low orbit and the number of satellites, the communication capacity of the "satellite link" system will be unprecedentedly increased, and the total system capacity will be as high as 94 TBPs. First, the laser communication in the satellite constellation uses optical signals to transmit information. The propagation speed of optical signals in vacuum is about 300000 kilometers per second, which is 1.5 times that of signals in optical fibers. In addition, in terrestrial optical fiber communication, the signal transmission in the optical fiber needs to be refracted repeatedly, so it takes more distance. And the signals in the optical fiber go through many transfers, resulting in higher transmission delay.

6. Conclusion

In this article, we mainly introduced RFID, RFA, RFIC, and the role of RF technology in satellite communication among many RF technologies, and analyzed the problems and shortcomings they encountered in their respective fields.

Nowadays, RF technology is almost ubiquitous in transportation, healthcare, aviation, logistics, anti-counterfeiting, communication, and even military fields. The development of the Internet of Things has led to a diversified and complex trend in application layer requirements. The empowerment of intelligent technology has revolutionized traditional industries, leading to a significant increase in RFID demand and becoming a new opportunity for industry development, Driving the sustainable development of China's RFID industry, we believe that RF technology can be developed more widely. It will permeate every aspect of our lives. We hope that this paper can provide some interest or inspiration for those who are not familiar with or hope to understand RF technology.

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