A Survey of Terahertz Wireless

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Abstract

This survey offers a thorough overview of terahertz wireless communication systems, focusing on the rising need for faster network data transmission rates due to new technologies like the Metaverse, cloud computing, and AI. The survey examines the advantages over traditional microwave communication and physical characteristics of the terahertz band (0.1-10 terahertz). A detailed analysis of terahertz system architectures is presented, including various methods for signal generation (electronics-based, photonics-aided, and quantum cascade laser) and reception techniques. The discussion also extends to advanced modulation and processing technologies, such as constellation shaping and multi-dimensional multiplexing, essential for achieving high data transmission rates. In addition, current technical challenges in hardware components and physical layer technologies, including waveform design, modulation optimization, and encoding strategies, are addressed. The survey concludes by identifying future research directions and potential solutions for the practical implementation of terahertz communication systems.

Keywords: Terahertz Communication, Terahertz wireless, Wireless Networks, Terahertz Signal Generation, Terahertz Signal Reception, Quantum Cascade Laser, Signal Processing, Constellation Shaping, Multi-dimensional Multiplexing, Electromagnetic Spectrum

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1 Introduction

With the introduction of the Metaverse, cloud computing, and AI, the number of wireless network users and the demand for higher network data transmission rates have increased dramatically. According to the Ericsson Mobility Report released in June 2024, the total mobile network traffic is estimated to reach 466 EB by 2029 [Ericsson2024]. This significant rise in data traffic causes great challenges to existing network equipment. Traditional microwave communication struggles to meet the demands of emerging industries, as conventional microwave frequency bands have reached their capacity limits. Therefore, carriers in higher frequency bands are necessary to increase bandwidth and provide higher transmission capacity.

1.1 Advantages of the Terahertz Band for Communication

The terahertz band, an emerging candidate for high-frequency communication, addresses many challenges faced by current wireless communication systems. First, the terahertz band, spanning from 0.1 to 10 terahertz, offers bandwidths 1,000 times greater than the total bandwidth of the microwave band. This extensive bandwidth can be divided into multiple bands for communication. Specifically, the World Radiocommunication Conference 2019 (WRC-19) officially approved 275-296 GHz, 306-313 GHz, 318-333 GHz, and 356-450 GHz, totaling 137 GHz of bandwidth resources available for fixed and land mobile services. Additionally, WRC-23 COM6/17 identifies five bands for the development of next-generation mobile communications: 102-109.5 GHz, 151.5-164 GHz, 167-174.8 GHz, 209-226 GHz, and 252-275 GHz. Second, the shorter wavelengths in the terahertz range result in reduced diffraction in free space and enhanced directivity. This leads to lower transmit power requirements and decreased signal interference from different antennas. Furthermore, due to strong atmospheric attenuation, terahertz waves are less susceptible to intermediary eavesdropping over long distances, enabling secure communication through the terahertz channel [Wu2023].

Given the limitations of current communication systems and the distinctive advantages of the terahertz frequency band, both academia and industry have increasingly focused on terahertz-based communication, recognizing it as a pivotal technology for the next generation of wireless communication.

1.2 Physical Characteristics on Terahertz Band

The terahertz band is located at 0.1~10 terahertz, with a wavelength of 3 mm~30 I1/4m. It sits between the microwave band and the far-infrared light band. The longer wavelengths within this band overlap partially with the millimeter wave band, while the shorter wavelengths overlap with the infrared light band. This position represents a transition from macroscopic classical theory to microscopic quantum theory and from electronics to photonics. Due to its unique position in the electromagnetic spectrum, terahertz waves possess both the penetrative and absorptive properties of microwaves, as well as the characteristics of light. These waves are characterized by their transient, coherent, penetrating, low-energy, and frequency-selective absorptive nature [Yu2021].

Compared to the microwave band, the terahertz band exhibits unique characteristics. In addition to path loss, the rising frequency of electromagnetic waves gradually approaches the vibration and rotational energy levels of molecules, leading to molecular resonance absorption. In particular, oxygen and water molecules absorb terahertz waves most dramatically. As shown in Figure 1, significant absorption by oxygen molecules can be observed around 100 GHz. Above 110 GHz, the total absorption curve and the water vapor absorption curve almost completely overlap, indicating that water molecules play a major role in transmission loss in the high-frequency terahertz band [Siles2015].

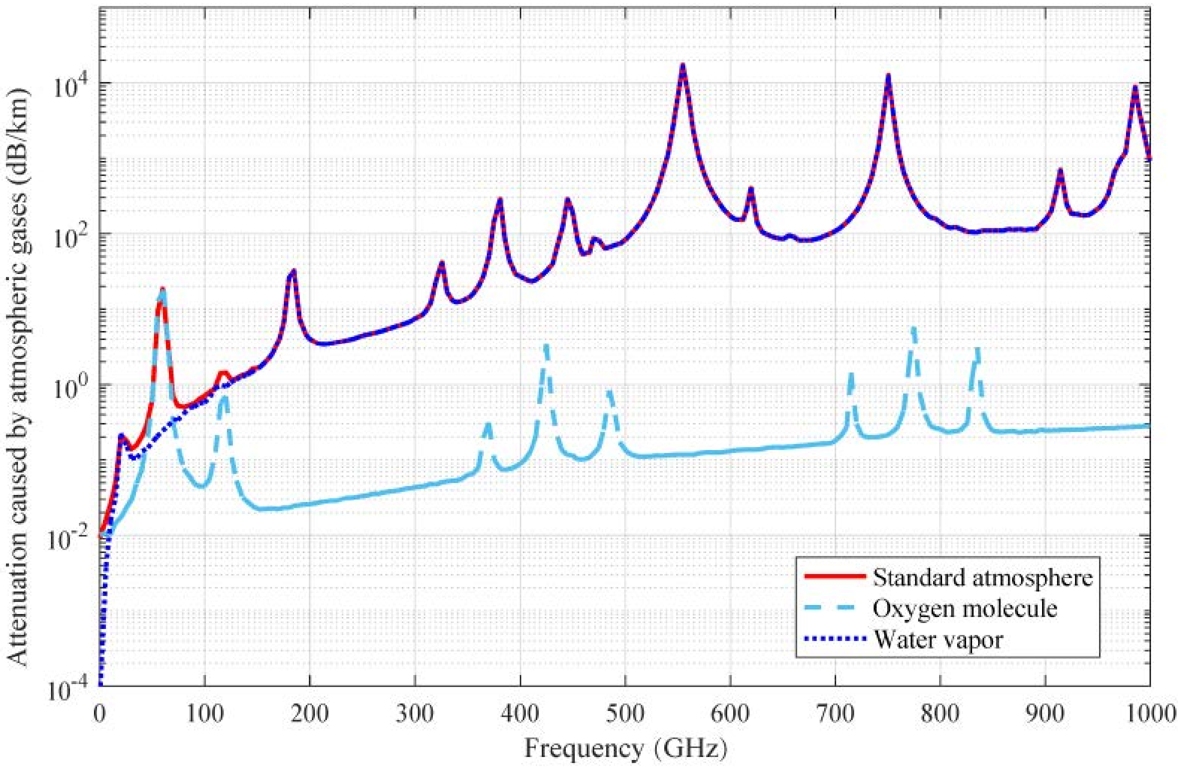

Figure 1: Terahertz wave attenuation caused by atmospheric gases [mdpi]

Moreover, water molecules not only cause absorption attenuation but also introduce dispersion effects into the transmission of electromagnetic signals [Strecker2020]. The above figure describes the transmission attenuation of terahertz waves in clear sky conditions. In more complex weather conditions (such as cloudy or snowy weather), the presence of water droplets that cover the terahertz wavelength range results in stronger attenuation. Under these conditions, the transmission attenuation of terahertz waves is positively correlated with the rainfall rate. For a constant rainfall rate, the attenuation initially increases and then decreases as the electromagnetic wave frequency increases. When the frequency exceeds 1 terahertz, the attenuation decreases as the frequency approaches 10 terahertz.

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2 System Architecture of Terahertz Wireless Communication

Understanding the intricate system architecture of terahertz wireless communication is crucial for advancing this cutting-edge technology. The architecture not only involves the generation and reception of terahertz signals but also encompasses the various components and processes that enable efficient communication at such high frequencies. This includes developing both electronics-based and photonics-based methods for generating terahertz waves. Besides, the reception of these signals requires specialized components and finely-tuned processes to ensure accurate data transmission. The following sections will dive deeper into the mechanisms and technologies underpinning both signal generation and reception in terahertz wireless communication systems.

2.1 Terahertz Signal Generation

Terahertz communication systems can be classified into two categories based on the method of signal generation: electronics-based and photonics-based. The photonics-based methods can be further subdivided into photonics-assisted and quantum cascade laser types.

2.1.1 Electronics-based

Electronics-based terahertz communication systems typically consist of two main components at the transmitter [Zhang2021]: the baseband and the RF front end. The baseband signal is usually processed on a field-programmable gate array, which allows for high-speed computations. Source sequences are converted into baseband signals after scrambling, encoding, and modulation, as shown in Figure 2. The front end consists of a baseband system, frequency multiplier, mixer, local oscillator, power amplifier, and antenna, as shown in Figure 2.

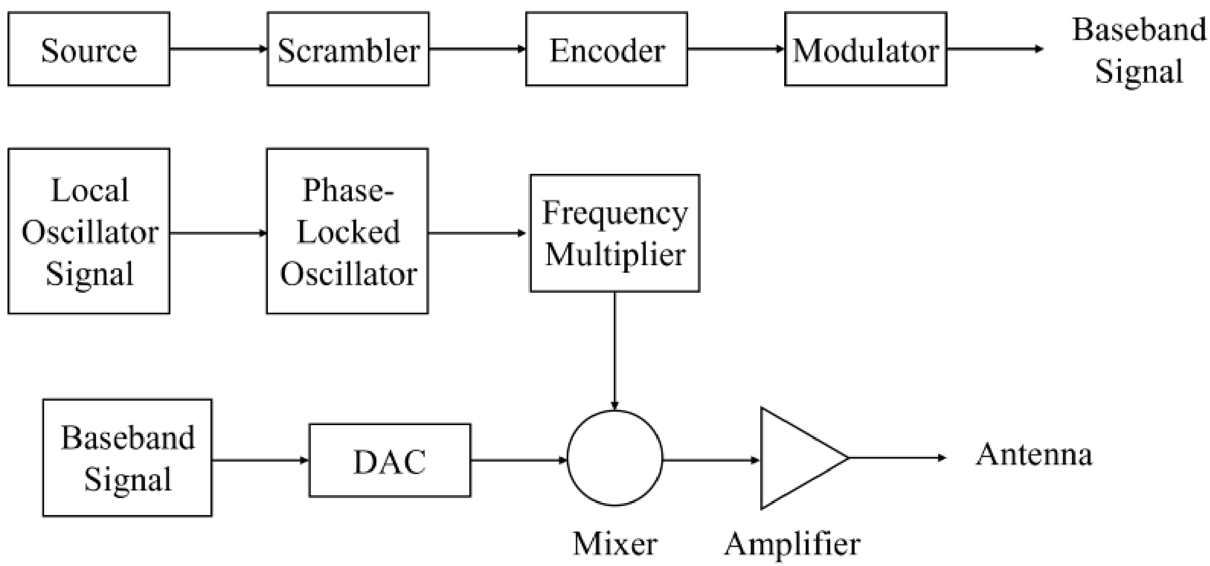

Figure 2: Transmitter architecture on electronics-based terahertz communication systems

The digital signal generated by the baseband is processed by a digital to analog converter (DAC), converting it into an intermediate frequency analog signal. In the RF section, the low-frequency local oscillator signal is passed through a phase-locked oscillator and a frequency multiplier, moving it to a higher frequency band. Subsequently, the mixer utilizes multiple harmonics of the signal to mix the intermediate frequency analog signal into the designated terahertz frequency band. Finally, the resulting terahertz signal is amplified by a power amplifier and transmitted via an antenna.

Electronics-based devices are compact and feature high integration density, which is advantageous for the miniaturization of communication systems. They also have high transmission power, enabling wireless transmission over longer distances. However, the design and processing of semiconductors are limited, and it is difficult to generate terahertz signals with extremely high frequencies (a Y1 terahertz) using frequency multipliers. Moreover, the modulation, demodulation, and encoding-decoding processes are also restricted by the capabilities of baseband signal processing chips, making it challenging to achieve transmission rates at the level of 10^11 bit/s or higher. Due to the positioning of the terahertz band between microwave and infrared waves, photonic methods can be utilized to generate terahertz signals with higher frequencies and broader bandwidths, leveraging its near-light properties.

2.1.2 Photonics-assisted

The photonics-assisted method generates terahertz signals through photoelectric conversion [Pang2022]. By leveraging the ultra-high frequencies of light waves and the large bandwidth of optical devices, it overcomes the bandwidth limitations of electronic devices. This method is currently the most common approach for terahertz communication systems.

Uni-traveling carrier photodiodes (UTC-PDs) are widely used as the photoelectric conversion device at the transmitter due to their ultra-wide bandwidth, fast response, high sensitivity, and ease of integration. The transmitter end of a photonics-assisted (single optical carrier modulation) terahertz communication system based on UTC-PD mainly consists of an external cavity laser (ECL), a Mach-Zehnder modulator (MZM), an optical coupler, an optical amplifier, a variable optical attenuator, and a UTC-PD, as shown in Figure 3.

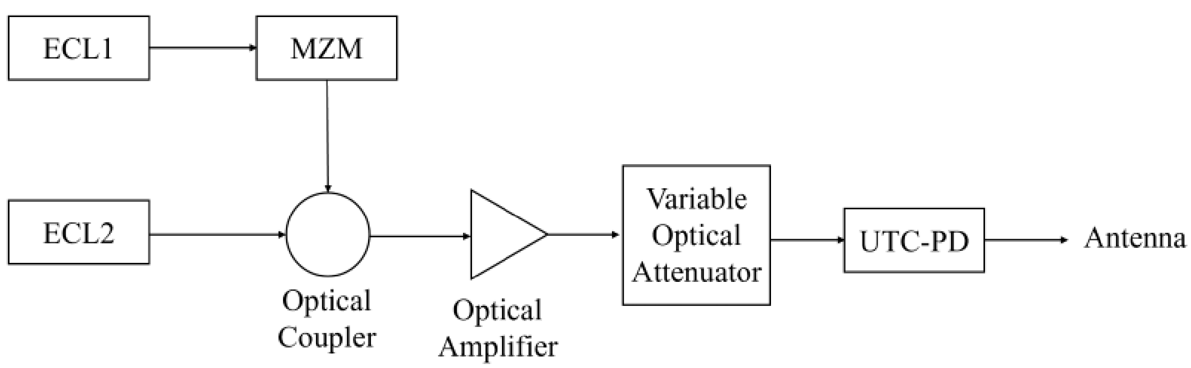

Figure 3: Transmitter architecture on photonics-based terahertz communication systems

Two ECLs generate optical signals with frequencies of f1 and f2, respectively. The optical signal with frequency f2 is digitally modulated by an MZM, while the optical signal with frequency f1 remains unmodulated and is directly inputted to the optical coupler as the local oscillator signal. After coupling, the two optical signals pass through the optical amplifier and the variable optical attenuator in sequence and are finally sent to the UTC-PD for heterodyne detection, generating a terahertz signal with a carrier frequency of f2-f1.

Compared to electronics-based method, the photonics-assisted method for generating terahertz waves has the following advantages:

- The frequency of the terahertz signal is adjustable over a wide range.
- It offers good frequency utilization, low harmonic interference, and low phase noise.

- Optical modulation can be used to increase capacity.
- It supports the seamless integration of terahertz wireless communication with optical fiber communication [Richardson2013].

2.1.3 Quantum Cascade Laser

The frequency of terahertz signals generated by both electronic-based and photonics-assisted methods generally does not exceed 1 terahertz. To produce terahertz signals above 1 terahertz, quantum cascade laser methods (also known as direct modulation laser methods) are typically required. In this approach, the most commonly used device is the terahertz quantum cascade laser (THz-QCL), which can be directly modulated at a high rate. However, this device has strict environmental requirements, needing low temperatures to operate [Khalatpour2020], which significantly limits the practical application of the quantum cascade laser method in actual terahertz communication systems.

2.2 Terahertz Signal Reception

Terahertz signal reception is a critical aspect of the terahertz communication system, which involves capturing and processing signals in the terahertz frequency range (0.1-10 terahertz). This section dives into the key components and processes involved in effectively receiving terahertz signals.

2.2.1 Receiving Components

The receiver devices for terahertz communication systems can be classified into electronics-based and photonics-based devices. Common electronics-based receiver devices include the Schottky Barrier Diode (SBD), the Superconductor-Insulator-Superconductor (SIS) mixer, and the Hot Electron Bolometer (HEB) mixer. Both SIS and HEB mixers require low-temperature operating environments and only support heterodyne detection. In contrast, the SBD can operate at room temperature. It can perform both direct detection and heterodyne detection. Additionally, the SBD is easy to make and has a low rate of wear and tear. These advantages make the SBD the most widely used receiver device in terahertz communication systems. Common photonics-based receiver devices include the Quantum Well Photodetector (QWP) and the Photoconductive Antenna (PCA). The QWP is generally used in terahertz communication systems with Quantum Cascade Lasers as transmitters for direct detection, though its practical use is relatively limited. Conversely, the PCA can function both as a transmitter and a receiver for terahertz signals, commonly used in heterodyne detection. The PCA is one of the development trends for future ultra-wideband, ultra-high-speed terahertz communication systems in terms of both transmission and reception [Burford2017].

2.2.2 Receiving Process

The methods for receiving terahertz signals can be divided into direct detection and heterodyne detection. In terahertz communication systems that use direct detection, the structure of the receiver is shown in Figure 4. The terahertz signal received by the antenna is directly input into a diode detector, and then converted into a baseband signal for digital processing. In terahertz communication systems that use heterodyne detection, the structure of the receiver is shown in Figure 5. The terahertz signal received by the antenna and the local oscillator signal are both input into a diode mixer, where the mixer performs heterodyne detection.

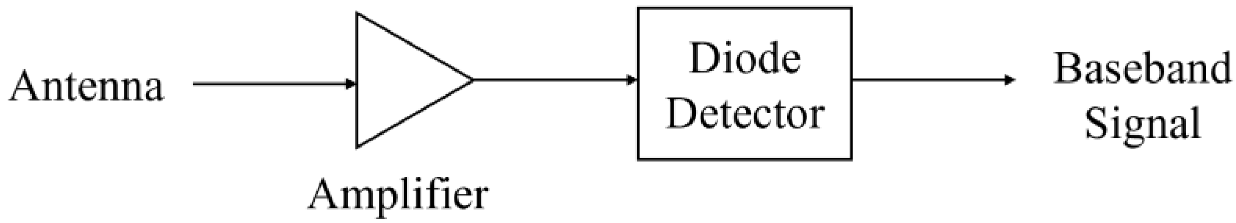

Figure 4: Receiver architecture for terahertz communication systems using direct detection

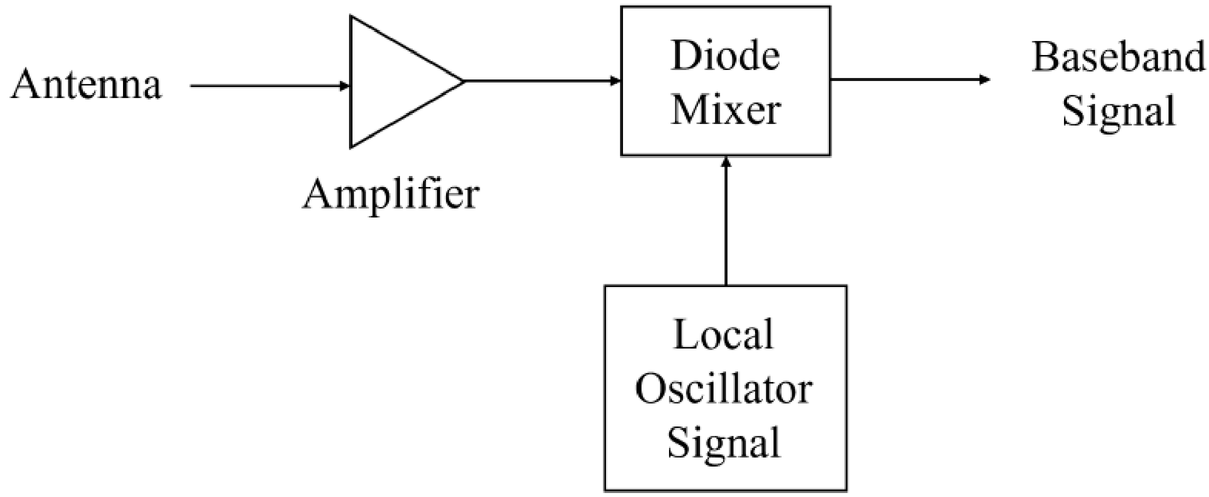

Figure 5: Receiver architecture on photonics-based terahertz communication systems using heterodyne detection

The receiver structure based on direct detection is simple and has low power consumption, but it is only suitable for lower-order amplitude modulation formats and is less applicable to higher-order modulation methods such as QAM. In contrast, heterodyne detection is suitable for a variety of modulation methods, including higher-order QAM, frequency modulation, and phase modulation. It offers high detection sensitivity, ultra-wide bandwidth, and high spectral efficiency. This makes it capable of overcoming the detection challenges posed by high path loss in the terahertz frequency band, making it the most widely used reception method in terahertz communication systems.

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3 Terahertz Communication Technology

Terahertz communication technology is emerging as a fundamental component for the next generation of wireless communication systems. The inherent properties of terahertz waves, such as their ability to support high data rates and low latency, make them particularly suitable for various advanced applications. However, to fully utilize the advantages of terahertz communication technology, several technical challenges need to be addressed, including efficient modulation and processing techniques.

Modulation and processing are critical components in the context of terahertz communication technology, as they determine the efficiency and reliability of data transmission through these high-frequency waves. Effective modulation techniques are essential for encoding information onto terahertz carrier waves, enabling the robust transmission of data over varying distances. Alongside modulation, advanced signal processing methodologies are necessary to mitigate the challenges posed by terahertz frequencies, such as high path loss and atmospheric absorption. These processing techniques enhance signal integrity, reduce noise, and optimize channel capacity, thereby ensuring high-performance communication links. Within this context, several specific approaches and innovations are being explored to maximize the potential of terahertz communication systems.

3.1 Constellation Shaping

Traditional wireless communications commonly use single-carrier modulation formats such as On-Off Keying (OOK) or Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM). OOK/ASK has low modulation orders, resulting in low bandwidth efficiency and consuming more bandwidth resources, making it difficult to meet the transmission rate demands exceeding 10^11 bits per second. QAM can achieve higher transmission rate by using higher-order modulation. However, as the modulation order increases, the bit error rate also increases. Also, there is always a performance gap between high-order QAM and the Shannon limit. Therefore, it is essential to find a way to improve the reliability of high-order QAM.

Constellation shaping technology can enhance noise tolerance, extend transmission distances, and improve spectral efficiency [Bocherer2015]. It is widely combined with QAM modulation to improve the performance of terahertz wireless communication systems. Constellation shaping is divided into two types: Geometric Shaping (GS) and Probabilistic Shaping (PS). GS maintains equal probability for all constellation points and maximizes mutual information by altering the Euclidean distances between constellation points. PS retains the original constellation shape with equal spacing between constellation points. It typically uses a Constant Composition Distribution Matching (CCDM) before QAM modulation to map a uniform bit stream to a non-uniform amplitude information sequence. In an additive white Gaussian noise (AWGN) channel, the optimal probability distribution for PS is the two-dimensional Maxwell-Boltzmann distribution. The PS technology based on this distribution can make the channel capacity approach the Shannon limit [Cho2019].

3.2 Multi-dimensional Multiplexing Modulation

In the field of wireless communication, multi-dimensional multiplexing modulation techniques are essential for enhancing data transmission efficiency and reliability. By leveraging multiple dimensions such as frequency, space, and polarization, these advanced modulation schemes can significantly increase the capacity and performance of communication systems.

3.2.1 Multi-carrier Modulation

Orthogonal Frequency Division Multiplexing (OFDM) is the most typical multi-carrier modulation method. It divides the entire band into multiple parallel narrow sub-channels with sufficiently small bandwidths. OFDM improves spectral efficiency by overlapping the spectra of subcarriers, as shown in Figure 6. Besides, OFDM can resist the dispersion effects in photonics. Therefore, OFDM exhibits excellent performance across all types of terahertz communication systems.

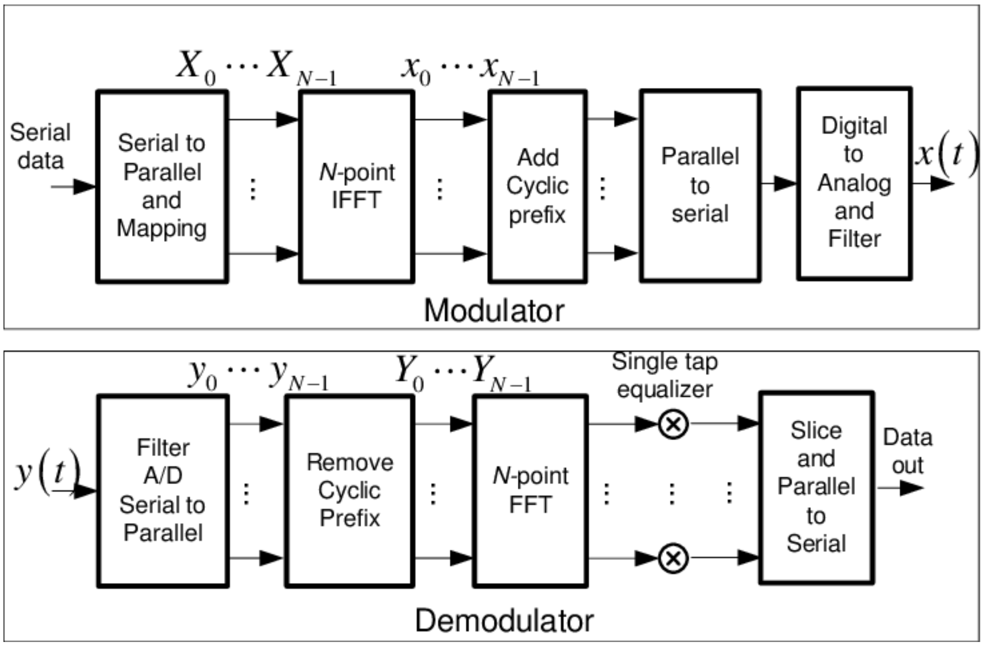

Figure 6: OFDM diagram [researchgate]

For photonics-assisted and quantum cascade laser systems, optical modulation methods can also be introduced to further increase the signal transmission dimensions. These methods include Wavelength Division Multiplexing (WDM) and Polarization Division Multiplexing (PDM). The principle of WDM is similar to Frequency Division Multiplexing, where two or more optical signals of different wavelengths are combined into one path through an optical coupler for transmission, with each optical signal carrying its own carrier information.

3.2.2 MIMO

MIMO (Multiple-Input Multiple-Output) is a spatial multiplexing technology. By deploying multiple antennas at both the transmitter and receiver ends of a communication system, MIMO establishes multiple channels, allowing multiple antennas to simultaneously transmit and receive multiple signals. It is often combined with multi-carrier modulation and antenna polarization multiplexing technologies to maximize wireless transmission capacity and range. The applicability of PS technology in MIMO has been theoretically proven in recent years [Kang2022], and related systems have been successfully tested.

3.2.3 Antenna Polarization Multiplexing

Antenna polarization refers to linear polarization, specifically horizontal (H) polarization and vertical (V) polarization. The two states are mutually orthogonal. In traditional MIMO systems, all antennas at both the transmitter and receiver ends have the same polarization state (either all H-polarized or all V-polarized). However, antenna polarization multiplexing uses several pairs of H-polarized and V-polarized antennas within a single MIMO system. Take a 2A-2 MIMO system as an example, shown in Figure 7. Compared to traditional MIMO wireless links, introducing antenna polarization multiplexing offers lower baud rate and can reduce system performance requirements for optoelectronic devices. However, this technology has strict requirements for the V polarization state, and there is crosstalk between links with the same polarization state, which requires additional linear compensation techniques.

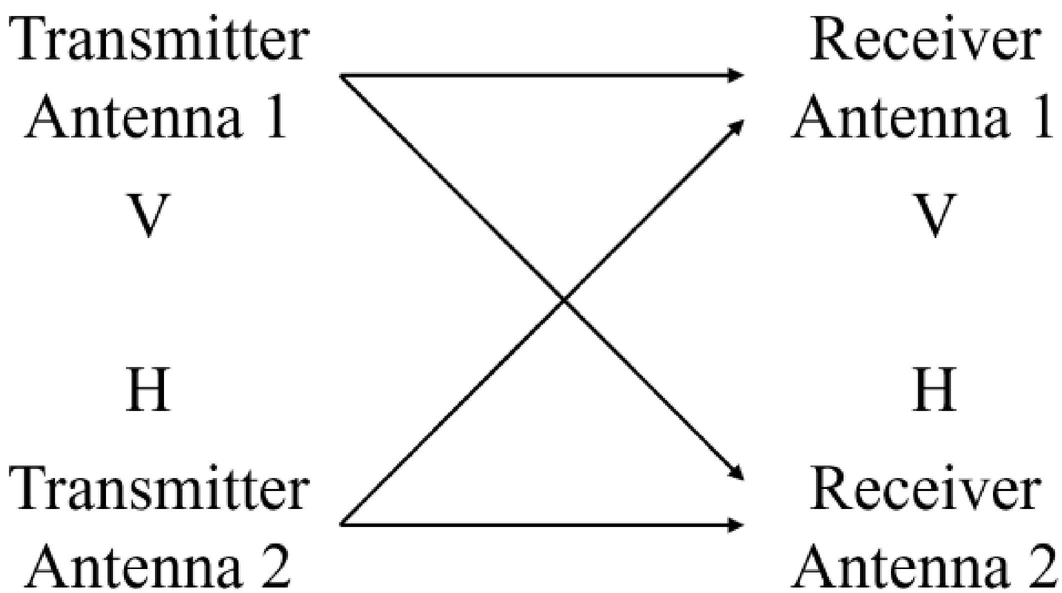

Figure 7: Antenna polarization multiplexing diagram

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4 Future Trends and Technical Challenges

As the demand for high-speed, reliable wireless communication continues to grow, the industry faces several future trends and technical challenges that must be addressed. Innovations in hardware and advancements in the physical layer of communication systems are crucial for meeting the increasing requirements of data transmission. Below, key areas of hardware components and physical layer are discussed.

4.1 Hardware Components

The performance of terahertz communication systems depends on the hardware of various devices, including ADC/DAC, antennas, power amplifiers, mixers, frequency multipliers, phase shifters, and others. The precision required by terahertz wireless is much more than traditional microwave and millimeter-wave devices. Front-end devices, particularly power amplifiers and large-scale array antennas, face significant challenges. At high frequencies, the stability of output current from transistors is not good. This results in difficulty in achieving high transmission power.

Additionally, ADC/DAC in the terahertz communication baseband system must support the sampling of signals with bandwidths of several to tens of GHz. The most advanced DAC in current research has successfully tested dual-channel multiplexing with a combined sampling frequency of up to 256 GSa/s, supporting a signal bandwidth of up to 128 GHz. However, its sampling resolution is extremely low (only 2 bits) and it has high power consumption [Nagatani2018].

4.2 Physical Layer

As we dive deeper into the technical specifics, a closer examination of the physical layer is necessary.

Waveform Technology: The new generation of terahertz communication waveforms must be designed to enhance traditional waveforms such as OFDM, OTFS, and Faster-than-Nyquist, addressing the characteristics of high frequency, large bandwidth, and significant Doppler shifts in high-mobility scenarios typical of terahertz frequencies.

Modulation: The optimal probability distribution of the existing PS technology is based on the assumption of an AWGN channel. The optimal probability distribution suited to the characteristics of the terahertz channel remains unknown.

Encoding: Power resources in terahertz communication systems are extremely valuable, and there is a trade-off between minimizing transmission power and minimizing encoding/decoding time. Therefore, in the future, it will be necessary to design high-gain, low-power, low-complexity channel coding solutions based on the requirements for capacity, power consumption, and latency in specific application scenarios.

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5 Conclusion

This survey begins by explaining the advantages of the terahertz band and highlighting some physical characteristics of terahertz signals. It then discusses the system architecture of terahertz wireless communication, detailing how terahertz signals are generated and received. Furthermore, it introduces modulation techniques and signal processing methods for terahertz signals. Finally, the survey addresses future trends and technical challenges in the field of terahertz wireless communication.

Acronyms

DAC: Digital to analog converter

UTC-PDs: Uni-traveling carrier photodiodes

ECL: external cavity laser

MZM: Mach-Zehnder modulator

THz-QCL: terahertz quantum cascade laser

SBD: Schottky Barrier Diode

SIS: Superconductor-Insulator-Superconductor

HEB: Hot Electron Bolometer

QWP: Quantum Well Photodetector

PCA: Photoconductive Antenna

OOK: On-Off Keying

ASK: Amplitude Shift Keying

PSK: Phase Shift Keying

QAM: Quadrature Amplitude Modulation

GS: Geometric Shaping

PS: Probabilistic Shaping

CCDM: Constant Composition Distribution Matching

AWGN: additive white Gaussian noise

OFDM: Orthogonal Frequency Division Multiplexing

WDM: Wavelength Division Multiplexing

PDM: Polarization Division Multiplexing

MIMO: Multiple-Input Multiple-Output

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