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Orthogonal Frequency Division Multiplexing: Status, Challenges and Directions

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Abstract: With the convergence of communication and radar technologies, Integrated Sensing and Communication (ISAC) is expected to be a pivotal focus area for future 6G networks. Orthogonal Frequency Division Multiplexing (OFDM) technology plays a crucial role in enabling ISAC. This paper examines the fundamental principles of OFDM, its applications in terahertz ISAC systems, related advancements such as Orthogonal Time Frequency Space (OTFS), and its potential integration into future air-space-ground networks. While OFDM technology demonstrates significant promise, it also presents several challenges. To address these, researchers have proposed various enhancement strategies. This study offers valuable insights to guide the future development of OFDM technology.

Keywords: Orthogonal Frequency Division Multiplexing, Orthogonal Time Frequency Space, Integrated Sensing and Communication

1. Introduction

In recent years, rapid advancements in electronic information technology have significantly accelerated the proliferation and intelligence of electronic devices. This exponential growth has intensified the scarcity of spectrum resources and heightened challenges related to electromagnetic interference. Integrated Sensing and Communication (ISAC) systems offer a promising solution by improving spectrum efficiency, reducing spatial requirements, mitigating electromagnetic interference, and lowering operational costs. As a result, the design and optimization of ISAC systems have become a central focus in modern communication research.

Two primary design paradigms exist for ISAC. The first leverages communication-based waveforms to achieve radar sensing capabilities, with techniques such as Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) being notable examples. The second embeds communication information into radar waveforms, with Frequency Modulated Continuous Wave (FMCW) as a representative approach. Among these paradigms, communication-based waveform design offers significant advantages: it is easier to implement, ensures stable communication system operation, achieves high resource utilization efficiency, and exhibits strong anti-interference capabilities. This approach involves shaping communication signals to enable radar sensing functionality, with OFDM waveforms standing out as a key area of research.

As a multi-carrier transmission technology, OFDM provides several unique advantages. It excels in spectrum utilization efficiency, is relatively straightforward to implement in practical engineering applications, and effectively mitigates multipath interference. However, OFDM also has limitations,

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notably its high Peak-to-Average Power Ratio (PAPR), which can constrain its performance and applications. Addressing this challenge will require continued research and innovation to further advance ISAC technologies.

While numerous studies have explored OFDM technology, comprehensive reviews encompassing its principles, applications, and areas for improvement remain limited. To bridge this gap, this paper reviews the fundamental principles of OFDM, its applications in terahertz ISAC systems, related technologies such as OTFS, and its potential role in future integrated air-space-ground networks.

Table 1 provides a summary of abbreviations used in this paper.

Table 1: Summary of Abbreviations.

Abbreviation	Full Name
OFDM	Orthogonal Frequency Division Multiplexing
OTFS	Orthogonal Time Frequency Space
FDM	Frequency Division Multiplexing
IFFT	Inverse Fast Fourier Transform
FFT	Fast Fourier Transform
MIMO	Multiple-Input Multiple-Output
ISAC	Integrated Sensing and Communication
GFDM	Generalized Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
ISI	Inter-Symbol Interference
ICI	Inter-Carrier Interference
DD	Delay - Doppler Domain
TF	Time - Frequency Domain
SloV	Smart Internet of Vehicles
OMA	Orthogonal Multiple Access
SFFT	Shifted Fast Fourier Transform
ISFFT	Inverse Shifted Fast Fourier Transform
CM	Constellation Modulation
CD	Constellation Demodulation

2. OFDM Basic Principles

2.1. Fundamental Concept of OFDM

OFDM is a pivotal technology whose core principle lies in converting a high-speed data stream into multiple lower-rate frequency subchannels through serial-to-parallel transformation, enabling parallel transmission of high-speed serial data.

As shown in Figure 1, traditional Frequency Division Multiplexing (FDM) systems rely on large guard bands to prevent interference, which significantly reduces spectrum efficiency. In contrast, OFDM uses orthogonal subcarriers to transmit multiple low-rate symbols in parallel. The orthogonality of these subcarriers enables spectrum overlap, effectively minimizing inter-carrier interference while greatly enhancing spectrum efficiency. This characteristic makes OFDM a robust foundation for efficient and reliable data transmission.

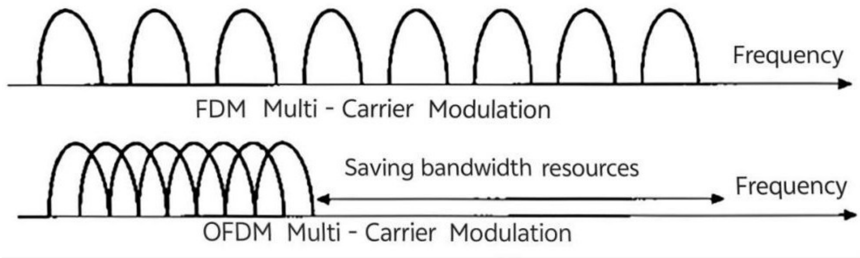

Figure 1: Comparison of Waveforms of FDM and OFDM Multi - Carrier Modulation.

2.2. OFDM Signal Processing Workflow

During the 1970s and 1980s, researchers developed various methods leveraging Fourier transforms to implement OFDM, laying the foundation for its current technological framework. OFDM signals demonstrate high spectral efficiency and are well-suited to counteract frequency-selective fading and narrowband interference. Furthermore, OFDM effectively reduces inter-symbol interference, making it ideal for high-speed data transmission in multipath environments and fading channels.

In addition to its communication capabilities, OFDM radar signals exhibit excellent pulse compression properties, providing high Doppler tolerance without Doppler-range coupling. This allows for independent, unambiguous distance and Doppler processing, enabling high-precision measurements of target range and velocity. As a result, OFDM signals offer substantial advantages for both communication and sensing applications in intelligent systems.

As illustrated in Figure 2, OFDM divides the frequency spectrum into N overlapping but orthogonal subchannels. The technique then splits a serial data stream into N parallel sub-data streams, each modulated onto a specific subchannel for transmission.

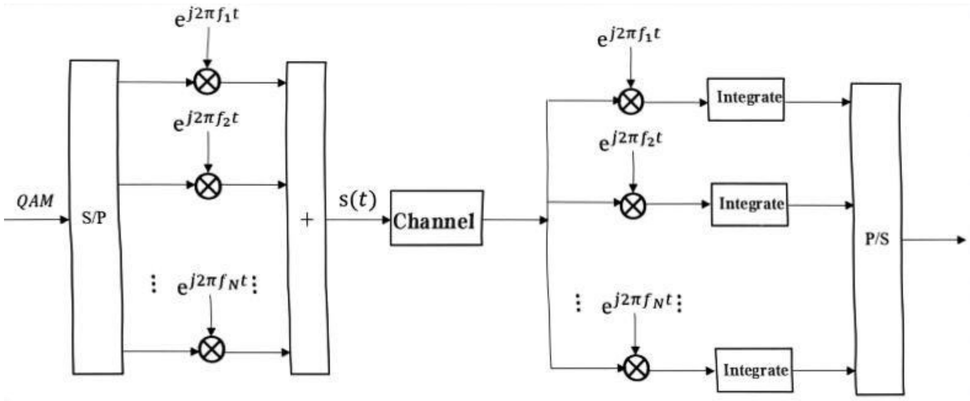

Figure 2: The system model of QAM signal transmission through a channel.

The variable T represents the width of the OFDM symbol, and $d_i(i = 0,1,\ldots,N-1)$ is the data symbol allocated to each subchannel. With $f_i = f_c + i/T(i = 0,1,\ldots,N-1)$, the OFDM symbol starting from $t = t_s$ can be expressed as:

$$s(t) = \begin{cases} \sum_{i=0}^{N-1} d_i \exp[j2\pi(f_c - \frac{i}{T})(t - t_s)] & t_s \le t \le t_s + T \\ 0 & t<t_s, t > t_s + T \end{cases} \quad (1)$$

To facilitate future theoretical analysis and derivation, the output signal of OFDM is often described using the following equivalent baseband signal:

$$s(t) = \sum_{i=0}^{N-1} d_i \exp[j2\pi \frac{i}{T}(t - t_s)] \quad t_s \le t \le t_s + T \quad (2)$$

After multiplexed data is modulated onto different subcarriers and superimposed, an OFDM symbol is formed. Each OFDM symbol carries multiple data streams, with these streams varying periodically according to the fundamental frequency, which corresponds to the duration of an OFDM symbol (the fundamental frequency is defined as the lowest frequency subcarrier with the longest period).

At the receiver, the in-phase and quadrature components of the received signal are inverse-mapped to retrieve the transmitted data, thereby completing subcarrier demodulation. Specifically, the demodulation process for the k-th subcarrier signal is as follows: the received signal is multiplied by the demodulation carrier $e^{-j2\pi f_i t}$ corresponding to the k-th subcarrier. The resulting product is then integrated over the duration T of the OFDM symbol, yielding the recovered transmitted signal $\hat{d}_i$, expressed as:

$$\hat{d}_i = \frac{1}{T}\int_{t_s}^{t_s+T} e^{-j2\pi\frac{i}{T}(t-t_s)} \sum_{k=0}^{N-1} d_k \quad e^{-j2\pi\frac{k}{T}(t-t_s)}dt = \frac{1}{T}\sum_{k=0}^{N-1} d_k \int_{t_s}^{t_s+T} e^{j2\pi\frac{k-i}{T}(t-t_s)}\,dt = d_i \quad (3)$$

In practical applications, the OFDM complex equivalent baseband signal defined in equation (2) can be implemented using the Inverse Discrete Fourier Transform (IDFT). By letting $t_s = 0$ and $t = kT/N(k = 0,1, \dots, N-1)$ in equation (2), the resulting expression is:

$$s_k = s\left(\frac{kT}{N}\right) = \sum_{i=0}^{N-1} d_i \exp(j\frac{2\pi ik}{N}) \quad 0\le k\le N-1 \quad (4)$$

From equation (4), it can be observed that s_k is the result of performing an IDFT on d_i. At the receiver end, to recover the original data symbols d_i, a Discrete Fourier Transform (DFT) can be applied to s_k, leading to equation (5):

$$\hat{d}_i = \sum_{k=0}^{N-1} s_k \exp(-j\frac{2\pi ik}{N}) = d_i \quad 0\le i\le N-1 \quad (5)$$

In an OFDM system, modulation and demodulation are achieved through IDFT/DFT operations, a fundamental characteristic that underpins the widespread application of OFDM. Specifically, N-point IDFT transforms frequency-domain data symbols into time-domain data symbols, which are then transmitted over the wireless channel after carrier modulation. At the receiver, coherent demodulation is performed first, followed by N-point DFT on the baseband signal to transform the time-domain data symbols s_k back into frequency-domain data symbols d_i. In practical applications, the computationally efficient Fast Fourier Transform (FFT/IFFT) is typically employed for modulation and demodulation. This approach significantly reduces computational load and simplifies system complexity. The corresponding block diagram is illustrated below:

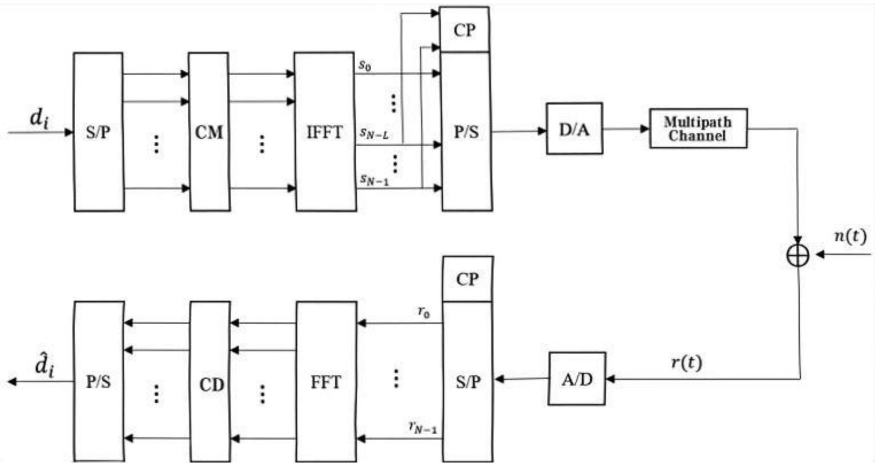

Figure 3: Signal Processing Flow of OFDM-based Communication System

3. Current Hot Technologies Based on the OFDM Framework

Due to its flexibility and compatibility, OFDM can integrate with various technologies, enabling modifications to the original OFDM system architecture to enhance hardware resource utilization.

3.1. OFDM-Based Terahertz Integrated Communication and Sensing System

With the rapid evolution of applications such as virtual reality, cloud computing, and the Internet of Things, the demand for greater bandwidth and capacity in wireless communication systems continues to grow [1]. Terahertz (THz) frequency bands, ranging from 300 GHz to 10 THz, provide an extensive bandwidth resource capable of supporting mobile data transfer rates at the terabit-per-second (Tbps) level. This positions THz technology as a key enabler for high-capacity, short-range covert military communications, long-range satellite communications, and ultra-high-speed wireless systems. Against this backdrop, OFDM-based THz integrated communication and sensing systems have emerged as a significant area of interest [2–5].

As a high-speed communication and high-resolution sensing solution, the THz integrated system emphasizes efficient signal generation and processing techniques. Traditional sensing-centric waveform designs often suffer from limited data capacity, failing to meet the high-speed communication demands of the 6G era. In contrast, communication-centric OFDM waveforms offer a balance between high data rates and sensing performance, making them a leading candidate for integrated waveform designs.

3.1.1. THz OFDM Integrated Communication and Sensing System Framework

The design of THz OFDM-based systems aims to achieve dual objectives: precise target sensing and efficient information transmission, thereby enabling both high data rates and high-precision sensing capabilities [6].

In these systems, the transmitter begins by generating binary data, followed by QAM modulation and applying an IDFT or IFFT to produce a baseband signal. This signal is then transmitted through a THz radio frequency front-end. On the communication reception side, the system demodulates the signal, while on the sensing side, communication components are removed, and a 2D-FFT is applied to extract sensing information [7–8].

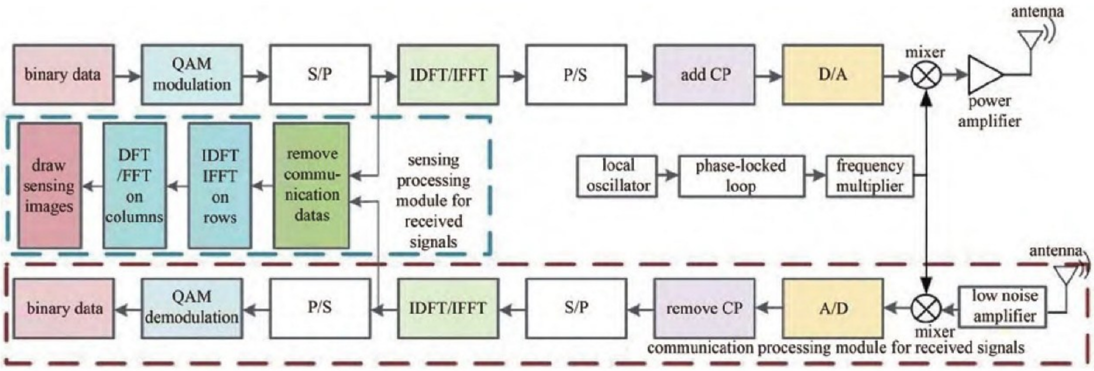

Figure 4: A framework for terahertz integrated sensing and communication system based on OFDM [9].

By isolating the sensing module, the remaining system mirrors the architecture of traditional OFDM communication systems. This architecture can leverage 5G air interface technologies to support future integrated designs, providing a foundational framework for THz integrated communication and sensing systems in the 6G era [10].

3.1.2. Prospects and Applications of THz OFDM

In the THz frequency range, the efficiency of transmitter power amplifiers is highly sensitive to the Peak-to-Average Power Ratio (PAPR) of transmitted signals. Lower PAPR is crucial for achieving broader coverage. However, conventional OFDM signals suffer from high PAPR, which limits amplifier efficiency and exacerbates nonlinear effects in THz links. To address this, enhancements such as CE-OFDM, DFT-spread-OFDM, and OCDM have been developed. These low-PAPR modifications are expected to play a vital role in future THz waveforms, advancing THz communication and sensing technologies [11].

THz radar-communication integration also allows waveform adaptation to various transmission windows and application requirements, supporting satellite communications, smart transportation, industrial IoT, high-resolution imaging, and precise positioning. As the foundational waveform for 4G and 5G systems, OFDM-based integrated waveforms are poised to play a pivotal role in THz technologies, fostering the seamless integration of communication and sensing across diverse scenarios.

Nevertheless, OFDM systems in THz applications face challenges such as high PAPR, which reduces power efficiency, and nonlinear distortions in THz links. Further, evolving mobile vehicular systems introduce issues like Doppler shifts, inter-channel interference, and radar-communication signal clashes. Addressing these challenges is essential for advancing THz OFDM systems.

3.2. OTFS Technology

As technological advancements drive the development of three-dimensional integrated networks, encompassing terrestrial cellular systems, satellite networks, high-altitude platforms, and UAVs, high mobility emerges as a defining characteristic of future communication scenarios [12].

While OFDM remains a dominant modulation technique in current mobile communication systems, it struggles in high-mobility environments due to doubly selective fading in time-frequency channels. This results in significant inter-symbol interference (ISI) and inter-carrier interference (ICI), disrupting the orthogonality of subcarriers and degrading transmission quality in high-mobility scenarios [13].

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To overcome these limitations, Hadani et al. [14] introduced OTFS, a two-dimensional modulation scheme in the Delay-Doppler (DD) domain. OTFS maps transmitted signals to the DD domain, leveraging its time-invariant properties to resist time-selective fading caused by Doppler shifts [15].

OTFS achieves reliable communication in time-frequency dispersive channels by uniformly spreading symbols across the entire domain, enabling joint time-frequency diversity [16]. Unlike OFDM, which faces challenges in channel estimation and signal detection under high Doppler shifts, OTFS simplifies these processes by exploiting the sparsity of DD domain channels [17]. Consequently, OTFS achieves superior performance in high-mobility scenarios, delivering robust and reliable data transmission [18–19].

3.2.1. Principles of OTFS

Let the number of data symbols be N and the number of subcarriers be M. The OTFS modulation process begins with data preprocessing, where the input information sequence undergoes symbol mapping for modulation. The modulated symbols are then placed onto a DD domain grid, forming the transmission signal. Subsequently, the Inverse Shifted Fast Fourier Transform (ISFFT) is applied to convert the DD domain signal into a TF domain signal. The TF signal is further processed through a time-frequency modulator to generate the transmitted waveform, completing the Heisenberg transform. Using the Wigner transform, the TF domain grid signal can be derived, and reciprocally, the DD domain signal can be reconstructed through the Shifted Fast Fourier Transform (SFFT). Finally, after a series of demodulation, decoding, and other processing steps, the output information stream is successfully obtained.

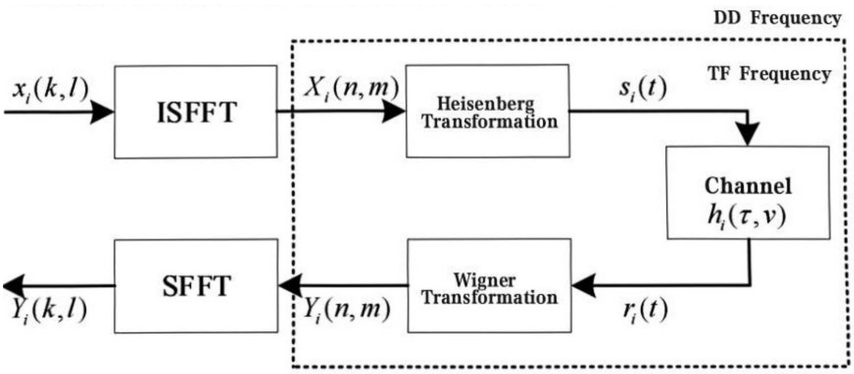

Figure 5: Transformation Example of OTFS Signals [20].

3.2.2. Current Research on OTFS Technology

Research efforts in OTFS technology center on optimizing channel estimation and symbol detection algorithms to enhance both system performance and spectral efficiency. A major focus is on OTFS-assisted multiple access technologies, aimed at expanding spectrum utilization, which is crucial in addressing technological bottlenecks in terahertz communication. These advancements are expected to support efficient spectrum utilization and system optimization, significantly contributing to progress in terahertz communication technologies.

The integration of OTFS with other technologies has emerged as a promising research avenue, offering several advantages such as enhanced spectral efficiency, improved multipath fading resistance, reduced latency, increased system capacity, and greater flexibility. These features collectively enhance the performance and user experience of wireless communication systems [21].

The combination of OTFS with multiple access technologies, including Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) [22], represents a key research direction in 5G and beyond. While power-domain NOMA remains a prominent area, OTFS integration with code-domain NOMA introduces innovative opportunities. Further exploration of OTFS with advanced access techniques like Pattern Division Multiple Access (PDMA), Sparse Code Multiple Access (SCMA) [23], Time-Slotted Multiple Access (TSMA), and Rate-Splitting Multiple Access (RSMA) [24] can drive significant advancements tailored to diverse scenarios.

Despite its advantages in high-mobility environments, OTFS faces challenges that require further investigation. The two-dimensional Fourier transform modulation employed by OTFS leads to higher computational complexity than OFDM, making it less suited for real-time communication requirements of future networks. Additionally, OTFS must achieve improved stability and reliability under high-mobility conditions [25].

In MIMO systems, OTFS detector complexity significantly exceeds that of OFDM detectors, posing hurdles to hardware implementation and widespread adoption. To address these issues, research should prioritize developing efficient algorithms that balance performance and computational feasibility [21].

When considering OTFS and terahertz-based OFDM, their application scenarios diverge. OTFS excels in dynamic channel conditions, while terahertz-based OFDM leverages the immense bandwidth of the terahertz spectrum for ultra-high-speed data transmission. Both technologies benefit from enhancements via MIMO and NOMA techniques.

For OFDM: MIMO improves data throughput, interference resistance, and spatial utilization, while NOMA enhances spectral efficiency and system capacity by enabling multi-user signal multiplexing on the same subcarrier.

For OTFS: MIMO and NOMA work synergistically to boost performance in high-mobility scenarios, dynamically adjusting power allocation and user multiplexing strategies to strengthen system adaptability [26–27].

Future research must address critical factors such as fractional time delays, Doppler shifts, signal fading, multipath effects, and coding schemes to optimize both sensing and communication signals.

4. OFDM Technology in Low-Earth Orbit Satellite Networks and Space-Ground Integrated Information Networks: Applications and Challenges

4.1. Application Prospects of OTFS in Vehicular Internet

The integration of LEO satellite networks with terrestrial systems is critical for realizing 6G's vision of seamless global communication. However, high latency and limited bandwidth of traditional satellite communications hinder their effectiveness in supporting high-speed data transmission and vehicular internet applications. By bridging these gaps, LEO networks deliver uninterrupted communication services to vehicular terminals in diverse scenarios [28–29].

SIoV communication faces challenges due to differences in signal propagation characteristics between satellite and terrestrial channels [30]. While OFDM offers high spectral efficiency and multipath resistance, its vulnerability to Doppler shifts in high-mobility SIoV scenarios leads to inter-carrier interference (ICI) and degraded performance. OTFS modulation has shown promise in mitigating these issues, significantly enhancing reliability in such environments [31]. However, challenges such as high Doppler shifts and atmospheric attenuation remain and necessitate further exploration.

4.2. Prospects and Challenges of OFDM in Low-Earth Orbit Satellite Networks

LEO satellite networks are dynamic, multi-layered systems with varying channel conditions. While OFDM is widely adopted due to its multipath resistance and implementation simplicity, its high PAPR and stringent orthogonality requirements hinder its performance in high-mobility, diverseservice scenarios typical of LEO networks [32]. Developing stable, flexible, and efficient waveforms tailored to these conditions is crucial [33].

Emerging technologies like Generalized Frequency Division Multiplexing (GFDM) inherit the advantages of OFDM while offering improved spectral efficiency and reduced out-of-band emissions, making them a promising alternative [34]. OTFS surpasses both OFDM and GFDM in balancing performance metrics, exhibiting superior reliability in high-mobility scenarios [35].

5. Conclusion

OFDM and its derivatives, such as OTFS and terahertz-based OFDM systems, are pivotal in modern wireless communication. While OTFS excels in dynamic environments by leveraging time-frequency modulation to resist multipath fading, terahertz-based OFDM systems utilize vast bandwidths for ultra-high-speed data transmission. In LEO networks, these technologies bridge terrestrial and satellite communications, supporting applications like IoT, telemedicine, and vehicular internet.

Despite their advantages, challenges remain, such as high PAPR in OFDM and computational complexity in OTFS. Future research should focus on waveform optimization, AI integration, and advanced access methods to overcome these limitations and broaden their applicability in next-generation communication systems.

References

[1] *Li, J. L., Zhang, Z. Y., & Zhao, F. (2024). Experimental research on wireless transmission of optical terahertz signals based on OFDM technology. Journal of Optoelectronics·Laser, 1-10. Retrieved October 29, 2024, from http://kns.cnki.net/kcms/detail/12.1182.o4.20241029.1251.002.html.*

[2] *Liu, Y. J., Li, H. S., Li, J., et al. (2024). Power budget analysis of terahertz polarization-maintaining subwavelength waveguide links. Journal of Optoelectronics·Laser, 35(5), 449-458.*

[3] *Su, X., & Liu, X. L. (2023). A scheme of frequency 20-tupling millimeter-wave generation based on dual-cascaded MZM. Journal of Optoelectronics·Laser, 34(12), 1233-1240.*

[4] *You, H. D., Xu, J., Xu, J., et al. (2023). A radio over fiber transmission system based on two paralleled Mach-Zehnder modulators. Journal of Optoelectronics·Laser, 34(10), 1091-1096.*

[5] *Li, X. Y., Yu, J. J., Zhao, L., et al. (2019). 1-Tbit/s millimeter-wave signal wireless delivery at D-band. Journal of Lightwave Technology, 37(1), 196-204.*

[6] *Wei, Z. Q., Feng, Z. Y., Li, Y. H., et al. (2022). Terahertz joint communication and sensing waveform: status and prospect. J Commun, 43, 3–10.*

[7] *Huang, Y. X. (2022). Integrated waveform design and signal processing for communication radar [Doctoral dissertation, University of Electronic Science and Technology of China].*

[8] *Shi, H. C., Yang, C., & Peng, M. G. (2023). 6G terahertz communication: architecture, technology and challenges. Chinese Journal of Radio Science. Retrieved November 20, 2023, from [具体网址，如果有].*

[9] *Deng, M. K., Yang, C., Shi, H. C. (2024). OFDM-based waveform design and performance analysis of terahertz integrated communication and sensing. Journal of Terahertz Science and Electronic Information Technology, 22(06), 671-678.*

[10] *Uysal, F. (2020). Phase-coded FMCW automotive radar: system design and interference mitigation. IEEE Transactions on Vehicular Technology, 69(1), 270-281. https://doi.org/10.1109/TVT.2019.2953305.*

[11] *Chen, Z., Liu, K., Li, L. X., et al. (2024). A review of integrated terahertz communication and sensing technology. Science China Information Sciences, 54(05), 1215-1235.*

[12] *Gao, M. Q., Dai, J. M., Zhu, S. B., et al. (2024). OTFS technology: Research status and development trends. Telecommunication Engineering, 1-14. https://doi.org/10.20079/j.issn.1001-893x.240311002.*

[13] *Wei, Z., Li, S., Yuan, W., et al. (2023). Orthogonal time frequency space modulation–Part I: Fundamentals and challenges ahead. IEEE Communications Letters, 27(1), 4–8.*

[14] *Hadani, R., Rakib, S., Tsatsanis, M., et al. (2017). Orthogonal time frequency space mo-dulation. In Proceedings of WCNC 2017: Wireless Communications and Networking Conference (pp. 1-6). San Francisco: IEEE.*

[15] *Matz, G., & Hlawatsch, F. (2006). Time-varying communication channels: Fundamentals, recent developments, and open problems. In Proceedings of 2006 14th European Signal Processing Conference (pp. 1-5). Florence: IEEE.*

[16] *Yuan, W., Wei, Z., Yuan, J., et al. (2020). A Simple Variational Bayes Detector for Orthogonal Time Frequency Space (OTFS) Modul-ation. IEEE Transactions on Vehicular Technology, 69(7), 7976-7980.*

[17] Zhang, J., Jin, F., Tan, Z., et al. (2014). Performance analysis of high-speed railway communication systems subjected to co-channel interference and channel estimation errors. IET Communications, 8(7), 1151-1157.

[18] Wei, Z., Yuan, W., Li, S., et al. (2021). Transmitter and receiver window designs for orthogonal time-frequency space modulation. IEEE Transactions on Communications, 69(4), 2207-2223.

[19] Augustine, R. M., Surabhi, G. D., & Chockalingam, A. (2019). Space-time coded OTFS modulation in high-Doppler channels. In IEEE 89th Vehicular Technology Conference (pp. 1-6). Kuala Lumpur, Malaysia: IEEE.

[20] Zhou, W., Chen, L., Xiang, Z., et al. (2024). Research on joint power domain and code domain NOMA-OTFS system. Journal of Nanjing University of Posts and Telecommunications (Natural Science Edition), 1-8. Retrieved November 13, 2024, from http://kns.cnki.net/kcms/detail/32.1772.tn.20241113.1435.012.html.

[21] Gao, M. Q., Dai, J. M., Zhu, S. B., et al. (2024). OTFS technology: Research status and development trends. Telecommunication Engineering, 1-14. https://doi.org/10.20079/j.issn.1001-893x.240311002.

[22] McWade, S., Farhang, A., & Flanagan, M. F. (2023). Low-Complexity Reliability-Based Equalization and Detection for OTFS-NOMA. IEEE Transactions on Communications, 71(11), 6779-6792.

[23] Wen, H., Yuan, W., Liu, Z., et al. (2023). OTFS-SCMA: A Downlink NOMA Scheme for Massive Connectivity in High Mobility Channels. IEEE Transactions on Wireless Communications, 22(9), 5770-5784.

[24] Ma, Y., Ma, G., & Ai, B. (2024). Orthogonal Time Frequency Code Space Modulation Enabled Multiple Access under Compactness-Reduced Channel Spreading Function. IEEE Transactions on Wireless Communications, 23(3), 1810-1826.

[25] Xian, Y. J., Zhao, R. H., Xing, Z. T., et al. (2024). Research on PAPR suppression in OFDM systems for integrated communication and sensing. Journal of Xidian University, 1-13. https://doi.org/10.19665/j.issn1001-2400.20240914.

[26] Li, X. W., Zhang, C. S., Tian, X. J., et al. (2020). 5G non-orthogonal multiple access technology. Machinery Industry Press.

[27] Huawei WLAN LAB, Doron Ezri, & Shimi Shilo. (2021). MIMO-OFDM technology principle. Posts & Telecommunications Press.

[28] Chen, S. Z. (2020). Analysis on low earth orbit satellite communication and suggestions on its development in China. Telecommunication Science, 36(6), 1-13.

[29] Ma, T., Qian, B., Qin, X. H., et al. (2024). Satellite-terrestrial integrated 6G: an ultra-dense LEO networking management architecture. IEEE wireless communications, 31(1), 62-69. https://doi.org/10.1109/MWC.011.2200198.

[30] Chen, S. Z., Sun, S. H., & Kang, S. L. (2020). System integration of terrestrial mobile communication and satellite communication—the trends, challenges and key technologies in B5G and 6G. China communications, 17(12), 156-171. https://doi.org/10.23919/JCC.2020.12.011.

[31] Ma, Z. X., Xue, J. Z., & Zhou, H. B. (2024). A satellite Internet of Vehicles system based on OTFS modulation and its performance evaluation. ZTE Technology Journal, 1-12. Retrieved October 24, 2024, from http://kns.cnki.net/kcms/detail/34.1228.TN.20241024.1226.004.html.

[32] Yang, G. H., He, G. N., Chen, R. R., et al. (2024). Research progress and prospects of 6G wireless air interface transmission technology. Science China Information Sciences, 54(5), 1078-1113. https://doi.org/10.3969/j.issn.1003-3114.2021.06.001.

[33] Shen, J. W., Hong, T., & Zhang, G. X. (2024). Access and transmission technologies for low earth orbit satellite networks. ZTE Technology Journal, 1-10. Retrieved October 17, 2024, from http://kns.cnki.net/kcms/detail/34.1228.TN.20241017.1705.008.html.

[34] Wang, Y. (2023). Research on satellite random access technology integrated with 5G [Doctoral dissertation, Xi'an University of Posts and Telecommunications]. https://doi.org/10.27712/d.cnki.gxayd.2023.000030.

[35] Sheikh-Hosseini, M., Rahdari, F., Ghasemnezhad, H., Ahmadi, S., & Uysal, M. (2024). A Comparative Performance Evaluation of OFDM, GFDM, and OTFS in Impulsive Noise Channels. IEEE Open Journal of the Communications Society. https://doi.org/10.1109/OJCOMS.2024.3506723