The Orthogonal Time Frequency Space (OTFS) Technique In 6G Wireless Communications

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Abstract. The orthogonal time-frequency space (OTFS) technique is a potential waveform modulation method that modulates data in the delay-doppler (DD) domain. OTFS differs from traditional multiplexing techniques by utilizing two-dimensional modulation to switch between the time-frequency (TF) domain and the delay-Doppler domain. This allows for handling Doppler shifts caused by fast-moving objects, a capability lacking in traditional modulation techniques like orthogonal frequency division multiplexing (OFDM). The primary goal of this paper is to offer an overview and short survey of this new topic, highlighting its system model. We also examine key aspects of OTFS modulation such as data detection methods, channel estimation, MIMO, and multiuser systems.

1. Introduction

MIMO-OTFS can further boost spectral efficiency, while OFDM offers easy implementation, strong resilience to multipath fading and narrowband interference, and excellent spectral efficiency. OTFS modulation is a promising method for ensuring reliable communication in situations where people are moving around a lot. Wireless communication has seen rapid development since the 1960s, with LTE being one of the main approaches for new-generation wireless transmission frameworks. The LTE Advanced (LTE-A) framework uses MIMO and OFDM methods to achieve maximum data rate communications. The motivation for MIMO in current wireless frameworks is to improve capacity-constrained systems, quality and inclusion improvement, misuse of Long-Term Evaluation to expand the limit, inclusion range, and information transmission dependability of the wireless frameworks [1]. One of the prevalent wireless frameworks is Wireless Local Area Networks (WLANs) which interconnect laptops, Personal Digital Assistants (PDA), cell phones, and other handheld gadgets as shown in Figure 1.

LTE is a wireless and mobile communication technology that offers new features and advantages compared to other technologies [2]. Its main goals include increased downlink and uplink data rates, flexible data transfer capacity, improved ghostly proficiency, and increased client limit. LTE/LTE-A is raising communication advancements in transit toward a 5G transmission scheme as appeared in Figure 2.

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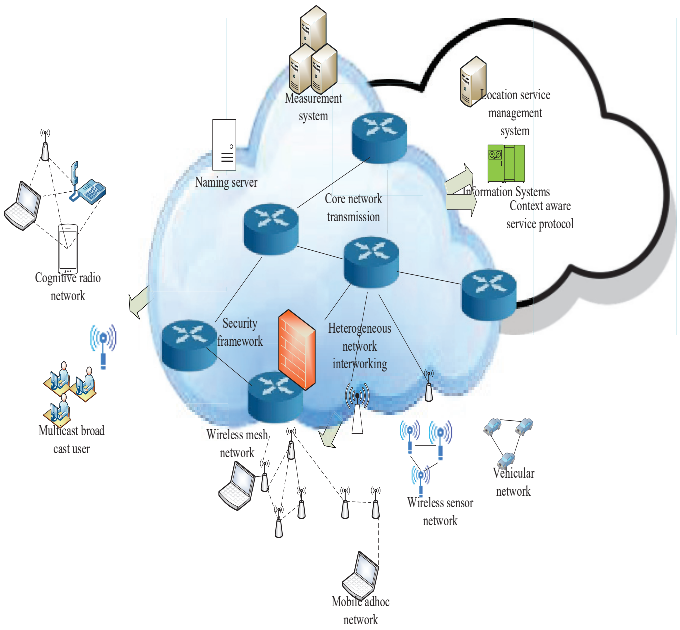

Fig. 1. Wireless communication.

LTE-A standards aim to expand range productivity and support spectrum proficiency by reducing the number of antennas used in devices. Antennas used in digital communication systems include Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and Multiple Input Multiple Output (MIMO). Multipath fading is a noise factor that reduces signal quality, and it is recommended to have multiple antennas at both ends for better signal quality analysis [3].

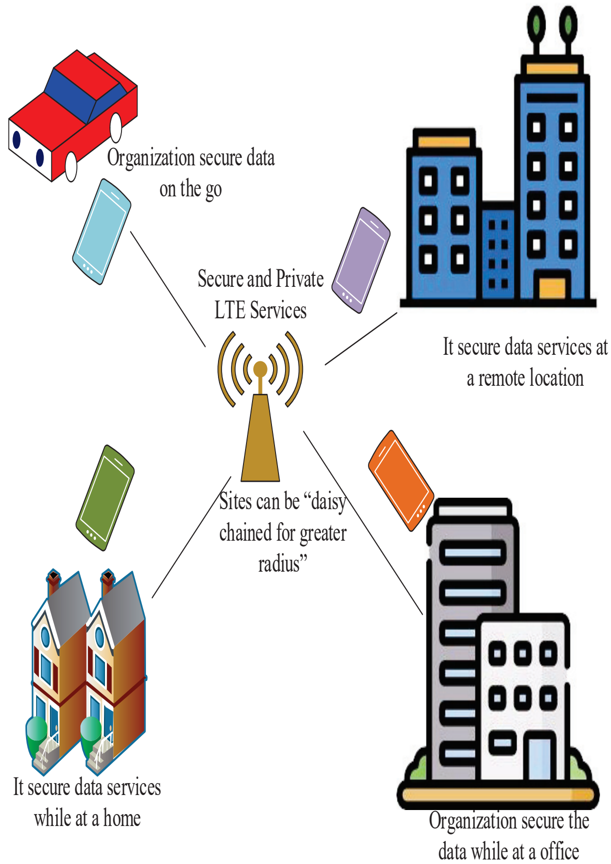

Fig. 2. Communication Systems.

Multiple input multiple output (MIMO) systems are traditional wireless communication systems that use single-user systems for downlink communication [4], as shown in Figure 3.

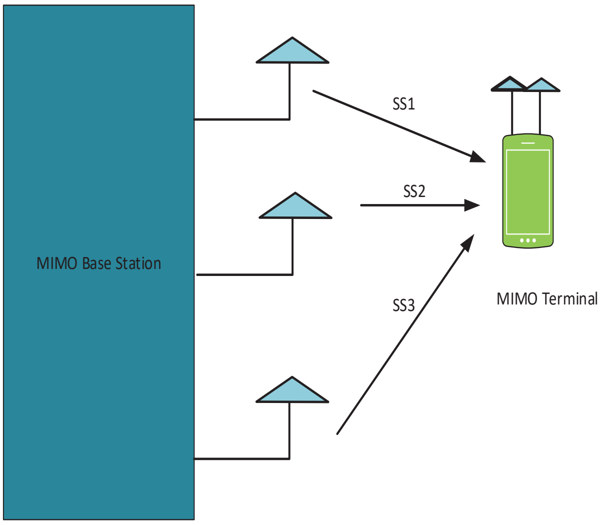

Fig. 3. Single-User MIMO System in Downlink.

MIMO networks use multiple antennas at both ends of a transmission stream, enhancing transmission reliability and reducing disturbance. However, a compromise must be found between diversity and multiplexing gain, as the highest multiplexing gain and maximum diversity cannot be used simultaneously. The IEEE 802.16 standard for broadband wireless access uses numerous antennas, with IEEE 802.16e providing an additional benefit of SM for 2x2 downlink MIMO systems and doubling communication speed [5]. Multiuser MIMO systems, shown in Figure 4, can be configured in co-located or distributed configurations, with the co-located configuration aiming to expand coverage and reduce outages.

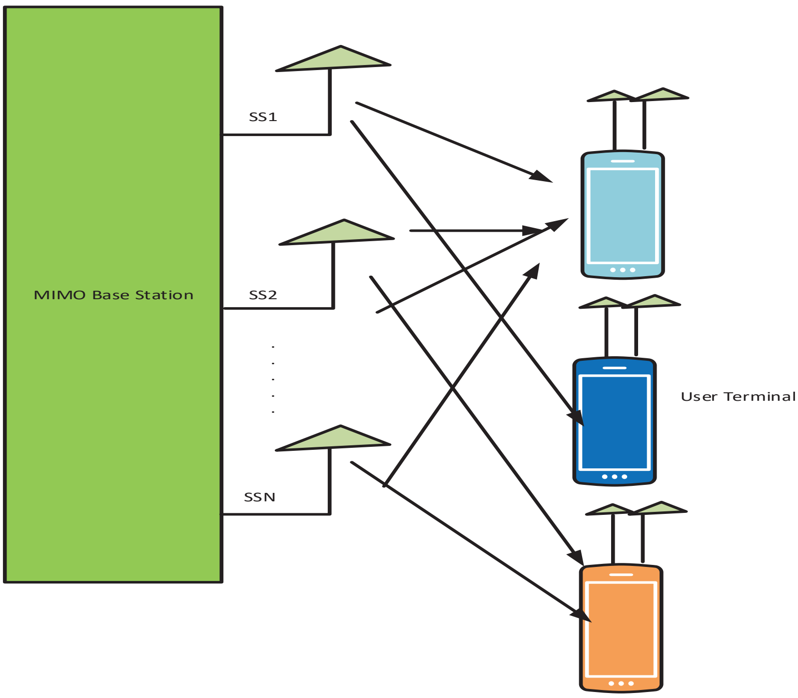

Fig. 4. Multi-User MIMO System for Downlink.

M-MIMO is a critical technology for 5G and future mobile transmission schemes, involving a large number of BS antennae and users. This paper examines Single-user and MU Massive MIMO technologies in a single-cell downlink system, focusing on the capacity of the sum rate [6].

Wireless communication uses two alternative duplexing mechanisms: Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) [7], as shown in Figure 5.

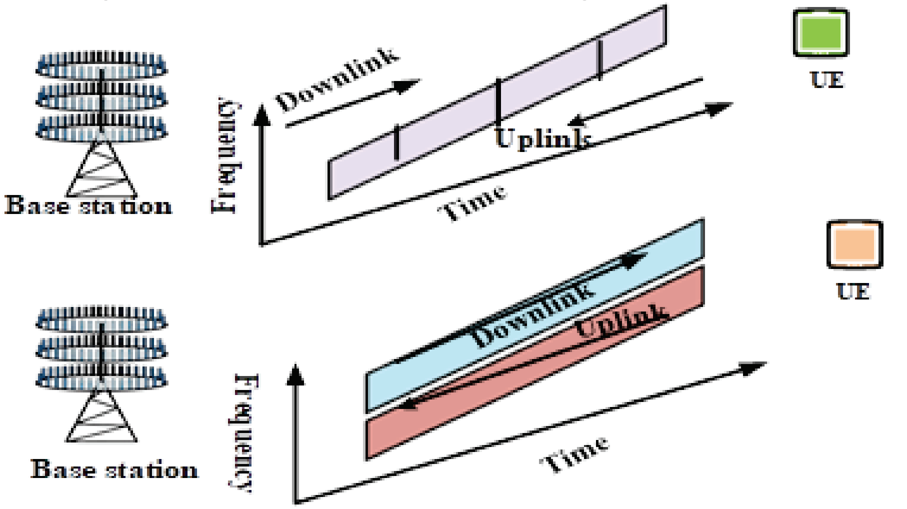

Fig. 5. Pilot and Data Transmission in TDD and FDD System.

In TDD, different time slots with the same frequency spectrum are used for transmission in UL and DL scenarios, but channel reciprocity is not applicable in FDD transmission. In M-MIMO, the DoF can be improved and transmitted power can be reduced, with large numbers of antennas providing more samples for signal processing. M-MIMO also offers advantages such as simple precoding and detection, favorable propagation and channel hardening, inter-user interference reduction, improved sum capacity, and sharp beamforming [8].

In MU-MMIMO with TDD mode, the channel is considered flat for the coherence interval time T as shown in Figure 6. In each coherence interval, four processes are performed: training phase, channel estimation, transmission of downlink data, and uplink communication [9].

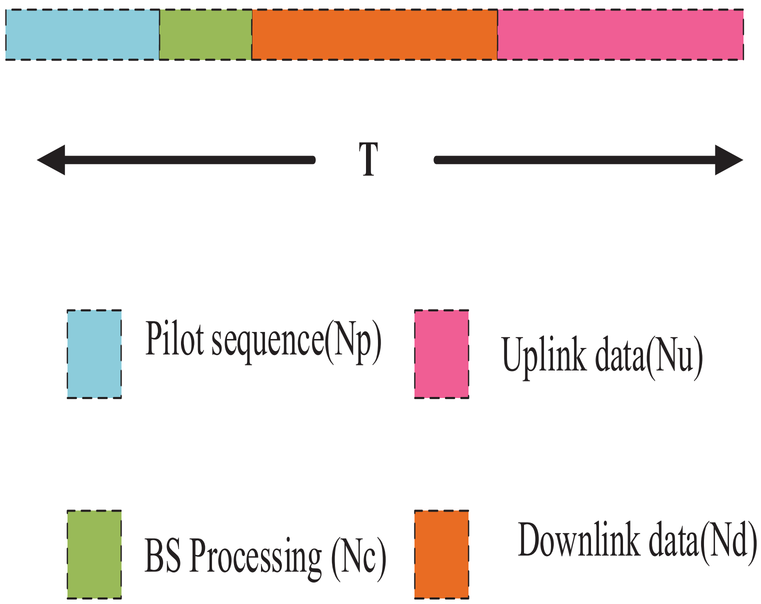

Fig. 6. TDD Protocol.

Massive MIMO, with a larger number of transmitter antennas, can handle two-way communication between transmitter and receiver, providing dedicated links and a large amount of connectivity for serving IoT devices. Figure 7 shows the block diagram of the massive MIMO system with an M transmitting antenna serving K users. Usually, M is very enormous compared to K [10].

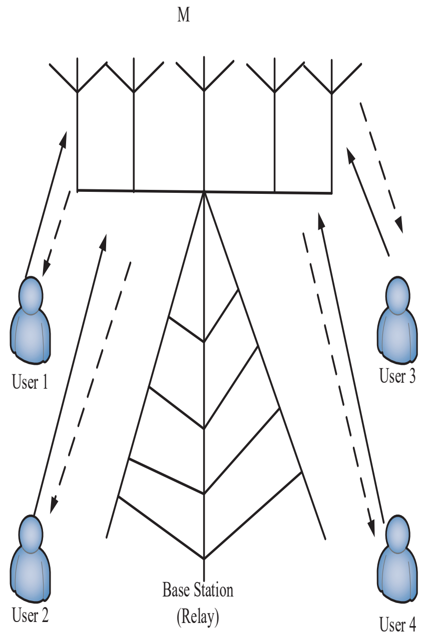

Fig. 7. Massive MIMO Communication Model.

Beam-forming is a method of transmitting signals from a base station to a radio, enhancing signal strength and coverage in specific directions. Figure 8 shows the beam-forming type of communication from the antenna array of 5G BS [11].

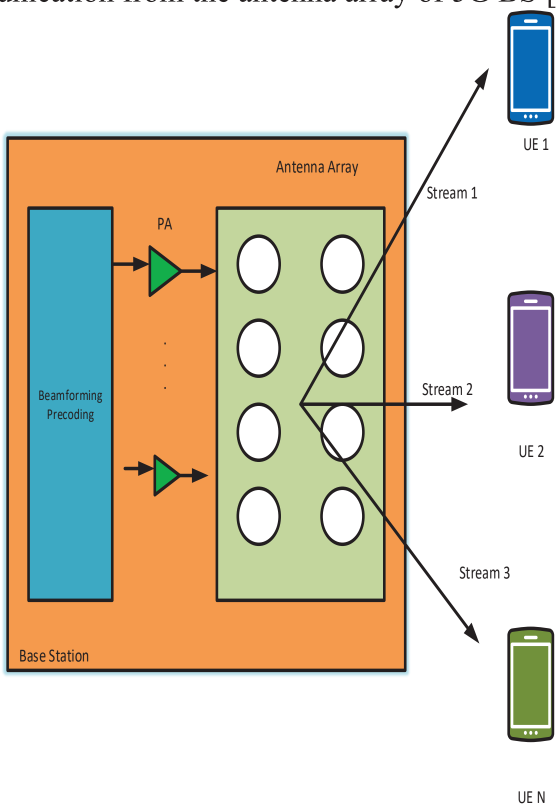

Fig. 8. Beam Forming Model of Communication.

In a Time Division Duplex Mode Operation (TDD) massive MIMO system, the CSI is obtained from uplink training and controlling channel reciprocity. In the TDD M-MIMO structure shown in Figure 9, the training series is broadcasted in the uplink direction to avoid the huge amount of transmission of orthogonal pilot series in a downlink [12].

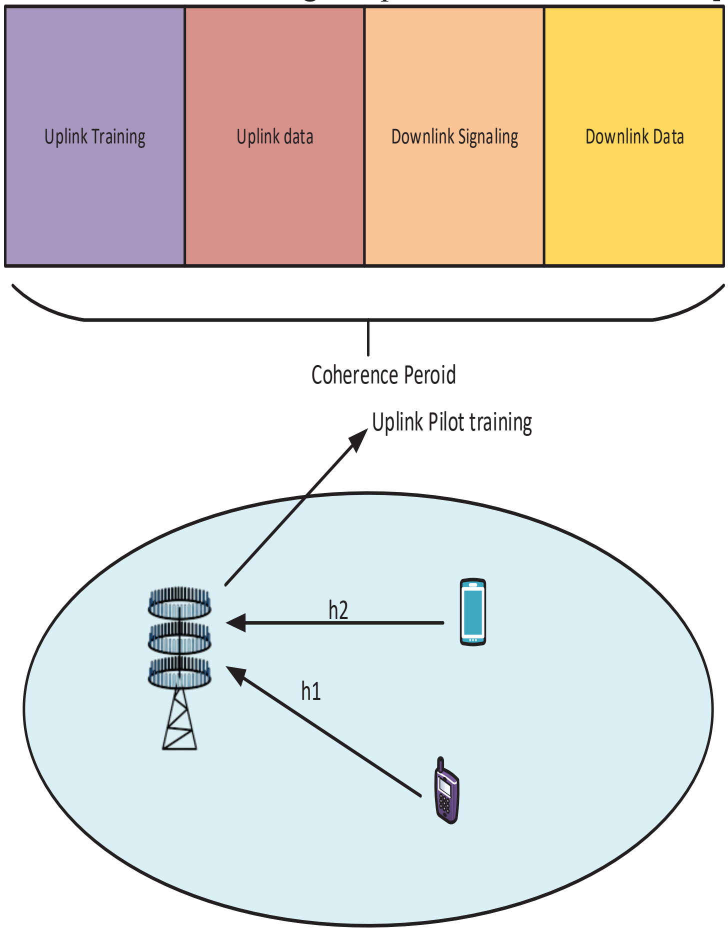

Fig. 9. TDD mode operation in channel estimation Process.

This method ensures improved performance in mobile systems by separating uncorrelated noises and intra-cell interference. The CSI is used for data transmission and channel acquisition, and the base station calculates the CSI using the reciprocity among channels and the pilot training in an uplink path. The excess of BS antennas can offer spectral efficiency gains, but pilot contamination or pilot pollution can occur. MIMO has several benefits, including Spatial Diversity Gain, Array Gain, and Spatial Multiplexing Gain. Spatial Diversity Gain combats fading by creating many duplicates of the signal, while Array Gain increases signal reliability and quality by making the array more resistant to noise. Spatial Multiplexing Gain increases data rate without additional bandwidth or transmission power and reduces interference by increasing separation distance among users [13].

2. Literature SURVEY

This section discusses Massive 6G MIMO – OTFS, Pilot Design-based Channel Estimation, Superimposed Pilot Design, and Channel Estimation and Data Detection, and finds the research gaps in relevant recently published papers.

The paper [14] highlights a novel path division multiple access (PDMA) approach that leverages the OTFS for huge MIMO networks across high mobility in both the UL and DL directions. The authors present a high mobility DL CE approach, a new LCD that enables the Unit (UT) to independently demodulate each DD domain information signal, and an Estimation of channels method and randomized pilot design-based CSI collection system for

DL M-MIMO-OTFS in the presence of a fractional Doppler. They propose a deterministic pilot framework and tensor-based OMP technique for downlink CSI collection.

The paper [15] discusses low-complexity transmitter precoding for MU MIMO-OTFS, proposing two methods that lower computational complexity and performance loss compared to BD precoding. The study concludes that these methods offer promising solutions for large MIMO networks.

The paper [16] presents an OTFS modulation approach for large MIMO networks, using channel estimation to minimize ISI. The method uses 3D inner product proportion reduction difference structured orthogonal matching pursuit (3D-IPRDSOMP) to merge features of 3D structured sparse channels. The SM-OTFS model is examined, showing better performance than STC-OTFS in various MIMO situations. The low complexity detector for MIMO systems is based on OTFS modulation, using the MRC technique to linearly merge transmitted symbol vectors.

The paper [17] explores various methods to improve channel estimation in high-mobility MIMO-OTFS frameworks. It focuses on reducing processing latency and improving channel estimation frameworks. The study introduces DD alignment modulation (DDAM), a method that removes the Doppler impact of multi-path signal mechanisms and allows all multipath signal mechanisms to arrive at the receiver simultaneously and constructively.

The paper [18] presents a pilot design for channel evaluation (CE) in the MIMO-OTFS network based on OTFS, a low-complexity approach for channel matrix calculation with Doppler and fractional delay, and a new OTFS system called SIM-OTFS. The study also discusses the performance of the SIM-OTFS design in high-mobility vehicle schemes in intelligent transportation networks. The authors also discuss the integration of CE and device activity identification in grant-free RAS with significant differential DD shifts enabled by LEO satellites.

The paper [19] presents a time-division duplex technique based on ML that can significantly increase prediction quality for both low and high-mobility scenarios. They also present a pilot-based CE method in the MIMO-OFDM framework, which is determined instantaneously by the estimation algorithm and the pilot design. They also describe a downlink pilot design technique for OFDM systems using DL-based channel estimates (ChannelNet). The deterministic pilot design and CE algorithm-based CSI collection technique for DL, M-MIMO-OTFS, is proposed.

The paper [20] analyzes the downlink of massive MIMO systems without cells and proposes two pilot-based CE schemes: "EP-CHE" and "SP-CHE". The proposed techniques for data identification and CE are iterative and use an overlaid pilot pattern to enhance spectrum effectiveness. The UL NOMA scheme is proposed for massive MIMO-OTFS networks, addressing user connectivity issues. The 2D-OTFS modulation technique performs better than traditional multicarrier modulation systems, providing low-complexity linear equalizers for a 2 × 2 MIMO output-to-feedback scheme.

The paper [21] proposes a 2-timescale CE methodology, utilizing a dual-link pilot communication strategy and coordinate descent to estimate quasi-static BS-RIS channels. The passive beam forming approach with low complexity channel estimate is also proposed.

The paper [22] addresses hybrid combining and channel estimation issues in wideband THz mMIMO using uniform planar arrays. It provides a time-delay-based low-complexity beam squint mitigation technique and a new version of the orthogonal matching pursuit (OMP) technique for effective channel estimation. The authors also propose a data-aided channel estimation approach to increase spectral efficiency for stacked pilot and data communication systems. They also offer a DL-based channel estimate and pursuing technique for vehicle mmWave communications.

The paper [23] proposes novel and effective channel estimation (CE) methods for the double-IRS-assisted MIMO interaction framework, including anchor-assisted CE, multi-user huge multi-input multi-output millimeter wave systems, and time-division duplex techniques. They also introduce a time-division duplex technique based on ML that allows temporal channel correlation to be used to get CSI.

The paper [24] proposes a beamspace channel estimation technique based on prior-aided Gaussian mixture LAMP (GM-LAMP) and a multi-user uplink CE technique for mmWave large MIMO systems. They develop a dual-wideband channel model and a conditional generative adversarial network (cGAN) for large MIMO systems. They examine CE challenges in MIMO-OFDM systems using a hybrid IRS framework and algebraic techniques. The proposed methods perform better in terms of precision, speed, and complexity than conventional methods.

The paper [25] presents an uplink mMTC S-IoT system using an SPs code domain non-orthogonal multiple access over a satellite-ground channel model with route loss and shadowed-Rician fading. They propose a MIMOOFDM-IM compromise between SE and system performance, using a superimposed pilot scheme to achieve greater SE without sacrificing BER performance. The paper also discusses the generalized superimposed training (GST) approach for uplink cell-free mMIMO frameworks, examining the SE of a UL hardware-constrained "cell-free MIMO system with MRC receiver filters". The authors also analyze the PAPR for the OTFS waveform using transmit frame architectures for channel estimation methods.

The paper [26] presents adaptive channel estimation algorithms for MU-MIMO systems using LMS and BLMS methods. These systems have lower computational costs and do not require initial and 2nd-order understanding of time-varying MU-MIMO channel statistics. The proposed architecture streamlines receiver design and uses a combined approach and data-driven receiver architecture. A novel PSI-based adaptive primary guard strategy for transfer lines is presented, ensuring strong protection in the event of poor source networks. The IAP-SP method ensures correct channel recovery while lowering computational cost. The BR-MP-EM method modernizes communication for combined UAD and CE issues and uses EM methods in outer iterations. The study presents USC modulation, which includes new OTFS and OTSM techniques for channel estimation and detection. The paper also examines the concepts of Superimposed Pilot Design, Pilot Design Channel Estimation, Massive MIMO-OTFS, and Channel Estimation and Data Detection.

Furthermore, Table 1 below covers the main research gaps in the recently published papers.

Table 1. Research Gaps of Existing Work

Category	Methods	Research Gap
Massive MIMO – OTFS.	PDMA scheme [27], Delay Doppler [28].	• Interference Management. • Robustness to Channel Variability.
Pilot Design Based Channel Estimation.	DRL [29], DL [30].	• Computational Complexity. • Computational Resources.
Superimposed Pilot Design.	Message Passing Algorithm [31], Gaussian Distribution [32].	• Computational Complexity • Robustness to Channel Variability.
Channel Estimation & Data Detection.	Expectation Maximization [33], Discrete Fourier Transform [34].	• Scalability. • Complexity.

3. OTFS and 6G

OTFS modulation is a 2D modulation approach that uses information symbols multiplexed in the DD domain, allowing for a stable and sparse channel. It is better than OFDM for both coded and uncoded systems and is robust to delay-Doppler shifts. OTFS also benefits from combined time-frequency diversity, ensuring dependable communications across doubly dispersive transmissions. However, it poses challenges for the design of transceiver architectures and algorithms, especially when dealing with fractional inter-doppler interference (IDI). The IDI is the primary constraint on the channel estimate performance of OTFS systems, and a practical strategy is needed to lessen channel broadening caused by fractional Doppler. Windowing in the TF domain may increase efficient channel sparsity in the DD domain, but no approach is provided for designing windows [35]. The modulation and demodulation of OTFS are shown in Figure 10.

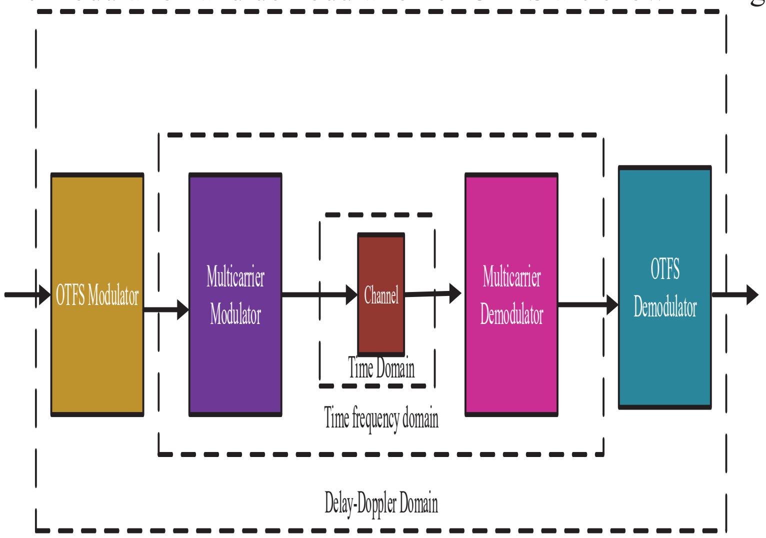

Fig. 10. Modulation and Demodulation for OTFS.

OTFS modulation has potential applications in next-generation wireless networks, including vehicular networks, millimeter-wave communications, non-terrestrial networks, and underwater acoustic communications. It offers improved traffic safety, cooperative control, and support for self-driving cars. It also provides strong protection against oscillator phase noise, making it ideal for mmWave telecommunications. OTFS's Doppler resilience makes it better for data sent in the DD domain, making it suitable for underwater acoustic channels. Its low power consumption and complexity make it a desirable trade-off between complexity and performance [36].

6G is a new generation of wireless technology that aims to provide a widely distributed, intelligent, safe, scalable, and stable wireless system. It will use space connections to create a wireless network that is everywhere. Key performance indicators (KPIs) for 6G design include system capacity, system latency, system management, increasing intelligence and automation, and enhancing network coverage beyond the terrestrial domain [37]. It will need ground-breaking discoveries in every area of wireless communications to meet the KPIs listed in Table 2.

Table 2. Performance Indicator of 5G and 6G

Key Performance Indicator (KPI)	5G	6G
1. System Capacity		
Highest Data Rate (Gbps)	20	1000
Knowledgeable Data Rate (Gbps)	0.1	1
High Spectral Efficiency (B/S/Hz)	30	60
Knowledgeable Spectral Efficiency (B/S/Hz)	0.3	3
Ideal Channel Bandwidth (Ghz)	1	100
Capability Of Area Traffic (Mbps/m2)	10	1000
Density Of Connections (Devices/Km2)	10^6	10^7
2. Latency of the Network		
Total Lag (ms)	1	0.1
Latency Jitter (ms)	NA	10^{-3}
3. System Administration		
Energy Effectiveness (Tb/j)	NA	1
Dependability (PER)	10^{-5}	10^{-9}
Mobility (km/h)	500	1000

The KPIs include maximum channel bandwidth, area traffic capacity, connecting density, PDR, experience data rate, and peak spectral effectiveness. The 6G scheme may require peak data rates of up to 1 Tb/s, which is 100 times faster than 5G. The THz band's potential bandwidths must be explored to meet this demand [38].

The design of low-cost and energy-efficient Nano-transceivers for THzCom applications is challenging due to the varying absorption loss in the THz band over long transmission distances. To address this, carrier-based modulation-based spectrum allocation algorithms are being investigated for THzCom designs. These algorithms use TW bandwidths to modulate data into single-carrier waveforms and/or pulses, which are then upshifted via cascaded frequency multipliers to higher THz band frequencies. However, the influence of IBI (power leakage) is a significant performance-limiting issue, especially when users require numerous sub-bands to meet their QoS needs. To increase throughput fairness among users in multiuser THzCom design, DAMC-based spectrum allocation algorithms may be used. To increase the SE, new multi-band spectrum distribution techniques should be investigated, such as dividing the TW into sub-bands with uneven bandwidth and using ASB. Enhanced

DSS (Digital Signal Processing) is needed to maximize spectrum utilization and encourage high levels of adaptiveness among operators under assured QoS and priority [39].

In the 6G future, spectrum control is crucial for effective DSS implementation, as it impacts both conveyed services and communication [40], these technologies are represented in Figure 11.

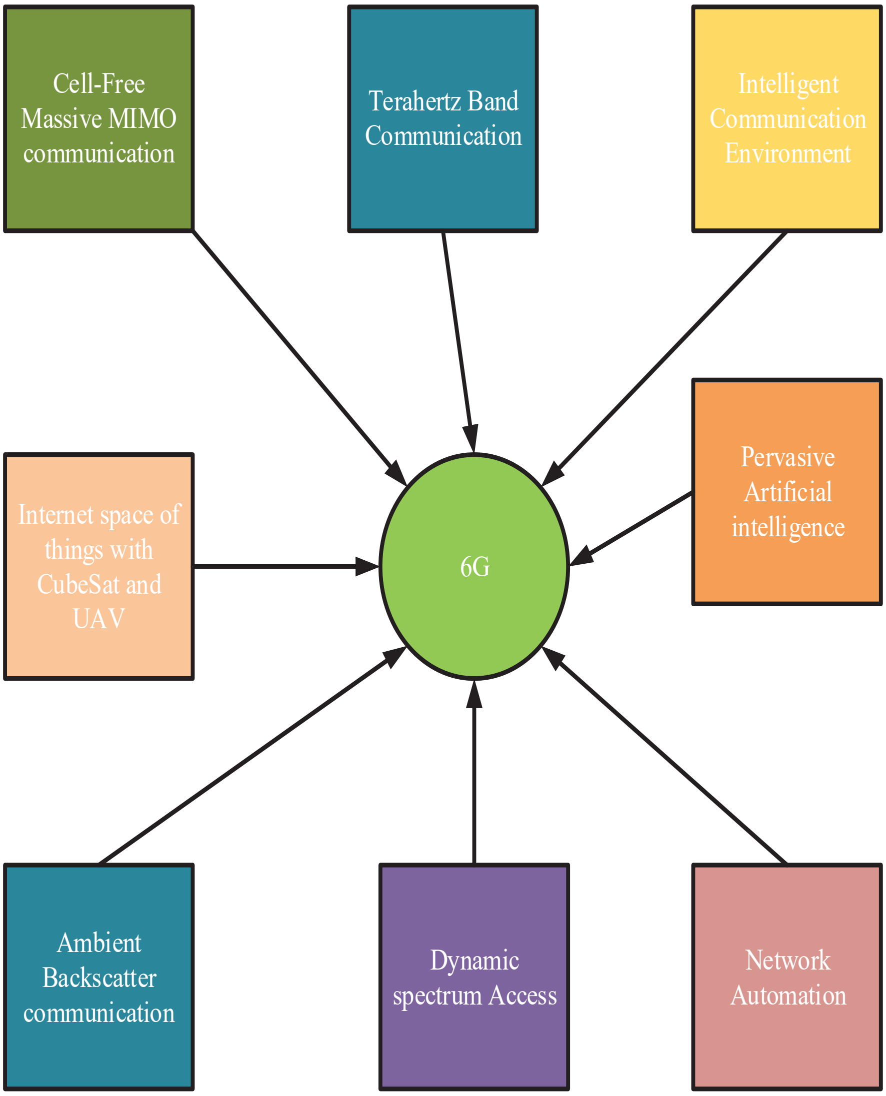

Fig. 11. 6G Enabling Technologies.

Blockchain offers a comprehensive solution for regulating spectrum security, as it can store tamper-proof spectrum-sharing events and transmit details on the chain. Current DSS architectures include centralized and decentralized keys [41], Figure 12 and Figure 13.

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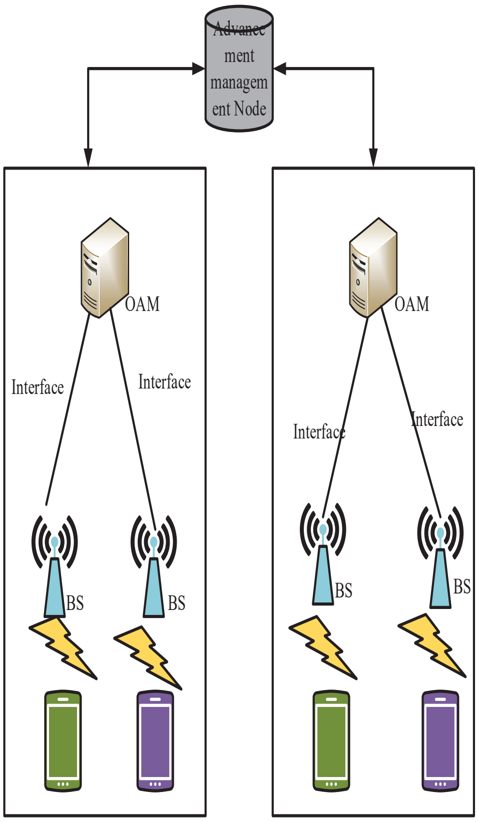

Fig. 12. Centralized DSS Architecture.

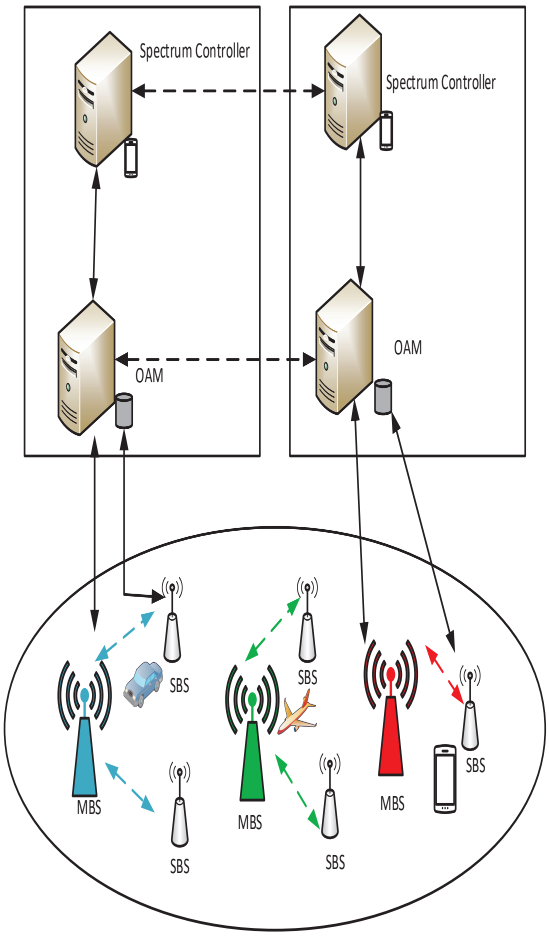

Fig. 13. Decentralized DSS Architecture.

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Centralized DSS architectures use AMNs to reduce mutual interference among operators and manage common spectrum resources unifiedly. Operator-level DSS architectures use AMNs to oversee spectrum allocation and forecasting. Decentralized DSS architectures use spectrum controllers to communicate with each other and determine spectrum requirements. However, practical adoption has lagged due to security, privacy, incentive structures, and QoS guarantees. Innovative technologies like blockchain and AI are needed for flexible and effective spectrum management in 6G [42].

The 6G vision aims to outperform 5G by 2030, focusing on four key aspects: intelligent connection, deep interaction, holographic connection, and prevalent connectivity. To achieve these objectives, 6G networks must meet certain prerequisites and challenges, such as a peak rate of 10 Tb/S, reliable global connectivity, energy efficiency, constant connection, ubiquitous information, confidence, convergence of sensing, computation, interaction, and management, and nontechnical difficulties like industrial hurdles, politics, and consumer habits. Potential technologies include THz interactions, ultraviolet interactions, large-scale receivers, advanced channel coding, and holographic radio. The research and development stage is still ongoing, with some fields dependent on other fields [43].

Given the above 6G vision, as well as the present stage of growth and developing trends in the accompanying tools, we predict that the key methodological aspects of 6G will consist of the features illustrated in Figure 14.

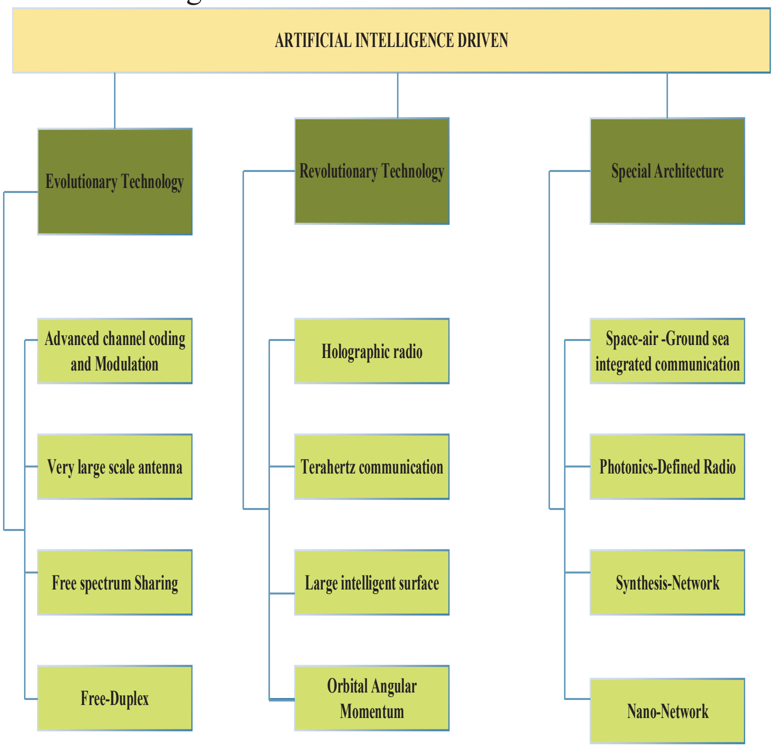

Fig. 14. Potential Technologies of 6G.

This section explores potential ground-breaking technology in wireless communication, particularly in the field of radio holography. The current 5G system is facing challenges due to advancements in the physical layer, leading to the need for new ideas and frameworks for 6G. Holographic radios, which record the electromagnetic field in space, can achieve ultra-high-density, pixelated spatial multiplexing, and holographic images. These radios can regulate electromagnetic radiation, boost network bandwidth and spectral efficiency, and achieve RF confluence of setting, imaging, and wireless communication. However, processing hologram radio information requires an AI infrastructure with minimal latency, reliability, and scalability. 6G energy consumption, latency, and adaptability requirements require an ordered hybrid optoelectronic computation and signal processing system. The terahertz wavelength band, from 0.1 to 10 THz, is expected to deliver up to Tbps data speed, enabling high throughput, minimal delay, and novel request possibilities for 6G [44].

Terahertz bands offer advantages in wireless communication, such as managing Tbps networks with large bandwidths and high temporal domain elimination. However, they also have challenges such as high path loss, extreme attenuation, low diffraction impact, susceptibility to blocking and shadows, less vulnerability to moisture and rainfall, and high channel fluctuations. THz component manufacturing is improving, and more output power is expected soon. Key research areas for THz communications include propagation measurements, channel modeling, and utilizing meta-materials and semiconductors. Technical progress is expected to enhance service quality in the 6G era [45].

Terahertz (THZ) transmissions are primarily achieved through the layout of the emitter, with two types of devices: optics- and electronics-based technologies. Photonics-based methods offer high modulation order and can be used for high-rate data transmission. However, transmission distances are often close due to high propagation loss and low power. Electronics-based methods are practical for wireless networks in the 100-150 GHz range, with frequency multiplication being the most popular technique. Mixed processes, such as a hybrid microwave photonics strategy, can combine both technologies for better performance. The International Telecommunication Union and the World Radio Council need to work together to promote worldwide agreement on THz [46].

4. Conclusions

This paper provides an overview of the OTFS-MIMO-6G wireless communication technique. MIMO and OTFS are two cutting-edge technologies for 6G networks, aiming to provide reliable and smooth connectivity for networks on the go. The paper has focused on 6G visions, requirements, scenarios, critical technologies, and system designs. This paper aims to help researchers in industry and academia get a comprehensive understanding of the OTFS-MIMO-6G technique and stimulate additional research in this field.

5. Future Work

In our next work, we aim to provide reliable communication during channel estimation and data detection using OTFS-MIMO for 6G communications with low pilot overhead, complexity, and high spectrum efficiency. The main objectives include improving signal quality through noise suppression, extracting uplink and downlink parameters, proposing Dual-Tree Complex Wavelet Transform for high-mobility scenarios, and reducing inter-symbol interference (ISI) from the channel. The major contributions of this approach include entropy-based adaptive filtering, the Dynamic Orthogonal Matching Pursuit algorithm, improved naive Bayes, a hybrid method combining approximate message passing and linear minimum mean square, and a three-stage equalizer using Rock Hyraxes Swarm Optimization. The quality of the recommended work is evaluated using performance parameters such as SNR (DB) vs. MSE, Detection Probability, Pilot Overhead vs. NMSE, User velocity vs. NMSE, BER vs. NMSE, Throughput vs. number of users, SNR vs. Throughput (%), and Latency vs. Number of Users.

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