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SURVEY

Profuse Channel Estimation and Signal Detection Techniques for Orthogonal Time Frequency Space in 6G Epoch: A Survey

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ABSTRACT Orthogonal time frequency space (OTFS) modulation is a booming multicarrier modulation technique and a promising candidate for achieving quality of services in high mobility scenarios of 5G new radio (NR) and beyond wireless communication systems. OTFS addresses the high Doppler channel environment aiding the 2D delay-Doppler (DD) domain rather than the conventional time frequency domain. OTFS exploits several 2D transformations to transform a temporally variant multipath channel into a nearly invariant DD. The information symbols are embedded and the channel is represented sparsely in the DD domain. OTFS combats the challenges like inter-symbol interference, inter-carrier interference, etc., and outperforms the orthogonal frequency division multiplexing scheme. This paper presents a detailed survey of various channel estimation (CE) and signal detection (SD) techniques with vital mathematical expressions adopted to achieve enhanced performance. The significant benefits, techniques aided, and challenges in CE and SD for OTFS to a wide range of applications in high mobility scenarios are also discussed. Moreover, the crucial lessons erudite from the review along with the future research directions and key challenges in integration of OTFS with recent technologies for achieving 6G benchmarks are conversed in this paper.

INDEX TERMS Channel estimation, delay Doppler, high mobility, signal detection, sparse channel, Wigner transform, Zak transform.

I. INTRODUCTION

5G and beyond (5GB) wireless communication demands for seamless and reliable communication between devices along with the superior quality of services (QoS) even in high mobility communication environments like V2V (vehicle to vehicle), V2X (vehicle to everything), bullet trains, millimeter wave (mmWave) applications, and aircraft [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. These environments are doubly-dispersive in nature, possessing both time and frequency dispersions due to multipath delay spread and Doppler spread [12], [13]. Orthogonal frequency division multiplexing (OFDM), a traditional technique is used to reduce the impact of inter symbol interference (ISI) due to time dispersion and aids for more user connectivity with sub-carriers. However, due to significant Doppler or frequency shift dispersion observed in highly dynamic circumstances, orthogonality between the OFDM subcarriers is lost [14], [15]. This results in inter carrier interference (ICI) and the equalization of multiple Doppler is tedious which in turn severely degrades the modulation scheme's bit error rate (BER) performance [16], [17]. Furthermore, to support high mobility scenarios, OFDM requires complex architectures and the computation of signals from sub-carriers

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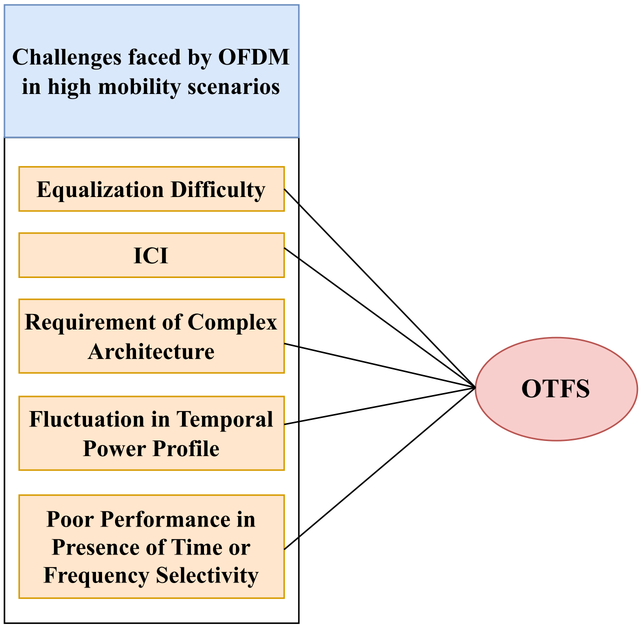

FIGURE 1. Challenges of OFDM in high mobility scenarios.

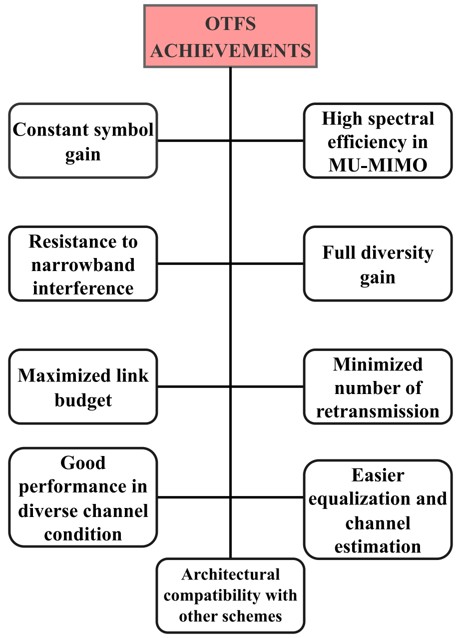

FIGURE 2. Achievements of OTFS.

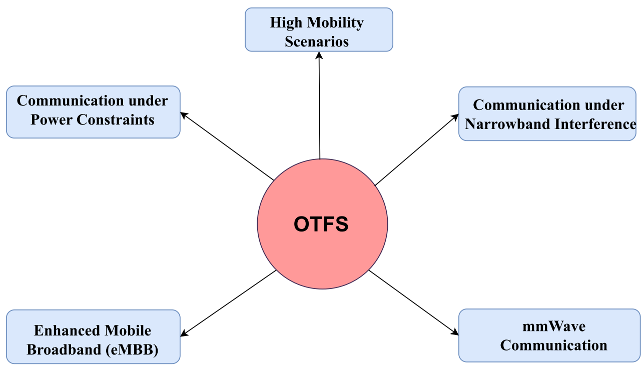

FIGURE 3. Major use cases of OTFS.

is a challenging task. Also, in OFDM, fluctuation in the temporal power profile is high and sub-channel gains are not equal which pulls down the system performance resulting in poor QoS [18].

To mitigate the aforementioned challenges of conventional OFDM, recently a novel modulation scheme has been proposed viz., Orthogonal time frequency space (OTFS) modulation which provides better QoS in high mobility scenarios with seamless connectivity [18], [19], [20], [21]. The major challenges of OFDM are shown in Fig. 1 and the one-step solution to mitigate these issues is OTFS. In environments of fast channel fading due to high Doppler frequency shift, OTFS provides superior robust, and reliable performance in which the data symbols are multiplexed in a signal domain called the delay-Doppler (DD) representation. In par with Heisenberg's uncertainty principle, a signal can't be localized in both time and frequency; nevertheless there exist signals which are parallelly localized in time and frequency. In the time-frequency (TF) domain, the signals are delocalized but in the DD representation, they are localized pulses, indexed by points on the DD grid parameterized by two variables viz., delay τ and Doppler υ. Moreover, τ and υ are prominent physical representations of the mobile channel and thus the multipath channel is sparsely represented in terms of these parameters with the Doppler-variant impulse response given by $h(\tau, \upsilon)$ [22]. OTFS executes modulation and demodulation in the 2D DD domain where the delay and Doppler appear stationary for a long duration of time. This transforms the rapid time-varying multipath channel into an almost time-invariant channel. All the information symbols of an OTFS frame in the DD domain experiences constant gain due to the time invariant nature of the channel [18]. The important achievements of the OTFS modulation scheme as well as the major use cases are listed in Fig. 2 and Fig. 3 respectively. Nevertheless, low complexity with enhanced performance is necessary in OTFS which could be achieved through effective estimation of the channel and detection of the signal at the receiver end for doubly dispersive environment. Besides the enormous research findings and few survey articles [23], [24], [25] on OTFS, there is no proper reporting that could elaborately discuss the channel estimation (CE) and signal detection (SD) techniques in OTFS with its capabilities, pros, and cons. To the best of the author's knowledge, this is the first work that exclusively elaborates an extensive study on the latest CE and SD techniques in OTFS for next-generation communication networks. The highlights of the paper are listed below and the overview of this article is sketched out in Fig. 4.

- OTFS with various transforms required for the modeling of doubly dispersive channels is discussed in a nutshell.
- Presents the recent techniques adopted for CE in OTFS along with mathematical equations for channel modeling in high mobility scenarios.
- Discuss contemporary OTFS SD schemes with low complexity receivers and their associated mathematical models.

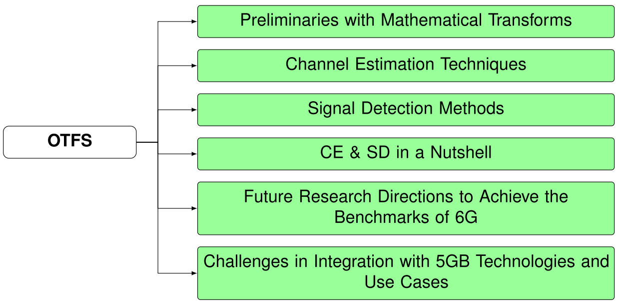

FIGURE 4. Overview of the article.

- The up-to-date CE and SD techniques for achieving better QoS in OTFS are exclusively tabulated with their corresponding achievements and challenges.
- Furthermore, the BER performance at low and high signal-to-noise ratio (SNR) regime with computational complexity analysis for various SD schemes is tabulated.
- The future research directions and challenges for integration of OTFS with 5GB technologies are widely discussed which helps for achieving the needs of 6G.

Moreover, this article attracts researchers working in 5GB communication and helps them to gain knowledge on the basic concepts of OTFS with a mathematical background, and various CE and SD techniques with their uniqueness and challenges. The hot spot of the paper is the future research directions and challenges in the integration of OTFS with recent technologies for 5GB use cases. Also, this paper opens up profuse pathways for researchers to carry out research activities in OTFS to meet the benchmarks of 6G.

This paper is organized as follows: Section II describes the basic concepts and block diagram of OTFS. The various CE techniques with mathematical models for doubly dispersive channels due to high mobility are elaborated in section III. Likewise, the SD methods at the receiver end supported with analytical equations are deliberated in section IV. Existing CE and SD schemes are represented as a tree diagram and a dedicated table for SD schemes with their capabilities and challenges are tabulated in section V. The future research directions and challenges in the integration of OTFS with 5GB technologies and conclusions are gathered in sections VI and VII, respectively. For ease of referencing, all the abbreviations used in this paper are listed in Table 1.

II. PRELIMINARIES OF OTFS

OTFS can be implemented by introducing pre-processing and post-processing blocks to any existing modulation scheme like OFDM. Fig. 5 shows the realization of OTFS from OFDM technique [20]. However, it is not a straightforward task, since OTFS and OFDM are fundamentally different techniques designed for different channel characteristics. While OTFS is optimized for time-varying channels, OFDM is designed for relatively stationary channels. Transitioning from OFDM to OTFS would typically involve a significant redesign of the system. Fig. 6 sketches the block diagram of OTFS modulation which provides a better understanding

TABLE 1. Abbreviations.

Abbreviation	Definition
2D	2 Dimensional
3D SOMP	3 Dimensional Structured Orthogonal Matching Pursuit
5GB	Fifth Generation and Beyond
AEP	Approximate Expectation Propagation
AI	Artificial Intelligence
AoD	Angle-of-Departure
BC	Back-scatter Communication
BER	Bit Error Rate
BF-MMP	Breadth First-Multipath Matching Pursuit
BR	Block Reorganization
BS	Base Station
BSBL	Block Sparse Bayesian Learning
CE	Channel Estimation
CNN	Convolutional Neural Network
CoSaMP	Compressive Sampling Matching Pursuit
CS	Compressed Sensing
CSC	Convolution Sparse Code
CSI	Channel State Information
DA	Data Augmentation
DAMP	Denoising Approximate Message Passing
DBN	Deep Belief Network
DC	Dolph-Chebyshev
DD	Delay-Doppler
DDLCSI	Delay-Doppler Location Channel State Information
DensNet	Dense Network
DFE	Decision Feedback Equalizer
DF-MMP	Depth First-Multipath Matching Pursuit
DFO	Doppler Frequency Offsets
DL	Deep Learning
DNN	Deep Neural Network
DnCNN	Denoising Convolutional Neural Network
eMBB	enhanced Mobile Broadband
EP	Expectation Propagation
FSS	Fractional Spaced Sample
GNN	Graph Neural Network
IASC	Integrated Sensing and Communication
ICEDD	Iterative Channel Estimation Data Detection
ICI	Inter-Carrier Interference
ICMP	Iterative Combining Message Passing
ICSI	Imperfect Channel Sate Information
IDI	Inter-Doppler Interference
IM	Index Modulation
IRS	Intelligent Reflecting Surface
ISFFT	Inverse Symplectic Finite Fourier Transform
ISI	Inter Symbol Interference
LMMSE	Linear Minimum Mean Square Error
MAP	Maximum a Posteriori
MCMC	Markov Chain Monte Carlo
MF	Matched Filter
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
mMTC	massive Machine Type Communication
mmWave	Millimeter Wave
MP	Message Passing
MRC	Maximal Ratio Combining
MSP	Modified Space Pursuit
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OMP	Orthogonal Matching Pursuit
OTFS	Orthogonal Time Frequency Space
PAPR	Peak Average Power Ratio
PDF	Probability Density Function
PIC	Parallel Interference Cancellation
PMF	Probability Mass Function
PN	Pseudo-Random Noise
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QRD	QR Deconstructed

of various transformations employed for the conversion of information symbols from the DD to the TF domain and vice versa. The symplectic duality i.e., translation between

TABLE 1. *(Continued.)* **Abbreviations.**

RDN	Residual Dense Network
ResNet	Residual Network
RIS	Reconfigurable Intelligent Surface
RSMA	Rate Splitting Multiple Access
SAGIN	Space Air Ground Integrated Network
SBL	Sparse Bayesian Learning
SCMA	Sparse Code Multiple Access
SD	Signal Detection
SDR	Software Defined Radio
SER	Symbol Error Rate
SFFT	Symplectic Finite Fourier Transform
SIC	Successive Interference Cancellation
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
TF	Time Frequency
TMP	Turbo Message Passing
UAMP	Unitary Approximate Message Passing
UAV	Unmanned Aerial Vehicle
URLLC	Ultra-Reliable Low Latency Communication
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VB	Variational Bayes
VLC	Visible Light Communication
ZF	Zero Forcing

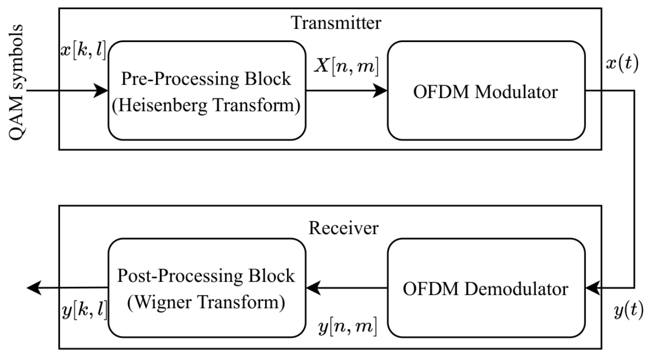

FIGURE 5. **OTFS through OFDM.**

the DD and TF grids with 2D inverse symplectic finite Fourier transform (ISFFT) and 2D symplectic finite Fourier transform (SFFT) is shown in Fig. 7. The TF plane is discretized by sampling time axes at interval T and the frequency axes at interval Δf to obtain a $M \times N$ grid $\Lambda = (nT, m\Delta f), n = 0, 1, \ldots, N-1, m = 0, 1, \ldots, M-1$. Similarly, the DD plane is discretized to obtain a $M \times N$ grid $\Gamma = (\frac{k}{NT}, \frac{l}{m\Delta f}), k = 0, 1, \ldots, N-1, l = 0, 1 \ldots, M-1$, where $\frac{1}{m\Delta f}$ and $\frac{1}{NT}$ are the quantization steps in the delay and Doppler axes, respectively. The NM information symbols are arranged on the DD grid, represented by $x[k, l]$, where k and l indicates Doppler and delay indices. Using a transmit window function $W_{tx}[n, m]$ and a 2D ISFFT [26], the information symbols $x[k, l]$ in the DD domain are translated to TF domain symbols $X[n, m]$, which is expressed as,

$$X[n, m] = W_{tx}[n, m]\ ISFFT(x[k, l]), \tag{1}$$

where n and m are the time and subcarrier indices, respectively. Heisenberg transform [27], [28] parameterized by TF domain symbol $X[n, m]$ operating on transmit pulse

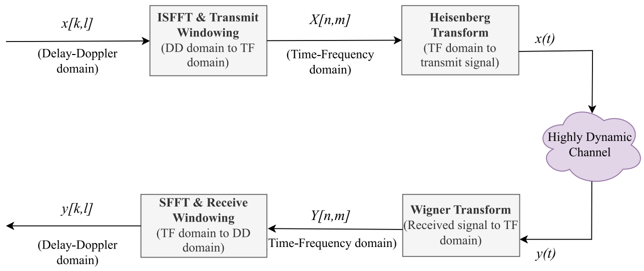

FIGURE 6. **OTFS block diagram.**

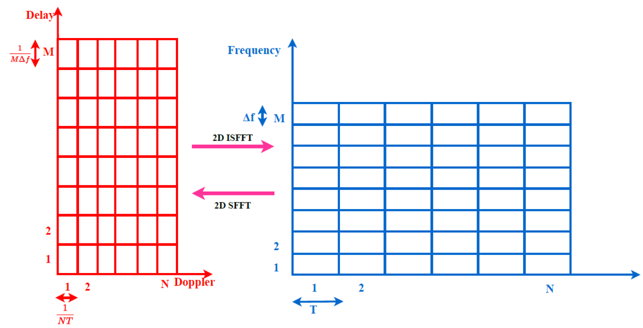

FIGURE 7. **Translation between delay-Doppler domain and time-frequency domain.**

g_{tx}, maps the symbols onto a transmit signal $x(t)$ as,

$$x(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X[n, m]\, g_{tx}(t - nT)\, e^{j2\pi m\Delta f(t-nT)}. \tag{2}$$

From (2), $x(t)$ can be inferred as the superposition of delays as well as modulate operations on the transmit pulse g_{tx}. At the receiver, the received signal $y(t)$ can be interpreted as the sum of reflected copies of the transmitted signal $x(t)$, delayed in time (τ) and shifted in frequency (υ). Mathematically expressed as,

$$y(t) = \int_{\upsilon} \int_{\tau} h(\tau, \upsilon) x(t - \tau) e^{j2\pi\upsilon(t-\tau)} d\tau\, d\upsilon. \tag{3}$$

The received signal undergoes Wigner transform [27], [28] where $y(t)$ in the TF domain is converted back to $Y[n, m]$ by matched filtering with received pulse g_{tx} as,

$$A_{g_{rx}, y(\tau,\upsilon)} = \int g_{rx}^{*}(t - \tau)\, y(t) e^{-j2\pi\upsilon(t-\tau)} d\tau d\upsilon, \tag{4}$$

where, $A_{g_{rx}, y(\tau,\upsilon)}$ is the cross ambiguity function sampled at interval $\tau = nT$ and $\upsilon = m\Delta f$ which yields the 2D sequence $Y[n, m]$ as,

$$Y[n, m] = A_{g_{rx}, y}(\tau, \upsilon)\, |\tau = nT, \upsilon = m\Delta f. \tag{5}$$

To the sequence $Y[n, m]$, a receive window function $W_{rx}[n, m]$ is applied to obtain a shaped time-frequency sequence as,

$$Y_W[n, m] = W_{rx}[n, m]. \tag{6}$$

Finally, the SFFT [26] is applied to $Y[n, m]$ in the TF domain to obtain $y[k, l]$ and mathematically described as,

$$y[k, l] = SFFT(Y[n, m]). \tag{7}$$

Thus, the signal is again converted back to the DD domain and this helps in modeling the high mobility scenario channel with less computational complexity. In general, OTFS utilizes quadrature amplitude modulation (QAM) modulated symbols and uses pilot carriers for CE. The following section encapsulates a detailed survey on various CE schemes in OTFS employing algorithms like maximum likelihood (ML), minimum mean square error (MMSE), and various compressed sensing and neural network techniques. Moreover, SD algorithms like maximal ratio combining (MRC), MMSE, etc., with deep learning methods are also discussed with mathematical background.

III. CHANNEL ESTIMATION IN OTFS

Channel estimation in OTFS is usually performed by using pilot-based approach. The channel path is first determined by transmitting the pilot and comparing the received signal to a threshold, after which the channel coefficient is estimated [29], [30], [31], [32], [33]. To avoid interference between the pilot and the information symbols, an adequate guard band should be provided for the pilot. However, in real-time scenario, a large number of devices with different mobilities and delay spread is expected to be served by the base station, which requires a large guard band, thereby reducing the spectral efficiency. Moreover, if the guard band isn't adequate, the BER performance deteriorates and there exists a trade-off. Various CE techniques have been adopted to ensure enhanced performance in terms of BER, spectral efficiency, and data rate. CE techniques are broadly classified into two types, viz., pilot-based methods and compressed sensing (CS) techniques. In the former scenario, the pilots are employed in such a way that they are standalone or superimposed or embedded.

A. PILOT BASED TECHNIQUES

Pilot arrangements play a vital role in estimating the channel and aid in enhancing the performance of OTFS. So far in literature, CE is carried out by three kinds of pilot nature viz., separate pilots, superimposed pilots and embedded pilots. PN sequence characteristics are also aided for CE [34] in which the PN sequence enacts as pilots. The estimation is done by evaluating three main channel parameters, viz., fading coefficient (α_i), delay shift (δ_i) and Doppler shift (υ_i) of the ith path, for $i = 1, 2, \ldots, P$, where P represents the number of channel paths or the sparsity. The impulse response in the DD for the n^{th} path is expressed as,

$$h(\tau, \upsilon) = \sum_{i=1}^{P} h_i \delta(\tau - \tau_i)\delta(\upsilon - \upsilon_i), \tag{8}$$

where τ_i, υ_i and h_i represents the delay, Doppler and fading coefficient for i^{th} path. The input and channel relation is mathematically expressed as,

$$y(t) = \sum_{i=1}^{P} h'_i e^{j2\pi\upsilon_i t} x(t - \tau_i) + \nu(t) \tag{9}$$

where $h'_i = h_i e^{j2\pi\upsilon_i\tau_i}$. The PN sequence $S \in \hbar$ is used as pilot, where $\hbar$ denotes the complex-valued functions of integers from 0 to $N_p - 1$, where N_p represents the addition and multiplication modulo [32]. The received signal is sampled at an interval $T_s = \frac{1}{W}$ from time $\frac{K}{W}$ where $K = \lceil WT_{spread} \rceil$ and sequence $R[n]$ is obtained as,

$$R[n] = \sum_{i=1}^{P} \alpha_i e(\omega_i n) S[n - \delta_i] + \nu[n], \tag{10}$$

where, if $\alpha_i = h'_i e^{j2\pi\upsilon_i K/W}$, $\delta_i = \tau_i W$ and $\omega_i = N_p \upsilon_i / W$ are estimated, h', τ_i and υ_i can be computed for $i = 1, 2, \ldots, P$, which solves the CE problem. The problem of estimating (δ_0, ω_0) is done by defining matched filter matrix Υ of R and S as,

$$\Upsilon(R, S)[\delta, \omega] = \langle R[n], e(\omega n) S[n - \delta] \rangle. \tag{11}$$

If the PN sequence $S \in \hbar$ is of norm one and length N_p then the expression for $\Upsilon(R, S)[\delta, \omega]$ (10) can be obtained with probability of one, as N_p tends to infinity and written as, [33].

$$\Upsilon(R, S)[\delta, \omega] \begin{cases} 1 + \epsilon'_{N_p} & if\,(\delta, \omega) = (\delta_0, \omega_0) \\ \epsilon_{N_p} & if\,(\delta, \omega) \neq (\delta_0, \omega_0), \end{cases} \tag{12}$$

where, $|\epsilon'_{N_p}| \leq \frac{1}{\sqrt{N_p}}$ and $|\epsilon_{N_p}| = \frac{(C+1)}{\sqrt{N_p}}$ for some $C > 0$. From this α_i can be obtained as,

$$\alpha_i \approx \Upsilon(R, S)[\delta_i, \omega_i]. \tag{13}$$

In [30], an embedded pilot-aided CE which relies on the arrangement of pilot, data and, guard symbols on the OTFS frame for minimum overhead is proposed. The arrangement is done to ensure minimum interference between the data and the pilot symbol. CE is performed using the threshold method and its value is chosen with different pilot arrangements, to improve the accuracy. Moreover, the estimation of the multipath channel with both integer as well as fractional Doppler shift is taken into consideration. For the CE in an integer Doppler scenario, the pilot symbol x_p and the data symbols x_d are arranged such that it can be separated at the receiver into two groups. The arrangement of pilots, data, and guards in the OTFS frame for three different scenarios namely, integer Doppler, fractional Doppler with full guard symbols and, fractional Doppler with reduced guard symbols are summarized in Table 2. Here, $[k_p, l_p]$ is any arbitrary DD grid location while l_τ and k_ν represents maximum delay and Doppler values of channel taps. In both integer and fractional Doppler cases, if a path exists, threshold-based method is used for estimation. In the case of fractional Doppler scenario, in contrast to the integer Doppler, the channel parameter is estimated when at least one path with a certain delay tap exists. If the number of guard symbols is increased, the accuracy of CE increases but at the cost of low spectral efficiency. By increasing the number of data symbols and reducing the number of guard symbols, the spectral efficiency can be improved.

TABLE 2. Pilot, data and guard arrangement in the OTFS frame.

	Integer Doppler	Fractional Doppler with full guard symbols	Fractional Doppler with reduced guard symbols
Pilot (x_p)	$k = k_p, l = l_p$	$k = k_p, l = l_p$	$k = k_p, l = l_p$
Guard (0)	$k_p - 2k_v < k < k_p + 2k_v$, $l_p - l_\tau \leq l \leq l_p + l_\tau$	$0 < k < N-1$, $l_p - l_\tau \leq l \leq l_p + l_\tau$	$k_p - 2k_v - 2\hat{k} < k < k_p + 2k_v + 2\hat{k}$, $l_p - l_\tau \leq l \leq l_p + l_\tau$
Data (x_d)	otherwise	otherwise	otherwise

Alternatively, a linear MMSE channel detector with message-passing (MP) is employed in OTFS where a single impulse pilot is used with a simple threshold decision for CE [32], [35]. Under highly noisy conditions, this classical estimation scheme will have poor performance mainly due to false path detection and miss path detection. Likewise, in [36] ML path detection is proposed, which evaluates the channel path's likelihood at the considered delay and Doppler bins to choose the path with the highest likelihood. Together with MMSE CE, which is flexible even with the less powered pilot, the overall pilot power is shown to be reduced significantly. The received symbol $y[k,l]$ is approximated as a Rayleigh distributed random variable having parameters $\sigma^2_{P_{k,l}}$ and $\sigma^2_{WP_{k,l}}$ irrespective of the pilot contribution. For the i^{th}delay path present at grid point $(k_i, i) \in R$, the likelihood is calculated for every k_i using the received symbol $y[k_i, \ i]$ as,

$$L(k_i, i) = Pr(k_i)\, U_{k_i,i}(y[k_i, i]) \prod_{k_j \neq (k_i)} (1 - Pr(k_i)) \times W_{k_j,i}\left(y\left[k_j, i\right]\right), \quad (14)$$

where, U and W are the PDFs of y when the pilots contribute or not respectively, and it is expressed as,

$$U_{k,l}(y) = \frac{|y|}{\sigma^2_{P_{k,l}}} e^{-\frac{|y|^2}{2\sigma^2_{P_{k,l}}}}$$
$$W_{k,l}(y) = \frac{|y|}{\sigma^2_{P_{k,l}}} e^{-\frac{|y|^2}{2\sigma^2_{P_{k,l}}}}. \quad (15)$$

The valid channel path $(\hat{k}_i)$ is identified by choosing the maximum value of likelihood $L(k_i, i)$ as,

$$\hat{k}_i = argmax[L(k_i, i)]. \quad (16)$$

Consequently, multiple impulse-based CE is proposed in [37] to increase the accuracy of CE. Here, additionally the prior channel information is also considered, i.e., the maximum delay and maximum Doppler shifts. Since multiple impulses are employed, in order to cope with the challenge of miss path detection impulse diversity gain is extracted in this approach. The range of maximum Doppler shift υ_{max} and maximum multipath delay τ_{max} can be obtained from $k_{max} = (NT) * \upsilon_{max}$ and $l_{max} = M\Delta f * \tau_{max}$, respectively. At the receiver, prior knowledge of υ_{max} and τ_{max} is utilized to counteract the impact of false path detection, resulting in improved performance over single impulse channel estimating techniques. From each grid, the weighted delay and Doppler is acquired with which the estimated channel matrix is generated. Nonetheless, in most of the prevailing pilot-based CE approaches, the pilot, data, and guard symbols are arranged in the DD grid [38]. The guard symbols in the frame will prevent interference between the data and the pilot but reduce the spectral efficiency of the transmission significantly. In scenarios where the size of the frame is constrained to be short, due to guard symbols, spectral efficiency is highly compensated [35]. To overcome this and to enhance the spectral efficiency, a superimposed pilot and data symbols without including the guard symbols is proposed in [39]. Only a single pilot superimposed with one data symbol is used for CE, therefore the whole frame is utilized for data transmission. As the pilot and data are transmitted in one grid, their interference is unpreventable and the received symbols will have an interference term. The pilot data arrangement is expressed as,

$$x[k,l] = \begin{cases} x_p + x[k_p, l_p] & k = k_p, l = l_p \\ x[k,l] & \text{otherwise,} \end{cases} \quad (17)$$

where, x_p denotes the pilot and $x[k,l]$ denote the data symbols, while k_p and l_p are arbitrary points in the grid. The channel is first roughly estimated using a threshold that considers both the noise and interference of data and symbols. Using the roughly estimated channel, the OTFS symbol detection is carried out using a maximum a posteriori (MAP) detector. Using the Bayes algorithm [40], the channel is more precisely estimated by canceling the interference through symbols detected and roughly estimated channel. However, in practice due to noise, the interference will not be perfectly canceled. Therefore, an iterative algorithm is proposed for the i^{th} iteration in which symbols are detected using the channel estimated in $i-1^{th}$ iteration. Thus, the symbols detected in i^{th} iteration and the channel estimated during $i-1^{th}$ iteration is used for interference cancellation.

Windowing techniques impact the CE accuracy and optimal selection of window design is needed both at the transmitter and receiver in OTFS. To address the CE error through window design a Dolph-Chebyshev (DC) window is adopted to estimate the channel in the DD domain [41]. The DC window makes the channel sparser thereby suppressing the channel spread due to fractional Doppler to a great extent and reduces the error function. The proposed DC windowing technique is superior to conventional rectangular and sine window techniques in terms of reducing the CE error. OTFS with non-orthogonal multiple access (NOMA) for spectral efficiency is proposed in [42], [43], and [44] and the CE technique for OTFS-Sparse code multiple access (SCMA) with NOMA is addressed in [45]. The convolution sparse coding (CSC) technique is utilized for OTFS-SCMA in the uplink scenario. An alternate input-output relation is formed and embedded sparse pilots are aided for CE which takes the upsides of OTFS as well as SCMA. The proposed scheme requires minimal overhead even in dense environments and enhanced performance is achieved in terms of BER, NMSE and spectral efficiency.

In [46] pilot-aided CE is performed with Frank arrays in MIMO systems to enhance the spectral efficiency. The key idea is to arrange pilots in DD domain as orthogonal matrices depending on Frank arrays aiding code division multiple access, thereby mitigating the pilot pollution. This arrangement offers the pilot to share the guard and data symbols with zero sidelobes. Also to further reduce the CE error a threshold-based algorithm is proposed for the MIMO system. Another superimposed pilot-aided OTFS CE is carried out in [47]. The key contribution is two folds viz., no specific slots for pilots are allocated as in conventional methods and as a consequence spectral efficiency is high. The CE in the initial step is performed by considering the data as interference and possesses large NMSE at a high SNR regime which is mitigated by the iterative procedure in the second step. Further, optimal power allocation between data and pilot is carried out which results in high spectral efficiency with less complexity. Likewise, to improve the CE accuracy with less overhead a leakage suppression technique is proposed in [48] by minimization of the isotropic discrete gradients in the TF domain and combining it with standard channel main diagonal estimation.

The CE with enhanced spectral efficacy and low peak average power ratio (PAPR) is proposed in [49]. Here, the pilots are scattered in multiple patterns and the pilots with low power are imposed with data in DD. The multiple data-aided iterative approach is exploited in which multiple received signals are considered for CE and interference between the data symbols is neglected. Another approach viz., threshold-based iterative superimposed pilot technique for MIMO OTFS is exploited for CE in [50]. This work considers the interference by data symbols along with additive noise factor for CE and the interference cancellation is employed at each iteration. The iterative CE data detection (ICEDD) proved to be an efficient method for enhancing the BER, spectral efficiency and MSE with less computational complexity. Whereas, in [51] the fine DD resolution is exploited to decouple the joint estimation of the channel parameters of all paths from the estimation of the channel parameters for individual path. The received DD signal along a given path is a product of a delay term and a Doppler term that decouples the joint two-dimensional estimations of the delay and Doppler shift of a specific path into two distinct estimations. Further, in [52] the pilots are positioned in the TF domain, and along with data it is exploited for estimating the fractional delays and Doppler. The CE is carried out in threefold viz., the pilots and data are overlayed with both TF and DD domain, the pilots and data coincide with TF domain but not on DD and the third scheme with pilots and data not coincided with TF and DD domain. The interference between the data and pilots is mitigated through successive interference cancellation (SIC) and the line fitting technique is aided in estimating the Doppler. The proposed scheme enhances the spectral efficacy, BER performance and reduces the PAPR. Another approach for estimation of fractional Doppler shifts is carried out as two folds in [53] to mitigate the inter Doppler interference (IDI) and reduce the system complexity. Initially, the coarse position of non-zero Doppler is identified through correlation of basis function and the exact position is estimated through quasi-Netwon method in which re-estimate is performed based on previous fractional Doppler estimate in an iterative manner. Analysis reveals that the achieved BER is close to perfect channel state information (CSI) and contributes for less NMSE.

B. COMPRESSED SENSING AND NEURAL NETWORK-BASED TECHNIQUES

CE in OTFS for a massive MIMO environment in the context of the downlink is much needed for overcoming the deficit of channel reciprocity. However, as the number of base station antennas is huge, CE by traditional impulse-based methods turns out to be challenging [30], [32] owing to the fact that time variant massive MIMO channel in the DD domain can be represented as a sparse multipath channel. CE is considered to be a sparse recovery problem and it is estimated through compressed sensing (CS) algorithms [54]. Also, the traditional impulse method under massive MIMO scenarios leads to a high pilot overhead due to the large number of transmit antennas. One of the greedy algorithms viz., 3D structured orthogonal matching pursuit (3D SOMP) is proposed in [55] for OTFS to evaluate delay (τ_i), Doppler frequency (υ_{s_i}) and physical angle-of-departure (AoD) (θ_{s_i}) of the MIMO channel. The down link time-varying channel with N_P dominant path is considered for analysis which turn consists of N_s subpaths. The gain of the subpath at i^{th} dominant path be α_{s_i} and the time-variant channel due to $(p+1)^{th}$ antenna of uniform linear array (ULA) can expressed in terms of τ_i, υ_{s_i} and spatial angle θ_{s_i} as,

$$H_{k,l,p} = \sum_{i=1}^{N_P}\sum_{s_i=1}^{N_s} \alpha_{s_i} e^{j2\pi \upsilon_{s_i} KT_s} p_{rc}(lT_s - \tau_i) e^{-j2\pi p \varphi_{s_i}} \quad (18)$$

where $\varphi_{s_i} = \frac{d}{\lambda} sin\theta_{s_i}$ in which $d = \frac{\lambda}{2}$ and $\theta_{s_i} \in [-\pi/2, \pi/2]$, p_{rc} is the pulse shaping filter and φ_{s_i} is the spatial angle associated with θ_{s_i}. The DD space channel impulse response in terms of l, k, p (delay, Doppler, space) is expressed as,

$$H^{DDS}_{l,k,r} = \sum_{n=1}^{N} h(n-1)(M + N_{CP}) + 1, (l)_M, \quad pe^{j2\pi(n-1)\frac{k}{n}}. \quad (19)$$

The DD angle channel is calculated by taking inverse discrete Fourier transform to the DD-space along p and is expressed as,

$$H_{l,k,r}^{DDA} = \sum_{i=1}^{N_p} \sum_{s_i=1}^{N_s} \beta_{s_i} \Upsilon_N \left(\upsilon_{s_i} NT - k\right) p_{rc}\left((l)_M T_s - \tau_i\right) \times \Upsilon_N \left(r - \varphi_{s_i} N_t\right), \quad (20)$$

where, $\beta_{s_i} = \alpha_{s_i} e^{j2\pi \upsilon_{s_i} T_s}$, and $\Upsilon_N(x) = \sum_{n=1}^{N} e^{j2\pi \frac{x}{N}(n-1)}$, The function $\Upsilon_N(x)$ is approximately zero if $|x| > 1$. So, $H_{l,k,r}^{DDA}$ will have non-zero value when $k \approx \upsilon_{s_i} NT$, $l \approx \tau_i M \Delta f$ and $r \approx \varphi_{s_i} N_t$. Due to the limited number of dominant paths, the channel is sparse along the delay dimension l. The Doppler frequency will always be less than that of the system bandwidth, giving rise to block sparsity along the Doppler dimension. Moreover, the angle spread of the antennas is small which leads to burst sparsity along the angle dimension. Thus, the downlink channel is formulated as a sparse recovery problem and mathematically simplified to CS problem [55] which is expressed as,

$$y = \Psi h + v, \quad (21)$$

where, y is the received vector, Ψ is the sensing matrix, h is the channel matrix and v is the noise added. The initial step for 3D SOMP is similar to that of traditional OMP and the correlation vector is evaluated between the sensing matrix (Ψ) and the residue (r). Subsequently, the correlation vector is transformed to a 3D tensor and the dominant paths are found consecutively with the aid of each support element. The iterative process of each dominant path contributes to the channel matrix.

In an uplink context of OTFS multiple access (OTFS-MA), the channel matrix can also be sparsely represented in the dD domain and the estimation of the channel can be modeled as a sparse recovery problem [55]. In [56], the CE technique is carried out through orthogonal matching pursuit (OMP) [57] and modified space pursuit (MSP) [58]. In the OMP algorithm, the received signal is projected to the sensing matrix for obtaining the highest correlation till the stopping criterion (threshold ϵ applied on the energy of residue) is met. The key benefit of this algorithm is that the number of paths or gains on these paths is not required to be known. Compared to the OMP algorithm, the space pursuit (SP) algorithm is known to obtain more resilient sparse recovery. However, understanding the underlying sparsity is critical for the SP algorithm and MSP evaluates the support (number of paths) and computes the estimated support values (channel gains) by itself in an iterative manner.

Moreover, instead of estimating the effective DD domain channel response, which is frequently used in the literature, sparse Bayesian learning (SBL) is adopted in [59] for CE. The original DD domain channel response is considered, to prevent channel spreading brought on by fractional delay and Doppler shifts and to fully utilize the channel sparsity in the DD domain. The on-grid and off-grid components of the delay and Doppler shifts are separated for estimate in the OTFS channel estimation issue, which is described as an off-grid sparse signal recovery problem based on a virtual sampling grid constructed in the DD space. Specifically, the entry indices in the reconstructed sparse vector with significant values jointly determine the on-grid components of the delay and Doppler shifts. Then, in the suggested SBL framework, the associated off-grid components are modeled as hyper parameters that may be calculated using the expectation-maximization method. The normalized mean square error (NMSE) is reduced thereby; achieving CE is an efficient way.

To enhance signal reconstruction in high-Doppler situations, Compressive Sampling Matching Pursuit (CoSaMP) CE with interleaving is suggested for the downlink OTFS massive MIMO system in [60]. Also, Gauss-Seidel based MMSE is aided for uplink OTFS to reduce complexity. Every delay-Doppler constellation symbol is viewed as being independent by the proposed CoSaMP-based CE approach, and a transmission group is assumed to be many subsequent delay-Doppler symbols. From the computational complexity analysis it is shown that the proposed CoSaMP CE with interleaving outperforms conventional techniques. Moreover, to achieve enhanced data rates in OTFS, millimeter wave is exploited for its large bandwidth but the transceiver design and CE is a challenging task with MIMO systems. In par with this, analog and hybrid beam-forming transceivers are designed to enhance the QoS in [61]. Initially, the input-output relation is established for analog and hybrid transceivers and then Bayesian learning and block-sparse Bayesian learning techniques are aided for achieving the CE accuracy. Likewise in [62], the block sparse Bayesian learning (BSBL) technique is adopted for CE in OTFS with MIMO configuration for reducing the complexity and enhancing the performance. Here, the multiple Doppler shifts with same delay is considered as one path and iteratively the size of the non-sparse block is updated. The block reorganization is performed along with BSBL to enact the system robust to noise and reduce complexity. However, to overcome the degradation of system performance due to prior DD shifts, a special case of hard threshold pursuit-based CE is proposed in [63]. The DD locations and its CSI along with DD paths is estimated through two-choice hard threshold pursuit in which the knowledge of the prior number of DD paths is not required. This CE technique is based on hard threshold pursuit and superior to BSL methods in terms of performance and computational complexity. In the case of cross-domain CE such as air to ground, the Bayesian learning technique is adopted for hybrid beam-forming. In [64] the Bayesian learning based block expectation-maximization is proposed for millimeter wave hybrid beam-forming to exploit the off-grid parameters. Initially, the TF and DD domains are determined and CE is performed through parallel sparse recovery Bayesian algorithm. Apart from these compressed sensing techniques, CE in OTFS is also performed through neural networks which are more efficient, accurate and possess less complexity. In [65] the model driven deep-learning algorithm combines elements of traditional signal processing techniques viz., denoising approximate message passing (DAMP) and state evolution equation with modern deep learning approach termed as denoising convolution neural network (DnCNN) to enhance the performance of a communication system that utilizes SISO OTFS modulation. The algorithm's goal is to improve the accuracy of signal recovery, particularly in the presence of noise. The state evolution equation provides a theoretical framework for predicting the algorithm's performance, specifically in terms of NMSE. Likewise, the deep learning-based approach for estimating the fractional Doppler channel intended for air-to-ground communication scenarios that involve high-dynamic Doppler shifts is proposed in [66]. The proposed approach combines the principles of OTFS modulation, traditional pilot patterns, and deep neural networks to estimate the fractional Doppler channel in air-to-ground communication scenarios with high-dynamic Doppler shifts. The DNN processes received pilots in the DD domain to estimate channel parameters, which are then used to enhance signal demodulation using the MRC algorithm.

For ease of inference, the various CE for OTFS with the techniques adopted, analysis carried out, achievements and challenges of each are listed as a nutshell in Table 3.

IV. SIGNAL DETECTION IN OTFS

In this section, the major works related to SD in OTFS are discussed with its mathematical background. From the literature, SD can be broadly classified into two, viz., linear/non-linear detection and deep learning-based detection methods. SD is also a key factor in deciding the QoS and it impacts the BER, spectral efficiency and data rate.

A. LINEAR AND NON-LINEAR DETECTION

1) MESSAGE PASSING TECHNIQUE

The detector with low complexity and less computation has gained major attraction in OTFS systems. An iterative approach, based on MP for OTFS SD, is proposed in [32]. In [67], the input-output relation for SD with n_a number of antennas is given by,

$$y_{MIMO} = H_{MIMO}x_{MIMO} + v_{MIMO}, \tag{22}$$

where, $x_{MIMO} = [x_1^T, x_2^T, \cdots, x_{n_a}^T]^T$, $y_{MIMO} = [y_1^T, y_2^T, \cdots, y_{n_a}^T]^T$, $v_{MIMO} = [v_1^T, v_2^T, \cdots, v_{n_a}^T]^T$ and

$$H_{MIMO} = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1n_a} \\ H_{21} & H_{22} & \ldots & H_{2n_a} \\ \vdots & \vdots & \ddots & \vdots \\ H_{n_a1} & H_{n_a2} & \ldots & H_{n_an_a} \end{bmatrix}.$$

The non-zero positions of H_{MIMO} in (22) are formulated as a vector graph which is sparsely connected with each variable and observation node. For each iteration t, the mean $(\mu_{ba}^{(t)})$ and variance $((\sigma_{ba}^{(t)})^2)$ of the interference term I_{ba} is passed as a message from the observation node y_b to the variable node x_a. The corresponding probability mass function (pmf) vector $p_{ab}^{(t+1)}$ with the elements is given by,

$$p_{ab}^{(t+1)} = \Delta p_{ab}^{(t)}(a_j) + (1-\Delta)\Delta p_{ab}^{(t-1)}(a_j), \tag{23}$$

where, the damping factor Δ is used for improving the convergence rate at the range $(0, 1]$. Messages are passed from y_b to x_a and from x_a to y_b until the required condition in (20) is satisfied which determines the number of iterations or till the allowed number of iterations is achieved.

$$max \left| p_a b^{(t+1)}(a_j) - \Delta p_a b^{(t)}(a_j) \right| < \in . \tag{24}$$

The output symbol is detected according to the MAP decision rule. The detected symbol, $\hat{x}_a$ is given as,

$$\begin{aligned} \hat{x}_a &= \arg max\ p_a\left(a_j\right),\ a \in 0, 1, 2, \ldots, n_aNM - 1, \\ p_a\left(a_j\right) &= \prod_c Pr\left(y_c | x_a = a_j, H_{MIMO}\right), \end{aligned} \tag{25}$$

where, a_j belongs to the constellation of symbols and c belongs to the set of non-zero positions in a^{th} column of H_{MIMO}. Thus, the signal is detected from the DD domain through the MP technique. In multiuser and MIMO systems, to achieve less number of computation and iterations, the Markov chain Monte Carlo (MCMC) [68] sampling-based SD technique is proposed in [34], for OTFS. MCMC-based Gibbs sampling is employed with a vectorized formulation as given in [67], where the joint PDF for detection is mathematically expressed as,

$$p\left(x_1, x_2, \ldots, x_{NM} | y, H\right) \propto exp\left(-\frac{\|y - Hx\|^2}{\sigma^2}\right). \tag{26}$$

An initial vector $x^{(k=0)}$ is chosen randomly for initiating the algorithm, where k denotes the iteration index of the input symbol x. After every iteration, all NM coordinates in delay-Doppler grid are updated and the update of $(k+1)$th iteration is given by,

$$x_{NM}^{(k+1)} \sim p\left(x_{NM} \left| x_1^{(k+1)}, x_2^{(k+1)}, \ldots, x_{NM-1}^{(k+1)}, y, H\right.\right). \tag{27}$$

For the next coordinate update, the acquired solution vector is sent to the $(k+1)$th iteration. Once the distribution converges to a stationary distribution, samples are obtained from the converged distribution. The symbol vector having the least cost $f_{ML}(x) = \|y - Hx\|^2$ in all the iterations is taken as the detected symbol vector. The Gibbs sampling algorithm on the other hand, suffers from stalling, which affects performance at higher SNR. To overcome stalling and reduce the number of iterations, a randomized Gibbs sampling algorithm using temperature parameter α is proposed and given by,

$$p\left(x_1, x_2, \ldots, x_{NM} | y, H\right) \propto exp\left(-\frac{\|y - Hx\|^2}{\sigma^2\alpha^2}\right). \tag{28}$$

2) ZERO FORCING BASED MMSE DETECTION

A low-complexity MMSE and a ZF equalizer-based SD are proposed in [69], which exploits the channel matrix's inherent block circulant nature to minimize the complexity. It utilizes

TABLE 3. Overview of CE techniques.

Ref.No.	Proposed Technology	Analysis Performed	Achievements	Challenges
[30]	CE using threshold method after optimal arrangement of pilot, data and guard symbol	BER versus SNR for integer and fractional Doppler cases	SD and CE performed utilizing a single frame thereby minimizing overhead	Threshold method cannot be extended to massive MIMO
[32]	• MP based iterative algorithm for SD • Pilot impulse based CE	• BER performance of MIMO-OTFS for SISO, 2×2 and 3×3 MIMO systems • BER performance comparison between MIMO-OTFS and MIMO-OFDM in a 2×2 MIMO system • Forbenius norm variation of estimate error as a function of pilot SNR • BER performance of MIMO-OTFS using the estimated channel	• Good yield even at high Doppler frequencies • Less BER degradation for the CE scheme	• CE and SD done in consecutive frames • The estimates get out-dated quickly
[34]	• MCMC sampling based SD • PN pilot based CE	• BER performance of OTFS using Gibbs sampling algorithm • Variation of estimation error as a function of pilot SNR	• For long pilot PN sequence lengths, there exists a small estimation error and BER deterioration • Robust detection at higher Doppler	Done in time-frequency domain, so doesn't utilize the doubly-dispersive nature of channel thereby have high implementation complexity
[36]	• ML based channel path detection and MMSE channel estimator • Pilot-based CE	BER comparison between the CE scheme of pilot aided and proposed ML-MMSE CE scheme	• Flexibility in choosing guard band of pilots • Works well in the presence of data symbol interference and low-power pilot is used	Under massive MIMO and large user environment, more pilots are required which reduces the spectral efficiency
[37]	• CE with multiple impulses and priori channel information	NMSE performance comparison of classical threshold single impulse and multiple impulse CE scheme	• Overcomes the challenge of miss path and false path detection present in single impulse CE • Requires less transmitted pilot-power	Prior channel information is required and system is less efficient as sparsity increases
[39]	MAP coarse symbol detection followed by interference cancellation and refined CE using modified threshold	NMSE performance comparison of proposed schemes with classical schemes	Improvement in spectral efficiency	No improvement in BER performance compared to traditional approaches
[41]	DC window based CE in DD	MSE performance with DC and rectangular window	Enhancement in Channel sparsity and CE	Does not address large channel paths
[45]	CSC-SCMA based CE in uplink scenario	BER, SE and NMSE analysis for high Doppler scenario	Reduced guard band, less complexity and enhanced BER	Optimization of pilot vector to reduce mutual coherence is required
[46]	Frank array based pilot arrangement and integer Doppler estimation	• Auto and cross correlation function for Frank array with 23×23. • NMSE and pilot overhead analysis	NMSE similar to single pilot case and pilot overhead better than single pulse with multiple antennas	Optimization of array size is required
[47]	Leakage suppression based CE in OTFS	Channel main diagonal estimation for Non-line of sight vehicular channel	Enhanced performance in terms of BER and NMSE	Performance in presence of large number of channel paths and reflection need to be considered
[48]	Iterative and non-iterative based Superimposed pilots design	BER, spectral efficiency and MSE analysis with various velocity, Doppler shifts and pilot power	Enhanced spectral efficiency with minimum degradation in BER	Data reliant superimposed pilots and mean extraction is required

TABLE 3. ***(Continued.)*** **Overview of CE techniques.**

[50]	ICEDD threshold technique with data symbol interference and additive noise	ICEDD iterations, BER, spectral efficiency and MSE analysis	Interference cancellation and iterates between data aided CE and signal detection	Optimization of threshold value is challenging if the receiver moves with various velocity
[51]	Fine DD and separability technique for fractional DD	Symbol error rate (SER), and NMSE analysis	No need of matrix inversions and iterative estimation of delay, Doppler separately	The normalized energy threshold value should be wisely made to decrease the number of iterations.
[52]	TF domain CE with pilots and data	BER, MSE and normalized root MSE analysis with various configurations of data and pilots	Estimates fractional delays and Doppler, enhances the BER, spectra efficacy and reduces the PAPR	SIC for interference cancellation and 2D frequency estimation
[53]	Correlation of basis function and quasi-Netwon method for CE of fractional Doppler shifts	BER and NMSE analysis with fixed velocity	Estimates the fractional Doppler shift and mitigates the IDI	Optimal initial value of correlation and stopping value for quasi-Newton need to be chosen wisely.
[55]	Compressed sensing based 3D structured OMP algorithm	NMSE performance comparison against pilot overhead ratio, number of BS antennas, SNR and user velocity	Superior performance compared to other traditional CE methods	Large number of iterations are required if correlation is too close which leads to more computation
[56]	Compressed sensing based technique OMP and MSP based algorithm for CE in uplink OTFS-MA	NMSE performance comparison of MSP, OMP and impulse based CE schemes	• OMP algorithm doesn't require information about the number of paths in the channel • MSP achieves more robust sparse recovery	In OMP, understanding the underlying sparsity is critical
[59]	CE based on 1D and 2D off grid sparse Bayesian learning	NMSE analysis with respect to pilot length, number of paths, Doppler resolution	• Channel spreading is condensed • CE accuracy is improved • System performance (BER) is enhanced	Data aided CE for interference reduction need to be done
[60]	CoSaMP based CE for MIMO OTFS system	• NMSE analysis over velocity and pilot overhead • BER analysis on number of antenna, and number of iteration	Enhanced system performance with less complexity for MIMO systems	Performance in Massive MIMO scenario need to be assessed
[61]	Analog and Hybrid beam forming based transceiver design	NMSE analysis for analog and hybrid beam forming with multiple RF chains	• Enhanced data rate through mmWave • Reduction in terms of Symbol error rate • Low pilot overhead	Estimation of delay and Doppler in single stage
[62]	CE through BSBL-BR for MIMO-OTFS	NMSE and BER analysis with various number of Doppler	• Robust to noise • Enhanced system performance • Multiple Doppler shift in single path cluster	Convergence rate is slow.
[63]	Two choice hard threshold pursuit based CE	NMSE, sparsity and BER analysis with various algorithms	• DD location CSI estimation without prior knowledge of DD paths • Covergence rate is faster • Computational complexity is low	Requires optimal sparsity and hard thresholding for fast convergence.
[64]	Bayesian learning based hybrid beam forming CE with off grid parameters	NMSE analysis with various algorithms	• Cross domain CE (space to ground) • Suitable for mmWave MIMO system	Requires optimal sparsity and hard thresholding for fast convergence.
[65]	DAMP and DnCNN based CE	NMSE analysis with various velocity and grid elements	Robust and achieves target NMSE at low SNR	state evolution analysis is required

the vectorized input-output relation [35] where G_{MMSE} and G_{ZF} are the matrices for transformation in MMSE and ZF equalizers and it is expressed as,

$$G_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H, \; G_{ZF} = (H^H H)^{-1} H^H \tag{29}$$

The channel matrix H is block circulant in nature and it is expressed as,

$$H = (F_M \otimes F_N)^H \Lambda (F_M \otimes F_N). \tag{30}$$

where, F_M and F_N denotes the DFT matrices of size $M \times M$ and $N \times N$, $\otimes$ indicates the Kronecker product matrices, $\Lambda = diag\{\lambda_1, \lambda_2, \ldots, \lambda_{MN}\}$ and λ_i indicates the ith eigenvalue of matrix H. From the property of block circulant matrix ($\mathcal{B}_{M,N}$), it can be shown that $G_{MMSE} \in \mathcal{B}_{M,N}$. Thus, G_{MMSE} can be decomposed as,

$$G_{MMSE} = (F_M \otimes F_N)^H \Psi (F_M \otimes F_N). \tag{31}$$

The property that eigenvalues of G_{MMSE} can be evaluated using the eigenvalue of H is the key feature which reduces the complexity of the proposed MMSE receiver. Ψ is a diagonal matrix with the eigenvalues of G_{MMSE} as element and is obtained from (29) and (30) and given as,

$$\Psi = (\Lambda^* \Lambda + \sigma^2 I)^{-1} \Lambda^*. \tag{32}$$

Thus, from the eigenvalue of H, the eigenvalues of G_{MMSE} is written as,

$$\Psi = diag\left\{\frac{\lambda_1^*}{|\lambda_1|^2 + \sigma^2}, \frac{\lambda_2^*}{|\lambda_2|^2 + \sigma^2}, \ldots, \frac{\lambda_{MN}^*}{|\lambda_{MN}|^2 + \sigma^2}\right\}. \tag{33}$$

The evaluation of eigenvalues of H is done in two steps: computing $\Lambda_i s$ from the eigenvalues of H and computing Λ as,

$$\begin{aligned}\Lambda &= \sum_{i=0}^{M-1} \Omega_M^i \otimes \Lambda_i \\ &= diag\left\{\sum_{i=0}^{M-1} \Lambda_i, \sum_{i=0}^{M-1} e^{\frac{j2\pi i}{M}} \Lambda_i, \ldots, \sum_{i=0}^{M-1} e^{\frac{j2\pi(M-1)i}{M}} \Lambda_i\right\}.\end{aligned} \tag{34}$$

Similarly, for ZF equalizer, the eigenvalues of G_{ZF} are evaluated from the eigenvalue of H as,

$$\Psi = diag\frac{1}{\lambda_1}, \frac{1}{\lambda_2}, \cdots \frac{1}{\lambda_{MN}}. \tag{35}$$

Since, the equalization is done in the delay-Doppler domain, the proposed equalizers have less complexity.

3) ITERATIVE CIRCULANT DETECTION

Likewise, a linear complexity iterative rake detector is proposed in [70], to achieve low complexity in SD for the OTFS modulation system. The input-output relation of OTFS is reformulated in vectorized form by adding a few null vectors in the DD grid to take the aid of the channel matrix block circulant characteristic. This property enables the design of a low-complexity OTFS detector using maximum ratio combing (MRC). The complexity of the system depends on frame size (MN), number of symbol vector estimates L and the number of MRC detector iterations S. The input-output relation from [71] can be mathematically written in a vectorized 2D convolution form as,

$$y_m(n) = \sum_{i=1}^{P} h_i \alpha_i(m,n) X\left([m-l_i]_M, [n-k_i]_N\right), \tag{36}$$

where, P is the total number of paths, h_i, l_i and k_i are the path gain, delay and Doppler shifts, respectively. Since, the pulse-shaping waveform is not ideal in nature, this imperfect bi-orthogonality adds an additional phase shift $\alpha_i(m,n)$ to each channel coefficient h_i. A circular convolution of X with the varying channel is observed due to the phase term and it is expressed as,

$$\alpha_i(m,n) = \begin{cases} e^{-j2\pi \frac{n}{N}} z^{k_i([m-l_i]_M}, & \text{if } m < l_i \\ z^{k_i([m-l_i]_M}, & \text{if } m \le l_i \\ 0, & \text{otherwise,} \end{cases} \tag{37}$$

where, $z = e^{\frac{j2\pi}{MN}}$. From (33), for the condition $m < l_i$ phase shift is dependent on both m and n but for $m \le l_i$ it depends only on m. The first case which depends on n, can be ignored by positioning null symbol vector x_m in the last $l_m ax$ rows of X, and is given by,

$$h_i \alpha_i(m,n) x_{[m-l_i]_M}([n-k_i]_N) = 0, \text{ if } m < l_i, \tag{38}$$

where, $x_{[m-l_i]_M}([n-k_i]_N) = x_{[m-l]_M}([n-k_i]_N)$. Hence, $x_m(n) = 0$, if $m \ge M - l_{\max}$, can be set for $n = 0, 1, \ldots, N-1$. The output y_m can be written as the circular convolution between two vectors which is expressed as,

$$y_m = \sum_{l \in \zeta} \upsilon_{m,l} \circledast x_{m-l}, \tag{39}$$

where, υ_l is the channel Doppler spread vector and $\zeta = l_i$ is the set of delay tap indices of received paths. Further, the circular convolution is converted into product of a vector and a circulant matrix by defining a new vector $K_{m,l}$ expressed as,

$$\begin{aligned} K_{m,l} &= circ[\upsilon_{m,l}(0), \ldots, \upsilon_{m,l}(N-1)], \\ &= \begin{bmatrix} \upsilon_{m,l}(0) & \upsilon_{m,l}(N-1) & \ldots & \upsilon_{m,l}(1) \\ \upsilon_{m,l}(1) & \upsilon_{m,l}(0) & \ldots & \upsilon_{m,l}(2) \\ \vdots & \ddots & \ddots & \vdots \\ \upsilon_{m,l}N-1 & \upsilon_{m,l}(2) & \ldots & \upsilon_{m,l}(0) \end{bmatrix}. \end{aligned} \tag{40}$$

The inter symbol interference (ISI) in the branches intended for combining are repeatedly cancelled in the proposed MRC decoder, thereby enhancing the SNR at MRC output. The output of MRC ($\hat{x}_m$) is given by,

$$\hat{x}_m(n) = \arg\min_{a_j \in Q} \left| a_j - c_m(n) \right|. \tag{41}$$

After the estimate $\hat{x}_m$ is updated, m is incremented and the steps are repeated to estimate every symbol vector $\hat{x}_m$ utilizing the estimate of previously decoded symbol vector as a decision feedback equalizer (DFE) [72]. By estimating the first estimate of the symbols, the MRC detector iterations is reduced, thereby minimizing the computational complexity.

Similar to [69], the block circulant property of the MIMO channel matrix is utilized to minimize the computational complexity of ZF and MMSE equalizers and it is proposed in [73]. Matrix H_{MIMO} is block circulant with size $2NM \times 2NM$ where each block H_{ij} is also a block matrix of size $N \times N$. So, H_{ij} can be written in the form of eigenvalue decomposition and is expressed as,

$$H_{ij} = (F_M \otimes F_N)^H \Lambda_{ij}(F_M \otimes F_N). \tag{42}$$

The term Λ_{ij} is a diagonal matrix having the eigenvalues of H_{ij}. The elements of Λ_{ij} are given by,

$$\Lambda_{ij} = \sum_{k=0}^{M-1} \Omega_M^k \otimes {\Lambda_{ij}}^{(k)}. \tag{43}$$

where, $\Omega_M = \text{diag}\left\{1, \omega, \ldots, \omega^{M-1}\right\}$ with $\omega = e^{j2\pi/M}$ and ${\Lambda_{ij}}^{(k)}$ is a diagonal matrix consisting of the eigenvalue of kth circulant block of H_{ij}. The proposed equalizer is based on the lemma 1, proposed for G_{MMSE} and G_{ZF}.

Lemma 1: If a 2×2 matrix H_{MIMO} is block circulant in nature with blocks $H_{ij} \in \mathcal{B}_{M,N}$, then the matrices G_{MMSE} and G_{ZF} are also 2×2 block circulant matrix with blocks in $\mathcal{B}_{M,N}$. The initial step is to compute the eigenvalue of each block H_{ij} of the matrix H_{MIMO} which is given as,

$$\Lambda_{ij} = diag\left\{\sum_{k=0}^{M-1} {\Lambda_{ij}}^{(k)}, \sum_{k=0}^{M-1} e^{\frac{j2\pi k}{M}} {\Lambda_{ij}}^{(k)}, \ldots, \right\} \times \left\{\sum_{k=0}^{M-1} e^{\frac{j2\pi(M-1)k}{M}} {\Lambda_{ij}}^{(k)}\right\}. \tag{44}$$

From the eigenvalues of H_{ij}, the eigenvalues of G_{MMSE} is calculated and computation of $G_{MMSE}y_{MIMO}$ is done by,

$$G_{MMSE}y_{MIMO} = I_{n_t} \otimes (F_M \otimes F_N)^H \Gamma_{eff} \times \left(I_{n_t} \otimes (F_M \otimes F_N)\right), \tag{45}$$

where, I_{n_t} is an identity matrix, Γ_{eff} denotes the matrix containing the eigenvalues of G_{ij}, which in turn is a block in the matrix G_{MMSE}. Similar to the MMSE equalizer, low-complexity ZF equalizer is proposed taking into account the key property that the matrix G_{ZF} is also block circulant in nature. G_{ZF} can be written as,

$$G_{ZF} = I_{n_t} \otimes (F_M \otimes F_N)^H \Upsilon_{eff} \left(I_{n_t} \otimes (F_M \otimes F_N)\right). \tag{46}$$

The computation of Υ_{eff} from Λ_{ij} is similar to computing Γ_{eff} from Λ_{ij}, and the rest of the steps are the same as that of MMSE equalizer.

4) MULTIPLE ANTENNA AND BEAM FORMING DETECTION

OTFS receiver for the high-mobility V2X communication is proposed in [74] where multiple antennas provide high-spatial resolution with separate multiple Doppler frequency offsets (DFOs) associated with multiple paths. Due to this, the channel sparsity is improved and the complexity of SD is reduced [75], [76], [77]. A beam-forming network is adopted in the base station(BS) with a ULA which helps to keep only the signal from any chosen direction while eliminating all other signals. A matched filter (MF) beam former is utilized [78] and the weight vector of direction θ_p is given by,

$$w(\theta_p) = \frac{a(\theta_p)}{N_r}, \tag{47}$$

where, $a(\theta_p)$ is the steering vector and N_r is the number of receiver antennas. The beam formed received signal $\widetilde{r}(\theta_p)$, towards the direction θ_p is expressed as,

$$\widetilde{r}(\theta_p) = R.w^*(\theta_p), \tag{48}$$

where, R is the received signal. The received signal $\widetilde{r}(\theta_p)$ is demodulated using an OFDM demodulator followed by a post-processing block which is mathematically written as,

$$y(\theta_p) = \underbrace{\left(F_N \otimes F_M^H\right)}_{\text{SFFT}} \overbrace{W_R}^{\text{Windowing}} \underbrace{(I_N \otimes F_M)}_{\text{DFT}} \overbrace{(I_N \otimes R_{CP})}^{\text{CP removal}} \widetilde{r}(\theta_p), \tag{49}$$

where, I_N is an identity matrix of size $N\ X\ N$ and R_{CP} is the CP removal matrix. Due to the sparse nature of the channel, MP detection technique is modeled on a sparsely connected factor graph having variable and observation nodes. A joint MP-MRC iterative algorithm is designed in order to reduce the complexity of MP algorithm. The OTFS received symbols on pth beam forming branch can be reformulated [74] and MAP detection rule for the estimation of transmitted data symbols is expressed as,

$$\hat{x} = \arg\max_{x \in \mathbb{A}^{MN}} Pr\left(x \left| y(\theta_p), H(\theta_p)\right.\right), \tag{50}$$

where, the modulation constellation is given by $\mathbb{A}$, the estimated transmitted symbol on pth beam forming branch is $\hat{x}$ and θ_p is the steering vector. The symbol-by-symbol MAP detection rule is given by,

$$\hat{x}_c \simeq \arg\max_{a_j \in \mathbb{A}} \prod_{e \in \varphi_{pb}} Pr\left(y(\theta_p) \left| x_c = a_j, H(\theta_p)\right.\right), \tag{51}$$

where, φ_{pb} is the non zero position in the b^{th} column of $H(\theta_p)$. Iteratively the output for the transmitted symbol is computed and the final decision is established. The complexity depends on the frame size, number of beam forming paths, sparsity level of the channel S and the modulation constellation.

5) PULSE SHAPING AND FEEDBACK TECHNIQUES

The input-output relation with ideal pulse shaping and the rectangular waveform is framed in [79] which contribute for inter-Doppler interference (IDI) and ICI, ISI respectively. A low complexity message-passing algorithm that relies on sparse factor graph and Gaussian approximation is proposed for interference cancellation with phase shifting. Also, the iterative detection method provides convergence of signal and contributes to low complexity in OTFS. The MAP for estimating the transmitted signal is expressed as,

$$\hat{x} = \arg \max_{x \in \mathbb{A}^{MN \times 1}} \Pr(x \mid y, H). \tag{52}$$

The symbol-by-symbols detection of M and N for $c = 1, 2, \ldots..MN$ is mathematically expressed as,

$$\hat{x}[c] = \arg\max_{a_j \in \mathbb{A}} \frac{1}{Q} \Pr\left(y \mid x[c] = a_j, H\right) \tag{53}$$

where $a_j \in \mathbb{A}$ are equally likely and Q is the modulation size. Thus, the system complexity depends on frame size, sparsity, modulation size and maximum number of iterations (n_{iter}). A Linear MMSE (LMMSE) receiver is employed in [80] for achieving low complexity signal detection in OTFS without degrading the performance of BER. The sparsity and quasi-banded structure of the channel matrix in the DD domain are analyzed. The channel matrix with $MN \times MN$ dimension at the receiver end is expressed as,

$$H = \sum_{p=1}^{P} h_p \pi^{l_p} \Delta^{k_p} \tag{54}$$

where, $\pi = circ[0\ 1\ 0 \ldots 0]^T_{MN \times 1}$ is the circulant delay matrix and $\Delta = diag[1\ e^{j2\pi 1/MN} \ldots e^{j2\pi(MN-1)/MN}]$ is the diagonal Doppler matrix. Moreover in [81] an iterative rake detector with a feedback equalizer is proposed for reducing the complexity of OTFS system. The SNR of the signal is improved through maximal ratio combining technique and a simple input-output relation is framed. Further, the decision feedback equalizer in time domain is aided to detect the signals and Gauss-Seidel parameter is utilized in the rake detector for faster convergence of detection. The symbols in the DD grid are grouped into vectors based on their delay indices, and then the relationship between the transmitted and received frames is reformulate using these transmitted and received vectors. By introducing null symbols through zero-padding in the DD domain, the input-output relationship is simplified, enabling the use of maximal ratio combining for the design of a low-complexity detector in OTFS. The additional overhead introduced by the null guard symbols, which are essential for the proposed detection scheme, also allows for the insertion of pilot symbols. These null symbols in the DD domain effectively act as interleaved zero-padding guard bands in the time domain. Leveraging this interleaved time-domain zero-padding, an alternative low-complexity time-domain maximal ratio combining-based detection method for OTFS is also carried out. The complexity of the system is similar to iterative circulant detection technique.

6) VARIATIONAL BAYES AND CLIPPING TECHNIQUE

To further reduce the system complexity in MAP-based techniques, a Variational Bayes (VB) detector is employed in [82] for OTFS system. The optimal value for MAP is attained through kullback-Leibler divergence and then VB is aided to maximize the evidence lower bound thereby achieving low complexity in detection. In contrast to traditional MP receivers, the benefits of the suggested VB approach are: the right choice of the distribution family for the VB method, which makes the maximization of the evidence lower bound problem strictly convex. This means that the globally optimal solution can be efficiently obtained, ensuring a guaranteed convergence for the receiver. Second, the VB approach demands significantly lower complexity compared to MP algorithms. Likewise, a matched filtering-based message-passing detector with a probability of clipping is proposed in [83] for the OTFS system. The sparsity of the original channel matrix is preserved even after matched filtering in TF domain and a channel hardening exploiting message-passing detector is aided for signal detection. The clipping function makes the symbols variance close to each other and helps in achieving low complexity with less BER. After matched filtering the system can be described as,

$$Z = JX_r + V, \tag{55}$$

where, $Z = H_r^T$, $J = H_r^T H_r$ and $V = H_r^T W_r$. Thus. the detection problem is simplified as,

$$\hat{x_{r,i}} = \arg\max_{a_k} \Pr\left(x_{r,i} = a_k \middle| Z_i,\ J\right), \tag{56}$$

where, $a_k \in \mathbb{A}, k = 1, 2 \ldots \mathbb{A}$. The system complexity majorly depends on frame size and modulation constellation.

7) MAP AND UNITARY APPROXIMATION DETECTION

The trade-off between detection complexity and error performance is addressed in [84] where a hybrid maximum a posteriori parallel interference cancellation (MAP-PIC) based detection is proposed. Depending on the channel gains, symbols are classified into two sets with partitioning rule and power optimality between symbols is achieved through hybrid detection. The MAP and PIC techniques are applied to symbols with strong and weak channel gains respectively to mitigate the trade-off. The near optimal symbol wise detection is carried out through symbol wise MAP rule which is mathematically expressed as,

$$\hat{x}[k, l] = \arg \max_{x[k,l] \in \mathbb{A}} \Pr(x[k, l] | Y), \tag{57}$$

where, $\hat{x}[k, l]$ is the element at K^{th} and l^{th} row and column, respectively of the estimated symbol. The decrease in performance of the proposed algorithm when compared to the nearly optimal symbol-wise MAP algorithm is expected to be minimal. This expectation arises from the fact that the employed channel code typically offers accurate estimations of the transmitted symbols. In most cases, an iterative process between the detector and channel decoder is necessary to facilitate the exchange of valuable information from the decoder to the detector. The complexity of detection experiences an exponential increase only with respect to L (number of delay), rather than P (number of paths), which is the case for the nearly optimal symbol-wise MAP algorithm. To strike a balance between performance and complexity, different values of L can be chosen based on the prevailing channel conditions. In [85] detector based on the unitary approximate message passing (UAMP) technique is adopted for reducing the system complexity under the large number of channel paths. The noise estimation in OTFS is also achieved by the UAMP technique and no separate estimator is required. The UAMP allows for efficient signal detection utilizing the block circulant matrix with the circulant block of the channel. Further, the UAMP is also exploited in coded OTFS scenarios for achieving joint iterative detection and decoding. The computational complexity of the UAMP-based detector scales with the logarithm of the OTFS block length per symbol per iteration, and this is irrespective of the value of S (sparsity). Moreover, due to the inherent robustness of the UAMP method, the UAMP-based detector consistently offers significantly improved performance.

8) FRACTIONAL AND EXPECTATION PROPAGATION TECHNIQUE

The rectangular pulse shaping OTFS transmission with fractional spaced sample (FSS) is performed where the sampling rate is multiple integer of symbol rate for imperfect channel state information (ICSI) with a single CP in [86]. The channel equalization is done through iterative combining message passing (ICMP) and turbo message passing (TMP) which helps in reducing the system complexity and also increases system performance. The extrinsic information chart is utilized for analyzing the TMP and weak edges in the factor graph are truncated to achieve reduced complexity. The objective is to attain substantial diversity gain, especially in the presence of high-mobility and time-varying channels. Notably, this approach takes into account the use of practical rectangular pulses, and efficiently incorporates just a single CP for each OTFS frame. Additionally, the unrealistic assumption that delay or Doppler shifts align perfectly with the grid is eliminated. Instead, the design of two efficient receivers viz., ICMP and TMP is aimed at mitigating ISI in the context of OTFS modulation. The complexity of the receiver depends on the number of delay and Doppler, modulation size (Q), channel paths (G), largest terms in channel coefficients (R), maximum number of iterations (n_{iter}) and the terminating iteration (n_t).

Another iterative receiver with a expectation propagation (EP) algorithm is proposed in [87] for reducing the system complexity and signal detection in coded OTFS. The fundamental principle of the EP algorithm is to project a Gaussian distribution onto the complex posterior distribution in the message updating steps. Thus, means and variances calculation can take the role of the complex belief computation. An approximate EP (AEP) approach is proposed by combining many edges on the factor graph into a single edge during the message-passing process to reduce the computational complexity. The OTFS system can be depicted as a factor graph with a sparse structure. In this representation, every variable node is linked to factor nodes, and each factor node is similarly connected to variable nodes. The computational complexity of the receiver depends on the computation of messages from factor nodes to variable nodes and vice versa, with the calculation of the a posteriori probabilities at variable nodes. Similar to MP, to enhance the system performance and reduce the complexity, Gaussian approximate message passing (GAMP) is proposed in [88]. This technique utilizes joint factor graph design and joint message-passing for interference cancellation and also models the a posteriori probabilities through the Gaussian variable. The joint factor graph encompasses all transmit symbols generated in the DD domain. These symbols are transmitted by M subcarriers over N time slots and serve as variable nodes. Additionally, all received symbols in the DD domain is represented as check nodes. The number of update in variable nodes and check nodes decides the computational complexity of GAMP.

9) MMSE AND GRAPH DETECTION

Similar to LMMSE, MMSE-based iterative SD is carried out in [89] for the OTFS system. The highlight of MMSE detection is that it concentrates on each sub channel and the signal is detected across each layer where it is processed both in the time and DD domain. SIC helps to improve the system performance and detection in the time domain paves the way for fewer MMSE coefficients. The detection of transmit signals will be performed by classifying them into distinct layers or levels. To enhance signal quality, the noise and interference from other layers is mitigated using MMSE filtering. The SINR is maximized for the currently targeted layer. In the SIC scheme, systematically the interference introduced by symbols or layers from previous time slots is subtracted in a sequential manner during each iteration. Furthermore, interference originating from subsequent time slots using the estimates obtained in the preceding iteration is canceled such that the overall reception quality is enhanced. The largest delay spread and MN decides the complexity of the receiver.

Moreover, in [90] analysis of the vectorized channel model for OTFS reveals that the tanner graph corresponding to the input-output relation has a small girth. The presence of such a small girth may cause the MP approach to converge to a local optimum and significantly reduce the final performance. Additionally, it is demonstrated that the delay-Doppler channel is a sparse upper block Heisenberg matrix that can be QR deconstructed (QRD) quickly by adding interleavers at the transmitter and receiver. The sorted and unsorted SIC detectors with higher modulation order are built using the channel matrix's QRD. The computational complexity of QRD-based detection is primarily attributed to the QRD operation performed on the sizable channel matrix. The complexity reduction strategy revolves around reducing the number of elements that require elimination below the main diagonal of channel matrix and leveraging the sparsity of channel, which, in turn, diminishes the number of multiplicative operations needed. Unlike UAMP, in [91] several small submatrices (blocks) from the large channel matrix in the time domain is created and a factor graph to visualize the system is proposed. A message-passing receiver built from the graph representation is made to handle the blocks using UAMP. The suggested receiver offers promising performance while not necessitating frequent use of CPs or null symbols. The detection complexity depends only on computation of M and N.

10) INDEX MODULATION AND SUPERIMPOSED PILOT DETECTION

The development of efficient signal detectors for OTFS modulation can be achieved through index modulation (IM) [92]. These detectors include MMSE-based linear equalizers and their associated soft-aided decisions. IM in OTFS is a modulation technique that leverages the spatial diversity of the wireless channel. OTFS itself is designed to combat the challenges posed by time-varying channels, and IM is a concept that can be applied within OTFS to enhance performance. In Index Modulation, information is conveyed not only by the modulation symbols but also by selecting the indices or positions in a predefined set of channel states or resources. This can be particularly useful in systems where the channel conditions vary significantly over time, making it difficult to predict the optimal set of subcarriers or resources for each symbol. By selecting the right indices based on channel conditions, Index Modulation can adapt to the changing channel more effectively. The specific implementation of IM in OTFS can vary based on the system's requirements, the available resources, and the channel model. It typically involves complex signal processing techniques for estimating the channel, selecting the resources, and performing the modulation.

The key advantage of IM in OTFS is its adaptability to time-varying channels. By intelligently selecting resources for each symbol, it can enhance the communication performance in challenging environments, such as wireless systems with significant mobility or fast-changing channel conditions. To enhance the performance, vector-by-vector MP detector which treats each IM symbol as a vector and uses message-passing techniques for detection is utilized. This combination of techniques aims to optimize the detection process in the context of OTFS-IM systems, improving the accuracy of symbol recovery and overall communication system performance. The capability to efficiently identify the active index combination and decode the constellation symbols generated by active blocks, significantly reduces the computational complexity compared to the MMSE and ML detectors. The key factors contributing to complexity are number of users (k), number of DD data (n), number of iterations (T) and number of groups (g). Moreover, in [50] the CE and SD is jointly performed iteratively with adapted MP algorithm for uncoded OTFS. The proposed algorithm aims to enhance the spectral efficiency of a system using a superimposed pilot pattern. The algorithm iterates between data-aided channel estimation, where a threshold method adapts to interference and noise, and message-passing-aided data detection. Additionally, an interference cancellation scheme is introduced to enhance channel estimation efficiency. This algorithm seeks to optimize both channel estimation accuracy and data detection performance while maximizing spectral efficiency.

B. DEEP LEARNING BASED DETECTION

One of the significant features of OTFS is that, the modulated complex symbols have constant gain throughout the frame which in turn aids in achieving full diversity of the channel. However, OTFS requires an enhanced detection method to achieve full diversity. Nowadays, deep learning (DL) techniques play a vital role in enhancing the efficiency of wireless communication systems [93], [94], [95] and provide massive computational capability with a flexible nature. DL-based approaches are employed for SD in OTFS to reap the full diversity gain.

1) DNN BASED DETECTION

In [96] a low complexity, OTFS SD is proposed based on a deep neural network (DNN) which enables low complexity detection even in non-Doppler conditions because of long channel coherence observed in the DD domain. Fully connected DNN can be used for the detection of 2D symbols, where the size of received symbols and input signal set determines the number of input and output neurons. The challenging task is that the number of parameters required to be learned is enormous, i.e., one DNN for one symbol in the transmit symbol vector results in the utilization of several DNNs. This approach reduces complexity as well and the number of output neurons increases linearly and not exponentially as in the case of [97].

In OTFS SD, the MN symbols in the DD grid have to be detected, i.e., $MN \times 1$ transmit vector is estimated, if the received vector y and the channel matrix H are known. The DD symbol-DNN architecture consists of MN DNNs each corresponding to each one of the symbols in the delay-Doppler grid. There are $2MN$ input neurons corresponding to the real as well as imaginary parts of vector y, which is input to the network. The size of the modulation alphabet is the same as the number of output neurons and the probability of each symbol in the alphabet is given by each output neuron. The symbol with the highest probability is chosen

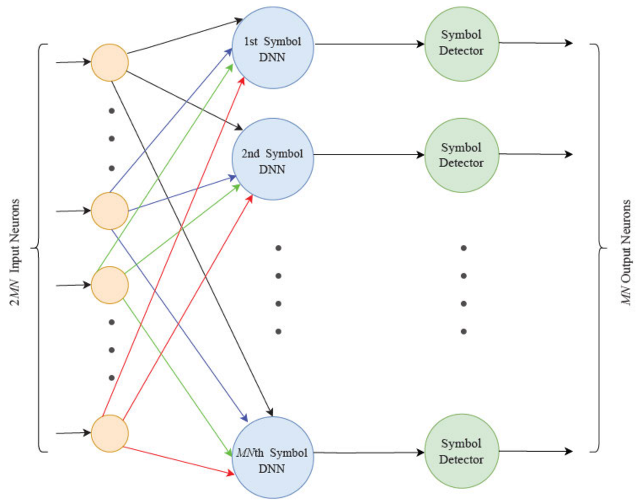

FIGURE 8. DNN architecture for symbol detection in OTFS.

as the transmitted symbol. The DNNs are trained using training samples at both the transmitter and receiver. The number of training samples is chosen randomly, i.e., starting with less number of samples and is incremented until the performance is improved. After training, DNNs are used for training the phase of SD. During the testing phase, information symbols are randomly generated, then modulated using OTFS and transmitted through the channel. Already trained symbol-DNNs are used to detect the received symbols and each DNN learns to map a received vector to a symbol in the transmitted vector. To achieve ease of computation, Tensorflow and Keras frameworks are employed for training and testing which are open-source platforms. Fig. 8 sketches the generalized schematic model of DNN aided for SD in OTFS.

2) CNN BASED DETECTION

Likewise, in [98] DL and data augmentation (DA) based SD for OTFS with 2D convolution neural network (CNN) is proposed. The symbols in an OTFS frame are complex in nature having both real and imaginary parts. In most of the existing approaches, the imaginary part is either concatenated to the real part or eliminated leading to variations in the phase which leads to performance degradation. In this work, each $N \times M$ OTFS frame is given by two real matrices corresponding to the real and imaginary part which in turn is put together as a three-dimensional (3D) tensor ($N \times M \times C$), where $C = 2$ is the channel. Designing a DNN architecture signifies the parameter θ, to estimate $\hat{X}$ which is obtained from OTFS input-output relation as a function of $\hat{f}(Y, \theta)$. Here, MP algorithm has been used as a DA tool for optimizing the DNN model proposed. New features corresponding to the transmitted symbol X are added to the received signal Y to enhance the training features. CNN being well known for combining feature extraction and detection, is utilized to detect the transmitted OTFS symbols along with the DA tool. The model for detection consists of convolution layers succeeded by batch normalization and activation. Each CNN layer's filters extract key aspects from the input data by employing element-wise operations. The input data collected from the preceding layer's output is then normalized through batch normalization. The data is rectified and sent to the next layer using the ReLU activation function. The Sigmoid function is used to estimate the transmitted symbols at the output layer. Finally, the optimal value of the network is obtained from which SD is achieved. Fig. 9 displays the CNN architecture for SD in OTFS.

A Bayesian neural network-based signal detection is proposed in [99] for enhancing the system performance and reducing system complexity. This technique is mainly focused on rich scattering scenarios where more number of reflecting paths towards transmitter is observed. The integration of Bayesian implication and parallel interference cancellation contributes to less matrix inversion but the performance is poor if large numbers of reflectors are present. Also, NN for signal detection makes the system complex due to the presence of various layers to detect the signal. To minimize the CE error and system complexity Bayesian parallel interference cancellation network is adopted in which only three parameters viz., the Bayesian symbol observation, the Bayesian symbol estimate and the decision static combining need to be optimized in each layer of NN, making it an efficient technique. Likewise in [100], a two-dimensional convolutional neural network (2D-CNN)-based DL-based detector model that can easily take advantage of the delay Doppler channel to learn the input-output connection of MIMO-OTFS is proposed. To improve the proposed model's capacity for learning and detection, a data augmentation strategy based on an existing, computationally less expensive linear detector is utilized. Also, in this technique the channel as an input to study the features of the randomly varying channel is not required during training and online deployment, thereby achieving enhanced performance.

3) NN BASED DETECTION

In [101] the use of different neural network architectures for OTFS detection viz., residual network (ResNet), dense network (DenseNet), and Residual Dense Network (RDN), is introduced and compared with existing approaches like Fully Connected-Deep Neural Network (FC-DNN) and Standard CNN. These architectures aim to overcome challenges related to gradients and improve the utilization of hierarchical information in the data. The simulation results indicate that the RDN architecture provides the best performance due to its ability to combining shallow and deep features effectively, thereby, addressing the issue of underutilized hierarchical information. Likewise, the network model for SD without CSI is proposed in [102] called Viterbi-network. The detection process can be executed without prior knowledge of the channel conditions, which can simplify the overall system. This algorithm utilizes a neural network to replace log-likelihood calculations in the Viterbi algorithm and

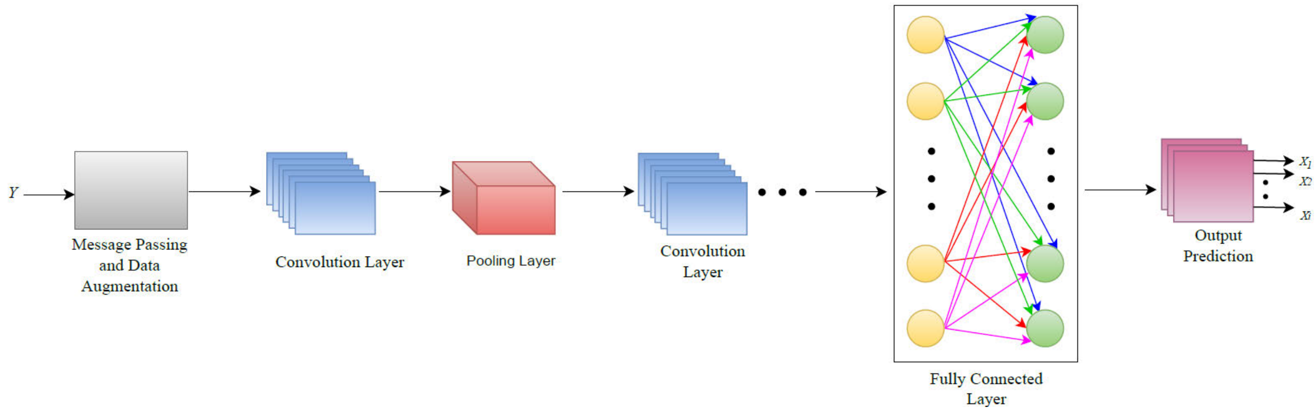

FIGURE 9. CNN architecture for SD.

achieves good performance with a small-sized neural network with a modest amount of training data due model-driven approach. The soft plus function smoothens the training process of the neural network and can potentially lead to faster convergence during the training phase. Whereas, in [103] the proposed approach leverages the power of expectation propagation, a model-driven algorithm, in combination with deep learning principles. By unfolding the EP algorithm into a layered network structure, the algorithm can be formulated in a way that is amenable to deep learning techniques and adding trainable parameters, the framework seeks to achieve faster convergence and improved detection performance for OTFS SD. This integration of model-driven and DL techniques has the potential to create a more effective and efficient solution for OTFS SD challenges. However, the conventional DL methods might struggle to effectively utilize the structural complexity of the input data, especially in the context of the OTFS system with its specific factor graph structure. To mitigate this, a graphical neural network (GNN)-based detector for OTFS is proposed in [104]. Transmit symbols are represented as nodes in a graph, and the GNN iteratively processes these nodes through aggregation, update, and output modules. The detector's goal is to improve signal detection accuracy by leveraging the GNN's ability to capture complex dependencies and relationships between transmit symbols. Further, the impact of hardware impairments on the DL-OTFS system for SD is exploited in [105]. The proposed DL model includes hardware impairments of in-phase and quadrature-phase (IQ) component mismatch and DC offset. Hardware impairments can degrade the quality of received signals and introduce errors. Additionally, the study explores the potential benefits of using data augmentation techniques to enhance the DL-OTFS system's robustness and performance in the presence of impairments.

V. SUMMARY OF CE AND SD TECHNIQUES

In this section, literary works on CE and SD in OFTS to enhance QoS through effective CE and SD thereby reducing computational complexity for high mobility scenarios is gathered in a nutshell. Fig. 10 summarizes the CE and SD in OTFS as a tree diagram to gain knowledge on various methods in CE and SD. Also, the OTFS system can be classified based on the antenna systems (SISO, SIMO, MISO, MIMO and massive MIMO), iterative and non-iterative procedures and linear and non-linear detectors. For ease of inference, the BER and computational complexity achieved by each SD technique are listed in Table 4 which gives a clear picture of the performance of the various state-of-the-art techniques in the OTFS system that could aid in a high mobility environment. Keen study reveals that the complexity of each technique depends on the frame size, the number of dominant paths, delay, number of users and the amount of DD data. To be precise, the linear and non-linear techniques computational complexity seems to be higher due to iterative process and updation involved with channel variations. The techniques, such as least squares estimation or MMSE, can indeed have higher computational complexity, especially when dealing with complex channel models and when iterations are involved.
Non-linear techniques might require iterative optimization processes. Moreover, DL techniques, particularly NN's, can offer advantages in terms of convergence speed and reliability under certain conditions. DL models are data-driven and can adapt to varying channel conditions if a sufficient amount of training data is available. They may converge faster because they can capture complex, non-linear relationships in the data without requiring manual tuning of parameters. However, the choice of SD technique depends on various trade-offs, including computational complexity, training data availability, hardware capabilities, and the specific requirements of the communication system. Also, DL techniques can be data-hungry. They perform well when trained on extensive and diverse datasets, but if insufficient training data is available or if the channel conditions change too rapidly, their performance can degrade. The computational complexity of DL techniques can be high during the training phase, where extensive matrix operations are involved. Inference (i.e., using the trained model for CE) can be more efficient. In some cases, DL techniques might require more computational resources (e.g., GPUs or TPUs) compared

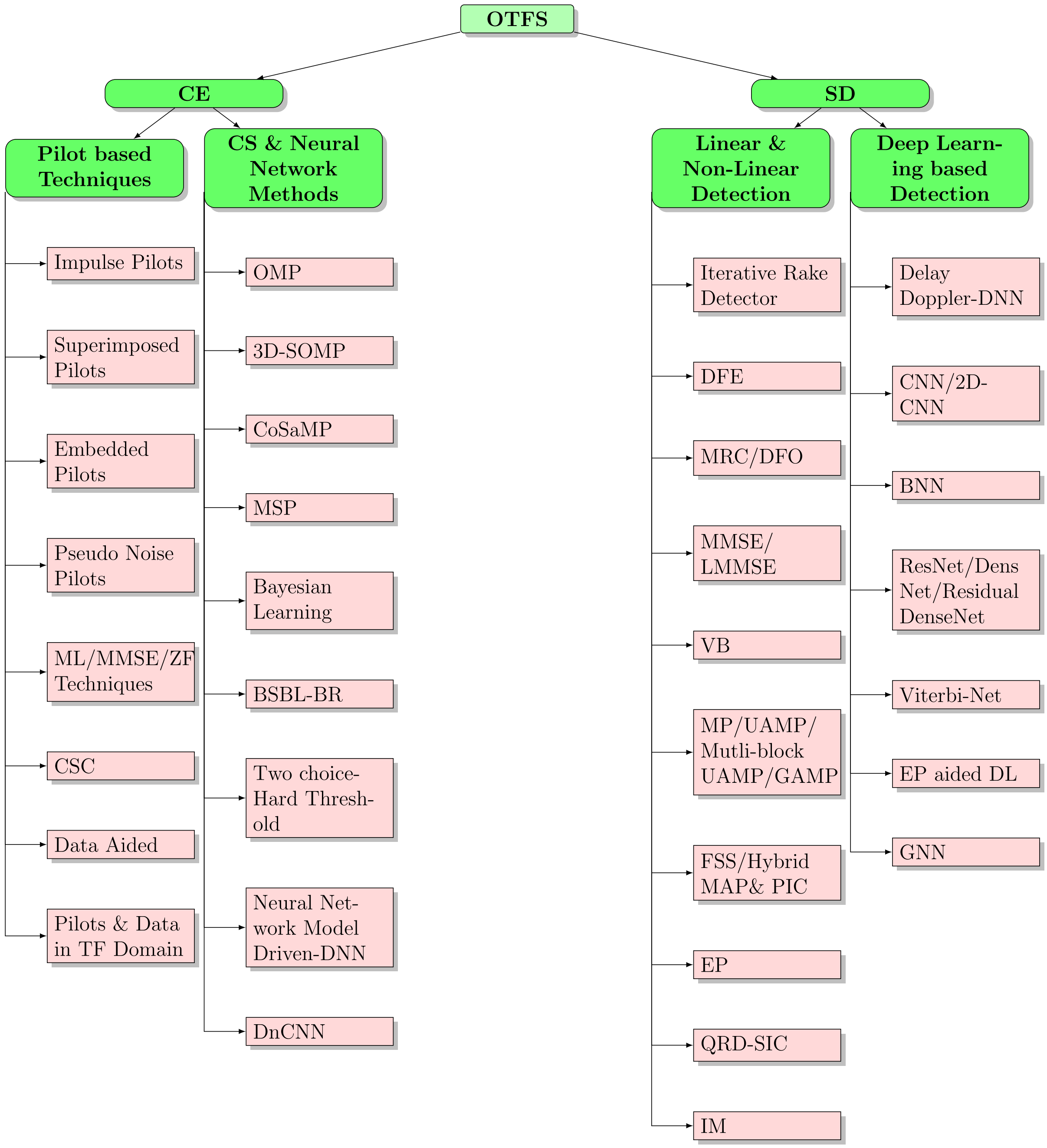

FIGURE 10. Various CE and SD techniques in OTFS.

to traditional linear methods. Furthermore, the technology-aided, analyses performed, achievements and challenges of each SD technique are tabulated in Table 5. (refer annexure)

VI. FUTURE RESEARCH DIRECTIONS AND CHALLENGES

The aforementioned techniques aid for better performance with less complexity in OTFS. However, with the growing ultra-dense network and demand for data rate (V2X, high-speed trains, etc.), it is challenging to stabilize the QoS in high fading environments. To bridge the gap, more recent technologies along with OTFS can be incorporated for achieving enhanced performance. The key aspects of enabling 5GB communication integrated with OTFS for the dynamic fading scenario are put forth in this section.

A. OTFS IN NETWORK SLICING

Network slicing involves creating isolated virtual networks, or slices, on a shared physical infrastructure. These slices are tailored to meet the unique needs of various applications, services, or user groups. This approach enables the coexistence of diverse use cases with varying performance, latency, and reliability demands within a single network.

TABLE 4. Computational complexity for various SD techniques.

Ref.No.	Techniques	BER at 5 dB	BER at 20 dB	Computational complexity
[69]	Linear Equalizer	10^{-1}	10^{-6}	$\mathcal{O}(MNlogMN)$
[70]	Iterative rake detector	10^{-1}	10^{-5}	$\mathcal{O}(SMNL)$
[73]	Linear Equalizer with 2×2 antenna	10^{-1}	10^{-5}	$\mathcal{O}(MNlogMN)$
[74]	Multi-antenna	10^{-2}	10^{-6}	$\mathcal{O}(pMNS\,\lvert\mathbb{A}\rvert)$
[79]	Interference cancellation and iterative detection	10^{-1}	10^{-6}	$\mathcal{O}(n_{iter}MNSQ)$
[81]	Iterative rake decision feedback equalizer	10^{-1}	10^{-6}	$\mathcal{O}(SLMN)$
[82]	VB Detector	10^{-1}	10^{-5}	$\mathcal{O}(\lvert\chi\rvert\, MNP)$
[83]	MP with probability clipping	10^{-1}	10^{-4}	$\mathcal{O}(MN(2\,\lvert\mathbb{A}\rvert + 8))$
[85]	UAMP	10^{-1}	10^{-6}	$\mathcal{O}(MNlog(MN)) + \mathcal{O}(MN\lvert\mathbb{A}\rvert)$
[86]	FSS (ICMP, TMP)	10^{-3}	10^{-7}	$\mathcal{O}(n_{iter}MNGR\,(11Q+1)$, $\mathcal{O}(n_t n_{iter}MNGR(11Q+1)$
[87]	EP	10^{-2}	10^{-6}	$\mathcal{O}(IMN\,(2^Q + S))$
[88]	GAMP	10^{-1}	10^{-5}	$\mathcal{O}(23\,\lvert S\rvert\, LMN + 23MNL)$
[89]	Iterative MMSE	10^{-1}	10^{-5}	$\mathcal{O}(MNL^3)$
[90]	QRD-SIC	10^{-1}	10^{-4}	$\mathcal{O}(M^2N^2)$
[91]	Multi-block UAMP	10^{-1}	10^{-6}	$\mathcal{O}(M^2NlogM)$
[92]	SD with IM	10^{-2}	10^{-6}	$(12n^2 + 14n)KgMNT$
[98]	2D CNN	10^{-2}	10^{-6}	$\mathcal{O}(MN)$
[100]	DL-CNN with MIMO	10^{-3}	10^{-7}	$\mathcal{O}(MNN_R)$
[101]	Data driven DL models	10^{-1}	10^{-5}	$\mathcal{O}(MN)$
[102]	Viterbi-Net	10^{-1}	10^{-4}	$\mathcal{O}(MN \times q^{2p})$
[103]	EP aided DL	10^{-1}	10^{-6}	$\mathcal{O}(TM^3N^3)$
[104]	GNN	10^{-1}	10^{-5}	$\mathcal{O}(N_1N_2MN)$

In 6G, the significance of network slicing persists, playing a pivotal role in accommodating the increasing complexity and varied requirements of applications, industries, and services [106], [107], [108]. The integration of network slicing and OTFS modulation in the context of 6G represents a powerful paradigm shift in designing communication systems that can efficiently cater to diverse and specialized requirements. This integration holds the potential to enhance the flexibility, reliability, and performance of communication networks in the 6G era, which opens exciting avenues for future research.

- Development of advanced algorithms to dynamically allocate resources, considering both the characteristics of OTFS modulation and the varying demands of different network slices, along with optimization of resource allocation for optimal performance and efficiency.
- Designing AI-driven orchestration mechanisms that leverage OTFS's delay-Doppler benefits to intelligently allocate slices based on real-time channel conditions, application requirements, and user needs.
- Investigation of interference management techniques that minimize interference between slices, especially when OTFS's characteristics interact with the dynamics of network slicing and channel conditions.
- Exploring the possibility of how OTFS-enhanced network slicing can improve security and privacy by isolating sensitive slices and using OTFS's robustness to mitigate potential threats.
- Studying the implications of slice mobility in dynamic environments and how OTFS modulation's resilience to channel changes can be harnessed to maintain slice connectivity.
- Exploring the effect of combining network slicing and OTFS modulation optimally to utilize edge and cloud resources for enhanced performance and low latency.
- Conducting comprehensive field trials and simulations to validate the benefits and challenges of integrating network slicing and OTFS modulation in realistic 6G scenarios.

The major challenges and impairments for adoption of OTFS in network slicing for high mobility scenarios are:

- Achieving accurate synchronization and CE becomes more complex when considering the DD characteristics of OTFS within the context of dynamic network slicing scenarios.
- Coordinating interference mitigation strategies between slices and considering the unique properties of OTFS modulation can be complex, particularly in multi-user and dynamic environments.
- Harmonizing the integration of OTFS and network slicing requires collaboration in standardization efforts to ensure seamless interoperability with 6G protocols and interfaces.
- Integrating OTFS modulation with network slices needs to account for dynamic channel variations over time, across slices, and with mobility.
- Ensuring secure isolation between slices while leveraging OTFS's robustness for security enhancement requires careful design and consideration of potential vulnerabilities.
- As slices change dynamically in response to user demands, accommodating these changes while optimizing OTFS modulation can be intricate.

TABLE 5. Overview of SD techniques.

[69]	Low-complexity MMSE and ZF equalizer SD	BER and computational complexity performance comparison of OTFS with conventional and proposed ZF and MMSE equalizers	Reduction in computational complexity	Does not yield exact solution in case of OFDM based OTFS systems where rectangular pulse is used
[70]	Iterative rake receiver using MRC scheme	BER performance comparison of MP, proposed MRC and MMSE-OFDM	Lower complexity and storage requirements	Needs Error control coding and turbo iterations to enhance the performance
[73]	Low-complexity MMSE and ZF equalizer SD	• BER performance comparison of proposed low-complexity MMSE and ZF equalizers for 2×2 MIMO-OTFS system • Investigation on complexity of the equalizers in terms of number of real operations as a function of M	Improvement in computational complexity when compared to conventional MIMO-OTFS equalizers	May not yield expected results when rectangular pulses are used
[74]	Joint MP-MRC SD with multiple antennas for high-mobility V2X	• BER performance comparison of proposed OTFS based receiver and OFDM based receiver • Convergence rate comparison of proposed multi-antenna joint MP-MRC algorithm and MP algorithm with single antenna	Better convergence performance and excellent diversity gain	More number of sub carriers are required if sparsity gets reduced and prior channel angle information is required
[79]	Joint interference cancellation based on message-passing	• BER analysis with ideal and rectangular pulse • BER study over various CE errors and velocity	• IDI, ICI and ISI are reduced • Low complexity signal detection through MP	Analysis under MIMO system and large number of channel gains is required
[80]	LMMSE based detection	BER analysis and comparison with OFDM	• Sparsity and quasi banded structure is exploited • Number of complex multiplication is reduced which results in low complexity signal detection	Three different algorithms are required for computation of received signal
[81]	Iterative rake detector with MRC and DFE	• Base band modelling of OTFS with delay taps • MRC DD analysis • BER, frame error rate and convergence speed analysis	• Input-output arrangement in terms of Delay- time domain • Iterative rake turbo decoder • Gauss-Seidel technique for reducing complexity • Successive over relaxed detector	Does not account for antenna gains and the impact of carrier frequency
[82]	Variational Bayes approximation method for SD	BER analysis in terms of noise variance and number of iterations	• Evidence lower bound maximisation through convex optimization • Quick convergence and efficient detection • Low complexity than MP algorithms	Performance under various velocity and Doppler shift is challenging
[83]	Message-passing detector with Matched filtering and probability clipping	BER evaluation under CE errors, ICSI, damping factor and number of paths	• Good performance in presence of CE errors • Probability clipping for optimal SNR gain	Number of iteration is large and time consuming
[84]	Hybrid MAP and PIC based SD	BER and FER analysis under damping and without damping scenarios	• Enhancement in error performance and complexity. • Symbol division rule according to channel gains • Symbol power optimality	Multi path with MIMO system is challenging

TABLE 5. ***(Continued.)*** **Overview of SD techniques.**

[85]	Unitary AMP based SD	BER analysis under various paths, Doppler shift, number of iterations, rectangular waveform and fractional Doppler	• Noise precision estimation • Iterative Turbo receiver • Joint detection and decoding	Matching simulation and analytical is tedious in AMP due to deflection of channel parameter
[86]	Fractional spaced sampling detection	BER analysis with various user velocity, number of paths, Doppler shift, ICSI and impact of approximation	• ICMP and TMP based receiver. • Extrinsic information chart for convergence of TMP. • Receiver equalization	The non-zero ISI channel is large and needs edge trimming which contributes for performance degradation
[87]	EP based SD with channel parameter awareness	BER analysis with various channel sparsity and subsets	• Approximate EP for channel awareness • Factor graph extraction • Less complex in large fading environments	Optimal channel sparsity and rectangular windowing
[88]	Joint MP aided and Gaussian approximate MP detector	BER analysis with large number of paths and user various velocity	• Joint factor graph based input-output relation • ISI approximation through Gaussian variables	Performance degrades with high user velocity due to Doppler shift
[89]	SIC based iterative MMSE	BER performance with noise power to symbol energy ratio for various detectors	• Exploitation of zero padded OTFS modulation • SIC-MMSE in time domain	Each symbol has to be detected in time domain and later converted to DD
[90]	SIC-QRD based SD	BER performance with various modulation schemes and block lengths	• Identification of short girth from tanner graph • Cancellation of cross-symbol interference through SIC • Adaption of interleavers at transceiver	Vectorized channel needs to be considered
[91]	UAMP based detector	BER performance with various blocks and number of transmission paths	• Less CP utilization without degradation in system performance • Factor graph representation of sub blocks	Turbo decoder system with log likelihood ratio
[92]	Vector-by-Vector MP technique with IM	BER performance with various velocity, modulation and detectors	Enhanced BER performance with aid of soft MMSE detectors	Number of sparsity decides the performance of the system
[96]	SD using DNN	BER performance comparison of OTFS using symbol-DNN, full-DNN and ML detection in static multipath channel	• Gives best performance for large cases in presence of correlated noise with less complexity • Less number of trainable parameters compared to full-DNN detection	Learning rate should be chosen wisely and requires more parameters to train the data set
[98]	2D CNN based SD	BER versus SNR performance comparison with other SD methods	Better performance in high Doppler channel compared to other traditional detectors	Optimal values for epochs and learning rate has to be identified
[99]	Bayesian PIC based NN detector	SER analysis with various number of paths and reflector velocity	• Amalgamation of Bayesian and PIC • Less number of parameter in NN • High detection	MIMO system requires additional parameter to be considered for NN
[100]	2D-CNN with data augmentation for SD	Validation loss calculation and BER analysis for multiple antenna	• Online detection with end-to-end analysis • Enhanced trade-off between detection and performance	Number of epochs need to be optimized for increase in user velocity

TABLE 5. ***(Continued.)* Overview of SD techniques.**

[101]	Data driven DL models (ResNet, DensNet, RDN)	BER analysis of each model with multiple channel	• Shallow and deep features extraction • RDN outperforms ResNet and DensNet	Optimization function need to be chosen wisely for fast convergence
[102]	Viterbi-based NN	BER performance with various velocity, CSI errors and detectors	• Requires only less training data and network • Soft plus function to smooth the training • Prior knowledge on CSI is not required	Physical implementation is challenging and accounts for hardware impairments
[103]	EP based DL approach	BER performance with various detectors, CSI errors and learnable and damping parameters	• Layer wise network analysis • Faster convergence with training parameter optimization	Execution time is more and requires distributed processing
[104]	GNN detector	BER performance with integer and fractional Doppler over various detectors	• Non-Euclidean spatial data handling ability • Replaces MP technique via Markov-random field and GNN • Trade-off between detection and complexity is mitigated	Hyper parameter values plays a vital role in system performance

B. OTFS FOR INTEGRATED SENSING AND COMMUNICATION (ISAC)

OTFS offers significant advantages for ISAC systems, aiming to combine communication and sensing functionalities in a unified framework, and allowing efficient use of resources and improved performance. OTFS provides a direct relation between transmitted signals and channel response in a unified DD domain, which makes it particularly suitable for ISAC systems. One key advantage of OTFS is its resilience to delay and Doppler spreads that occur due to various factors such as channel fading, mobility, and multipath effects. OTFS can effectively handle these distortions, leading to robust communication links even in challenging environments. By leveraging OTFS, ISAC systems can effectively combine communication and sensing functionalities. The unified DD domain simplifies signal processing and facilitates the design of flexible and adaptive communication strategies while maintaining robust sensing capabilities. Few works have explored the integration of OTFS with ISAC. The existing research in [109], [110], and [111] provides valuable insights into the potential benefits and challenges of using OTFS in ISAC systems. However, there are more research directions that need to be explored further to fully exploit the capabilities of this technology. Some of these research directions include:

- In ISAC, interference from sensing operations can impact communication performance and vice versa. Research is needed to devise interference mitigation techniques that allow concurrent sensing and communication without compromising the system's efficiency.
- Efficiently allocating time-frequency resources between sensing and communication tasks is essential to ensure the optimal utilization of the available spectrum and energy resources.
- Developing adaptive resource allocation algorithms that dynamically adjust based on changing channel conditions and user requirements is a challenging but necessary research direction.
- Expanding the capabilities of integrated OTFS systems by integrating multiple sensing modalities (e.g., radar, LiDAR, passive sensing) can open new opportunities for applications like target detection, localization, and environment sensing.
- As OTFS becomes more prevalent, ensuring the security and privacy of integrated sensing and communication systems will be critical. Research into secure communication protocols, authentication, and privacy-preserving techniques is necessary.
- Applying ML techniques to OTFS systems can enhance performance in terms of CE, interference cancellation, and resource allocation. Research in this area can lead to more efficient and adaptable integrated OTFS systems.

The encounters for integrating ISAC and OTFS are:

- OTFS requires sophisticated signal processing techniques for modulation, demodulation, and equalization in the DD domain, which can increase the computational complexity especially when dealing with large bandwidths and high mobility scenarios.
- In OTFS, estimating the channel response in the DD domain can be challenging, especially in dynamic and time-varying environments.
- In ISAC systems, there is a trade-off between communication performance and sensing performance. While OTFS enables joint optimization of both functionalities,

finding the right balance between communication data rate and sensing accuracy requires careful consideration.

C. OTFS IN MASSIVE MIMO

The integration of massive MIMO technology with OTFS modulation holds significant importance for the advancement of wireless communication systems. Massive MIMO allows for simultaneous communication with multiple users using many antennas. OTFS, with its inherent resistance to delay and Doppler spreads, can complement this spatial multiplexing capability by efficiently utilizing the delay-Doppler domain [112], [113], [114]. This combination can significantly boost spectral efficiency, enabling more data to be transmitted in a given bandwidth. Furthermore, OTFS modulation's inherent immunity to inter-symbol and multi-user interference can effectively counter the interference challenges encountered by massive MIMO, ultimately contributing to an elevated link reliability and expanded system capacity. The prospective avenues of future research for the integration of massive MIMO with OTFS are elucidated below:

- Develop algorithms that dynamically allocate antennas, time-frequency resources, and power to achieve maximum spectral efficiency and link reliability.
- The design of innovative interference cancellation and management techniques that leverage the unique properties of OTFS to mitigate interference in massive MIMO scenarios.
- Synchronization methods that account for the challenges of synchronizing massive MIMO and OTFS systems.
- Address security and privacy concerns arising from the integration of massive MIMO and OTFS. Methods to ensure secure communication and protect sensitive data in the combined system need to be explored.

The challenges for aiding massive MIMO for OTFS are:

- Integrating massive MIMO and OTFS technologies requires developing efficient CE techniques that can capture spatial and DD channel parameters accurately in real-time.
- Achieving synchronization between massive MIMO and OTFS components is challenging due to the different synchronization requirements of the two technologies. The synchronization complexity increases when considering both spatial and DD dimensions.
- While OTFS can mitigate multi-path and delay spread effects, interference management becomes complex when dealing with the additional dimension of spatial streams in massive MIMO. Developing effective interference mitigation techniques that address both domains is essential.
- Real-world implementation of massive MIMO and OTFS introduces hardware limitations, such as the number of antennas and processing capabilities. These limitations can impact the achievable performance and complicate integration.

D. OTFS WITH INTELLIGENT REFLECTING SURFACE

The integration of an intelligent reflecting surface (IRS) with OTFS improves the received power gain and enhances the effective diversity gain. These advantages align to create a promising solution that can address challenges in non-line of sight (NLoS) urban environments and high Doppler wireless communication environments. The synergy between IRS and OTFS offers the potential to overcome obstacles associated with signal attenuation, multipath fading, and Doppler shifts. Exploiting the power enhancement capabilities of IRS and the robustness of OTFS results in an overall performance improvement for NLoS urban scenarios and high Doppler environments [115], [116], [117]. Research efforts in this direction can lead to innovative solutions that redefine the boundaries of wireless communication in challenging conditions, unlocking new possibilities for urban connectivity and fast-moving applications. Other research directions include:

- Development of efficient algorithms for jointly optimizing resource allocation, including IRS reflection coefficients, subcarrier allocations, and power distribution, to maximize the combined benefits of IRS and OTFS in terms of signal enhancement and system performance.
- Design of accurate and robust channel estimation techniques that consider both the direct and reflected paths' characteristics.
- Exploration of synchronization methods that accommodate the presence of IRS in the signal path and account for its effects on time and frequency synchronization, especially in the context of OTFS modulation.
- Development of accurate and realistic channel models that account for the impact of IRS elements on signal propagation, including reflections, scattering, and multi-path effects.
- Exploration of unconventional applications that can benefit from the integration of IRS and OTFS, such as underwater communication, vehicular networks, and smart environments.

The major encounters for IRS assisted OTFS system are:

- Accurate CE is crucial for both IRS and OTFS. In the integrated system, CE becomes more complex, requiring techniques to estimate both direct and reflected paths while considering the dynamic nature of the IRS.
- Optimally allocating resources like antennas, subcarriers, power, and IRS reflection coefficients poses a significant challenge. Balancing trade-offs between signal enhancement, control overhead, and efficiency becomes complex.
- While IRS can enhance the signal at the receiver, it can also introduce additional reflections and multi-paths that need to be managed effectively. Designing algorithms to mitigate these effects is complex, particularly when combined with OTFS.
- Combining the complex signal processing of both IRS and OTFS introduces high algorithmic complexity.

Developing efficient algorithms that balance performance and computational requirements is a significant challenge.

E. OTFS IN BACK SCATTERING COMMUNICATION

Integrating backscatter communication (BC) with OTFS modulation presents an exciting opportunity to leverage both technologies for innovative wireless communication systems. BC involves the reflection of existing RF signals to transmit data, making it suitable for low-power and energy-efficient applications. When combined with OTFS, which excels in handling DD spread and multipath effects, a new dimension of capabilities can be unlocked. However, research into the integration of OTFS-aided backscatter communications is relatively unexplored, holding promising potential for exploration. The potential area set open for researchers would be:

- Investigation on how the combined strengths of BC and OTFS can contribute to ultra-reliable low latency communication (URLLC) applications. Developing techniques that enhance the reliability and reduce latency for critical communication scenarios, such as industrial automation, remote surgery, and autonomous vehicles.
- Studying the potential of BC-OTFS integration for creating smart environments through sensor networks. Develop energy-efficient sensing techniques that leverage BC while using OTFS for robust data retrieval.
- Developing dynamic resource allocation algorithms that consider the unique characteristics of BC-OTFS systems in 6G networks, and optimization of resource utilization, including time-frequency slots, power, and backscatter reflection coefficients.
- Investigation of hybrid communication architectures that combine BC-OTFS with other emerging technologies, such as terahertz communication, free-space optics, and network slicing, to create holistic communication solutions.

However, the challenges involved in the integration of OTFS with BC are:

- The use of existing RF signals for BC can introduce interference with neighboring communication systems. Integrating BC with OTFS requires effective interference management strategies to ensure reliable communication and minimize the impact on other users.
- BC involves weak signals, which can be challenging to detect and demodulate accurately, especially in dynamic and noisy environments. Integrating with OTFS modulation adds complexity to the signal processing, necessitating advanced detection techniques.
- BC-OTFS systems need to adapt to dynamic changes in the environment, such as variations in RF signals, mobility, and interference levels. Hence, it is important to develop adaptive strategies that ensure reliable communication.

F. OTFS FOR SPACE AIR GROUND INTEGRATED NETWORK

Space-air-ground integrated networks (SAGIN) are gaining attraction as a solution to extend connectivity beyond terrestrial limits. By combining space, aerial, and ground-based communication links, SAGIN offers customized QoS solutions for various applications [118], [119], [120]. However, integrating SAGIN with technologies like OTFS modulation presents challenges in managing diverse channels, interference, mobility, and security. Despite these challenges, the integration has the potential to provide adaptive, resilient, and multidomain connectivity, addressing connectivity gaps and diverse QoS requirements. OTFS modulation's resistance to multipath and Doppler effects can enhance the reliability of SAGIN's connections across different domains, ensuring seamless communication. The potential research possibilities include the following:

- Adaptive resource allocation that includes the development of algorithms for dynamically allocating resources among the space, aerial, and ground segments of SAGIN while considering OTFS modulation's unique delay-Doppler properties.
- Designing interference management strategies that leverage OTFS's interference-resistant capabilities to optimize performance across SAGIN's multidomain environment.
- Addressing synchronization challenges posed by the dynamic mobility of aerial and satellite components in SAGIN, ensuring accurate timing and phase alignment for OTFS.
- Investigation of energy-efficient solutions that optimize resource usage and power consumption while integrating OTFS modulation into the multidomain SAGIN environment.
- Exploring machine learning techniques to adapt OTFS modulation parameters and SAGIN's network configuration based on historical and real-time data.

This cross-domain approach sets more challenges which are to be addressed for establishing effective communication in SAGIN.

- SAGIN's multidomain nature introduces diverse channel characteristics, requiring adaptive OTFS modulation configurations to accommodate variations in space, aerial, and ground communication links.
- SAGIN involves dynamic aerial and satellite components, introducing synchronization and channel tracking complexities that impact the accurate application of OTFS modulation.
- Balancing resource allocation between different SAGIN domains and optimizing OTFS parameters introduces resource allocation trade-offs that need careful consideration.
- Ensuring consistent QoS guarantees across different domains of SAGIN, considering OTFS's benefits, poses challenges in performance optimization.

G. OTFS FOR VISIBLE LIGHT COMMUNICATION

The integration of OTFS modulation with Visible Light Communication (VLC) offers a compelling fusion of technologies with diverse benefits. VLC's capacity for high-speed indoor data transmission aligns well with OTFS's ability to handle multipath and dynamic channels. This integration has the potential to enhance indoor connectivity, improve spectral efficiency, and enable low-latency communication [121], [122]. The possible avenues for future research include:

- Exploring the synergy between terahertz communication and OTFS modulation in VLC systems, addressing challenges in channel modeling, synchronization, and resource allocation.
- Investigating the integration of massive MIMO techniques with VLC-OTFS to enhance spectral efficiency, mobility support, and interference management in dense 6G networks.
- Developing cross-domain mechanisms that ensure seamless QoS guarantees when transitioning between VLC and OTFS domains, critical for 6G's diverse use cases.
- Studying the integration of VLC-OTFS in URLLC scenarios, addressing latency requirements and reliability challenges.
- Exploring accurate user and device localization techniques by leveraging both VLC and OTFS characteristics, enabling precise indoor positioning in 6G environments.

The potential challenges of OTFS with VLC are:

- VLC operates in the optical spectrum with unique propagation characteristics, necessitating the adaptation of OTFS modulation to handle rapid light attenuation and indoor channel complexities.
- Achieving precise synchronization between VLC's light sources and OTFS modulation becomes intricate due to the speed of light and variable propagation times.
- Designing hardware platforms capable of supporting both VLC and OTFS modulation, while maintaining real-time processing and energy efficiency, poses implementation challenges.
- Enabling seamless QoS transitions between VLC and OTFS domains as users move within 6G networks presents difficulties in maintaining consistent performance

H. OTFS FOR URLLC

In the context of URLLC, which is a crucial component of 5GB wireless networks, the exploration of OTFS modulation has gained significance. URLLC is designed to offer communication services characterized by high reliability and minimal latency, catering to applications like industrial automation, remote surgery, and intelligent transportation systems in the upcoming 6G era [123], [124], [125]. OTFS, due to its inherent resilience to delay and Doppler effects, presents itself as a potential solution for scenarios involving multipath propagation and high mobility. Traditional modulation techniques often encounter challenges in handling fading and time-varying channel conditions. The distinctive structure of OTFS modulation enables effective equalization even in demanding environments, enhancing the ability to recover transmitted symbols even when the channel is severely impaired. The subsequent path of research aimed at integrating OTFS with URLLC encompasses the following areas:

- Develop low-latency algorithms for OTFS modulation and demodulation that meet the stringent latency requirements of URLLC applications. It involves optimizing signal processing steps while maintaining the benefits of OTFS.
- Since effective CE is crucial for reliable communication in URLLC scenarios, investigation of the CE and tracking techniques that work well with the unique delay-Doppler characteristics of OTFS signals is required.
- Develop adaptive resource allocation strategies that maximize the reliability and latency performance of OTFS-based URLLC systems that involve dynamically adjusting parameters such as time-frequency resources and power allocation based on channel conditions.

However, the major confrontation of OTFS for URLLC are:

- OTFS modulation and demodulation require complex processing, which can affect URLLC applications that demand low-latency communication.
- Estimation of the channel response in the delay-Doppler domain can be complex and challenging in dynamic environments.
- For rapidly changing channel conditions, achieving precise synchronization in the delay-Doppler domain may be demanding

I. OTFS FOR ENHANCED MOBILE BROADBAND

Enhanced mobile broadband (eMBB) focuses on significantly improving the capabilities and performance of broadband mobile communication services compared to previous generations of wireless technology [126], [127]. The integration of eMBB with OTFS modulation in the context of 6G wireless networks offers a transformative approach to address the diverse demands of future communication systems. The combination of eMBB's high data rates and OTFS's resilience to channel impairments can deliver an unparalleled hyper-connected experience, ensuring seamless high-speed connectivity for immersive applications like ultra-HD streaming, virtual reality, and augmented reality. Also, the integration of eMBB with OTFS enables 6G to cater to the massive connectivity needs of the internet of things (IoT). The combination of high-speed data rates and efficient handling of multiple devices in varying scenarios can enable the seamless connection of a multitude of IoT devices. Future research directions can encompass the following:

- Investigation of advanced interference management techniques that enable efficient coexistence of eMBB and OTFS signals in complex 6G networks, ensuring optimal performance in shared frequency bands.

- Explore methods to ensure consistent and adaptable QoS across eMBB and OTFS domains, enabling seamless transitions and optimal user experiences in diverse scenarios.
- Designing adaptive modulation and coding schemes that leverage both eMBB's high data rates and OTFS's channel resilience, optimizing performance based on real-time channel conditions.
- Investigating the integration of eMBB and OTFS to enhance URLLC capabilities, enabling critical applications with stringent latency and reliability requirements.

The challenges involved in aiding OTFS for eMBB are:

- The coexistence of eMBB and OTFS signals in the same frequency bands can lead to interference challenges. Developing effective interference mitigation techniques is crucial to maintain the QoS for both systems.
- Adapting OTFS to varying eMBB traffic loads and user requirements while maintaining its distinctive DD resilience necessitates complex algorithms and protocols.
- Conducting comprehensive real-world validation and testing of integrated eMBB-OTFS systems under various 6G scenarios poses practical challenges, especially in terms of testbed availability and complexity.
- Integrating eMBB and OTFS with other 6G components, such as network slicing for diverse use cases, demands seamless interoperation and compatibility, adding to the complexity.

J. OTFS FOR MASSIVE MACHINE-TYPE COMMUNICATIONS

The massive machine-type communications (mMTC)is one of the key use cases and service categories envisioned for 5GB wireless communication networks that focuses on providing connectivity to a massive number of devices and sensors that belong to the IoT ecosystem [128], [129], [130]. The integration of mMTC with OTFS modulation holds the promise of addressing the unique challenges posed by a massive number of low-power IoT devices within the context of advanced wireless communication systems. The research path for mMTC-OTFS integration includes:

- Explore the interference mitigation techniques tailored for mMTC-OTFS integration to ensure reliable communication amidst the high device density and spectrum-sharing challenges.
- Investigating further optimizing OTFS for ultra-narrowband communication, enabling even more efficient utilization of spectrum resources for mMTC devices.
- Studying the impact of mMTC-OTFS integration on highly mobile mMTC devices, addressing synchronization challenges, and adapting the system to fast-changing channel conditions.
- Investigating how distributed and cooperative mMTC communication paradigms can be seamlessly integrated with OTFS, optimizing connectivity, energy efficiency, and coverage

The challenges that have to be addressed are:

- Ensuring the mMTC-OTFS system scales to accommodate the anticipated massive number of IoT devices while maintaining reliable connectivity and efficient resource allocation.
- Balancing energy consumption for mMTC devices with OTFS's signal processing demands, ensuring prolonged device battery life while maintaining communication quality.
- Ensuring seamless coexistence of mMTC-OTFS with other services in 6G networks while managing interference and spectrum resources effectively.

K. EMPOWERING THE 6G ERA WITH OTFS

OTFS has unlocked a new realm of possibilities for data transmission and reception. Its unique approach enables unparalleled reliability, even in the face of challenging environments that have long plagued conventional systems. This innovation has sparked a global paradigm shift, empowering industries, communities, and the ever-expanding IoT with seamless connectivity. To establish a stable and fulfilled cross domain communication in the 6G era, most of the top funding agencies around the globe have spotted the light on OTFS, knowing its prime importance. Visionary agencies such as the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), the Defense Advanced Research Projects Agency (DARPA), the Natural Science Foundation of Chongqing, the National Natural Science Foundation of China, the National Key Research and Development Program of China, the Research and Development Program of Beijing Municipal Education Commission, the Natural Science Foundation of Sichuan Province, the Science and Technology Research Program of Chongqing Municipal Education Commission, the Science and Technology Research Project of Henan Province, the Science and Engineering Research Board, Department of Science and Technology, Government of India, the Australian Research Council (ARC), the ARC Laureate Fellowship, the Defence Science and Technology (DST) Group, the National Research Foundation of Korea (NRF), the Cohere Technologies, Inc., the Federal Ministry of Education and Research of Germany, the Qualcomm Innovation Fellowship, the European Research Council's Advanced Fellow Grant QuantCom, the Engineering and Physical Sciences Research Council Projects, the Royal Society's Global Challenges Research Fund Grant, the UNSW Digital Grid Futures Institute, UNSW, Sydney, the European Research Council (ERC), and the European Space Agency (ESA) have recognized the transformative potential of OTFS. Thus, OTFS stands poised to redefine the landscape of worldwide connectivity, ushering in an era of unprecedented possibilities over high-fading environments.

VII. CONCLUSION

In this survey, we present OTFS as a promising modulation technique under high mobility scenarios for future wireless communication systems. It is highly suitable for high delay and high Doppler fading environments. We present a detailed report of up-to-date techniques in OTFS for CE and SD. The analysis carried out in each scheme along with its attainments and challenges are put forth precisely. Moreover, complexity analysis and BER achieved by various SD techniques are also discussed in a nutshell. Further, the future research directions of OTFS with next-generation technologies is elaborately discussed and the key challenges that have to be addressed are put forth. This sets the platform to open up several research activities in OTFS under high mobility scenarios and motivates the researchers to work towards fulfilling the needs of 6G.

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