Orthogonal Time-Frequency Space Modulation: A Full-Diversity Next Generation Waveform

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Abstract—The sixth-generation (6G) wireless networks are envisioned to provide a global coverage for the intelligent digital society of the near future, ranging from traditional terrestrial to non-terrestrial networks, where reliable communications in high-mobility scenarios at high carrier frequencies would play a vital role. In such scenarios, the conventional orthogonal frequency-division multiplexing (OFDM) modulation, that has been widely used in both the fourth-generation (4G) and the emerging fifth-generation (5G) cellular systems as well as in WiFi networks, is vulnerable to severe Doppler spread. In this context, this article aims to introduce a recently proposed two-dimensional modulation scheme referred to as orthogonal time-frequency space (OTFS) modulation, which conveniently accommodates the channel dynamics via modulating information in the delay-Doppler domain. This article provides an easy-reading overview of OTFS, highlighting its underlying motivation and specific features. The critical challenges of OTFS and our preliminary results are presented. We also discuss a range of promising research opportunities and potential applications of OTFS in 6G wireless networks.

I. INTRODUCTION

The sixth-generation (6G) wireless networks are expected to support ubiquitous wireless connectivity to a wide range of mobile terminals, spanning from autonomous cars to unmanned aerial vehicles (UAV), low-earth-orbit (LEO) satellites, and high-speed trains with a velocity of up to 500 km/h. One of the critical challenges for these services is to provide reliable communications in high-mobility environments. Additionally, the spectrum congestion under 6 GHz creates a fundamental bottleneck for capacity improvement and sustainable system evolution. The ultra-high data rate requirements of panoramic and holographic video streaming push mobile providers to utilize higher frequency bands, such as the millimeter wave (mmWave) bands, where a huge chunk of unused spectrum is available. In general, wireless communications in high-mobility scenarios at high carrier frequencies are extremely challenging due to the hostile channel variations. Relying on adaptive coherent/non-coherent detection [1], [2] is beneficial for attaining a certain degree of robustness against channel variations. Nevertheless, recently an increasing amount of research attention has been dedicated to designing new modulation waveform and schemes for high-mobility communications of next generation wireless networks.

High-mobility communications operating at high carrier frequencies suffer from severe Doppler spread, mainly caused by the relative motion between the transmitter, receiver, and scatters. Conventional orthogonal frequency-division multiplexing (OFDM) modulation, which has been widely used in both the fourth-generation (4G) and the emerging fifth-generation (5G) cellular systems as well as in WiFi networks, suffers in high-mobility scenarios. In particular, OFDM waveform is impaired by the severe inter-carrier interference (ICI), which is aggravated by the fact that the highest and lowest subcarriers exhibit rather different normalized Doppler. Hence synchronization is also a challenge. Recently, a new two-dimensional (2D) modulation scheme referred to as orthogonal time-frequency space (OTFS) modulation [3] has been proposed as a promising candidate for high-mobility communications.

OTFS modulates information in the delay-Doppler (DD) domain rather than in the conventional time-frequency (TF) domain of classic OFDM modulation, which results in delay- and Doppler-resilience, whilst enjoying joint time-frequency diversity (termed as full diversity in [3]), which is the key for supporting reliable communications. Additionally, OTFS modulation has the potential of transforming a time-variant channel into a 2D quasi-time-invariant channel in the DD domain, where its attractive properties can be exploited. Given that most of the existing wireless communication designs have been conceived for low-mobility, low-carrier scenarios, OTFS introduces new critical challenges both in terms of transceiver architecture and algorithmic design. To unleash the full potential of OTFS, challenging fundamental research problems have to be addressed, including channel estimation, detection, as well as multiple antenna and multiple user designs.

This article portrays OTFS modulation conceived for communications over high-mobility environments by providing a comprehensive overview of its fundamental concepts, highlighting the challenges and potential solutions as well as exploring promising areas for future research. The rest of this article is organized as follows. The next section introduces the basics of high-mobility channels, of the delay-Doppler domain and of the OTFS transceiver architecture. The potential application scenarios and research opportunities of OTFS are also presented. Then, before concluding, we demonstrate the most important design challenges of OTFS and their potential solutions.
Time-selective channel models.

II. FUNDAMENTALS OF OTFS

A fundamental question to answer for motivating the research community and industry to investigate OTFS is why we shall perform modulation in the DD domain. Hence, commencing from the channel characteristics of high-mobility communications, we present the basic concepts and properties of the DD domain channels, the DD domain multiplexing, as well as OTFS transceiver architecture and signal waveform.

A. From Time-Invariant to Time-Variant Channels

As shown in Fig. 1, wireless channels can be modeled by a linear time-invariant (LTI) system, provided that the channel impulse response (CIR) is time-invariant or has a long coherence time. In the presence of multiple scatters, the dispersive LTI channel's output is a temporally smeared-out version of the transmit signal, but again, the CIR is time-invariant. In this case, a one-dimensional (1D) CIR in the delay domain $h(\tau)$ is sufficient for characterizing the time-dispersive channel. The Fourier transform (FT) of this CIR is a frequency-selective channel transfer function (CTF). As the delay spread of the CIR is increased, the selectivity becomes more severe, since the separation of the frequency-domain (FD) fades is increasingly proportional to the CIR-length.

However, the assumption of having LTI CIRs may no longer hold in the face of increased user mobility and carrier frequency. Therefore, the linear time-variant (LTV) channel model [4] has attracted considerable research attention in high-mobility scenarios. LTV channels give rise to frequency shifts due to the Doppler effect, yielding a spectrally smeared version of the transmitted signal, i.e., they are frequency-dispersive. Frequency-dispersive channels are time-selective and the separation of the channel's time-domain (TD) fades is increasingly proportional to the Doppler spread. In practice, the LTV channels of high-mobility scenarios are often doubly-dispersive due to the joint presence of dispersive multipath propagation and the Doppler effects, as illustrated in Fig. 1. The transmitted signals suffer from dispersion both in the TD and FD. In such scenarios, each tap of the CIR function is time-dependent, fluctuating according to the rate of $\Sigma$ between consecutive TD fades, as shown in Fig. 2, where $\lambda$ denotes the wavelength and $v$ is the relative speed between the transmitter and receiver. Hence, this results in a 2D CIR function $h(t, \tau)$ in the time-delay domain. In contrast to the traditional way of treating TD and FD dispersion as undesired channel impairments, we can beneficially exploit the additional degrees of freedom (DoF) of these channels for achieving reliable diversity-aided communications over high-mobility channels.

B. LTV Channels in TF and DD Domains

Apart from the time-delay domain channel $h(t, \tau)$, the LTV channels can be equivalently described in either the TF or DD domain, as shown in Fig. 4. To emphasize the TF selectivity, the TF domain channel, $H(t, f)$, can be obtained by the FT of $h(t, \tau)$ with respect to (w.r.t.) the delay $\tau$. Note that $H(t, f)$ can be interpreted as the complex CTF coefficient at time instant $t$ and frequency $f$. Due to the limited coherence time and coherence bandwidth (coherence region in Fig. 2) of LTV channels, channel state information (CSI) acquisition in the TF domain would be challenging and would impose a significant signaling overhead. For instance, for an OFDM system having a carrier frequency of $f_c = 3.5$ GHz and a subcarrier spacing of $\Delta f = 15$ kHz supporting a relative velocity of $v = 300$ km/h, the maximum Doppler shift is $v_{max} = 972.22$ Hz and the OFDM symbol duration including a 20% cyclic prefix (CP) is 80 µs. Assuming that the channel's coherence time is $1/v_{max} = 257.14$ µs, the channel's coherence interval can only accommodate at most 3 OFDM symbols.

Applying the FT to $h(t, \tau)$ w.r.t. $t$ yields the DD domain channel (spreading function), $h(\tau, \nu)$. The DD domain channel $h(\tau, \nu)$ characterizes the intensity of scatters having a propagation delay of $\tau$ and Doppler frequency shift of $\nu$, which directly captures the underlying physics of radio propagation in high-mobility environments. More importantly, the LTV channel in the DD domain exhibits the beneficial features of separability, stability, compactness, and possibly sparsity, as illustrated in Fig. 3 and detailed below, which can be exploited to facilitate efficient channel estimation and data detection.

- **Separability**: Additionally introducing the Doppler domain of wireless channels allows us to separate the propagation paths experiencing an identical delay in this domain. The separability of the DD domain channel fully exploits the maximum available DoF provided by channel fading for achieving the maximum attainable diversity order.
- **Stability**: Only the drastic change of propagation path lengths and moving speeds may cause channel variations
Fourier transform
\[ H(t, f) = \int_{-\infty}^{\infty} h(t, \tau) e^{-j2\pi f \tau} d\tau \]

Symplectic Fourier transform
\[ h(\tau, \nu) = \int_{-\infty}^{\infty} H(t, f) e^{j2\pi (\nu f - \tau \omega)} df \]

Fig. 2. LTV channels in the time-delay, TF, and DD domains.

in the DD domain. Consequently, the DD domain channel fluctuates much slower than the time-delay domain or TF domain channel.

- **Compactness**: It is worth noting that in typical wireless channels, we have \( 4\tau_{\text{max}}\nu_{\text{max}} \leq 1 \) [4], where \( \tau_{\text{max}} \) is the maximum delay and \( \nu_{\text{max}} \) denotes the maximum Doppler shift. As a result, the DD domain channel \( h(\tau, \nu) \) has a compact \((\tau, \nu)\)-domain support within the interval \([0, \tau_{\text{max}}]\) along the delay dimension and in the interval \([-\nu_{\text{max}}, \nu_{\text{max}}]\) along the Doppler dimension. This can be beneficially exploited for efficient equalization.

- **Potential sparsity**: When an open-space rural propagation environment having a limited number of moving scatters is considered, the DD domain exhibits a sparse response [5]. This facilitates accurate channel estimation at a low training overhead, resulting in low-complexity equalization in the DD domain.

Note that the above discussions are mainly related to the deterministic description of LTV channels. More details on the stochastic characterization of LTV channels can be found in [4], [6]. Parameterizing the channel characteristics with the aid of delay and Doppler is not new, and it has been widely used in the areas of radar and sonar. The main benefit of the OTFS waveform is the DD domain multiplexing, which will be detailed in the next section.

C. From TF to DD Domain Multiplexing

The classic modulation techniques typically multiplex data in the TD or FD, which are briefly introduced as follows.

- **Time-division multiplexing (TDM)**: TDM carries information (QAM) symbols in unique, user-specific time-slots, within the same frequency band.
- **Frequency-division multiplexing (FDM)**: FDM multiplexes streams or users in dedicated FD slots occupied at the same time.
- **Code-division multiple access (CDMA)**: The information symbols (of different users) are carried over unique (user-specific) single-carrier TD, multi-carrier FD or multi-carrier time-frequency-domain spreading sequences.
- **OFDM**: OFDM transmits its information symbols by overlapping sinc-shaped orthogonal subcarriers in parallel.
- **Index modulation (IM)**: IM relies on the generalized ON/OFF keying principle applied to any of the available signal resource domains to map the information bits to the indices of spatial-, time- and frequency-domain resources.

However, these traditional modulation techniques may not work well in the face of severe Doppler spread. For instance, the popular OFDM modulation efficiently transforms a frequency-selective fading channel to multiple parallel frequency-flat subchannels, hence allowing a low-complexity

[Notes: Fix the equations and figures to be consistent with the text.]

Fig. 3. OTFS transceiver architecture, the concept of DD domain data multiplexing and their coupling with DD domain channels.
single-tap equalization in the FD for transmission over LTI channels, which is very attractive for practical implementation. However, in high-mobility scenarios, the orthogonality of OFDM erodes when conventional wireless transceivers are adopted.

In contrast to the existing 1-dimensional TD or FD modulation techniques, OTFS is a 2-dimensional modulation technique. In OTFS, the information symbols are carried over 2D localized pulses defined on the DD domain which allows them to enjoy the multiplexing benefits from the aforementioned DD domain channel properties and its manner of interaction with the OTFS transmitted waveform. By increasing the time duration and bandwidth of the transmission, the carrier pulse can be localized to any desired degree, as illustrated in Fig. 3. This, in turns, allows for improved joint DD domain equalization under doubly dispersive channels, see and also where it has been demonstrated that OTFS significantly outperforms OFDM for transmission over high mobility channels in both uncoded and coded systems. The possibility for unlimited pulse localization in the DD domain stands in sharp contrast with the opposite situation in the dual TF domain where the Heisenberg uncertainty principle acts as a fundamental obstruction for localization.

To elaborate further on the benefits of DD domain localization to combat fading in doubly dispersive channels, we note that conventional wireless communication designs treat fading as an inevitable deleterious effect, aiming for combating or exploiting it while ignoring its basic underlying causes. By contrast, OTFS transmitted waveform is specifically designed to beneficially embrace the underlying physics of the propagation environment. In more details, the channel impairments of propagation time delay and Doppler frequency shifts are modeled as a pair of operations imposed by wireless channels on the transmitted waveform. In this setting, fading is viewed as a phenomenon that manifest itself at the channel’s output resulting from a destructive combined effect of this pair of fundamental operations.

By means of representing a signal in the DD domain, the OTFS transceiver generates a complete orthogonal family of waveforms which is closed under arbitrary combinations of operations of time delay and frequency shift. In other words, upon transmitting a signal in this family, the received signal will remain in the family under arbitrary channel impairment. The mathematical structure underlying this unique characteristic of the OTFS waveform family is the quasi-periodicity property of the DD domain signal representation, discussed in . This property gives rise to a 2D (quasi-) circular localized inter-symbol interference (ISI) pattern in the DD domain, representing the channel impairment, as illustrated in Fig. 3. Since both time and frequency shifts are being separated in the DD domain, destructive interference is greatly avoided, and phenomenon of fading is largely mitigated.

**D. OTFS Transceiver Architecture and Waveform**

The OTFS transceiver is shown in Fig. 3 where the modulated (pilot) symbols are firstly mapped to the DD domain. Then, an orthogonal 2D precoding, such as the inverse symplectic finite Fourier transform (ISFFT) and Walsh-Hadamard transform , transplants the DD domain signal into the TF domain. Then, a multi-carrier modulator, such as OFDM or filterbank multicarrier (FBMC) modulator, is employed in each time slot for further transforming the TF domain signal to the TD before being transmitted over the channel. At the receiver side, a cascaded combination of multi-carrier demodulation and 2D orthogonal decoding transforms the received signal back into the DD domain and retrieves the transmitted symbols in the DD domain using an appropriate channel estimator and equalizer. We can observe that the OTFS transceiver can be implemented based on the conventional OFDM transceiver architecture by adding some pre-processing and post-processing blocks, thus making OTFS attractive from an implementational point of view.

As illustrated in Fig. 3, a single pulse representing a symbol at in the DD domain will be spread across the whole TF domain, which is desirable for attaining the potential of full diversity over doubly dispersive channels, provided that each TD and FD sample experiences independent fading. The resultant TD waveform is the fluctuating pulse train seen in Fig. 3 where the fluctuation rate is determined by the Doppler frequency , while the pulse location within each time slot is determined by the delay . Consequently, the TD waveform of OTFS behaves locally like TDMA (localized pulses in the TD), globally like OFDM (localized pulses in the Doppler domain) and spreading like CDMA (2D spreading in the DD domain), thus inheriting their beneficial properties. For example, OTFS has a low peak-to-average power ratio (PAPR), exhibits resilience to narrow-band interference and it is eminently suitable for multi-user scenarios. Additionally, OTFS transforms the violently fluctuating TF domain channel into a quasi-time-invariant channel in the DD domain, which can potentially be exploited for striking a compelling trade-off between the performance, computational complexity and signaling overhead.

Apart from its potential of exploiting full diversity and Doppler-resilience, OTFS also has some further benefits over conventional modulation techniques. For example, despite its multicarrier nature, the PAPR of OTFS is much lower than that of both OFDM and of generalized frequency division multiplexing (GFDM), which is particularly beneficial for power-limited systems, such as the Internet-of-Things (IoT). Additionally, the guard intervals are only required between consecutive OTFS frames, rather than between each OFDM symbol and thus the associated idle time is significantly reduced. Furthermore, as a benefit of its Doppler-resilience, OTFS is more robust against the carrier frequency offset between the transmitter and receiver than OFDM. These advantages render OTFS eminently suitable for high-mobility, high-carrier scenarios.

**III. POTENTIAL APPLICATIONS AND OPPORTUNITIES**

OTFS has been proposed by Cohere back in 2017, but it is still in its infancy. In this section, we discuss its potential in next-generation high-mobility vehicular networks,
mmWave communications, non-terrestrial networks and possibly underwater acoustic communications.

A. Vehicular Networks

Vehicular communications, or vehicle-to-everything (V2X) communications, allow various vehicles to wirelessly exchange information with each other or with roadside units (RSUs) to provide a variety of benefits, including cooperative traffic management, road-safety improvements, and the support of autonomous driving as well as in-vehicle infotainment services. OTFS can play a key role in future vehicular networks owing to its intrinsic advantages in the face of high-mobility channels. The current standards of vehicular communications, such as IEEE 802.11bd and 5G NR V2X, mainly consider OFDM-based waveforms, where the impact of channel variations is mitigated either by inserting a midamble or by increasing the subcarrier spacing. By contrast, the potential channel stability of OTFS exhibited in the DD domain enables prompt initial link setup, agile sidelink scheduling, as well as predictive resource scheduling. Furthermore, the OTFS waveform enjoys a lower PAPR than OFDM, allowing a better communication coverage for vehicular networks. Moreover, as the delay and Doppler frequency are directly related to the distance and velocity, respectively, OTFS modulation is ideal for supporting joint radar sensing and communication services that can work well for vehicular networks.

B. Millimeter-wave Communications

The millimeter-wave frequency band possesses a large amount of under-utilized spectrum and has the potential of offering giga-bit-per-second communication services in future wireless networks. The Doppler effect becomes more severe upon increasing the carrier frequency even at a low/medium velocity. Although increasing the subcarrier spacing to mitigate the resultant ICI is feasible, the TD symbol duration will be shorter and inserting a CP for guarding against ISI will introduce a significant overhead. The excessive phase noise associated with high frequency oscillators also results in a time-varying composite channel. OTFS provides strong immunity to the oscillator phase noise, which is crucial for mmWave communications.

C. Non-Terrestrial Networks

Non-terrestrial networks (NTN) provide a new telecommunication infrastructure based on airborne or spaceborne vehicles, such as satellites, unmanned aerial vehicles (UAVs) or high altitude platforms (HAPs). They are capable of supporting the terrestrial 5G networks in the provision of global coverage and mobility, as well as ubiquitous connectivity and enhanced network reliability. Since the airborne and spaceborne vehicles usually move fast, the high Doppler spread experienced by the NTN imposes new challenges on its air interface design. OTFS modulation has rich potential in the NTN owing to its prominent capability of handling the Doppler effect. Additionally, airborne and spaceborne vehicles have limited on-board power supply and computing capability, hence the low PAPR and low complexity of OTFS is of pivotal importance. Moreover, the corresponding NTN communication links spanning to the ground terminals usually exhibit spatial channel sparsity in the DD domain, which allows OTFS to strike an attractive performance vs. complexity trade-off.

D. Underwater Acoustic Communications

Underwater acoustic (UWA) channels are regarded as one of the most challenging wireless channels, due to their high delay spread, limited bandwidth, and rapid time variations. Single-carrier modulation using decision feedback equalizers (DFE), OFDM and orthogonal signal division multiplexing (OSDM) are the most popular schemes for UWA communications. However, they all transmit information in the TF domain, where both the ISI and ICI equalization become tedious tasks. By contrast, OTFS is Doppler-resilient, hence transmitting information in the DD domain may outperform these TF domain modulation schemes in UWA communications. Furthermore, UWA channels tend to be sparse in the DD domain, where the equalization might be easier than that in the TF domain. Moreover, UWA communications are usually considered as wideband systems, since the ratio of acoustic signal bandwidth over the carrier frequency is typically much higher than that in terrestrial communications. Hence, the potential multipath-scale diversity of the DD domain channel \([4]\) can be beneficially exploited.

IV. CHALLENGES AND SOLUTIONS

As a fledgling waveform, OTFS modulation unveils new opportunities, but also has its own challenges. In this section, we introduce three fundamental research problems of OTFS and their potential solutions.

A. Channel Estimation

The channel envelope fluctuates violently even in a short time period in high-mobility environments. Accurately estimating the CIR in OTFS systems is a challenging but vital requirement for reliable detection. Thanks to the DD domain channel sparsity and quasi-stationarity, channel acquisition in the DD domain may be deemed more convenient than that in the TF domain, even for a lower training overhead, as illustrated in Fig. \([4]\). However, the channel may not always be sparse \([9]\), which imposes a challenge. A promising technique of dealing with this issue is to use a turbo-style receiver, where the reliably detected data symbols can be assumed to be known and hence used for refining the channel estimation results based on classic decision-directed principles and joint CIR as well as data estimation, rather than purely relying on the known pilot symbols. The refined channel estimates again can be used for OTFS symbol detection, which can further improve the receiver’s performance. However, the turbo process involves marginalization and complex multi-dimensional search, which is an open OTFS design problem.
Another direction to address this issue is improving the channel sparsity via designing a bespoke TF domain window. For example, when the exact Doppler frequency straddles a pair of finite-resolution bins in Fig. [3] rather than falling exactly into the 1-th bin, i.e., fractional Doppler [9], applying a Dolph-Chebyshev (DC) window at the transmitter or receiver [14] can suppress the channel spreading. As a benefit, due to the enhanced channel sparsity, the DC windowing achieves a much improved channel estimation mean squared error (MSE) over the conventional rectangular window [12], as seen in Fig. [4].

B. Efficient DD Domain Data Detection

As shown in [9], the output signal in the DD domain can be regarded as a 2D circular convolution of the input data symbols and the effective aggregate channel, which results in a rather specific interference pattern, where a pair of symbols far from each other in the DD domain may interfere with each other. Mitigating this peculiar interference requires a bespoke receiver. Adopting the optimal maximum a posteriori (MAP) detector would indeed perfectly mitigate the interference between symbols, but at an excessive complexity, precluding its deployment in practical systems. Hence, most OTFS detectors focused on the complexity reduction, based on the classic message passing algorithm (MPA) and its variants. The main problem of MPA-based detection is its poor convergence behavior in the face of short cycles, which may lead to performance degradation.

A potent solution is to adopt the variational framework of [13], which can adaptively construct the distributions of OTFS symbols according to their interference patterns. By appropriately constructing the distributions of OTFS symbols for variational purposes, we can design rapidly converging OTFS detection. An initial result adopting the variational Bayes (VB) OTFS detector achieves a modest performance gain over the MPA owing to its better convergence, as depicted in Fig. [5]. The performance of MAP detection is also provided as the baseline, which has the best performance, albeit at the cost of an excessive complexity. For all these detectors, the OTFS performance remains similar upon increasing the velocity from 150 km/h to 300 km/h. On the other hand, the detection performance of the minimum mean squared error (MMSE) OFDM detector remains poor due to the excessive ICI.

C. Coded OTFS System

Powerful channel coding and decoding schemes play a crucial role in ultra-reliable transmissions. They are even more vital for mitigating the severe channel impairments of high-mobility communications. While OTFS has the potential of attaining the maximum achievable diversity gain, the channel codes have to be carefully designed for OTFS modulation. More importantly, perfect detection at near-capacity signal-to-noise ratios (SNRs) may not be attained for practical OTFS systems due to the associated poor channel conditions. In such a case, the channel decoder has to cope with the OTFS detector’s residual errors at the receiver, which would require iterative OTFS receivers. However, how to design such a receiver and how to choose the coding parameters for near-capacity joint detection and decoding remains an interesting open issue at the time of writing.

Recent research has unveiled two interesting facts about the code design of OTFS systems [10]. It can be shown that there is a fundamental trade-off between the diversity gain and the coding gain. In particular, the diversity gain of OTFS systems improves with the number of independent resolvable channel paths, while the coding gain declines. Some preliminary results of coded OTFS systems are given in Fig. 6 where a simple half-rate convolutional code and maximum likelihood sequence estimation are applied. As observed from the figure, given the same channel code, the coding gain...
OTFS offers the potential of avoiding the multi-user interference. However, how to scale the systems for accommodating a large number of users without a significant overhead is an interesting open research problem. The coexistence of promising multiple access schemes and OTFS, such as non-orthogonal multiple access, spatial-division multiple access and interleave-division multiple access, are worth further exploring.

C. Joint Sensing and Communications using OTFS

Since the DD domain channel directly exploits the physics of propagation, relying on the distance, speed and scattering intensity, OTFS is eminently suitable for integrating sensing and communications solutions in a single platform. Efficient sensing algorithms to exploit the OTFS signal structure are still unknown. Furthermore, finding the optimal trade-off between the sensing and communication performances remains an interesting open question. Moreover, as location and velocity can serve as beneficial side information for improving the communication performance by predictive beamforming, a joint sensing and communication design relying on OTFS is an exciting open topic to investigate.

D. MIMO-OTFS

Applying OTFS in multiple antenna systems provides additional hitherto unexploited spatial DoF for multiplexing. In contrast to TF domain channels, which may fluctuate dynamically for different antennas in different time slots and subcarriers, the DD domain channels tend to remain quasi-stationary both in the time and antenna domains, which may result in efficient channel estimation and MIMO detection. How to design sophisticated beamforming/precoding to fully exploit all the available spatial DoFs and how to perform low-complexity detection for MIMO-OTFS constitute intriguing problems. Moreover, the analytical framework of MIMO-OTFS systems versus the number of antennas is also unexplored in the open literature.

VI. CONCLUSIONS

In a nutshell, OTFS constitutes a promising next-generation candidate. We commenced with an overview of the fundamental concept of OTFS, including the main features of the DD domain channel, the DD domain multiplexing and OTFS transceiver architecture. The critical challenges of OTFS, such as channel estimation, efficient data detection and coding/decoding problems were highlighted and pertinent preliminary results were provided. The potential applications of OTFS and several promising research directions were introduced. It is hoped that this article will help inspire future research in this exciting new area and pave the way for designing next-generation networks.

VII. ACKNOWLEDGEMENT

The authors would like to thank the support from the Telstra Corporation Ltd., particularly Dr. Paul G. Fitzpatrick, Dr. Taka Sakurai, and Mr. Paul Sporton for valuable discussions during this work.
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