Orthogonal Time Frequency Space Index Modulation based on Non-Orthogonal Multiple Access

Adnan Tariq, Muhammad Sajid Sarwar, Soo Young Shin, *Senior Member, IEEE*

***Abstract*—Wireless communication techniques always strive for advanced spectral efficiency in highly mobile environments. A recently developed Orthogonal Time Frequency Space (OTFS) modulation is considered an appropriate candidate to combat time and frequency offset in signals received from the doubly selective channels by employing the Delay Doppler domain. This paper presents a novel technique that utilizes the spectral advantage of Non-Orthogonal Multiple Access (NOMA) with OTFS-based Index Modulation (OTFS-IM), aiming to increase the spectral efficiency while reducing the transmit power and bit error rate (BER). Compared to conventional OTFS and OTFS-IM, the simulation results of OTFS-IM-NOMA reveal that it can accommodate more than one user using the same DD resources. The simulation results also show that the BER of OTFS-IM-NOMA users outperforms the conventional OTFS technique.**

***Index Terms*—Orthogonal Time Frequency Space Index Modulation (OTFS-IM), Non-Orthogonal Multiple Access (NOMA), OTFS-IM-NOMA.**

I. Introduction

Researchers are looking for innovative and compatible alternatives to the existing communications systems due to the rapidly increasing demand for band-limited, high-speed wireless mobile communications [1]–[3]. The rapidly changing transmission environment induces both time and frequency selectivity. The time and frequency selective channels disrupt the orthogonality among the sub-carriers in Orthogonal Frequency Division Multiplexing (OFDM), driving an investigation of alternative solutions. A novel technology that used the notorious delay and Doppler parameters of high mobility channels to modulate the information symbols called Orthogonal time-frequency space (OTFS) was considered a solution for doubly selective channels [4].

Index modulation (IM) techniques have contributed to a deeper understanding of spectrum efficiency, energy efficiency, and bit error rate (BER) in recent years. As highlighted in reference [6], it's been possible to establish an attractive trade-off between spectral and energy efficiency using IM for various application scenarios. In IM, the index of the transmitting resources, i.e., the Delay Doppler Resource Blocks (DDRB), transmit antennas, subcarriers, time slots, and RF mirrors, could be used to transmit additional information [5]. The transmitted data block was typically divided into two separate sections. The first component was modulated typically, whereas the second component activates a portion of the transmission resources. In [7], [8], it has been shown that IM-based OFDM (OFDM-IM) and IM-based OTFS (OTFS-IM) perform better in terms of BER compared to conventional OFDM and OTFS, respectively.

Power domain non-orthogonal multiple access (NOMA) in which different users superimpose over the same resources (i.e., Delay Doppler (DD) or time-frequency (TF)), was deeply explored to enhance the spectral efficiency while considering fairness among the users [9]. In NOMA, power domain multiplexing (assigning different power to different users based on channel condition and distance) was utilized on the transmitter side, while successive interference cancellation (SIC) separates the superposed signals at the receiver side [9]. In [3], a method was proposed to differentiate users based on their mobility profiles. The conventional OFDM scheme in the time-frequency plane modulated the one with low mobility, and the one with high mobility was modulated using the delay Doppler resources plane. NOMA was implemented to differentiate the high-mobility user when transformed into a TF plane from a DD plane using Inverse symplectic Finite Fourier Transform (ISFFT).

In [10], the OTFS-based NOMA (OBNOMA) was proposed in which different mobility profile users are grouped for uplink transmission. Here mobile users and stationary ones contain different resources of the delay-Doppler domain. And it has been shown that OBNOMA can reduce Co-Channel Interference (CCI). In [5], the formulation of the beamforming design to improve the attainable data rates for users employing NOMA with less mobility while also assuring that the anticipated data rate for users with high mobility could be met was presented.

The advantages of both NOMA and index modulation could be used in OTFS modulation-based communication. The ability to differentiate between the NOMA users' data at the receiver based on power allocation coefficient and adjustable delay Doppler resource activation gives the edge in spectral efficiency while reducing the BER. Therefore in this paper, a novel NOMA-based OTFS-IM technique is proposed.

II. System Model

This paper considers a downlink system model for OTFS-IM-NOMA for two users. Unlike the OFDM-IM-NOMA,

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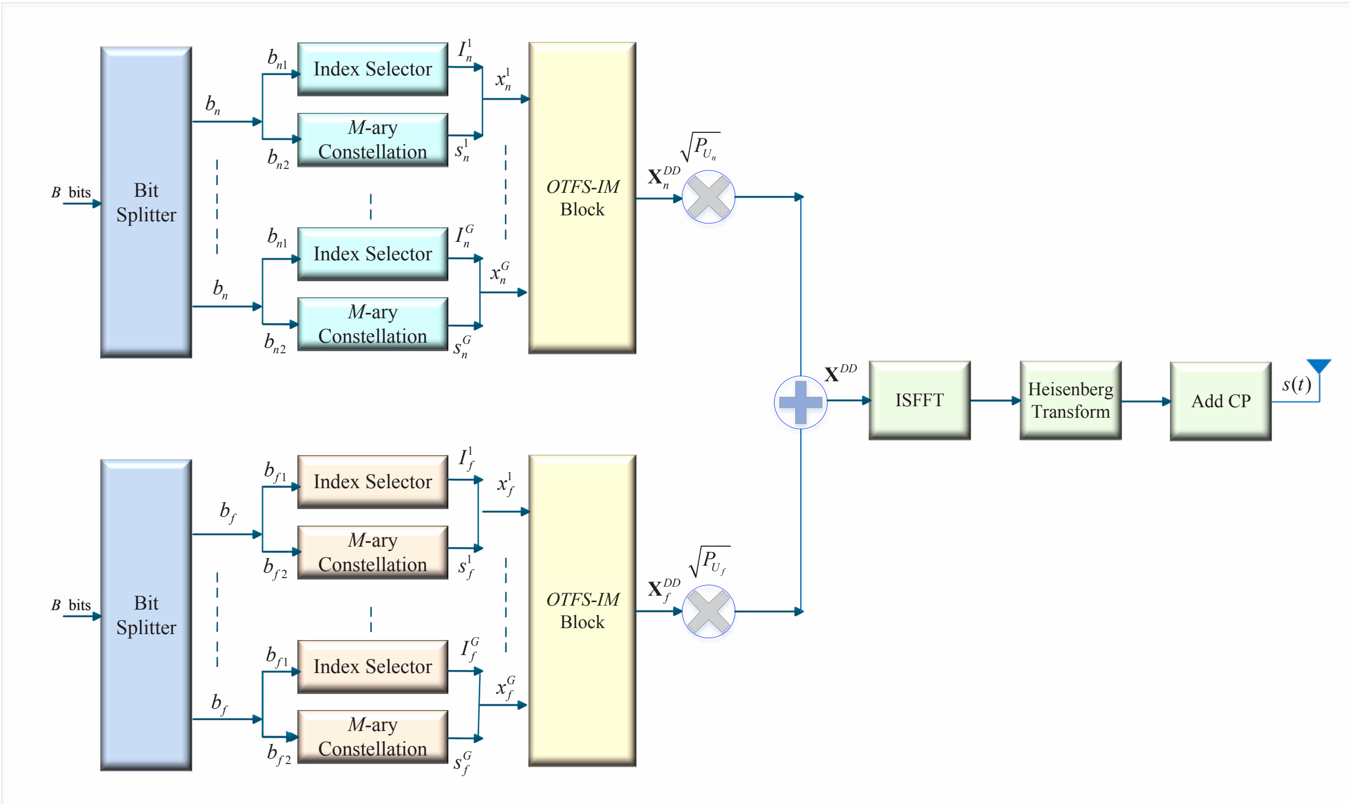

Fig. 1. Transceiver Block Diagram for OTFS-IM-NOMA.

which modulates the data on active sub-carriers, OTFS-IM-NOMA uses 2-dimensional active Delay-Doppler (DD) resources to modulate and transmit data. In OTFS modulation, each transformed DD resource will cover the whole TF plane. Based on the distance from the Base Station (BS) and channel conditions, one user is considered a near user U_n with a relatively good channel (having less distance from BS as compared to the second one) condition, and the other will be said a far user U_f. Both users and BS use a single antenna to receive and transmit the data.

As shown in Fig 1, the transmitting bits B_γ where $\gamma \in (n, f)$, n for the near user and f for the far user respectively, are divided into G groups i-e, $b_\gamma = B_\gamma/G$. The b_γ bits are further divided into two parts. The first $b_{\gamma 1}$ selects the indices of transmitting DD resources from a vectorised subblock of OTFS frame containing n transmitting resources, where $n = (M \times N)/G$. N is the number of Doppler resources, and M is the number of resources along the delay dimension. Using the $b_{\gamma 1}$, a active resources are selected from available n resources in a subblock β. The rest of $b_{\gamma 2}$ bits are mapped using conventional constellation to the delay-doppler resources corresponding to the a active indices. The active indices which are selected are given by

$$I_\beta = [i_{\beta,1}, \ldots, i_{\beta,a}],$$

where $i_{\beta,\alpha} \in \{1, \cdots, n\}, 1 \le \beta \le G, 1 \le \alpha \le a$. Now the total transmit bits b_γ will be the sum of $b_{\gamma 1}$ and $b_{\gamma 2}$.

$$b_\gamma = \left\lfloor \log_2 \begin{pmatrix} n \\ a \end{pmatrix} \right\rfloor + a \log_2(Q) \tag{1}$$

where Q is the modulation order. The subblock of modulated symbols is expressed as:

$$\boldsymbol{s}_\beta = [s_\beta(1), \cdots, s_\beta(a)]$$

where $\beta = 1, \cdots, G$, and $\alpha = 1, \ldots, a$.

Now the OTFS-IM block will create the main $M \times N$ transmitting matrix $\mathbf{X}_\gamma^{DD}$

$$\mathbf{X}_\gamma^{DD} = \begin{pmatrix} x_{1,1} & \ldots & x_{N,1} \\ \vdots & \ddots & \vdots \\ x_{M,1} & \ldots & x_{M,N} \end{pmatrix} \tag{2}$$

where $x_{k,l} \in \{0, s_\beta(\alpha)\}, l = 0, \cdots, M-1, k = 0, \cdots, N-1$.

Here the total power of the base station P_{BS} is considered to be unity, and $0 \le \alpha \le 1$. Now the power assigned to the transmit DD resources for the near and far users will be $P_{U_n} = \alpha P_{BS}$ and $P_{U_f} = (1-\alpha) P_{BS}$.

Now the combined NOMA signal is transmitted as follows

$$\mathbf{X}^{DD} = \sqrt{P_{U_n}} \mathbf{X}_n^{DD} + \sqrt{P_{U_f}} \mathbf{X}_f^{DD} \tag{3}$$

The transmit data symbols are converted via Inverse Symplectic Finite Fourier Transform (ISFFT) operation to Time-Frequency (TF) domain.

$$\mathbf{X}[n,m]=\frac{1}{MN}\sum_{l=0}^{M-1}\sum_{k=0}^{N-1}x_{k,l}e^{j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \tag{4}$$

where $n\in(0,1,...,N-1)$, $m\in(0,1,...,M-1)$ and $x_{k,l}$ are the elements of $\mathbf{X}^{DD}$. After converting the signal to the TF domain, the Heisenberg transform is used to convert the 2-dimensional TF domain signal to a 1-dimensional time-domain signal, which is then transmitted over a doubly selective channel with a cyclic prefix.

$$s(t)=\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\mathbf{X}[n,m]e^{j2\pi m\Delta f(t-nT)}g_{\mathrm{tx}}(t-nT) \tag{5}$$

where $g_{\mathrm{tx}}(t)$ is any basis transmit pusle. Here, the rectangular pulse is considered for analysis. The received signal by each user coming from time and frequency selective channel $h_\gamma(\tau,\nu)$ is

$$r_\gamma(t)=\iint s(t-\tau)h_\gamma(\tau,\nu)e^{j2\pi\nu(t-\tau)}d\tau d\nu+w(t) \tag{6}$$

where $w(t)$ is Gaussian noise signal and

$$h_\gamma(\tau,\nu)=\sum_{p=1}^{P_\gamma}h_{\gamma,p}\delta\left(\tau-\tau_{\gamma,p}\right)\delta\left(\nu-\nu_{\gamma,p}\right) \tag{7}$$

where $\tau_{\gamma,p}$, $\nu_{\gamma,p}$ and $h_{\gamma,p}$, denotes the delay, Doppler shift and complex channel gain associated with p^{th} channel path of γ user, respectively. P_γ denotes the total number of multi-paths. The TF domain signal is formed from a time domain received signal using the Wigner transform, as shown below

$$\mathbf{Y}_\gamma[n,m]=\int_{-\infty}^{\infty}g^*_{\mathrm{rx}}(t-nT)r_\gamma(t)e^{-j2\pi m\Delta f(t-nT)}dt \tag{8}$$

where the rectangular basis pulse at the receiver is $g_{\mathrm{rx}}(t)$. Finally, the symplectic finite Fourier transform is used to reverse the TF signal into a DD signal as

$$\mathbf{Y}[k,l]=\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}Y[n,m]e^{-j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \tag{9}$$

Direct demodulation is performed for the far user (U_f), and SIC is employed for the near user (U_n). And maximum likelihood detector is utilized to detect the information from the modulated symbols and indices of the modulated symbols.

$$\left(\hat{I}_\beta,\hat{\mathbf{s}}_\beta\right)=\arg\min_{I_\beta,\mathbf{s}_\beta}\sum_{\eta=1}^{k}\left|y^\beta\left(i_{\beta,\eta}\right)-h^\beta\left(i_{\beta,\eta}\right)s_\beta(\eta)\right|^2 \tag{10}$$

The predefined lookup table is known both at the transmitter and receiver. An example of a lookup table is shown in Table I., where s_χ and s_ζ are the active symbols among all n symbols in a group.

TABLE I
LOOK-UP TABLE IS SHOWN AS AN EXAMPLE $(n=4,a=2)$.

Bits	Indices	subblocks
$\begin{bmatrix}0 & 0\end{bmatrix}$	$\{1,2\}$	$\begin{bmatrix}s_\chi & s_\zeta & 0 & 0\end{bmatrix}^T$
$\begin{bmatrix}0 & 1\end{bmatrix}$	$\{3,4\}$	$\begin{bmatrix}0 & 0 & s_\chi & s_\zeta\end{bmatrix}^T$
$\begin{bmatrix}1 & 0\end{bmatrix}$	$\{2,3\}$	$\begin{bmatrix}0 & s_\chi & s_\zeta & 0\end{bmatrix}^T$
$\begin{bmatrix}1 & 1\end{bmatrix}$	$\{1,4\}$	$\begin{bmatrix}s_\chi & 0 & s_\zeta & 0\end{bmatrix}^T$

TABLE II
PARAMETERS FOR SIMULATION

Parameter	Value
Maximum Speed	$300\mathrm{km/h}$
Number of multi-paths	7
Carrier frequency	4GHz
No.of Delay Resouces (M)	32
No.of Doppler Resouces (N)	32
Subcarrier spacing Δf	15KHz
Bandwidth	MΔf
Frame duration	N/Δf
Channel Ideal estimation	Ideal

III. SIMULATION RESULTS

The BER comparison of the proposed OTFS-IM-NOMA with its traditional counterparts, such as OTFS and OTFS-IM, is shown in this section. For the purpose of simulation, an extended pedestrian A model with seven delay taps is taken into account. In Table II, the simulation parameters are listed. The BER performances in relation to transmitting SNR for high mobility channel conditions are assessed using the Monte Carlo simulation. The power assigned to the near and far user's signal is $P_{U_n}=0.3$ and $P_{U_f}=0.7$ for implementation of SIC. The total number of DD resources is 32×32 divided into 256 groups containing 4 DD resources in each group. Out of $n=4$ total resources in a group, only $a=2$ DD resources are activated for simulation results. All the BER analyses for proposed and existing techniques are carried out at the constant number of transmitted bits per group to observe a fair comparison.

Fig. 2 illustrates the BER of OTFS-IM-NOMA, where two users with different channel power gain are accommodated in the same resource block. Considering $(h_n(\tau,\nu)>h_f(\tau,\nu))$ where $h_n(\tau,\nu)$ and $h_f(\tau,\nu)$ are the complex channel gain of the near and far user respectively, the BER of the near user in the proposed OTFS-IM-NOMA technique is better than the traditional OTFS scheme. The improvement of almost $6\,dB$ at high SNR values is observed. At the same time, the BER of the far user in the proposed scheme is also comparable with the performance of conventional OTFS. The Bit Error Rate (BER) of OTFS-IM demonstrates superior performance compared to OTFS-IM-NOMA. This is due to the fact that OTFS-IM exclusively focuses on a single user, hence eliminating any potential inter-user interference. The OTFS-IM-NOMA demonstrates a promising potential to improve spectral efficiency in high mobility channel scenarios but with a marginal increase in BER compared to the OTFS-IM. In Figure 2, the number of bits communicated by each group is

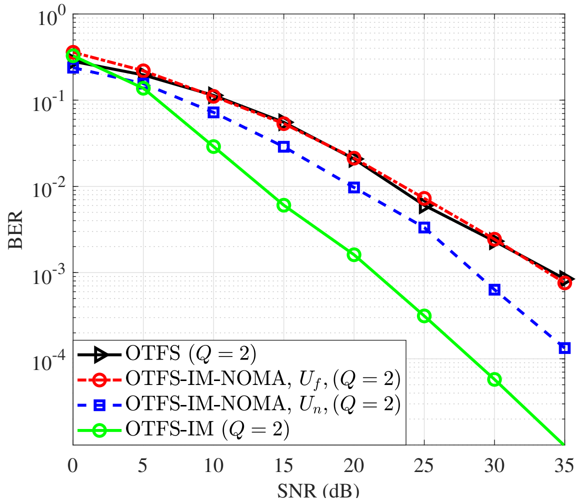

Fig. 2. BER comparison of OTFS-IM-NOMA, OTFS-IM and OTFS (4 bits per group)

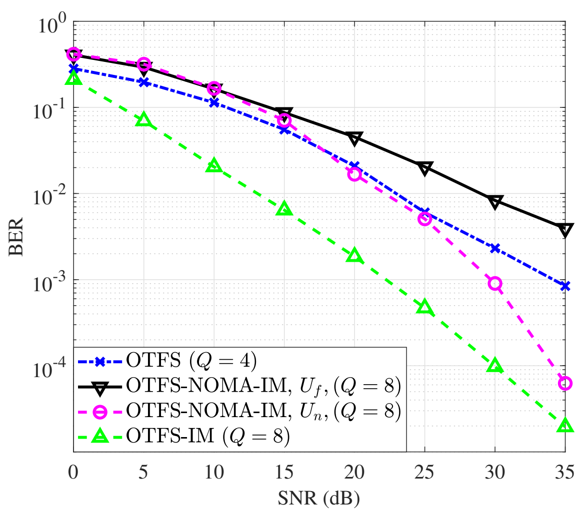

Fig. 3. BER comparison of OTFS-IM-NOMA, OTFS-IM and OTFS (8 bits per group)

4 for every comparison of BER.

Fig. 3 illustrates the BER analysis for OTFS-IM-NOMA, OTFS-IM and conventional OTFS at the 8 bits per group transmission rate. The modulation order for the conventional OTFS scheme is 4, while for the techniques involving IM, the modulation order is kept at 8 to have a consistent transmission rate. The near user of OTFS-IM-NOMA shows the increment of $3-5\,dB$ at higher SNR values concerning the traditional OTFS technique. The BER of the far user is less than the conventional OTFS due to the higher modulation order used for simulation to keep a fair comparison. OTFS-IM performs better in BER than OTFS-IM-NOMA and conventional OTFS due to its better tolerance against the Doppler effect. The proposed OTFS-IM-NOMA technique is superior in spectral efficiency for doubly selective channels.

IV. Conclusion

This study proposes a novel OTFS-IM-NOMA technique for DD resource sharing between two users with differing signal strengths. For lower modulation orders, OTFS-IM-NOMA outperformed traditional OTFS approaches in BER. The near NOMA user's BER outperformed the traditional OTFS method even with higher modulation orders. The single-user OTFS-IM performed better in BER due to inter-user interference in OTFS-IM-NOMA. Future research for this suggested methodology will examine OTFS-IM-NOMA-based multiple access to lower collision probability among different users' signals and improve spectral efficiency.

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