

**OTFS BASED ORTHOGONAL MULTIPLE ACCESS IN
HIGH DELAY AND DOPPLER WIRELESS
CHANNELS**

VENKATESH KHAMMAMMETTI



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
FEBRUARY 2023**

© Indian Institute of Technology (IITD), New Delhi, 2023

**OTFS BASED ORTHOGONAL MULTIPLE ACCESS IN
HIGH DELAY AND DOPPLER WIRELESS
CHANNELS**

by

VENKATESH KHAMMAMMETTI

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2023

Dedicated to

My SriSudha Family

(Srinivasa Rao Lingala, Sudha Rani Lingala,
Sahithi Lingala, Dhivya Sri Lingala)

Certificate

This is to certify that the thesis entitled “**OTFS Based Orthogonal Multiple Access in High Delay and Doppler Wireless Channels**” being submitted by **Mr. Venkatesh Khammammetti** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of bonafide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other University or Institute for the award of any degree or diploma.

Dr. Saif Khan Mohammed

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi, 110016, India

Date:

Place: New Delhi

Acknowledgments

“Legend has shown over and over again, that in life, the more you recognize the people responsible for your past successes, the more confident you become in taking on and successfully accomplishing the new ones.”

– Jack Canfield

The path that led to this thesis was amazing in its own right, full with obstacles and meandering. This success is largely thanks to the encouragement, support, and effort of a few exceptional individuals. This journey would not have been possible without the comfort and assistance of important individuals in my life. Above all, the universe worked together to put me on this path.

Thanks to God for giving me the strength, determination, self-assurance, energy, and insight I needed to finish my voyage.

First and foremost, I owe all I am to my upbringing parents, my uncle Mr. Srinivasa Rao Lingala and aunt Mrs. Sudha Rani Lingala, who nurtured me to become the person I am today. Thanks to your commitment and passion for education, I was inspired to push myself to new academic heights. It’s because of you two that I’ve been able to do so much. I owe you both a great debt of gratitude for getting me over lengthy battles and challenging circumstances. you both are my strength, my might, and my weakness. You have both been my rock-solid supporters, wisest advisors, and closest travelling companions during this research project and throughout my life. I will continue to adore you both for the rest of my life and want to make you both proud. I also take this moment to express my gratitude and love to my biological parents, Mr. K Manikyala Rao and K Satyavathi, for giving me life.

Secondly, I would want to thank my PhD advisor, Dr. Saif Khan Mohammed, for helping and teaching me in learning the fundamentals of academic research. His guidance and encouragement not only aided me in my research endeavours but also broadened my understanding of a number of subjects. His extensive background in academia and industry makes him a valuable asset when developing a research strategy with real-world implications. His knowledge provided an important basis for my thesis, allowing me to construct a comprehensive investigation. Because of his insightful observations, I was able to enhance the quality of my research. It was a privilege to do research under his direction. Thank you for fostering my development as a researcher and guiding me to the conclusion of my research journey.

Thirdly, to my student research committee, I extend my heartfelt thanks and appreciation, Prof. Shiv Dutt Joshi (Chairman), Prof. Seshan Srirangarajan (Internal Expert) and Prof. Mahesh P. Abegaonkar (External Expert) for providing me with the best reviews and comments at every stage of my research. This thesis wouldn't have been come near to perfection without your extremely useful insights and inputs.

I would like to take the opportunity to thank my M.Tech supervisor, Prof. Rajoo Pandey, NIT Kurukshetra, for encouraging and introducing me to the world of research. Every academic life of a researcher is incomplete without a group of close friends and colleague whom we share our day to day academic and personal experiences. I would like to mention the closet friend group at IIT Delhi, Mr. Y Amarnath, Mr. Prateek Yadav, Mr. Aqueeb Sohail Shaik, Mr. G Shivakumar, Mr. K Narender Reddy, Mr. S Vivek, Mr. D Eshwar, Mr. A Bharat Krishna and Mr. Y Ravi Kumar for being my happiness, strength and stress busters at IIT Delhi. I would also like to thank Mr. B Hari Krishna and Mr. P Venkatappareddy for all the support and strength during the toughest times at IIT Delhi. I would like to thank my friend Mr. A Deepak Santosh for helping me to mold myself. I would also like to mention my colleagues, Mr. Alok Kumar Sinha, Mr. Jinu Jayachandran, Mr. Kamal Biswas, Mr. Imran Ali Khan, Mr. Brijesh Chander Pandey, Mr. Rachit Mahendra, Mr. S Surya Prakash and Mr. B Dileep for all your support in my research and I am grateful to be a part of this team. I would also like to extend my sincere gratitude to all who encouraged and supported me in this journey.

Venkatesh Khammammetti

Abstract

The tremendous growth in cellular telephone subscribers proves that wireless communications is an effective and practical means of transmitting both voice and data. There have been successful rollouts of cellular networks at every generation from 1G to 4G. To accommodate the ever-increasing number of customers and the exponentially rising demand for data throughput, the future 5G cellular networks have more work to do. In cellular wireless systems prior to the fourth generation (e.g. long term evolution (LTE), LTE-Advanced (LTE-A), etc.), increasing spectral efficiency within a limited frequency range was a primary design goal. To address the growing need for spectrum resources and the challenge of constrained energy resources, 5G cellular networks integrate existing 4G-LTE technology and Wi-Fi standards. The Third Generation Partnership Project (3GPP) recommends that 5G networks include the Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC) categories of applications. Furthermore, 5G networks should be able to allow improved vehicle-to-everything communications. Modulation and multiple-access (MA) systems will need to be investigated further in order to accommodate these tweaks.

Orthogonal Time Frequency Space (OTFS) is a novel modulation scheme in which each transmitted symbol experiences a nearly constant channel gain even in channels with high Doppler or carrier frequencies. In this dissertation, we examine OTFS modulation based Orthogonal MA (OMA), where each user terminals (UTs) are allotted non-overlapping physical resources in the delay-Doppler (DD) and/or time-frequency (TF) domain. In the uplink of an orthogonal time frequency space modulation-based wireless communication system with significant Doppler and delay spread, we present a unique OMA approach called Interleaved Delay Doppler Multiple Access (IDDMA) where each UT is allocated delay-Doppler (DD)

resource elements that are evenly spaced throughout the DD domain. This restricts the time frequency (TF) transmit signal to a sub-domain of the whole TF domain. Multi-user interference (MUI) is eliminated by assigning non-overlapping portions of the TF transmit signal to different UTs. Analytical results demonstrate that the proposed MA technique (IDDMA) is MUI-free with ideal transmit and receive pulses and has a much better sum spectral efficiency than previous OMA approaches, Guard Band(GB) based MA (GBMA), and Interleaved Time Frequency MA (ITFMA), reported in the literature.

As ideal pulses are not realizable, in this thesis, we study the SE performance of the OMA methods with practical rectangular pulses. For these OMA methods, we derive the expression for the received DD/TF domain symbols at the base station (BS) receiver and the effective DD domain channel matrix when rectangular pulses are used. Study of these expressions demonstrates the existence of MUI when rectangular pulses are used, although the quantity of MUI in IDDMA is substantially less than in ITFMA. We also derive the expression for the achievable sum SE. Through simulations, for practical values of the received signal-to-noise ratio, we observe that with rectangular pulses the sum SE achieved by the IDDMA method is significantly higher than that achieved by the ITFMA and GBMA methods. The uncoded BER performance of various OMA techniques for BPSK and QPSK modulations is also studied in this thesis, and it is shown that our proposed IDDMA method has lower BER than the other existing OMA methods.

सार

सेलुलर टेलीफोन ग्राहकों में अद्भुत वृद्धि साबित करती है कि वायरलेस संचार आवाज और डेटा दोनों को प्रसारित करने का एक प्रभावी और व्यावहारिक साधन है। 1जी से 4जी की हर पीढ़ी में सेलुलर नेटवर्क को चरणबद्ध सफलता मिली। ग्राहकों की लगातार बढ़ती संख्या और डेटा थ्रूपुट की तेजी से बढ़ती मांग को समायोजित करने के लिए, भविष्य के 5जी सेलुलर नेटवर्क को और अधिक काम करना होगा। चौथी पीढ़ी से पहले (जैसे लॉन्ग टर्म ईवोल्यूशन (एलटीई), एलटीई-एडवांस्ड (एलटीई-ए), आदि) सेलुलर वायरलेस सिस्टम में, सीमित आवृत्ति रेंज के भीतर स्पेक्ट्रल दक्षता बढ़ाना एक प्राथमिक डिजाइन लक्ष्य था। स्पेक्ट्रम संसाधनों की बढ़ती आवश्यकता और सीमित ऊर्जा संसाधनों की चुनौती को पूरा करने के लिए, 5जी सेलुलर नेटवर्क मौजूदा 4जी-एलटीई तकनीक और वाई-फाई मानकों को एकीकृत करता है। थर्ड जेनरेशन पार्टनरशिप प्रोजेक्ट (3जीजीपी) अनुशांसा करता है कि 5जी नेटवर्क में एन्हांस्ड मोबाइल ब्रॉडबैंड (इएमबीबी), अल्ट्रा रिलायबल लो लेटेंसी कम्युनिकेशंस (युआरएलएलसी) और मैसिव मशीन टाइप कम्युनिकेशंस (एमएमटीसी) श्रेणी के एप्लिकेशंस शामिल हैं। इसके अलावा, 5G नेटवर्क बेहतर वाहन-से-सब कुछ संचार की अनुमति देने में सक्षम होना चाहिए। मॉड्यूलेशन और मल्टीपल-एक्सेस (एमए) सिस्टम को इन सुधारों को समायोजित करने के लिए और जांच करने की आवश्यकता होगी।

ऑर्थोगोनल टाइम फ्रीक्वेंसी स्पेस (ओटीएफएस) एक अद्वितीय मॉड्यूलेशन योजना है जिसमें प्रत्येक प्रेषित प्रतीक उच्च डॉपलर या वाहक आवृत्तियों वाले चैनलों में भी लगभग सतत चैनल लाभ का अनुभव करता है। इस निबंध में, हम ओटीएफएस मॉड्यूलेशन आधारित ऑर्थोगोनल एमए (ओएमए) की जांच करते हैं, जहां प्रत्येक उपयोगकर्ता टर्मिनल (युटी) को डिले-डॉपलर (डीडी) और/या टाइम-फ्रीक्वेंसी (टीएफ) डोमेन में गैर-अतिव्यापी भौतिक संसाधन आवंटित किए जाते हैं। प्रभावी डॉपलर और विलंब प्रसार के साथ ऑर्थोगोनल टाइम फ्रीक्वेंसी स्पेस मॉड्यूलेशन-आधारित वायरलेस संचार प्रणाली के अपलिक में, हम इंटरलीव्ड डिले डॉपलर मल्टीपल एक्सेस (आईडीडीएमए) नामक एक अद्वितीय ओएमए दृष्टिकोण प्रस्तुत करते हैं जहां प्रत्येक युटी को डिले-डॉपलर (डीडी) संसाधन तत्व आवंटित किए जाते हैं जो पूरे डीडी डोमेन में समान रूप से स्थित होते हैं। यह टाइम-फ्रीक्वेंसी (टीएफ) संचारित सिग्नल को पूरे टीएफ डोमेन के एक उप-डोमेन के लिए सीमित करता है। टाइम फ्रीक्वेंसी सिग्नल के गैर अतिव्यापी भागों को विभिन्न युटीस को सौंप कर मल्टी-यूजर इंटरफेरेंस (एमयूआई) को समाप्त कर दिया गया है। विश्लेषणात्मक परिणाम दर्शाते हैं कि प्रस्तावित एमए तकनीक (आईडीडीएमए) आदर्श ट्रांसमिट और रिसीव पल्स के साथ एमयूआई मुक्त है और इसमें साहित्य

में उल्लेखित पिछले ओएमए दृष्टिकोण, गार्ड बैंड (जीबी) आधारित एमए (जीबीएमए) और इंटरलीव्ड टाइम फ्रीक्वेंसी एमए (आईटीएफएमए) की तुलना में कहीं बेहतर योग स्पेक्ट्रल दक्षता है ।

जैसा कि आदर्श पल्सेस संभव नहीं हैं, इस थीसिस में, हम व्यावहारिक आयताकार पल्सेस के साथ ओएमए विधियों के एसई प्रदर्शन का अध्ययन करते हैं। इन ओएमए विधियों के लिए, आयताकार पल्सेस का उपयोग करते हुए, हम बेस स्टेशन (बीएस) रिसीवर पर प्राप्त डीडी/टीएफ डोमेन प्रतीकों के लिए अभिव्यक्ति और प्रभावी डीडी डोमेन चैनल मैट्रिक्स प्राप्त करते हैं। इन अभिव्यक्तियों का अध्ययन एमयूआई के अस्तित्व को प्रदर्शित करता है जब आयताकार पल्सेस का उपयोग किया जाता है, हालांकि आईडीडीएमए में एमयूआई की मात्रा आईटीएफएमए की तुलना में काफी कम है। हम प्राप्ति योग एसई के लिए अभिव्यक्ति भी प्राप्त करते हैं। सिमुलेशन के माध्यम से, प्राप्त सिग्नल-टू-नॉइज़ अनुपात के व्यावहारिक मूल्यों के लिए, हम देखते हैं कि आयताकार पल्सेस के साथ आईडीडीएमए विधि द्वारा प्राप्त योग एसई आईटीएफएमए और जीबीएमए विधियों द्वारा प्राप्त की तुलना में काफी अधिक है। बीपियसके और क्यूपियसके मॉड्यूलेशन के लिए विभिन्न ओएमए तकनीकों के अनकोडेड बीईआर प्रदर्शन का भी इस थीसिस में अध्ययन किया गया है, और यह दिखाया गया है कि हमारी प्रस्तावित आईडीडीएमए पद्धति की बीईआर अन्य मौजूदा ओएमए विधियों की तुलना में कम है।

Table of Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
List of Figures	x
List of Tables	xiii
List of Abbreviations	xiv
1 Introduction	1
1.1 History of Wireless Communication	1
1.2 Evolution of Wireless Technologies	3
1.3 MA Techniques used in Wireless Standards	5
1.4 MA in high delay and Doppler spread Channels	7

1.5	Motivation	8
1.6	Research Objectives and Scope of Work	9
1.7	Organization of the Thesis	10
2	Orthogonal Time Frequency Space (OTFS) Modulation	12
2.1	Introduction	12
2.2	Orthogonal Time Frequency Space (OTFS)	13
2.3	OTFS Modulation	16
2.4	OTFS Demodulation	17
2.5	Conclusion	20
3	OTFS based Multiple-Access in High Doppler and Delay Spread Wireless Channels	21
3.1	Introduction	21
3.2	System Model	22
3.3	Guard Band (GB) based MA scheme	23
3.3.1	Doppler domain GB based MA with ideal pulses	24
3.3.2	Delay domain GB based MA with ideal pulses	27
3.4	Proposed OTFS-MA scheme (IDDMA)	29
3.5	Numerical Results	33
3.6	Conclusion	37

4	Spectral Efficiency of OTFS Based Orthogonal Multiple Access with Rectangular Pulses	38
4.1	Introduction	38
4.2	System Model	40
4.3	IDDMA with rectangular pulses	40
4.3.1	IDDMA: BS receiver signal processing	42
4.3.2	Discussion: MUI in IDDMA	43
4.3.3	Sum SE of IDDMA with rectangular pulses	45
4.4	ITFMA with rectangular pulses	47
4.4.1	ITFMA: UT transmitter signal processing	48
4.4.2	ITFMA: BS receiver signal processing	49
4.4.3	Discussion: MUI in ITFMA	51
4.4.4	Sum SE of ITFMA with rectangular pulses	57
4.5	GB based MA methods with rectangular pulses	59
4.5.1	Sum SE achieved by Doppler domain GB based MA	59
4.5.2	Sum SE achieved by delay domain GB based MA	60
4.6	Numerical Results	62
4.7	Conclusion	73
5	Conclusion and Future Work	74

5.1	Introduction	74
5.2	Possible Future Extensions	75
5.2.1	Low Complexity Channel Estimation	75
5.2.2	Low Complexity Channel Equalization	75
5.2.3	Employing MIMO and massive MIMO systems	80
5.3	Conclusion	80
	Bibliography	80
	A Proofs for Chapter 3	87
A.1	Proof for Lemma 3.1	87
A.2	Proof for Proposition 3.1	88
A.3	Proof for Proposition 3.2	89
	Appendices	87
	B Proofs for Chapter 4	91
B.1	Proof of Lemma 4.1	91
B.2	Proof of Theorem 4.1	94
B.3	Proof of Lemma 4.2	95
B.4	Proof of Theorem 4.2	96
B.5	Proof of Theorem 4.3	97

B.6	Proof of Theorem 4.4	98
C	Received SNR Calculations	99
C.1	Received SNR of IDDMA method	99
C.1.1	DD receiver noise variance	102
C.2	Received SNR of GB based MA methods	103
C.2.1	Doppler domain GB based MA method	103
C.2.2	DD received noise variance	104
C.2.3	Delay Domain GB based MA Method	105
C.3	Received SNR of ITFMA method	107
C.3.1	DD receiver noise variance	109
	List of Publications	110
	Curriculum Vitae	111
	SRC Committee Members	113

List of Figures

1.1	5G New Radio (NR) requirements.	5
2.1	Mapping QAM symbols onto the delay-Doppler grid	14
2.2	Symplectic Fourier Duality	15
2.3	OTFS Modulation	16
2.4	OTFS Demodulation	18
2.5	Processing Steps of Multi-carrier OTFS. [28]	19
3.1	DDRE allocation in Doppler domain GB based MA ($M = N = 9, Q = 3, G = 2$) [42].	24
3.2	DDRE allocation in Delay domain GB based MA ($M = N = 9, Q = 3, G = 2$) [42].	25
3.3	Proposed allocation in DD domain ($M = N = 8, Q = 4, g_1 = g_2 = 2$).	29
3.4	Proposed allocation in TF domain ($M = N = 8, Q = 4, g_1 = g_2 = 2$).	30
3.5	Sum SE vs. SNR ($M = 36, N = 18, \nu_{max} = 300$ Hz).	34
3.6	Per-UT SE vs. Q ($M = 36, N = 18, \nu_{max} = 300$ Hz).	35

3.7	Sum SE vs. SNR ($M = 36, N = 18, Q = 6, g_1 = 3, g_2 = 2$).	36
3.8	Sum SE vs. SNR ($M = 36, N = 18, Q = 6, g_1 = 3, g_2 = 2, \nu_{max} = 300$ Hz).	37
4.1	TFRE allocation in IDDMA, ($M = N = 8, Q = 4, g_1 = g_2 = 2$) [42].	41
4.2	Allocation of TFREs to the UTs in the ITFMA method ($M = N = 8, Q = 4, g_3 = g_4 = 2$).	50
4.3	Ratio of variance of MUI to variance of useful term. (a) Ratio is plotted versus \tilde{m} (for IDDMA) and m' (for ITFMA). (b) Ratio is plotted versus \tilde{n} (for IDDMA) and n' (for ITFMA). ($M = N = 36, Q = 4$ UTs, $g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 1200, 5000$ Hz.)	54
4.4	Color plot for ratio of variance of MUI to variance of useful term in TFREs allocated to UT1 for IDDMA, ($M = N = 36, Q = 4$ UTs, $g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	56
4.5	Color plot for ratio of variance of MUI to variance of useful term in TFREs allocated to UT1 for ITFMA, ($M = N = 36, Q = 4$ UTs, $g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	57
4.6	Sum SE vs. SNR ($M = 36, N = 36, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2, \nu_{max} = 300$ Hz).	63
4.7	Sum SE vs. GB size G ($M = 36, N = 36, Q = 6$).	64
4.8	Sum SE vs. SNR ($M = 36, N = 36, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2, \nu_{max} = 1200$ Hz).	65
4.9	Sum SE vs. SNR ($M = 36, N = 144, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2, \nu_{max} = 1200$ Hz).	66
4.10	Sum SE vs. SNR ($M = 72, N = 72, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2, \nu_{max} = 1200$ Hz).	67

4.11	Sum SE vs. SNR ($M = 36, N = 36, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2$).	68
4.12	Sum SE vs. Q ($M = 36, N = 36, \nu_{max} = 1200$ Hz).	69
4.13	Sum SE vs. SNR ($M = N = 36, g_1 = g_3 = 3, g_2 = g_4 = 2, \nu_{max} = 600$ Hz).	70
4.14	SINR vs. SNR ($M = 36, N = 36, \nu_{max} = 600$ Hz).	71
4.15	Threshold γ_0 vs. $P(PAPR > \gamma_0)$ ($M = 36, N = 36, Q = 6, g_1 = g_3 = 3, g_2 = g_4 = 2$).	72
5.1	BPSK modulated uncoded BER vs. SNR ($M = 36, N = 36, Q = 4, g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	76
5.2	BPSK modulated uncoded BER vs. SNR ($M = 36, N = 36, Q = 4, g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	77
5.3	QPSK modulated uncoded BER vs. SNR ($M = 36, N = 36, Q = 4, g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	77
5.4	BPSK modulated uncoded BER vs. SNR ($M = 36, N = 36, Q = 4, g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	78
5.5	QPSK modulated uncoded BER vs. SNR ($M = 36, N = 36, Q = 4, g_1 = g_2 = g_3 = g_4 = 2, \nu_{max} = 5000$ Hz).	79

List of Tables

1.1	Evolution of wireless technology from 1G to 4G.	4
-----	---	---

Glossary

3D	Three dimensional
3GPP	Third Generation Partnership Project
AMPS	Advanced Mobile Phone System
AMT	Advanced Mobile Telecommunications
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple Access
CSI	Channel State Information
DD	Delay Doppler
DDRE	Delay Doppler Resource Element
DDRG	Delay Doppler Resource Grid
DL	Downlink
eMBB	Enhanced Mobile Broadband
e.g	for example
eV2X	enhanced vehicle-to-everything
GB	Guard Band
GBMA	Guard Band based Multiple Access
GSM	Global System for Mobile communication
GPRS	General Packet Radio Services
HD	High Definition
HSPA	High Speed Packet Access
i.i.d.	Independent and Identically Distributed
IDDMA	Interleaved Delay Doppler Multiple Access

IP	Internet Protocol
ITFMA	Interleaved Time Frequency Multiple Access
ICI	Inter-Carrier Interference
J-TACS	Japanese Total Access Communications System
LTE	Long Term Evolution
MA	Multiple Access
M2M	Machine-to-Machine
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
MUI	Multi-User Interference
NTT	Nippon Telephone and Telegraph
NMT	Nordic Mobile Telephone
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OTFS	Orthogonal Time Frequency Space
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SINR	Signal-to-Interference plus Noise Ratio
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TAC	Total Access Communications
TDMA	Time Division Multiple Access
TF	Time-Frequency
TFRE	Time-Frequency Resource Element
TFRG	Time Frequency Resource Grid
TV	Television
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UT	User Terminal
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access