RESOURCE ALLOCATION IN MULTI-CELL OTFS AND PRECODED ZAK-OTFS FOR LOW-COMPLEXITY RECEIVER EQUALIZATION

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Resource Allocation in Multi-Cell OTFS and Precoded Zak-OTFS for Low-complexity Receiver Equalization

by

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submitted

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Dedicated to

My Family & Friends

Certificate

This is to certify that the thesis entitled **"Resource Allocation in Multi-Cell OTFS and Precoded Zak-OTFS for Low-complexity Receiver Equalization"** being submitted by **Mr. Amit Kumar Pathak** 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.

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Abstract

Emerging 5G and beyond wireless networks predominantly rely on OFDMA (Orthogonal Frequency Division Multiple Access) based multi-cell systems. However, these systems are not robust in environments with high delay and Doppler spread, leading to degraded spectral efficiency (SE) and reliability. To address this, Multi-Carrier Orthogonal Time Frequency Space (MC-OTFS) modulation has been proposed. MC-OTFS maps information symbols in the delay-Doppler (DD) domain, where the wireless channel exhibits greater sparsity compared to the traditional time-frequency (TF) domain, offering improved robustness in high DD spread scenarios. While the performance of single-cell MC-OTFS under DD spread conditions has been studied, the analysis of multi-cell MC-OTFS systems in such environments remains limited. In our research, we investigated the spectral efficiency performance of multi-cell MC-OTFS in high DD spread channels and benchmarked it against traditional OFDM systems. Our findings showed that inter-cell interference (ICI) significantly limits the SE of multi-cell MC-OTFS.

To mitigate this limitation, we proposed a guard band (GB) scheme with reuse of DD resources across cells. This technique effectively reduces ICI in DD spread channels and enhances overall system spectral efficiency. Our evaluations demonstrated that the proposed GB scheme improves performance in multi-cell MC-OTFS systems under high delay and Doppler conditions. In the second part of our research, we addressed the challenge of low-complexity equalization in Zak-OTFS modulated systems. Although Zak-OTFS, a recently proposed variant, offers better robustness against DD spread compared to MC-OTFS, it requires joint DD-domain equalization, which is computationally intensive—particularly in downlink scenarios, where user terminals (UTs) have limited processing capabilities. To overcome this challenge, we propose two low-complexity equalization techniques for Zak-OTFS, transmitter side precoding/pre-filtering and receiver side post-filtering. In transmitter side precoding, we introduce an optimized precoder at the Zak-OTFS transmitter. By selecting an appropriate filtering scheme, we enabled single-tap equalization at the receiver, eliminating the need for complex joint equalization and reducing computational overhead. In receiver side post-filtering technique, we design an optimal post filter at the receiver that leverages the sparsity of the DD-domain channel. Since the DD-domain channel is more stationary than the TF-domain counterpart, it enables less frequent channel estimation, reducing pilot overhead and enhancing energy efficiency. This allows the system to maintain reliable performance over longer time intervals without re-estimating the channel frequently. Together, these contributions advance the understanding and practical viability of OTFS-based systems in realistic, high-mobility wireless environments. The proposed methods not only improve spectral and energy efficiency but also reduce system complexity, making them well-suited for future multi-cell deployments in 5G and beyond.

सार

उभरते हुए पाँचवीं पीढ़ी तथा उससे आगे की वायरलेस संचार प्रणालियाँ मुख्यतः ऑर्थोगोनल आवृत्ति विभाजन बहु-प्रवेश आधारित बहु-सेल संरचनाओं पर आधारित हैं। तथापि, अधिक विलंब तथा डॉप्लर प्रसार वाले परिवेश में ये प्रणालियाँ अपेक्षित दृढ़ता प्रदर्शित नहीं कर पातीं, जिसके परिणामस्वरूप स्पेक्ट्रल दक्षता तथा प्रणाली की विश्वसनीयता में उल्लेखनीय ह्रास होता है। इस समस्या के समाधान हेतु मल्टी-कैरियर ऑर्थोगोनल टाइम फ़्रीक्वेंसी स्पेस मॉड्यूलेशन तकनीक प्रस्तावित की गई है।

इस तकनीक में सूचना प्रतीकों का मानचित्रण विलंब-डॉप्लर क्षेत्र में किया जाता है, जहाँ वायरलेस चैनल की संरचना पारंपरिक समय-आवृत्ति क्षेत्र की तुलना में अधिक विरल पाई जाती है। इस विशेषता के कारण अधिक विलंब एवं डॉप्लर प्रसार की स्थितियों में यह तकनीक बेहतर दृढ़ता प्रदान करती है। यद्यपि विलंब-डॉप्लर प्रसार वाले परिवेश में एकल-सेल प्रणालियों के प्रदर्शन का विश्लेषण पूर्ववर्ती शोधों में किया गया है, तथापि बहु-सेल प्रणालियों के संदर्भ में ऐसा अध्ययन अभी भी सीमित रूप में उपलब्ध है।

प्रस्तुत शोध में अधिक विलंब-डॉप्लर प्रसार वाले चैनलों के अंतर्गत बहु-सेल प्रणालियों की स्पेक्ट्रल दक्षता का विस्तृत विश्लेषण किया गया है तथा इसकी तुलना पारंपरिक ऑर्थोगोनल आवृत्ति विभाजन मल्टीप्लेक्सिंग प्रणालियों से की गई है। प्राप्त परिणामों से यह स्पष्ट रूप से सिद्ध होता है कि अंतर-सेल हस्तक्षेप बहु-सेल प्रणालियों की स्पेक्ट्रल दक्षता को महत्वपूर्ण रूप से सीमित करता है।

उक्त समस्या के निराकरण हेतु इस शोध में एक गार्ड बैंड आधारित योजना प्रस्तावित की गई है, जिसमें विभिन्न सेल्स के मध्य विलंब-डॉप्लर संसाधनों का पुनः उपयोग किया जाता है। यह प्रस्तावित योजना विलंब-डॉप्लर प्रसार वाले चैनलों में अंतर-सेल हस्तक्षेप को प्रभावी रूप से न्यूनतम करती है तथा प्रणाली की समग्र स्पेक्ट्रल दक्षता में वृद्धि करती है। सैद्धांतिक एवं संख्यात्मक विश्लेषण से यह प्रमाणित हुआ है कि प्रस्तावित योजना अधिक विलंब तथा डॉप्लर स्थितियों में बहु-सेल प्रणालियों के प्रदर्शन में उल्लेखनीय सुधार प्रदान करती है।

शोध के द्वितीय चरण में ज़ैक-ऑर्थोगोनल टाइम फ़्रीक्वेंसी स्पेस मॉड्यूलेटेड प्रणालियों में कम-जटिलता समानीकरण की समस्या का अध्ययन किया गया है। यद्यपि यह तकनीक मल्टी-कैरियर ऑर्थोगोनल टाइम फ़्रीक्वेंसी स्पेस की तुलना में विलंब-डॉप्लर प्रसार के प्रति अधिक सक्षम है, तथापि इसमें संयुक्त विलंब-डॉप्लर क्षेत्र समानीकरण की आवश्यकता होती है, जो गणनात्मक दृष्टि से अत्यधिक जटिल है। यह समस्या विशेष रूप से डाउनलिंक परिदृश्यों में अधिक गंभीर हो जाती है, जहाँ उपयोगकर्ता टर्मिनलों की प्रसंस्करण क्षमता सीमित होती है।

इस चुनौती के समाधान हेतु इस शोध में ज़ैक-ऑर्थोगोनल टाइम फ़्रीक्वेंसी स्पेस प्रणालियों के लिए दो कम-जटिलता समानीकरण तकनीकें प्रस्तावित की गई हैं, अर्थात् प्रेषक-पक्ष प्रीकोडिंग अथवा प्री-फ़िल्टरिंग तथा रिसीवर-पक्ष पोस्ट-फ़िल्टरिंग। प्रेषक-पक्ष प्रीकोडिंग विधि में ट्रांसमीटर पर एक अनुकूलित प्रीकोडर का प्रयोग किया गया है, जिसके परिणामस्वरूप रिसीवर पर केवल एकल-टैप समानीकरण पर्याप्त सिद्ध होता है। इससे संयुक्त समानीकरण की आवश्यकता समाप्त हो जाती है तथा गणनात्मक जटिलता में उल्लेखनीय कमी आती है।

रिसीवर-पक्ष पोस्ट-फ़िल्टरिंग तकनीक में रिसीवर पर एक इष्टतम फ़िल्टर का अभिकल्पन किया गया है, जो विलंब-डॉप्लर क्षेत्र चैनल की विरल संरचना का प्रभावी उपयोग करता है। चूँकि विलंब-डॉप्लर क्षेत्र चैनल समय-आवृत्ति क्षेत्र चैनल की तुलना में अधिक स्थिर होता है, अतः बार-बार चैनल अनुमान की आवश्यकता नहीं पड़ती। इसके परिणामस्वरूप पायलट ओवरहेड में कमी आती है तथा ऊर्जा दक्षता में वृद्धि होती है, जिससे प्रणाली दीर्घकाल तक विश्वसनीय प्रदर्शन बनाए रखने में सक्षम होती है।

समग्र रूप से, यह शोध उच्च गतिशीलता वाले यथार्थपरक वायरलेस परिवेश में ऑर्थोगोनल टाइम फ़्रीक्वेंसी स्पेस आधारित प्रणालियों की सैद्धांतिक समझ एवं व्यावहारिक उपयोगिता को सुदृढ़ करता है। प्रस्तावित विधियाँ न केवल स्पेक्ट्रल एवं ऊर्जा दक्षता में सुधार करती हैं, अपितु प्रणाली की गणनात्मक जटिलता को भी न्यूनतम करती हैं, जिससे ये भविष्य की बहु-सेल वायरलेस संचार प्रणालियों हेतु अत्यंत उपयुक्त सिद्ध होती हैं।

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Glossary

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple Access
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
CSI	Channel State Information
DD	Delay-Doppler
DSS	Dynamic Spectrum Sharing
DZT	Discrete Zak Transform
EDGE	Enhanced Data Rates for GSM Evolution
eMBB	Enhanced Mobile Broadband
F-OFDM	Filtered Orthogonal Frequency Division Multiplexing
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FeMBB	Further Enhanced Mobile Broadband
FM	Frequency Modulation
Gbps	Gigabits per second
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSDPA	High Speed Downlink Packet Access

HSUPA	High Speed Uplink Packet Access
i.i.d	Independent and Identically Distributed
I/O	Input/Output
ICI	Inter Carrier Interference
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISI	Inter Symbol Interference
LTE	Long Term Evolution
LDPC	Low Density Parity Checking
MA	Multiple Access
Mbps	Megabits per second
MC-OTFS	Multi-carrier Orthogonal Time Frequency Space
MIMO	Multiple Input Multiple Output
MIMO-OFDM	Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing
ML	Machine Learning
MMS	Multimedia Messaging Service
mMTC	Massive Machine Type Communication
mmWave	Millimeter Wave
muRLLC	Massive Ultra Reliable Low Latency Communication
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OTFS	Orthogonal Time Frequency Space
PAPR	Peak-to-Average Power Ratio
PDR	Pilot to Data ratio
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RRC	Root Raised Cosine
RF	Radio Frequency
SMS	Short Message Service
SNR	Signal to Noise ratio

SER	Symbol Error Rate
TDMA	Time Division Multiple Access
TF	Time Frequency
TV	Television
UAV	Unmanned Aerial Vehicle
umMTC	Ultra-reliable and low-latency Machine Type Communication
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra Reliable Low Latency Communication
UT	User Terminal
Veh-A	Vehicle Type A
VoIP	Voice Over Internet Protocol
VoLTE	Voice Over LTE
W-CDMA	Wideband Code Division Multiple Access