DELAY-DOPPLER DOMAIN PULSE SHAPING FOR RELIABLE COMMUNICATION IN HIGH DELAY AND DOPPLER SPREAD WIRELESS CHANNELS

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by

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Dedicated to

My Family & Friends

Certificate

This is to certify that the thesis entitled **"Delay-Doppler domain pulse shaping for reliable communication in high delay and Doppler spread wireless channels"** being submitted by **Mr. Jinu Jayachandran** 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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"The woods are lovely, dark and deep,
But I have promises to keep,
And miles to go before I sleep,
And miles to go before I sleep."

– Stopping by Woods on a Snowy Evening, Robert Frost

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Abstract

Reliable wireless communication under high-mobility conditions, characterized by large delay and Doppler spreads, presents substantial challenges to conventional modulation schemes. Orthogonal Frequency Division Multiplexing (OFDM), though widely adopted, suffers severe performance degradation in such doubly dispersive channels due to loss of orthogonality and increased inter-symbol interference. To address these limitations, delay-Doppler (DD) domain modulation—specifically Zak-transform-based Orthogonal Time Frequency Space (Zak-OTFS) modulation—has emerged as a promising framework. Zak-OTFS operates natively in the DD domain and provides a quasi-periodic, crystalline input-output relation that improves robustness and predictability even under extreme channel conditions.

The first major contribution of this thesis is the design and analysis of a delay-Doppler domain Gaussian pulse shaping filter for Zak-OTFS systems. Unlike conventional rectangular or sinc pulses, the proposed Gaussian pulse achieves improved joint time-frequency localization, which enhances DD domain predictability and minimizes aliasing. Analytical expressions for the time-domain (TD), frequency-domain (FD), and effective DD domain channel response are derived. Simulation results demonstrate that Gaussian pulses offer superior Bit Error Rate (BER) performance and reduced time-bandwidth expansion compared to Root Raised Cosine (RRC) and sinc-based filters.

The second contribution focuses on joint sensing and communication (JSAC) using a turbo signal processing algorithm. A novel iterative framework is proposed to jointly refine channel estimation and data detection within Zak-OTFS transmissions that employ spread pilots. The proposed turbo algorithm exploits the quasi-periodic structure of Zak-OTFS and exchanges soft information between the sensing and communication modules. Numerical evaluations show that the BER performance using the turbo algorithm approaches that of perfect Channel State Information (CSI), particularly when using

Gaussian pulse shaping filters.

The third contribution addresses the limitation of fixed Doppler support in Zak-OTFS systems through the development of an interleaved pilot-based transmission strategy. In scenarios where the actual Doppler spread exceeds the preconfigured Zak period, conventional pilot arrangements fail to maintain predictability. To overcome this, multiple interleaved pilots are introduced to effectively extend the Doppler support without altering the fundamental delay or Doppler periods. Analytical models for the auto-ambiguity function and crystallization condition are derived, and simulations confirm that the method significantly enhances the region of reliable operation and improves BER performance, especially at high Doppler spreads.

Overall, this thesis advances the theoretical foundations and practical implementations of Zak-OTFS modulation by proposing innovative solutions in pulse shaping, iterative detection, and adaptive pilot placement. These developments contribute toward establishing Zak-OTFS as a viable candidate for next-generation 6G wireless systems that demand reliable, high-mobility communication and integrated sensing capabilities.

सार

उच्च गतिशीलता परिस्थितियों में, जहाँ बड़े डिले और डॉपलर स्प्रेड मौजूद होते हैं, विश्वसनीय वायरलेस संचार पारंपरिक मॉड्यूलेशन विधाओं के लिए महत्वपूर्ण चुनौतियाँ प्रस्तुत करता है। यद्यपि ऑर्थोगोनल फ्रीक्वेंसी डिवीजन मल्टीप्लेक्सिंग (ओएफ़डीएम) व्यापक रूप से अपनाया गया है, लेकिन डबली डिपर्सिव चैनलों में यह ऑर्थोगोनैलिटी के नुकसान और बढ़े हुए इंटर-सिंबल इंटरफेरेंस के कारण गंभीर प्रदर्शन गिरावट का सामना करता है। इन सीमाओं को दूर करने के लिए डिले-डॉपलर (डीडी) डोमेन मॉड्यूलेशन — विशेष रूप से ज़ैक ट्रांसफॉर्म-आधारित ऑर्थोगोनल टाइम फ्रीक्वेंसी स्पेस (ज़ैक-ओटीएफएस) मॉड्यूलेशन — एक आशाजनक ढांचा बनकर उभरा है। ज़ैक-ओटीएफएस मूल रूप से डीडी डोमेन में संचालित होता है और एक क्वाज़ी-पीरियॉडिक, क्रिस्टलीय इनपुट-आउटपुट संबंध प्रदान करता है, जो चरम चैनल परिस्थितियों में भी मजबूती और पूर्वानुमेयता में सुधार करता है।

इस शोध का पहला मुख्य योगदान ज़ैक-ओटीएफएस प्रणालियों के लिए डिले-डॉपलर डोमेन गॉसियन पल्स शेपिंग फिल्टर का डिज़ाइन और विश्लेषण है। पारंपरिक आयताकार या सिंक पल्स की तुलना में, प्रस्तावित गॉसियन पल्स बेहतर संयुक्त समय-आवृत्ति स्थानीयकरण प्राप्त करता है, जिससे डीडी डोमेन की पूर्वानुमेयता में सुधार होता है और एलियसिंग कम होता है। समय डोमेन, आवृत्ति डोमेन, और प्रभावी डीडी डोमेन चैनल प्रतिक्रिया के लिए विश्लेषणात्मक समीकरण व्युत्पन्न किए गए हैं। सिमुलेशन परिणाम दिखाते हैं कि गॉसियन पल्स, रूट-रेज़्ड कोसाइन फिल्टर (आरआरसी) और सिंक आधारित फिल्टर की तुलना में बेहतर बिट त्रुटि दर (बीईआर) प्रदर्शन और कम टाइम-बैंडविड्थ विस्तार प्रदान करता है।

दूसरा योगदान जॉइंट सेंसिंग एंड कम्युनिकेशन (जेएसएसी) के लिए टर्बो सिग्नल प्रोसेसिंग एल्गोरिदम पर केंद्रित है। इसमें एक नया इटरेटिव फ्रेमवर्क प्रस्तावित किया गया है जो ज़ैक-ओटीएफएस ट्रांसमिशन में स्प्रेड पायलट्स का उपयोग करते हुए चैनल अनुमान और डेटा डिटेक्शन को संयुक्त रूप से सुधारता है। प्रस्तावित टर्बो एल्गोरिदम, ज़ैक-ओटीएफएस की क्वाज़ी-पीरियॉडिक संरचना का लाभ उठाता है और सेंसिंग व कम्युनिकेशन मॉड्यूल्स के बीच सॉफ्ट सूचना का आदान-प्रदान करता है। संख्यात्मक मूल्यांकन यह दिखाते हैं कि गॉसियन पल्स शेपिंग फिल्टर के उपयोग से टर्बो एल्गोरिदम के साथ बीईआर प्रदर्शन परफेक्ट चैनल स्टेट इंफॉर्मेशन (सीएसआई) के समान पहुँच जाता है।

तीसरा योगदान ज़ैक-ओटीएफएस प्रणालियों में फिक्स्ड डॉपलर सपोर्ट की सीमा को संबोधित करता है, जिसके लिए इंटरलीव्ड पायलट-आधारित ट्रांसमिशन रणनीति विकसित की गई है। उन परिस्थितियों में जहाँ वास्तविक डॉपलर स्प्रेड पूर्वनिर्धारित ज़ैक पीरियड से अधिक होता है, पारंपरिक पायलट संरचनाएँ पूर्वानुमेयता बनाए रखने में विफल हो जाती हैं। इस समस्या को हल

करने के लिए कई इंटरलीव्ड पायलट्स पेश किए गए हैं, जो मौलिक डिले या डॉपलर पीरियड को बदले बिना प्रभावी डॉपलर सपोर्ट का विस्तार करते हैं। ऑटो-एंबिग्यूटी फंक्शन और क्रिस्टलाइज़ेशन कंडीशन के लिए विश्लेषणात्मक मॉडल व्युत्पन्न किए गए हैं, और सिमुलेशन पुष्टि करते हैं कि यह विधि विश्वसनीय संचालन के क्षेत्र को महत्वपूर्ण रूप से बढ़ाती है और विशेष रूप से उच्च डॉपलर स्प्रेड पर बीईआर प्रदर्शन में सुधार करती है।

कुल मिलाकर, यह शोध ज़ैक-ओटीएफएस मॉड्यूलेशन के सैद्धांतिक आधार और व्यावहारिक कार्यान्वयन को आगे बढ़ाता है, और पल्स शेपिंग, इटरेटिव डिटेक्शन और एडैप्टिव पायलट प्लेसमेंट में नवीन समाधान प्रस्तुत करता है। ये विकास ज़ैक-ओटीएफएस को अगली पीढ़ी की 6जी वायरलेस प्रणालियों के लिए एक व्यवहार्य विकल्प के रूप में स्थापित करने में योगदान करते हैं, जहाँ विश्वसनीय उच्च गतिशीलता संचार और एकीकृत सेंसिंग क्षमताओं की आवश्यकता होती है।

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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
DARPA	Defense Advanced Research Projects Agency
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
HetNet	Heterogeneous Network
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
ISAC	Integrated Sensing and Communication
ISI	Inter Symbol Interference
JSAC	Joint Sensing and Communication
LTE	Long Term Evolution
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
MUI	Multi User Interference
muRLLC	Massive Ultra Reliable Low Latency Communication
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM-IM	Orthogonal Frequency Division Multiplexing with Index Modulation
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
SON	Self Organizing Network
TDMA	Time Division Multiple Access

TF	Time Frequency
TV	Television
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
WAP	Wireless Application Protocol
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access