NEW METHODS OF WINDOWING FOR REDUCING THE OUT OF BAND EMISSION WITH LOW COMPLEXITY IN THE 5G WAVEFORM

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To the memory of my grandfather, my grandmother, who would have been glad to see me at this moment.
To my beloved mother for her constant, unconditional love throughout my life.
To my wife and beloved children, Taem, Tallen for their love and support.
To my brothers and my sisters for their support and encouragement.
To all my family members and friends for their love and support.

To science,
enlightening us.

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ABSTRACT

Various 5G waveform candidates are used for wireless communication in multicarrier waveform design. This specifically includes Filtered-Orthogonal Frequency Division Multiplexing (F-OFDM) and Universal Filtered Multicarrier (UFMC) waveforms adopted in the high-speed 5G system and beyond. Previous literature studies showed that a high level for out of band emission (OOBE) and attaining accurate KPIs in real applications are the main obstacles in the 5G communication. Thus, the present study contributed in three new methods in the time domain, namely, Kaiser Hankel subband Window (KHW), hybrid window group subcarrier-windowing (HWG subcarrier windowing), and Convolution New Window type-windowing (CNW windowing) to suppress the value of OOBE in F-OFDM and UFMC and improve Power Spectral Density (PSD) without degradation of Bit Error Rate (BER) in the system. On the other hand, two methods were proposed in the frequency domain to decrease the OOBE while maintaining a low computational complexity, namely, Array window subcarrier windowing (AWsubcarrer-windowing) and the Half subcarrier edge windowing (HSE-windowing). The OOBE decrease for KHW, HWG, and CNW is 70%, 75%, and 80% for the ACLPRG for KHW, HWG, and CNW, respectively. Moreover, ACLPRG for AW and HSE is 78% and 81% of either the traditional in frequency domain approach. The merging also reduces suppression ACLPRG OOBE by 88%. Also, difficult real-addition and multiplication operations have been reduced by 33-45%. The new methods helped reduce the value of OOBE without affecting the system's KPIs. The waveform could also coexist with a legacy system without affecting the core KPIs and key quality indicators (KQIs) by reduce the OOBE in the 5G waveform. Moreover, the study found that lowering OOBE did not increase system complexity. These findings have ramifications for academics, and 5G communication.

ABSTRAK

Pelbagai bentuk gelombang 5G digunakan untuk komunikasi tanpa wayar dalam reka bentuk gelombang berbilang pembawa. Ini secara khusus termasuk pemultipleksan pembahagian frekuensi orthogonal yang ditapis (F-OFDM) dan Pembawa Berbilang Penapis Universal (UFMC) yang diterima pakai dalam sistem 5G berkelajuan tinggi dan selanjutnya. Walau bagaimanapun, kajian literatur sebelum ini menunjukkan bahawa tahap pelepasan luar jalur (OOBE) yang tinggi dan mencapai petunjuk kualiti utama (KPI). yang tepat dalam aplikasi sebenar merupakan halangan utama dalam komunikasi 5G. Oleh itu, kajian ini menyumbang kepada tiga kaedah baharu dalam domain masa, iaitu, tetingkap sub-jalur Kaiser Hankel (KHW), tetingkap sub-pembawa kumpulan tetingkap hibrid (tetingkap sub-pembawa HWG), dan tetingkap jenis Tetingkap Konvolusi Baharu (tetingkap CNW). Ini adalah untuk memadatkan nilai OOBE dalam F-OFDM dan UFMC dan meningkatkan Ketumpatan Spektrum Kuasa (PSD) tanpa penurunan Kadar Ralat Bit (BER) dalam sistem. Sebaliknya, dua kaedah telah dicadangkan dalam domain frekuensi untuk mengurangkan OOBE sambil mengekalkan kerumitan pengiraan yang rendah, iaitu, tetingkap sub-pembawa tingkap tatasusunan (tetingkap AW sub-pembawa) dan tetingkap sudut sub-pembawa separuh (tetingkap HSE). Sehubungan itu, berbanding dengan teknik tetingkap tradisional dalam domain masa, pengurangan OOBE berkenaan Keuntungan Pengurangan Kuasa Bocoran Saluran Bersebelahan (ACLPRG) untuk KHW, HWG dan CNW masing-masing 70%, 75%, dan 82%. Selain itu, kaedah ACLPRG untuk AW dan HSE dibandingkan dengan kaedah domain frekuensi tradisional dengan 78% dan 81%, masing-masing. Tambahan pula, pengurangan ACLPRG OOBE penindasan untuk kaedah gabungan ialah 88%. Di samping itu, bilangan operasi tambah nyata dan pendaraban kompleks telah dikurangkan kepada 33-45%, masing-masing. Penemuan semasa mengakui bahawa kaedah baharu menyumbang kepada mengehadkan nilai OOBE ke tahap yang lebih rendah tanpa menjejaskan prestasi Petunjuk Prestasi Utama (KPI) dalam sistem. Selain itu, kewujudan bersama yang novel mencadangkan bentuk

gelombang 5G dengan sistem warisan tanpa penurunan dalam KPI utama dan petunjuk kualiti utama (KQI). Selain itu, kajian itu mengesahkan bahawa penurunan nilai OOBE tidak menyebabkan sebarang kerumitan yang tinggi dalam sistem. Kesimpulan ini boleh menarik implikasi kajian ini tentang bidang akademik dan komunikasi 5G yang realistik .

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LIST OF SYMBOLS AND ABBREVIATIONS

$T_{pts_s}^{groups}$	-	Type of Partitioning Method
Δf	-	Frequency Space between Subcarriers
3G	-	Third Generation
3GPP	-	Third Generation Partnership Project
4G	-	Fourth Generation
5G	-	Fifth Generation
ADC	-	Analog to Digital Converters
Ad-PTS	-	Adjacent Partitioning Scheme
AWGN	-	Additive White Gaussian Noise
B	-	Bandwidth of The Symbol
BER	-	Bit Error Rate
b_v	-	Phase Factors Elements
C	-	Number of The Candidate Signals
C_{add}	-	Number of Complex Addition Operations
CC	-	Computational Complexity Level
CCDF	-	Complementary Cumulative Distribution Function
C_{comp}	-	Number of Comparison Operations
$CCRR^{+}$	-	Addition Operations Ratio
$CCRR^{\times}$	-	Multiplication Operations Ratio
CFO	-	Carrier Frequency Offset
C_{mult}	-	Number of Complex Multiplication Operations
CP	-	Cyclic Prefix
C-PTS	-	Conventional Partial Transmit Sequence
D/A	-	Digital to Analogue
DAB	-	Digital Audio Broadcasting
DAC	-	Digital to Analog Converters
dB	-	Decibel

DVB-H	-	Digital Video Broadcasting-Handheld
DVB-T	-	Digital Video Broadcasting-Terrestrial
E	-	Length of DFT Block
$f(n)$	-	Spectrum Shaping Filter
FBMC	-	Filter Bank Multi-Carrier
FFT	-	Fast Fourier Transform
FMT	-	Filtered Multi-Tone
F-OFDM	-	Filtered-Orthogonal Frequency Division Multiplexing
G-C-PTS	-	Grouping Complex Iteration PTS Algorithm
Gray-PTS	-	Gray Code PTS Algorithm
H	-	Shift Number Sets
$h_{LPF}(n)$	-	Sinc Impulse Response
HPA	-	High Power Amplifier
H-PTS	-	Hybrid Random and Terminals Exchange Algorithm
I	-	Number of Iterations
IDFT	-	Inverse Discrete Fourie Transform
IFFT	-	Inverse Fast Fourier Transform
IL-PTS	-	Interleaving Partitioning Scheme
IoT	-	Internet of Things
ISI	-	Inter-Symbol Interference
J	-	Concatenated Factor
k	-	Frequency Domain Index
K	-	Number of Interleavers
l	-	Number of The Intermediate Data Sequence Stages
L	-	Oversampling Factor
LFSR	-	Left Feedback Shift Register
LPF	-	Low Pass Filter
LTE	-	Long Term Evolution Standard
LTE-A	-	LTE-Advanced
LTE-A-Pro	-	LTE-Advanced-Pro

M	-	Constellation Order
M2M	-	Machine to Machine
MATLAB	-	Matrix Lab Software
M-PSK	-	Phase Shift Keying
M-QAM	-	Quadrature Amplitude Modulation
MSR	-	Multiple Signal Representation
n	-	Discrete-Time Index
N	-	Number of Subcarriers
n-l	-	Number of The IFFT Stages in Lim's Method
O	-	Filter Length
OFDM	-	Orthogonal Frequency Division Multiplexing
OOBE	-	Out-Of-Band Emission
P/S	-	Parallel to Serial Converter
PAPR	-	Peak-to-Average-Power Ratio
$PAPR_0$	-	Threshold Value
PHY	-	Physical Layer
PM	-	Number of Partitioning Methods
PR-PTS	-	Pseudo-Random Partitioning Scheme
PRV	-	Phase Rotation Vectors
PSD	-	Power Spectral Density
PTS	-	Partial Transmit Sequence
pts	-	Transformed Subblocks in The Time-Domain
PTS-F-OFDM	-	F-OFDM Based on The PTS Technique
Q	-	Number of Cyclic Iterations
Q_n	-	Cost Function
r	-	Roll-Off Factor
RF	-	Radio Frequency
RRC	-	Rooted Raised Cosine Window
S/P	-	Serial to Parallel Converter
Sb-PTS	-	Subsets Partitioning PTS Scheme

SI	-	Number of Side Information Bits
SLM	-	Selective Level Mapping
SLM-CSS-PTS	-	Combining SLM and Cyclically Shift Sequence PTS
SNR	-	Signal-to-Noise Ratio
SS	-	Number of Conjugated Subblocks
SSCP	-	Number of Special Subblocks Circular Permutation
SS-PTS	-	Sine Shape PTS Scheme
T	-	Total Time of The Symbol
U	-	Total Number of Phase Rotation Factors in SLM
UTHM	-	Universiti Tun Hussein Onn Malaysia
V	-	Number of Subblocks
V2V	-	Vehicle to Vehicle
W	-	Number of Allowed Phase Factors
$w(n)$	-	Windowing Mask Impulse Response
WLAN	-	Wireless Local Area Networks
WMAN	-	Wireless Metropolitan Area Networks
$W_{\mathbf{N}}$	-	IFFT Matrix
W_N	-	Twiddle Factor
WPAN	-	Wireless Personal Area Networks
WRAN	-	Wireless Regional Area Networks
$X(k)$	-	OFDM Samples
$x(n)$	-	OFDM Time-Domain Samples
x^{opt}	-	Optimum OFDM Signal
α	-	Determination Value
ω	-	Channel Effect

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Internet services and multimedia applications have extensively been utilized in recent times due to the rapid development of smart services, including smart machines, mobile computers, and smartphones. These applications and resources have emerged from an urgent need for everyday activities and lives. In addition, an exponential expansion of the mobile wireless communication networks imparted further impetus to necessitating the high-speed data rates, thus satisfying the market demands [1, 2]. Consequently, various techniques have been evolved to deal with the high-speed data transmission rates [3]. In this view, the cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM) system can be regarded as a fundamental enabling technology for high-speed wireless communication [4].

Over the years, the wireless technology transformation from third-generation (3G) to fourth generation (4G) systems that mainly relies on the Cyclic Prefix – Orthogonal Frequency Division Multiplexing (CP-OFDM) scheme can be credited to the fundamental foundation for the waveform design in the 5th generation (5G) communication networks [5]. The CP-OFDM modulation technology has increasingly been gaining popularity in high-speed wireless communication environments because of its superior performance over other modulation techniques. The CP-OFDM modulation technology possesses high immunity against multipath fading [3], increased system capacity [4] [5] and efficient bandwidth utilization [6] [7]. Accordingly, diverse wireless communication systems have adopted the CP-OFDM design. Numerous studies have highlighted various limitations of the 4G communication network system in accomplishing the market demands [6], wherein

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APPENDIX D

LIST OF PUBLICATIONS

Journal and proceeding Articles

1. Hammoodi, A., Audah, L., Taher, M. A., Mohammed, M. A., Aljumaily, M. S., Salh, A., & Hamzah, S. A. "Novel Universal Windowing Multicarrier Waveform for 5G Systems." CMC-COMPUTERS MATERIALS & CONTINUA 67.2 (2021): 1523-1536. **(WoS indexed – Q1).**
2. Hammoodi, A., Audah, L., Taher, M. A., Mohammed, M. A., Aljumaily, M. S., Salh, A., & Hamzah, S. A." New 5G Kaiser-Based Windowing to Reduce Out of Band Emission" CMC-COMPUTERS MATERIALS & CONTINUA 2021 **(WoS indexed – Q1).**
3. Hammoodi, Ahmed, Lukman Audah, and Montadar Abas Taher. "Green coexistence for 5G waveform candidates: a review." *IEEE Access* 7 (2019): 10103-10126. **(WoS Indexed SCI Q1).**
4. Hammoodi, Ahmed Talaat, et al. "Under test filtered-OFDM and UFMC 5G waveform using cellular network." Journal of Southwest Jiaotong University 54.5 (2019). (**WoS Indexed SCI Q1).**
5. Hammoodi, A., Audah, L., Aljumaily, M. S., Mohammed, M. A., & Rasool, J. (2022). Neural Network Based Windowing Scheme to Maximize the PSD for 5G and Beyond. In *International Conference on Innovative Computing and Communications* (pp. 881-889). Springer, Singapore. **(SCOPUS Indexed 2022).**
6. Hammoodi, Ahmed, Lukman Audah, Mustafa S. Aljumaily, Montadar A. Taher, and Farooq Sijal Shawqi. "Green Coexistence of CP-OFDM and UFMC Waveforms for 5G and Beyond Systems." In *2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, pp. 1-6. IEEE, 2020. **(SCOPUS Indexed 2020).**

Co-authored Papers

1. Shawqi, Farooq Sijal, Lukman Audah, Salama A. Mostafa, Saraswathy Shamini Gunasekaran, Abdullah Baz, Ahmed Talaat Hammoodi, Hosam Alhakami, Mustafa Hamid Hassan, Mohammed Ahmed Jubair, and Wajdi Alhakami. "A new SLM-UFMC model for universal filtered multi-carrier to reduce cubic metric and peak to average power ratio in 5G technology." Symmetry 12, no. 6 (2020): 909. (**WoS Indexed SCI**).
2. Aljumaily, Mustafa S., Ahmed Hammoodi, Lukman Audah, Husheng Li, Farooq Sijal Shawqi, and Mustafa Maad Hamdi. "Combined Beamforming-Waveform Design using Mid-Band Frequencies for 5G and Beyond Networks." In *2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, pp. 1-5. IEEE, 2020. (**SCOPUS Indexed 2020**).
3. Shawqi, Farooq Sijal, Lukman Audah, Ahmed Talaat Hammoodi, Mustafa Maad Hamdi, and ALAA HAMID MOHAMMED. "A Review of PAPR Reduction Techniques for UFMC Waveform." In *2020 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, pp. 1-6. IEEE, 2020. (**SCOPUS Indexed 2020**).
4. Shawqi, Farooq Sijal, Ahmed Talaat Hammoodia, Lukman Audah, and Ammar Ahmed Falih. "PAPR Reduction of a Universal Filtered Multicarrier Using a Selective Mapping Scheme." *Journal of Southwest Jiaotong University* 54, no. 5 (2019). (**WoS Indexed SCI Q1**).
5. Ramli, Khairun, Montadar Taher, Lukman Audah, Nor Shahida Shah, Mustafa Ahmed, and Ahmed Hammoodi. "An enhanced partial transmit sequence based on combining Hadamard matrix and partitioning schemes in OFDM systems." *International Journal of Integrated Engineering* 10, no. 3 (2018).). (**WoS Indexed SCI**).