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論　文　名	「Studies on Precoding Techniques for Sidelobe Suppression in OFDM Systems」 「OFDM システムにおけるサイドローブ抑圧に適したプリコーディング法」
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論文要旨

In telecommunications field, wireless digital communication technology has been a main and remarkable topic in recent decades since it can provide new way of daily life for the information and communication technology era. On the other hand, today wireless digital communication technology must face a great challenge of unlimited desires of human beings although resources of radio frequency spectrum are so limited and almost depleted, and always has been groping for advanced techniques and new methods to utilize the resources efficiently and enhance capacity in wireless communication systems. In this background, orthogonal frequency-division multiplexing (OFDM), that has been active around 4G mobile systems represented by LTE and (mobile) WiMAX, is still a promising candidate in next 5G planning services on the order of a few Gbps and more future-generation communication systems as it appears now, and therefore required to be researched and developed more and more.

OFDM is a special form of multi-carrier transmission method where all the subcarriers are orthogonal to each other. A diversity derived from multi-carriers would avoid a fatal corruption of transmitted data in multipath fading environment, and the orthogonality leads to very high spectral efficiency. Furthermore, robustness against multipath fading can be improved by inserting the cyclic prefix (CP) in the guard interval (GI) as making a useful redundancy for synchronizations in the receiver, and the practical circuit can be implemented efficiently by digital signal processing technology, mainly by the FFT algorithm. These advantages are the reason why the OFDM has been adopted in several modern telecommunications systems, such as digital terrestrial television broadcasting, WLANs, LTE and WiMAX systems. However, the

OFDM signal has a serious problem of high sidelobe that is caused by the discontinuity of adjacent OFDM symbols and interferes with the adjacent band.

To solve this sidelobe problem, various methods have been proposed. *N*-continuous OFDM is a precoding method for sidelobe suppression, which modifies the data symbols to satisfy the constraints to smoothly connect the consecutive OFDM symbols up to the high order derivatives and can suppress out-of-band radiation of OFDM signals remarkably. An another precoding method to suppress sidelobe is Spectrum-Sculpting Precoder (SSP), which precodes the data symbols under the constraints that nullifies the power at chosen frequencies. Compared with the *N*-continuous OFDM, the SSP can shape spectral notch sharply and easily at in-band, which is often required in cognitive radio (CR) systems. These precoding methods do not reduce spectral efficiency or transmission efficiency, and keep the robustness against multipath fading. On the other hand, the order of computational complexity is high due to the size of the precoder matrix. The fundamental method to reduce the computational complexity by matrix decomposition is certainly proposed but will not be suitable for practical implementation since its relatively wide dynamic range does harm in circuit scale. Also, correction symbols added into the data symbols in the precoding affects the whole of OFDM symbol and it results in error rate degradation. To reduce this effect, an iterative algorithm for decoding has been proposed but non-negligible degradation might be left even if it is used many times. Orthogonal precoding of the *N*-continuous OFDM or the SSP is an excellent method that can achieve both identical sidelobe suppression performance and an ideal error rate performance; however, it does sacrifice the spectral efficiency due to the consumption of some subcarriers, and has the enormous computational complexity due to the large size of precoder matrix.

This thesis studies on precoding techniques for sidelobe suppression in OFDM systems as for the future generation wireless digital communications, which are obliged to solve a problem of almost depleted spectral resources and provide high data capacity and low power consumption of communication systems. The main efforts begin with improvements of the *N*-continuous OFDM. Next, the computational complexity reduction in the orthogonal precoding will be proposed. Furthermore to explore an excellent method based on the *N*-continuous, a novel precoding method named as *N*-continuous Symbol Padding OFDM (NCSP-OFDM) will be proposed, which adds the correction symbol of the *N*-continuous only into the CP to reduce the adverse effect on error rate performance. Lastly, the advanced studies will be discussed to propose improvement methods of the NCSP-OFDM.

The organization of this thesis is as follows.

Chapter 1

An overview of wireless digital communications is presented and summarized. It shows that the OFDM is a vivid key technology in the recent wireless systems of high speed and capacity but has a serious problem of high sidelobe interfering with the other systems, and then shows that the purpose of this thesis is to explore advanced techniques to suppress this sidelobe for next 5G and more future-generation wireless digital communications.

Chapter 2

It explains principles of OFDM and multipath fading, high sidelobe problem of OFDM signals and CR system in which OFDM is expected to adopt.

Chapter 3

It mentions various conventional methods to suppress sidelobe in detail, and reveals that candidates worthy to discuss in this thesis are the N-continuous OFDM possible to suppress out-of-band radiation effectively and the orthogonal precoding of SSP suitable for CR systems.

Chapter 4

Improvement methods of the N-continuous OFDM in error rate and complexity are proposed. Firstly, a practical method to reduce the computational complexity by singular-value decomposition (SVD) based decomposition of the precoder is exhibited, which leads to significant narrow dynamic range allowing the FPGA implementation to save circuit scale and power consumption by fixed-point arithmetic. Secondly, a novel method to improve the error rate without loss of spectral efficiency is shown, which is derived from an extension of the precoder matrix and intended to make all data subcarriers available for data transmission as maintaining performances in sidelobe suppression and computational complexity.

Chapter 5

An improvement method to solve the serious problem of the enormous computational complexity in the orthogonal precoding is proposed for CR systems. The proposed method is driven by a novel decomposition of the precoder matrix using QR-factorization with a guarantee for significant effect of computational complexity reduction, and can reduce the computational complexity drastically, e.g., into only 2.7%, and is completely superior to the conventional orthogonal precoding since the other performances, such as the remarkable sidelobe suppression and the ideal error rate, will not be degraded.

Chapter 6

It proposes a novel precoding method for sidelobe suppression without loss of spectral efficiency, named as NCSP-OFDM, which adds the correction symbol based on the N-continuous OFDM only into the CP in the GI to achieve continuous connections between OFDM symbols and allows the body of the OFDM symbol to convey the data symbol correctly. Numerical experiments show that the proposed method can suppress out-of-band radiation effectively like the conventional N-continuous OFDM and maintain the error rate and spectral efficiency of the original OFDM with moderate computational complexity, and is effective in a system with a small number of subcarriers, such as LTE systems and CR systems.

In the advanced studies, a practical method to reduce the computational complexity for a low-end FPGA implementation of the NCSP-OFDM is proposed. The proposed method based on the SVD of the precoder matrix allows the narrow dynamic range in the precoding and suitable for the implementation since circuit resources and power consumption can be saved significantly.

Also, the NCSP-OFDM with sub-band technique is proposed to create a spectral notch at in-band for CR systems. The proposed method can shape a deep notch comparable to that of the SSP and satisfy the spectral mask of -35 dB, and notably does not degrade the error rate in contrast the conventional schemes that degrade them severely.

The advanced studies then propose effective methods to reduce the complexities in the transmitter and the receiver for practical use of the NCSP-OFDM. For the transmitter, the proposed method based on the central finite differences to approximate the derivatives for continuous connections can reduce the computational complexity significantly; for example, the computational complexity increases by only about 20% in complex multiplication compared with that of the original OFDM. On the other hand for the receiver, the proposed method can reduce the computational complexity by the approximation derived from a Neumann series expansion of the inverse matrix calculated with high computational complexity, and numerical experiments finally confirms that it coincides with that of the usual OFDM, that is, the FFT and the one-tap frequency-domain equalizer are enough for the accurate demodulation in some practical fading channels, which surely will not require any extra computations and any structure modification.

The advanced studies lastly propose the two algorithms for coarse and fine timing synchronization of the NCSP-OFDM, named as the gap-corrected ML estimation and Reconstruction of CP (RCP) method, respectively. While the conventional synchronization methods based on the existence of CP degrades the synchronization performance since the symbol in the GI of the NCSP-OFDM is different from a complete CP, the proposed methods allow the NCSP-OFDM to perform the coarse timing synchronization that requires relatively low complexity and accuracy and then the fine one that needs relatively high complexity and accuracy.

Chapter 7

Conclusion of this thesis is presented.

論文審査結果の要旨

本論文では、次世代無線通信システムにおいて4Gに引き続き採用が有力視されている直交周波数分割多重(OFDM)通信方式に焦点を当て、そのシステムにおいて問題となる高い帯域外漏洩電力問題を解決し、周波数帯域の有効利用を可能にする新規ディジタル信号処理手法を提案したものである。データシンボルの修正を行うプリコーディングをベースとした提案法は効果的なサイドローブ抑圧性能と優れた誤り率性能を両立でき、さらに計算量や FPGA の実装面からの検証も行われている点で特色がある。得られた主な成果は以下の項目に要約できる。

(1)　隣接帯域サイドローブ抑圧のプリコーディング法 *N*-continuous OFDM の実装化に向けた改良法を提案している。特異値分解による狭いダイナミックレンジを実現する計算量削減法を提案し、また、FPGA 実装実験を通してリソース消費量や消費電力の観点からの有効性を示している。更に、従来のプリコーディング法を拡張した誤り率改善法を提案し、数値実験を通して、提案法の有効性を示している。

(2)　OFDM システムにおいて、選択帯域でのスペクトルノッチ形成が必要不可欠な次世代通信技術であるコグニティブ無線に適した従来法の問題点である計算量負荷を軽減する新たな手法を提案している。提案法は、従来法の巨大な行列に対して、効率的なアルゴリズムを利用し分解が可能であることを数学的に証明している。数値実験により、提案法が従来法の性能を全く劣化させずに、計算量を約 5.4%までに削減でき、FFT と同程度の実用的なレベルに達したことを示している。

(3)　新規サイドローブ抑圧手法 *N*-continuous Symbol Padding OFDM (NCSP-OFDM)を提案し、従来法の N-continuous OFDM における誤り率劣化の問題を解決している。数値実験により、効果的な隣接帯域サイドローブ抑圧および通常の OFDM と同等の誤り率性能を両立でき、実用的な計算量と電力特性を有することが示されている。さらに発展研究として、実用的な NCSP-OFDM の FPGA 実装法、NCSP-OFDM ベースのコグニティブ無線に向けた選択帯域でのサイドローブ抑圧法、送受信機双方での実用的なレベルまで計算量を削減する手法、計算量と正確性にそれぞれ優れた時間同期手法などを提案している。

以上の諸成果は、次世代無線通信システムのための基礎的な知見や基盤を与えるものであり、この分野の技術の発展に大いに貢献すると考えられる。また、申請者が自立して研究活動を行うに充分な能力と学識を有することを証したものである。本委員会は、本論文の審査ならびに最終試験の結果から、博士（工学）の学位を授与することを適当と認める。