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論　文　名	「On the Circuit Impairments and Self-Interference in Future Wireless Communication Systems」 「次世代無線通信システムにおける回路歪みと自己干渉に関する研究」
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論文要旨

Nowadays, wireless communication is essential in our daily life. People use mobile communication devices, such as smartphones, for various purposes, which include not only voice but also photo, music, movie and other digital contents. In response to the rapid growth of mobile data traffic, the next generation cellular systems, namely the 5th generation (5G) cellular systems, aim to gain more than 1,000 times capacity compared to the current 4th generation (4G) cellular systems. In order to achieve this challenging goal, new communication technologies with high transmission efficiency, for example, full-duplex wireless and Orthogonal Frequency Division Multiplexing (OFDM) with Offset Quadrature Amplitude Modulation (OQAM) (OFDM/OQAM) have attracted a lot of attention.

Despite the capability of doubling the throughput, full-duplex wireless, which is the simultaneous transmission and reception in the same frequency band, has not been adopted. The main reason is the self-interference, which is the loopback of own transmitted signal at the receive antenna. Therefore, the most important issue to realize full-duplex wireless is the effective self-interference cancellation, and it has been proposed to cancel the self-interference in the analog and the digital domains.

In 4G systems, OFDM is adopted because of its higher spectrum efficiency than the conventional frequency division multiplexing (FDM), and the strong robustness against the multipath fading channel by

using cyclic prefix (CP). However, the most significant drawback of OFDM is its higher sidelobe, thus, OFDM/OQAM is expected to be adopted in 5G systems instead, where the well-designed pulse shaping filter named prototype filter is utilized, which has much smaller sidelobe power than OFDM. Furthermore, no CP is added in OFDM/OQAM, since the symbol length is expanded while neighboring transmitted symbols are overlapped each other to keep the same transmission rate to OFDM. These attractive benefits are obtained by relaxing orthogonality among subcarriers to real field only, compared to complex orthogonality in OFDM. As a result, the received symbol inherently contains pure imaginary inter carrier interference (ICI) and inter symbol interference (ISI), which is called intrinsic interference. This means that the conventional digital signal processing (DSP) techniques for OFDM need to be reconsidered in the context of OFDM/OQAM.

In the practical implementation of these systems, transceiver circuit impairments cannot be ignored since they can limit the performance seriously. This thesis focuses on In-phase/Quadrature (I/Q) imbalance and phase noise (PN), both of which are major circuit impairments in the direct conversion transceivers widely employed in today's wireless communication systems. I/Q imbalance is a mismatch between the local oscillator (LO) signals in I and Q paths of the transmitter (Tx) or receiver (Rx), while PN is a random phase fluctuation of the LO signal. These impairments need to be corrected prior to the demodulation, otherwise they cause the interference which results in severe demodulation errors. Therefore, one purpose of this thesis is to propose approaches to eliminate or mitigate the interference caused by the I/Q imbalance and PN in full duplex and OFDM/OQAM wireless systems.

On the other hand, confidentiality is a fundamental problem in wireless communications since anyone within the cover area of the Tx can listen the transmitted signal and has a potential to demodulate then decode it maliciously. The increasing demands for secure wireless communications have largely driven the research of physical layer security (PLS). In contrast to PLS schemes which achieve information theoretic security by exploiting channel characteristics, physical layer encryption (PLE) directly encrypts the transmitted signal, which is similar to the upper layer encryption schemes. To the best of our knowledge, PLE scheme has not been sufficiently studied in OFDM/OQAM systems, thus, another purpose of this thesis is to propose a novel PLE method for OFDM/OQAM systems.

The organization of this thesis and the contributions are summarized below.

Chapter 1

The history and background of wireless communications, especially the cellular systems, are summarized. The goal of 5G systems and its candidate technology, namely, full-duplex wireless and OFDM/OQAM are briefly introduced. Transceiver circuit impairments such as I/Q imbalance and PN, and the security in wireless communications are explained, then, the purpose of this thesis is presented.

Chapter 2

The mathematical model of Tx/Rx I/Q imbalance is considered, then, the conventional estimation and compensation methods are discussed. Additionally, the "properness" of the complex-valued signal and Widely-Linear (WL) filtering are introduced. On the other hand, the mathematical model of PN is also presented, and conventional compensation methods are summarized. Finally, the time domain PN approximation based on orthonormal basis is presented.

Chapter 3

This thesis considers the DSP-assisted analog self-interference cancellation because of its low complexity, low cost and easy reconfiguration. The impact of I/Q imbalance on the cancellation performance is investigated, and the numerical simulation results show that considerable residual self-interference still remains after the ordinary cancellation. Taking Tx I/Q imbalance into account, the proposed cancellation method applies WL filtering to generate the cancellation signal. The closed-form optimal WL filter coefficients are derived, and an adaptive algorithm to directly obtain the coefficients is proposed. In addition to Tx I/Q imbalance, the impact of Rx I/Q imbalance is also analyzed. The result shows that the proposed adaptive algorithm can obtain the same optimal WL filter even in the presence of Rx I/Q imbalance. For practical implementation, an algorithm based on the Augmented Complex Least Mean Squares (ACLMS) algorithm is proposed to obtain the necessary WL filter coefficients, which can work without the I/Q imbalance knowledge. The steady state behavior of the proposed algorithm is analyzed in terms of the residual self-interference power after the cancellation. Computer simulations are provided to verify the superior cancellation performance of the proposed ACLMS algorithm. Moreover, the performance in the presence of other circuit impairments, such as power amplifier nonlinearity and PN, is evaluated to verify the tolerance to these impairments.

Chapter 4

The preamble-based channel and I/Q imbalance estimation is considered in OFDM/OQAM systems. A mathematical model of the reconstructed OFDM/OQAM symbol in the presence of I/Q imbalance is derived, and the least squares (LS) estimation of channel and I/Q imbalance parameters by the pilot symbols in the preamble is proposed. One of the main contributions of this thesis is to notice that the distinctive characteristics of OFDM/OQAM signal only requires one loaded pilot symbol for the estimation, whereas at least two differently loaded pilot symbols are necessary for OFDM. This advantage comes from that the intrinsic interference caused by one pilot symbol will spread to its neighboring symbols, which can be treated as another pilot symbol. Assuming white Gaussian noise in the frequency domain, an approximated CRB of the estimation is obtained, then, a lower bound of the approximated CRB is employed to design an optimized pilot symbol. Numerical simulations are performed to show the superior performance of the proposed method.

Chapter 5

The PN estimation and compensation methods are considered in OFDM/OQAM. A mathematical model of the OFDM/OQAM received symbol in the presence of PN is derived. Since the ISI is no longer imaginary in the presence of PN, PN should be corrected prior to the analysis processing of OFDM/OQAM symbols. For this reason, this thesis proposes a time-domain compensation scheme to perform symbol-wise PN approximation based on DCT basis. The proposed method exploits the distinctive signal structure of OFDM/OQAM that PN samples in consecutive OFDM/OQAM symbols have common parts, and a relationship between adjacent weighting vectors for PN approximation is employed for obtaining the weighting vector. In addition, by taking into account the shape of the prototype filter, a truncated PN estimation is proposed, which leads to a reduced-complexity PN compensation. Finally, the superior performance of the proposed compensation method is confirmed by numerical simulations.

Chapter 6

The PLE based on the intrinsic interference is proposed for OFDM/OQAM. The real-valued intrinsic interference is utilized for PLE, which is intentionally induced by inserting additional pure imaginary symbols in the transmitted symbols, namely, key symbols. The eavesdropper cannot subtract the interference without the key knowledge even if the perfect channel state information is available. On the other hand, the legitimate receivers are able to cancel the interference by the prior key knowledge, as a result, the data symbols can be obtained. The key generation and its loading patterns are investigated, and the performance of the proposed encryption in terms of the vulnerability to the channel estimation errors, the robustness

against the cyphertext attacks, and Information Leakage (IL), respectively. Finally, several numerical simulations are performed to provide the validity of the proposed encryption.

Chapter 7

Conclusions and future works are described.

論文審査結果の要旨

本論文では、第 5 世代（5G）無線通信システムにおいて利用が期待されている全二重無線通信とオフセット直交振幅変調を用いた直交周波数分割多重（OFDM/OQAM）の 2 つの通信方式に焦点を当て、これらの実装において問題となる I/Q 不均衡および位相雑音の推定、補正、ならびに、物理層セキュリティの強化を実現するディジタル信号処理手法を提案したものである。得られた主な成果は、以下の項目に要約できる。

（1） 本論文では、DSP-assisted Analog Cancellation における I/Q 不均衡を考慮した Widely-Linear（WL）干渉除去信号生成法と、適応アルゴリズム（ACLMS）による WL フィルタ係数推定法を提案している。さらに、定常状態における提案法の性能下界を導出し、数値シミュレーションにより、I/Q 不均衡存在下において、提案法は従来法よりも優れた除去性能を達成できることを示している。

（2） OFDM/OQAM システムにおける送受信機 I/Q 不均衡推定法を提案している。提案法では、OFDM/OQAM 特有のシンボル間・キャリア間干渉（ISI/ICI）を有効活用することで、I/Q 不均衡推定に必要なパイロットシンボル数を 1 つに削減するとともに、パイロットシンボルの最適化を行っている。また、数値シミュレーションにより、従来法よりも少ないパイロットシンボル数で、より優れた推定性能を達成できることを示している。

（3） OFDM/OQAM システムにおける位相雑音の推定、補正法を提案している。提案法では、離散コサイン変換基底を用いて位相雑音サンプルを時間領域において近似し、OFDM/OQAM の信号特性である送信信号のオーバーラップを利用した基底係数の推定法を提案している。また、数値シミュレーションにより、従来の位相雑補正法よりも、提案法は優れたビット誤り率を達成できることを示している。

（4） OFDM/OQAM システムにおいて、固有干渉を利用した物理層暗号化を提案している。提案法では、虚数の送信シンボルを意図的に送信することで、受信側で固有干渉を発生させることで、悪意のあるユーザによる盗聴を防ぐ。暗号化シンボルの生成法および配置パターンを提案するとともに、チャネル推定誤差の影響、鍵攻撃への耐性、および、情報漏洩度を解析している。また、数値シミュレーションの結果から、提案法は優れた秘匿性を持っていることを示している。

以上の諸成果は、5G システムの実用化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貢献するところ大である。また、申請者が自立して研究活動を行うのに必要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。