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論　　文　　名	「Analog Impairments Compensation in OFDM　Direct-Conversion Receiver (ダイレクトコンバージョンOFDM 受信機におけるアナログ損失補償)」
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論文要旨

The history of wireless communications began in 1886, when Hertz generated electromagnetic waves. Based on this, the radio communication by Morse code across the Atlantic Ocean had been established in 1901. More than one century has passed, since then. Today, telecommunication has become so indispensable that we almost cannot imagine our lives without it.　From satellite transmission, radio and television broadcasting to the now ubiquitous mobile telephone, wireless communications have revolutionized human society. In contrast to the poor information-carrying ability of the early telecommunication system, instantaneous transferring of a large number of information, such as multimedia information, becomes possible.

Under the increasing demand to high-speed, high-spectral efficiency of radio communication, the digital-communication employing orthogonal frequency division multiplexing (OFDM) had emerged. The origin of OFDM started in 1966, when the structure of OFDM was proposed, where the concept of using orthogonal overlapping multi-tone signals was given. At that time, although the theory of OFDM was well developed, the implementation of OFDM systems still had some difficulties due to the hardware. In 1971, the idea of using a discrete Fourier transform (DFT) to perform baseband modulation and demodulation of the signals was introduced. This presented an opportunity of an easy implementation of OFDM, especially with the use of fast Fourier transform (FFT). In 1980, to combat mutipath fading, the cyclic prefix (CP) was introduced. Then, communication of OFDM had become possible according to the development of digital signal processor (DSP) circuit. As a result, in 1987, OFDM was used in the European digital audio broadcasting (DAB) standard. Nowadays, OFDM is well-known modulation scheme, which has been adopted in many wireless communication systems such as DAB, digital video broadcasting (DVB), and IEEE 802.11 wireless local area network (WLAN).

OFDM is well-known by its high spectral efficiency, high-data rate, and robustness against multi-path fading channel. The main drawback of OFDM systems is it's sensitivity to carrier frequency offset (CFO). Orthogonality among subcarriers is the fundamental of OFDM systems. CFO, mainly caused by frequency mismatch between the transmitter and receiver local oscillators (LOs). While CFO occurs, the spectrum of the received signal will be shifted. This will destroy the required orthogonality and result in severe performance degradation. Therefore, the estimation/compensation of CFO is very crucial in OFDM systems. Conventionally, the CFO can be estimated easily from the autocorrelation of periodic pilot (PP).

On the other hand, according to the receiver architecture, the receivers can be classified to the superheterodyne receiver and direct-conversion receiver (DCR). The superheterodyne principle was introduced in 1918 by the U.S. Army major Edwin Armstrong in France during World War I, which is generally thought to be the receiver of choice owing to its high selectivity and sensitivity. About 98% of radio receivers use this architecture. In a superheterodyne receiver, the input signal is first converted by an offset-frequency local oscillator to a lower intermediate frequency (IF), and substantially amplified in a tuned IF. Direct-conversion receiver, also known as homodyne, synchrodyne, or zero-IF receiver was developed in 1932 by a team of British scientists searching for a method to surpass the superheterodyne. DCR is a radio receiver that demodulates the incoming signal by a local oscillator signal synchronized in frequency to the carrier of the wanted signal. Therefore, the wanted modulation signal is obtained immediately by low-pass filtering, without further detection. Thus a direct-conversion receiver requires only a single stage of detection and filtering. In recent years, direct-conversion receiver (DCR) has attracted a lot of attention, for its smaller size and lower cost over the traditional superheterodyne receivers. However, the price is the additional disturbances, such as DC offset (DCO), and I/Q (in-phase and quadrature-phase) imbalance.

DCO is induced by the self-mixing associated with the imperfect isolation and is known as the most serious problem of DCR. The I/Q imbalance is caused by the mismatched components between the in-phase (I) and quadrature-phase (Q) branches, i.e., is basically any mismatch between the I and Q branches from the ideal case.

Therefore, the estimation/compensation of CFO in the presence of I/Q imbalance and the DCO is a critical problem in an OFDM DCR. In the absence of DCO, the CFO can be estimated easily from the autocorrelation of periodic pilot (PP). Considering DCO, several joint compensation schemes have been proposed. Some works discussed the CFO estimators in the presence of DCO and of I/Q imbalance. However, all of these works treated the DCO as time-invariant. In practice, automatic gain control (AGC) is usually used to keep the received signal amplitude proper fixed level. Also, a high pass filter (HPF) is often employed in the DCR to reduce DCO. Therefore, the gain shift in the low noise amplifier (LNA) will cause a TV-DCO, whose high frequency components may pass through the HPF. As a result, the ordinary CFO estimation will be corrupted by the residual TV-DCO. Until now, there is only one CFO estimator taking the residual TV-DCO into account. In this scheme, a differential filter is used to eliminate the residual TV-DCO, and then the CFO is estimated by the conventional autocorrelation-based method. Since the differential filter increases the noise variance and the residual TV-DCO cannot be eliminated completely, this method will cause performance loss.

On the other hand, the one reason of that OFDM has been selected for high-speed communication systems, is its good performance in multipath channels. In order to fight multipath, the cyclic prefix (CP), which is also referred to as guard interval (GI), is inserted between symbols. While the length of GI is longer than channel delay spread, it can protect received signal from inter-symbol interference (ISI). However, the price is the transmission speed. In order to increase the transmission speed, several attempts have been made to the cancellation of ISI and ICI (inter-carrier interference) in OFDM systems with insufficient GI. Since GI insertion reduces transmission efficiency, some works discussed OFDM systems without GI. In the absence of GI, eliminating ISI between adjacent symbols is a crucial problem. A method was introduced to cancel interference in OFDM systems without GI. In this work, it was proposed to compensate ISI distortion by using null subcarriers, i.e., inactive subcarriers, which is usually being placed at the edges of the frequency band and the DC to avoid aliasing and ease transmit filtering. In another work, an iteration method was proposed to eliminate the ISI and ICI. However, the iteration increases the complexity of computing and also results in error propagation, specially for high-degree constellation.

The main components of this thesis and the major results of the presented work can be summarized as follows:

Chapter 1 introduces the history of wireless communication, briefly explains the impairments of OFDM systems with direct-conversion receiver, and gives an overview of this thesis.

Chapter 2 describes the mathematical model of baseband OFDM systems, then explains the reason of ISI and the impairments such as CFO, DCO, and I/Q imbalance, where also gives their mathematical model by matrix form.

Chapter 3 investigates CFO estimation in OFDM-DCR in the presence of time-varying DCO. Until now, there is only one CFO estimator taking the residual TV-DCO into account. In this scheme, a differential filter is used to eliminate the residual TV-DCO, and then the CFO is estimated by the conventional autocorrelation-based method. Since the differential filter increases the noise variance and the residual TV-DCO cannot be eliminated completely, this method will cause performance loss. We develop a novel CFO estimation method in the presence of TV-DCO. It was shown the residual DCO after high-pass filtering varies in a linear fashion. Based on this observation, we model the residual DCO using a linear function. Then, from the periodicity of the training sequence, we derive a CFO estimator in closed-form.

Chapter 4 focuses on the joint estimator of CFO and I/Q imbalance in the presence of TV-DCO. To the best of our knowledge, until now, only a few works considered the scenario of the coexistence of CFO, I/Q imbalance, and TV-DCO. The idea is to employ a differential filter to ease the effect of the TV-DCO, and then estimate the CFO by the conventional autocorrelation-based method. However, the differential filter not only fails to completely eliminate the TV-DCO, but also enhances the noise. Also, the CFO estimation is severely biased by the remaining uncompensated I/Q imbalance. Moreover, in this method, only a CFO estimator was proposed and how to estimate/compensate the I/Q imbalance in this situation was not mentioned. We develop a novel joint estimation method for CFO and I/Q imbalance in the presence of TV-DCO, where similarly we approximate TV-DCO by linear function. From the periodicity of the pilot, we derive a low-complexity estimator, which can obtain the necessary estimates in closed-form.

Chapter 5 develops a novel ISI cancellation method for OFDM systems without GI. Since GI insertion reduces transmission efficiency, beside the common GI insertion, some studies discussed the OFDM systems without GI. In these methods, an iteration method was proposed to eliminate the ISI and ICI. However, the iteration increases the complexity of computing and also results in error propagation, specially for high-degree constellation. To obtain a good performance with the low-complexity, a novel ISI cancellation method is developed. While the channel is minimum phase, we derive a novel ISI cancellation method, by using the channel information and signal achieved at the tail part of OFDM symbols after frequency domain equalization (FDE). For the channel which is not minimum-phase, the proposed method is also applicable after converting the channel into minimum-phase by using a proper filter.

Chapter 6 concludes this thesis and gives some topics for future research.

審査結果の要旨

本論文は、ダイレクトコンバージョン OFDM 受信機(OFDM-DCR)における時変直流オフセット(TV-DCO)下でのアナログ損失補償、すなわち、搬送波周波数オフセットおよび I/Q 不均衡を補正するための新たな技術を提案すると共に、高速通信を目指したガードインターバルを用いない OFDM システムの新たな技術を提案するものであり、以下の成果を得ている。

(1) OFDM-DCR において TV-DCO が生じた際に、搬送波周波数オフセットを推定・補正するため、時間領域での TV-DCO を線形近似し、搬送波周波数オフセットに対する解析解を導出している。

(2) OFDM-DCR において TV-DCO が生じた際に、搬送波周波数オフセットおよび I/Q 不均衡を補償するため、TV-DCO の線形特性を利用した搬送波周波数オフセットおよび I/Q 不均衡補正の新たなジョイント法を提案し、その有効性を検証している。

(3) OFDM システムでは、シンボル間干渉を除去するためガードインターバルを各シンボル毎に挿入しているが、ガードインターバルを利用せず、かつシンボル間干渉を引き起こさない OFDM システムの新たな技術を提案し、伝送効率の改善を図っている。

以上の諸成果は、次世代移動通信システムに求められる伝送特性および伝送効率改善の実用化に向けた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に十分な能力と学識を有することを証したものである。学位論文審査委員会は、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。