論 文 の 内 容 の 要 旨

論文題目 Analysis and Calibration Techniques of Modulated Wideband Converter for High-Precision Sub-Nyquist Sampling System
(高精度サブナイキストサンプリングシステムのための変調広帯域変換器の解析と補正技術)

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This thesis focused on analysis and calibration techniques of the modulated wideband converter (MWC) for a high-precision sub-Nyquist sampling system. We addressed the theoretical analysis of the noise figure for the MWC to facilitate the system-level optimization of the MWC-based receiver architectures in terms of noise performance. The noise figure of the MWC strongly depends on the carrier position of the input signal due to the unlikeness of the Fourier series coefficients of the PSF. The simulation result shows that the analytic noise figure successfully estimates the simulated NF of MWC, created with different design parameters. In the practical case, as the sampling rate and the number of channels are limited, most MWC-based applications such as spectrum analyzer and cognitive radio have a great interest in the region of the total number of channels “mq” much lesser than the number of bands “L” within the band of interest. Even though the noise figure of the MWC becomes considerably high when “mq < L”, with an appropriate choice of low-NF, high-gain RF front-end circuits, the overall noise figure can be reduced to target specification. The proposed theoretical analysis on NF of the MWC systems will facilitate the system-level optimization of the MWC-based receiver architectures in terms of noise performance. The choice of the PSF determines the worthiness of the sensing matrix. In other words, the PSF decides the NF of the particular carrier location of the input signal. Thus, the remaining challenge in the topic is how to build the PSFs with minimized noise figures.

The simulation results obtained from our created MWC platform on MATLAB show that the time-domain waveform reconstruction can be correctly done under ideal situations. When the wideband signal is not clean sparse, the sidebands should also be considered for the reconstruction to improve the performance. For example, the MWC is used for reconstructing Bluetooth EDR signal to demonstrate its feasibility in practical signals. Theoretically, the Bluetooth signal occupies 1 MHz at the carrier frequency. However, the sideband emissions always exist in the actual spectrum of the signal, and they contribute to the perfect demodulation. In the simulation of the MWC, by reconstructing the adjacent two sidebands with the central band of the Bluetooth signal, the EVM reaches an acceptable range of 1% for Bluetooth device testing. The simulation of jitter impacts in MWC demonstrates that the jitter impact in the mixing function is more significant than the jitter impact of the ADC. Also, by increasing the total channel number "mq" of the MWC, the jitter impact in the mixing function can be reduced.

We proposed a new method for constructing a digital compensation filter to equalize a non-ideal frequency characteristic of an analog filter. Without the compensation filter, the reconstruction performance of the MWC is not satisfactory. Thus, the digital compensation filter is necessary for practical realizations to maximize the performances. The previous works by other researchers were impossible to estimate the LPF without disconnecting the LPF circuit from the MWC circuit, which makes the method infeasible in some practical implementations. The other issue was that the compensation filter building method could not be used in the advanced MWC case. The proposed method can be directly used in the advanced MWC circuit without disconnecting any component. The proposed advanced digital compensation filter relaxes the analog filter requirement in the practical implementation of the MWC.

We proposed a novel calibration method for simultaneous estimation of all the actual sensing matrix components based on a single measurement with a non-sparse multi-tones signal. Not only the number of measurements is reduced in the proposed method, but also the impact of the measurement-to-measurement timing fluctuations on the calibrated sensing matrix is fundamentally suppressed. The disadvantage of the multi-tones signal with uniformly spaced frequencies is its sensitiveness in non-linearity. To improve the proposed calibration technique based on the multi-tones signal, we proposed an algorithm to obtain a robust frequency set for the non-linearity. The simulation result shows that the proposed calibration method with non-uniformly spaced frequencies has better performance than the calibration with uniformly spaced frequencies.

We demonstrated the measurement results of the MWC taken from the practical implementation. The measurement result of the noise figure in MWC validates the correctness of the theoretical noise analysis. The proposed calibration technique for the MWC estimated the actual sensing matrix coefficients with single measurements. In contrast, conventional calibration needs many measurements. The calibration performance has been demonstrated in NMSE and IRR compared to the uncalibrated performance; more than 50 dB and 42 dB improvements have been achieved on NMSE and IRR, respectively. Suppose the non-linearity of the circuits is significant. In that case, the frequency set of the proposed calibration should be obtained by the algorithm to make it robust for the non-linearity. In the test of practical signal, we used the Bluetooth Enhanced Data Rate (EDR) signal as an example to demonstrate the feasibility of the MWC. In the reconstruction of the Bluetooth EDR signal, even though it is not recognizable as a Bluetooth signal at the output of the ADCs, the MWC successfully reconstructs the time-domain waveform of the signal based on the proposed calibration. Though the total number of channels "mq" is small as close to the necessary condition, the EVM was still under 1%, which is totally acceptable in Bluetooth device testing applications.

In terms of power consumption in the implementation, the total power consumption of the 4-channel MWC was 4.82 Watt. At the same time, a single off-the-shelf ADC can obtain the same total sampling rate with 2.5 Watt. However, the MWC can be an impressive choice for some applications which use a multiband sparse signal around a few GHz. In those applications, the MWC can reduce the sampling rate of the ADC to improve the precision by utilizing multi-channel. In contrast, a single ADC with a high sampling rate consumes more power and suffers precision. The dominant part of the total power consumption is undoubtedly the active mixer. The custom-designed switching type mixer should be made to reduce the power consumption more.

The presented work in the thesis improves the overall performance of the MWC reconstruction, especially in practical implementations. There are numerous application fields that the MWC can be used. One of those fields is automatic test equipment (ATE) for wireless device testing. Using the sparsity of the wireless signals, the MWC can efficiently capture the analog information into the digital domain. In the ATE environment, there are many low sampling rate high-precision

ADCs, which is a perfect place to exploit the MWC. Because utilizing existing components is very important for the ATE in terms of cost. Based on the results throughout the thesis, the practical implementation of MWC can be done in a straight-forwarding way. Confirming the MWC performance more to broaden the application area, the performance of the MWC reconstruction with orthogonal frequency-division multiplexing (OFDM) modulated signal should be done to measure Long Term Evolution (LTE) standardized signals in the future.