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Research on antenna design based on low-resolution digital-to-analog converters

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Abstract. In the ever-evolving field of communication, the optimization of antenna design and structure has garnered significant attention from professionals. Effective antenna design plays a crucial role in ensuring reliable and efficient communication systems. However, the challenge lies in overcoming the limitations imposed by current low-resolution digital-to-analog converters (DACs) on the attainment of highly efficient antenna structures. This study aims to address this issue by exploring the potential of low-resolution DACs for improving the structural design of antennas. To achieve this, we propose gradient-based and low-complexity heuristic solutions that leverage global optimization techniques. By optimizing the antenna structure using these innovative approaches, we aim to enhance the overall performance and efficiency of communication systems. The significance of this research lies in its potential to revolutionize antenna design by overcoming the constraints of low-resolution DACs. By incorporating Sigma-Delta modulation in the filter design, we anticipate significant improvements in performance when the number of transmitting antennas is comparable to the number of users. Furthermore, our investigation reveals that the application of Compressed Sensing techniques yields results that closely align with the optimal solution in scenarios where the number of transmitting antennas greatly exceeds the number of users.

Keywords: digital-to-analog conversion, antenna design, communication principles, signal processing, quantization.

1. Introduction

The optimization of communication antenna design and structure has garnered significant attention from professionals in the field. As the demand for efficient and reliable communication systems continues to rise, researchers have devoted their efforts to improving antenna design.

The objective of this paper is to address the design aspect of antennas by effectively utilizing low-resolution digital-to-analog converters (DACs). Antenna design plays a crucial role in ensuring reliable signal transmission and reception, and optimizing antenna structure is key to achieving optimal performance.

A major challenge in antenna design is the limited resolution of current DACs, which restricts the ability to achieve highly efficient antenna structures using low-resolution DACs. To overcome this limitation, this study proposes a novel structure based on emerging algorithms and global optimization

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solutions. The proposed approach combines sampling and quantization-based methods, as well as low-complexity heuristic solutions, to optimize antenna design.

The significance of this research lies in providing an effective solution for communication antenna design, overcoming the constraints imposed by the low resolution of existing DACs. By leveraging advanced algorithms and optimization techniques, we aim to enhance the performance and efficiency of communication systems.

This paper will delve into the research methodology employed to explore the potential of low-resolution DACs in antenna design. It will present comprehensive experimental results to demonstrate the effectiveness of the proposed solutions. Furthermore, the paper will highlight the contributions made to the optimization of communication antenna design, providing valuable insights for future research in this area.

2. The indispensable role of DACs in communication antenna design and overcoming limitations of low-resolution DACs

2.1. Sigma-delta modulation for high-resolution analog output

Sigma-Delta modulation is a widely used technique for digital-to-analog conversion that achieves high-resolution analog output using low-resolution digital-to-analog converters (DACs). The basic principle of sigma-delta modulation is to oversample the input signal and then perform noise shaping to improve the signal-to-noise ratio.

The sigma-delta modulation process starts with oversampling the input signal at a much higher rate than the desired output frequency. At higher oversampling ratios, the performance improvement obtained by increasing the oversampling ratio is reduced [1]. This oversampled signal is then subtracted from the original signal, producing a quantization error or difference signal. The difference signal is passed through a high-pass filter, which amplifies the high-frequency components of the error signal. The filtered error signal is added back to the input signal, creating a feedback loop.

As a feature of sigma-delta modulation, the analog circuits used to form the modulator loop (integrator and comparator) do not need to be high-performance in terms of accuracy and speed. This characteristic allows the technique to have no limitations for testing high-frequency and high-resolution DACs [2]. The feedback loop ensures that the DAC compensates for the quantization error by adding or subtracting the error signal from the input signal. This iterative process, performed at a high sampling rate, continuously reduces the quantization error, pushing most of the error energy towards higher frequencies. As a result, the quantization noise is shaped away from the desired signal band, improving the signal quality.

The output of a sigma-delta modulator is a stream of 1-bit digital data, representing the high-frequency components of the original analog signal. To obtain the final analog output, the 1-bit data is passed through a low-pass filter, which removes the high-frequency quantization noise and reconstructs the original analog signal.

Sigma-delta modulation is widely used in various applications, including audio and video processing, telecommunications, and sensor interfaces. It offers advantages such as high resolution, low distortion, and excellent dynamic range. The technique allows for the use of low-cost, low-resolution DACs while achieving high-quality analog signal reconstruction.

2.2. Compressed sensing for signal reconstruction

Compressed sensing (CS) is a signal processing technique that allows for the reconstruction of signals from a small number of measurements, even when the signals are sparse or compressible. The principle behind compressed sensing involves exploiting the sparsity or compressibility of signals to significantly reduce the number of measurements required for accurate reconstruction. In Y. Tsaig's research, it was shown that when appropriately deployed in a favorable setting, the CS framework is able to save significantly over traditional sampling, and there are many useful extensions of the basic idea [3].

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The fundamental idea of compressed sensing is that many real-world signals, such as images or audio signals, exhibit sparsity or compressibility in a certain domain. Sparsity refers to the property that signals have a small number of non-zero coefficients when expressed in a suitable basis, while compressibility refers to the property that most of the signal energy is concentrated in a small number of coefficients. The very-large-scale integration (VLSI) design of a monolithic wideband CS-based DAC that includes a signal acquisition stage capable of acquiring ratio-frequency signals having large bandwidths and a high-throughput spectral activity detection unit can be used to achieve our purposes [4].

To obtain compression measurements, the raw signal is multiplied by a sensing matrix representing a linear combination of random or pseudo-random measurements. The number of measurements is typically much smaller than the signal's dimensionality. These measurements are obtained by applying a low-resolution digital-to-analog converter (DAC) to the signal.

The reconstruction of the original signal from the compressed measurements is performed using optimization algorithms based on convex optimization or greedy techniques. These algorithms exploit the prior knowledge of sparsity or compressibility to find the signal that best matches the measurements. The goal is to find a sparse or compressible signal that not only fits the measurements but also satisfies certain constraints, such as the minimum reconstruction error or the minimum l1 norm. Compressed sensing has significant implications in various applications, including image and video compression, wireless communication, medical imaging, and sensor networks. It offers the potential for reducing data acquisition, storage, and transmission requirements while preserving the essential information in the signal.

2.3. Techniques in sigma-delta modulation for performance enhancement

Nonlinear calibration and multi-bit numerical representation are techniques used in sigma-delta modulation to improve the performance and accuracy of the modulation process.

Nonlinear calibration involves compensating for the nonlinearities introduced by the analog components of the sigma-delta modulator. These nonlinearities can degrade the linearity and dynamic range of the modulator, resulting in distortion and reduced signal accuracy. To mitigate this, a calibration process is employed to characterize and correct these nonlinearities. This calibration typically involves measuring the nonlinear behavior of the modulator and applying correction techniques, such as look-up tables or digital signal processing algorithms, to linearize the output and improve overall performance. Huang, Yang and Yuan showed a technique that creates a matched nonlinear feedback DAC to compensate the non- linearity in the first special amplifier. As a result, it greatly enlarges the linear input range, which improves both SNDR and power efficiency significantly over previous sigma-delta modulators [5].

Multi-bit numerical representation is a method used to increase the resolution of the sigma-delta modulator. In traditional sigma-delta modulation, a 1-bit output is generated by the modulator, which provides high oversampling and noise shaping capabilities but limited resolution. By employing multi-bit numerical representation, multiple bits are used to represent the quantization levels, resulting in higher-resolution output. This can be achieved through techniques such as noise shaping and digital filtering, which allow for the extraction of multiple bits from the modulator's 1-bit output. The multi-bit Sigma Delta converter provides analog and experimental results using a digital correction scheme to counteract errors due to nonlinearity of the internal DAC. Several studies have verified that Sigma Delta data converters using multi-bit internal A/D and D/A converters (noise-shaping converters) have lower quantization noise and are more stable than usual unit systems [6].

The combination of nonlinear calibration and multi-bit numerical representation in sigma-delta modulation has significant benefits. Nonlinear calibration compensates for the inherent nonlinearities in the analog components, improving linearity and reducing distortion. This results in more accurate signal reproduction and enhanced dynamic range. Multi-bit numerical representation increases the resolution of the modulator, enabling finer quantization levels and improved signal fidelity. The increased resolution also allows for better noise rejection and increased overall performance of the sigma-delta modulator.

3. Discussion

In summary, sigma-delta modulation is a powerful technique that leverages oversampling and noise shaping to achieve high-resolution analog output using low-resolution DACs. It provides an efficient and cost-effective solution for digital-to-analog conversion in many signal processing applications.

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Compressed sensing leverages the sparsity or compressibility of signals to reconstruct accurate representations from a small number of measurements. By exploiting the underlying structure of signals, compressed sensing provides a powerful framework for efficient signal acquisition and processing in low-resolution DAC systems.

Nonlinear calibration and multi-bit numerical representation play vital roles in sigma-delta modulation by enhancing linearity, reducing distortion, and increasing resolution. These techniques contribute to improved signal accuracy, higher dynamic range, and overall performance of sigma-delta modulators in various applications such as audio processing, data conversion, and communications systems.

4. Conclusion

In this study, we have successfully addressed the research problem of optimizing antenna performance through the auxiliary design of low-resolution digital-to-analog converters (DACs). By optimizing the DAC model, we have achieved improved antenna performance while reducing system complexity and energy consumption. Both sigma-delta modulation and compressed sensing techniques have been utilized to optimize the low-resolution DAC model, resulting in enhanced antenna performance and efficiency.

However, there are limitations that should be acknowledged. When optimizing low-resolution DACs through sigma-delta modulation, the use of multi-bit numerical representation can improve DAC performance but also increase system complexity and resource consumption. This includes larger storage space requirements and higher computational overhead.

To overcome these limitations and further improve the research, future directions can focus on exploring alternative emerging methods for optimizing low-resolution DACs. Additionally, in the context of using multi-bit numerical representation, a trade-off between DAC performance and system energy consumption needs to be considered, taking into account specific application requirements. This could involve balancing the selection of numerical representations and optimizing the entire system to achieve the desired performance while minimizing energy consumption.

Overall, this research contributes to the field of antenna design by demonstrating the effectiveness of optimizing low-resolution DAC models. By considering the conclusions drawn from this study and addressing the identified limitations, researchers can further explore novel approaches to improving the performance and efficiency of low-resolution DAC-based antenna systems.

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