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Development Of Accelerated Fast Fourier TransformFor 5g Communication System

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Abstract:

The rapid evolution of communication technologies, particularly with the advent of 5G, demands efficient processing techniques to handle vast amounts of data. According to a recent report by the Global Mobile Suppliers Association, 5G subscriptions are expected to exceed 1.7 billion by 2025, significantly increasing the need for high-speed data processing capabilities. The Discrete Fourier Transform (DFT), while fundamental in signal processing, presents inherent limitations in computational efficiency, particularly as the size of the data increases, leading to longer processing times that can hinder real-time applications. This work presents a novel approach to accelerate the Fast Fourier Transform (FFT) specifically designed for 5G communication systems. By optimizing the traditional FFT algorithm through advanced VLSI techniques, we achieve significant improvements in computational speed and efficiency. Our proposed accelerated FFT utilizes innovative hardware architectures and algorithms, enabling rapid signal processing that meets the stringent demands of 5G applications. The advantages of this approach include enhanced throughput, reduced latency, and improved energy efficiency, making it a critical advancement for the future of high-speed wireless communications.

Keywords: FFT, DFT, Accelerated FFT, Signal Processing, Inherent, Latency, Efficiency, Throughput.

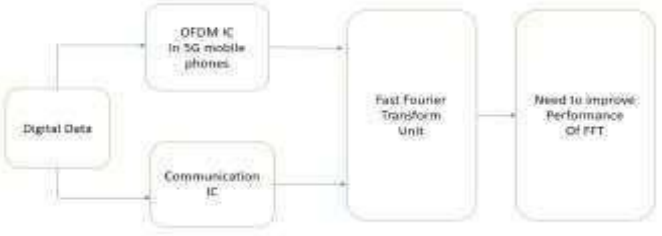
1. INTRODUCTION

Fast Fourier Transform have numerous applications in various fields such as solving differential equations, radar and solar studies, crystal structures, Wi-Fi, and 5G, making them a crucial numerical algorithm in signal processing. FFT initially developed by Cooley and Tukey in the 1960s, FFT gained prominence due to its ability to compute the Discrete Fourier Transform DFT more rapidly. FFT algorithms are commonly employed to implement transformation, optimizing signal processing in 5G networks for tasks like channel estimation and modulation/demodulation. The FFT has played a crucial role in 5G communication systems by enabling efficient signal processing.

The FFT is not only a widely used algorithm in various technologies, but it was also discovered by scientists trying to detect covert nuclear weapons tests, highlighting its significant impact beyond signal processing. Real-world signals are not infinite and continuous, but finite and made up of individual samples or data units, leading to the need for a DFT.

In 5G, FFT is used for OFDM (Orthogonal Frequency Division Multiplexing) modulation/demodulation. OFDM's ability to handle high data rates and spectrum efficiency makes it a key component in 5G. FFT allows for the rapid conversion of signals between time and frequency domains, facilitating the handling of multiple subcarriers simultaneously. The deployment of FFT in 5G systems has significantly enhanced data transmission speed, spectral efficiency, and overall performance, contributing to the evolution of wireless communication technologies.

The motivation behind VLSI-based Network-on-Chip (NoC) design in VLSI systems, particularly within the realm of FFT processing, is grounded in the imperative of optimizing data transmission for enhanced communication efficiency. In a typical scenario, User 1 initiates the transmission of data, and this information undergoes FFT processing within the integrated circuits of a Wireless Local Area Network (WLAN) router equipped with NoC technology. The efficiency of the NoC integrated circuits is critical in ensuring seamless data transfer. If the NoC ICs are designed with precision and effectiveness, they enable the perfect reception of the processed data by User 2. This underscores the significance of robust and well-designed NoC architecture to achieve optimal data flow and minimize latency in the complex landscape of 5G systems.



However, the converse scenario highlights the potential consequences of an inefficient NoC design. If the NoC ICs fail to operate at peak efficiency, data loss becomes a looming concern. In FFT for 5G, where high data rates and low latency are paramount, any compromise in the integrity of the NoC design result in a breakdown of communication channels. This, in turn, jeopardizes the accuracy and completeness of FFT processing, leading to suboptimal or even detrimental outcomes for the end-users. The motivation to pursue VLSI-based NoC design is thus intensified by the critical role these integrated circuits play in ensuring the reliability and success of FFT operations within the broader context of 5G systems.

In essence, the motivation for VLSI-based NoC design for FFT in 5G was encapsulated as the quest for an optimal balance between efficient data transmission and reception. The intricacies of FFT processing demand a meticulously crafted NoC architecture that not only expedites data flow but also mitigates the risk of data loss. As users increasingly rely on seamless and high-speed communication in the 5G era, the pursuit of effective VLSI-based NoC designs becomes paramount for realizing the full potential of FFT applications in this advanced technological landscape.

FFT is an algorithm used to efficiently compute the DFT of a sequence. The basic building blocks for implementing FFT are adders and multipliers. In its most straightforward form, the FFT algorithm is implemented using a divide-and-conquer approach, breaking down the computation of DFT into smaller subproblems. This decomposition is recursively applied until reaching base cases that was easily computed using basic arithmetic operations.

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At its core, the FFT algorithm relies on the butterfly operation, where pairs of complex numbers undergo addition and multiplication operations. The adders are used to combine the results of intermediate computations, while the multipliers perform the necessary complex multiplications. The recursive nature of FFT ensures that the overall computation is significantly more efficient than a direct computation of the DFT, particularly for large input sequences. By utilizing basic adders and multipliers, the FFT algorithm minimizes the computational complexity and is widely employed in various applications such as signal processing, communications, and scientific computing.

2. LITERATURE SURVEY

Morselli, Flavio, Sara Modarres Razavi,et.al [1] presented accurate location information is crucial for a variety of new verticals and use cases enabled by 5th generation (5G) wireless networks. While existing localization techniques for cellular networks are continuously evolving in the standardization process, the stringent key performance indicator requirements defined by the 3rd Generation Partnership Project (3GPP) have not been met yet.

Khandelwal, Hardika,et.al [2] designed Non-Orthogonal Multiple Access (NOMA) is emerging as a capable aspirant for 5G technology. High spectral efficiency and massive connectivity demands are satisfied by NOMA along with OFDM. In this article, we describe the NOMA technique with the OFDM channel selection technique.

Lynch, Charles, Ajibayo O. Adeyeye,et.al [3] In this literature work, for the first time, a 5G/mm-Wave harmonic frequency modulated continuous wave (FMCW) radar with dual Rotman lens-based harmonic millimeter identification (mmID) ranging system is proposed enabling ultralong range highly accurate localization for future localized sensing cyberphysical systems (CPSs).

Baskaran, S., A. Srinivasan,et.al [4] This literature provided information as a first step for individuals who are thriving to get a bird's eye view of the aspects underlying the optical networking in 5G technology. Apart from capacity requirement challenges targeted by 5G coverage, it requires a lot of fibers to be successfully provisioned to achieve formidable performance goals of 5G such as diversified capacity requirements, availability, and coverage issues.

Molodtsov, Vladislav,et.al [5] In this literature we proposed new trainable FFT structures to increase the accuracy of beamspace transformation in the multi-user (MU) mode of Massive MIMO receiver. The FFT is a widely employed beamspace transformation technique, thanks to its low transforming complexity.

Roman Bychkov, Alexander Osinsky, et.al [6] in this literature, we proposed new DFT-based beamspace selection algorithms for, MIMO receiver operating in realistic MU scenarios. In practical uplink scenarios, there is a power ratio between signals received from different users that complicates performance analysis in MU cases.

Barrios-Ulloa, Alexis, et.al [7] The deployment of 5G around the world continues to progress at a rapid pace, especially in North America and Asia. Its advantages and efficiency as a data transmission network have been widely demonstrated in different fields such as agriculture, education, health, and surveillance. However, this process does not have the same dynamics in Latin America, specifically in Colombia.

Wei, Zhiqing, Hanyang Qu,et.al [8] designed Integrated sensing and communication (ISAC), with sensing and communication sharing the same wireless resources and hardware, has the advantages of high spectrum efficiency and low hardware cost, which is regarded as one of the key technologies of the fifth generation advanced (5G-A) and sixth generation (6G) mobile communication systems.

Srinivasan, Varun, and V. Thanikaiselvan,et.al [9] During communication, the transmitted signal passes through a channel, owing to which noise and distortions are added to the signal through various sources. These need to be removed for proper analysis of the received signal. To do this, the first step is to figure out the characteristics of the channel that the signal has passed through.

Wang, Xuanzhong, Yanan Zhang ,et.al [10] The IoT plays an important role in 5G communications. Large number of 5G end modules supports the communications of different types of IOT applications, which constantly put forward requirements for high capacity communication technology.

Silva, Andre Tavora de A ,et.al [11] The 5G wireless system is becoming more present in today's reality. Understanding the electromagnetic compatibility (EMC) requirements is critical for preparing future device designs to conform to the upcoming standards. This article provides an overview of EMC's role in the certification process and provides an updated standardization guide, comparing emissions and immunity tests of the latest 3GPP/ETSI andITU recommendations.

Chen, Wanshi, Xingqin Lin ,et.al [12] Since the start of 5G work in 3GPP in early 2016, tremendous progress has been made in both standardization and commercial deployments. 3GPP is now entering the second phase of 5G standardization, known as 5G-Advanced , built on the 5G baseline in 3GPP Releases 15, 16, and 17.

Yao, Yihao ,et.al [13] This paper proposes an improved minimum variance distortion less response (MVDR) based TOA estimation algorithm for 5G NR signals under multipath environments. The proposed algorithm achieves high resolution by exploiting a large number of subcarriers of 5G signals and reduces the dimension of the covariance matrix involved in MVDR substantially by utilizing a novel smoothing scheme.

Guo, Haitao ,et.al [14] Rotating Fourier transform ultraviolet Raman spectrometer (RFTURS) is an ideal and valuable tool for atmospheric CO2 detection. However, due to the short excitation wavelength and the nonlinear relationship between the optical path difference (OPD) and the rotating angle, it is difficult for RFTURS to produce linear interference signals.

Li, Jilong, Songnian Fu ,et.al [15] Short-time Fourier transform (STFT) is a vital tool to observe spectral dynamics of non-stationary signals. Conventional STFT based on digital signal processing (DSP) usually suffers from a limited acquisition frame rate within 10 6 Fourier transforms per second (FTs/s).

Víctor Manuel, Mario Garrido ,et.al [16] presented new serial butterflies for non-power-of-two (NP2) FFT architectures. The literature considers radices 2, 3, 4, and 5, which are used in FFTs for 5G systems. Current designs for non-power- of-two FFTs are mostly based on the single-path delay feedback (SDF) architecture.

Ferrer, Pierre, François Rivet,et.al [17] presented the first Arbitrary Waveform Generator (AWG) based on Walsh's theory for wideband radio frequency (RF) conversion. The architecture is dedicated to 5G- FR1 applications (sub-6GHz) to perform a direct and large bandwidth conversion while achieving the highest energy efficiency.

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Tingyong, Yuxin Wang ,et.al [18] developed the upcoming 5G communication is committed to providing ultra-high throughput and ultra-low delay service. However, DSP technologies will be a critical challenge with the increasing bandwidth and transmitting streams. Especially, traditional FFT architectures are hard to meet the high- speed, high-performance, and low-overhead requirements.

Shadangi, Ashish Ranjan, et.al [19] developed itself as a dependable protocol for high-speed vehicular communication. This pioneering technique operates within a novel two-dimensional (2D) delay- Doppler domain waveform. When juxtaposed with conventional modulation methods like OFDM, OTFS demonstrates superior performance enhancements in scenarios involving rapidly moving wireless channels.

Iqbal, Shajeel, Anders Lund, Metodi P. Yankov, et.al [20] They proposed a new polar encoder architecture based on the radix-k processing and FFT concepts. They also introduced the hardware architectures for cyclic redundancy check (CRC) interleaver and rate matcher for 5G NR PDCCH.

Malladhi, Nagarjuna, K. Narsimha Reddy, et.al [21] proposed work combines R2B, R4B, and R8B using signal delay feedback FFT architecture. R2B SDF FFT architecture has complex and large computations, and many stages are being used. To overcome this problem, Radix-4 and Radix-8 FFT are built to increase efficiency and decrease computational steps to incorporate in DUC and DDC filters and OFDM modules of 5G based modules.

3. PROPOSED METHODOLOGY

FFT stands for Fast Fourier Transform, which is a mathematical algorithm used to efficiently compute the DFT and its inverse. The Fourier Transform is a mathematical operation that transforms a signal from the time domain to the frequency domain, revealing the frequency components present in the signal. The basic idea behind the FFT is to divide the DFT computation into smaller parts by recursively breaking down the signal into smaller sub-signals. This divide-and-conquer approach significantly reduces the number of mathematical operations required compared to the naive computation of the DFT, making it much faster, especially for larger input sizes. The FFT has numerous applications across various fields, including signal processing, audio processing, image processing, data compression, and more. It is widely used in DSP to analyse and manipulate signals in the frequency domain efficiently.

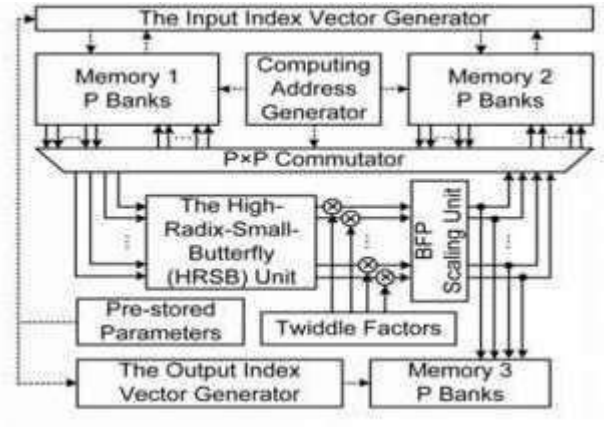


Figure 1: Proposed FFT system.

Storing the final FFT output in memory banks facilitates seamless integration with subsequent processing stages, improving throughput and computational resource utilization.

The detailed analysis is given as follows:

- Digital Input: The input data provided to the FFT is typically a sequence of discrete time-domain samples. This sequence represents a digital signal, which was generated from various sources such as audio recordings, sensor readings, or any other time-varying phenomenon that was sampled. The digital data was obtained from instruments like microphones, accelerometers, or digital cameras.
- Digital Input Index Vector Operation : It seems like you're referring to the indexing operation used in FFT algorithms, specifically in digital inputs. Often manipulate vectors representing the input signal.
- Indexing Operation: During the FFT algorithm, you manipulate this input data to perform various operations such as butterfly operations, twiddle factor multiplications, etc. Indexing operations involve accessing specific elements of the input data based on their position.
- Input to Output Mapping: The input-output mapping is based on a specific pattern that facilitates efficient computation of the Fourier transform.
- Introduce the prime factor or multiplication coefficent : In FFT, prime factors or multiplication coefficients typically refer to the factors or coefficients used in the decimation- in-time (DIT) or decimation-in-frequency (DIF) algorithms to optimize the computation process.
- final input,output addresses: The memory location where the input data for the FFT algorithm is stored.The input data is usually a sequence of complex or real numbers representing the samples of the input signal.
- Memory Bank Allocation: These segments are then allocated or stored in different memory banks. The number of memory banks typically corresponds to the degree of parallelism available in the hardware architecture
- Address Generator: In FFT , the address generator is a crucial component responsible for generating the memory addresses of the input data during the computation. It is typically used in the Cooley-Tukey algorithm, a widely used FFT algorithm.
- P×P commutator: No of paths ,subpaths in each butterfly unit divided by p×p commutator. It act as crossbar switching network and it is responsible for packet (data) sharing.
- High Radix Small Butterfly (HRSB) units are pivotal in accelerating FFT computations, particularly in scenarios where high-radix butterfly operations are advantageous.
- Twiddle Factor: In FFT, the twiddle factor plays a crucial role in manipulating the complex roots of unity during the computation.
- BFP Scaling: In the FFT algorithm, the butterfly operation plays a central role in efficiently combining the outcomes of smaller DFTs into larger ones.
- BFP Scaling: In the FFT algorithm, the butterfly operation plays a central role in efficiently combining the outcomes of smaller DFTs into larger ones.
- Store the final FFT Output in Memory Bank : In FFT implementations, storing the final FFT output in memory banks is a crucial step for subsequent processing or analysis.

Applications:

The following are key medical applications where FFT in 5G communication systems plays a pivotal role:

- Biomedical Signal Processing: ECG and EEG Analysis: FFT aids in processing electrocardiogram (ECG) and

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electroencephalogram (EEG) signals, enabling accurate frequency domain analysis for early detection ofabnormalities.

- Telemedicine and Remote Patient Monitoring: Vital Sign Monitoring: 5G with FFT enables high-speed data transmission for real-time monitoring of vital signs such as heart rate, respiratory rate, and blood pressure.
- Imaging and Diagnostics: Medical Imaging: In applications like MRI and CT scans, FFT accelerates the processing of imaging data, providing faster and more detailed results.
- Wearable Devices: FFT in 5G facilitates the processing of data from wearable health sensors, allowing for continuous monitoring of physiological parameters.
- Doppler Ultrasound: FFT is employed in the analysis of Doppler ultrasound signals, aiding in the detection of blood flow abnormalities.
- Robotic Surgery: In telesurgery scenarios, where surgeons operate remotely, FFT ensures real-time analysis of signals from robotic instruments. The low latency provided by 5G is essential for precise and responsive control.
- IoT Integration: FFT supports the integration of healthcare Internet of Things (IoT) devices, processing data from diverse sensors for health monitoring. 5G's adaptability and high data rates enable seamless connectivity for a multitudeof devices.
- Smart Drug Delivery: FFT aids in processing data from smart drug delivery devices, ensuring precise and timely administration of medication. The reliability and low latency of 5G are crucial for real-time adjustments in drug delivery.

Advantages:

FFT is a fundamental tool in 5G systems, providing several key advantages that are instrumental in meeting the complex demands of 5G communication.

- Spectral Efficiency: FFT allows for efficient spectral analysis, enabling precise modulation and demodulation in the frequency domain.
- High Data Throughput: 5G demands unprecedented data rates, and FFT accelerates signal processing, facilitating high-speed data throughput. Rapid transformation of time- domain signals to the frequency domain supports gigabit and terabit-speed data transmission.
- Low Latency: FFT algorithms, especially those optimized for VLSI, contribute to minimizing signal processing latency. Low latency is essential for real-time applications such as autonomous vehicles and augmented reality in 5Gnetworks.
- Automatic Enhancement: While customization is available, LIME can also operate with default settings, making it suitable for users who may not have expertise in image processing.
- Energy Efficiency: FFT was implemented in energy- efficient VLSI architectures, contributing to overall system power optimization. In energy-conscious 5G designs, FFT helps balance performance and power consumption.
- Adaptability to Multiple Access Schemes: 5G supports diverse communication scenarios with various multiple access schemes.
- Beamforming and MIMO Implementation: FFT is essential for implementing advanced antenna technologies like beamforming and Multiple Input Multiple Output (MIMO) in 5G. These technologies enhance communication capacity and reliability, and FFT plays a pivotal role in processing signals for optimal performance.\
- Versatility and Standard Compatibility: FFT supports different modulation schemes and is adaptable to evolving 5G standards. Its versatility ensures compatibility with emerging technologies, making it a future-proof solution for 5G systems.

4. EXPERIMENTAL ANALYSIS

In Figure 2,the existing simulation results for FFT with parameters N=8 (number of data points) and DW=16 (data width) offer insights into the performance and accuracy of FFT algorithms under specific conditions. The diagram likely illustrates the frequency domain representation of the input signal, depicting transformed data points alongside their corresponding magnitudes and phases. These results serve to validate the effectiveness of conventional FFT implementations in accurately analyzing signals and decomposing them into their constituent frequency components. Additionally, performance metrics such as execution time and resource utilization was included to provide a comprehensive evaluation of the FFT algorithm's efficiency under the given configuration.

Figure 2: Existing Simulation Result for N=8,DW=16



Figure 3 To shows the existing area measurements for N=8.Here, 734 number of LUT's are used out of available 1,34,600, which consumes 0.55% of utilization. Here,65 number of DSP are used out of available 740, which consumes 8.78% of utilization. Here,64 number of IO are used out of available 500, which consumes 12.80 % of utilization.

Resource	Estimation	Available	Utilization...
LUT	734	134600	0.55
DSP	65	740	8.78
IO	64	500	12.80

Figure 3: Existing for Area N=8,DW=16

In Figure 4, the proposed simulation results for FFT with parameters N=8 (number of data points) and DW=16 (data width) depict the efficiency and accuracy of the FFT algorithm under specific conditions. Here,64 number of IO are used out of available 500, which consumes 12.80 % of utilization. Here,65 number of DSP are used out of available 740, which consumes 8.78% of utilization.
Here,734 number of LUT's are used out of available 1,34,600, which consumes 0.55% of utilization.

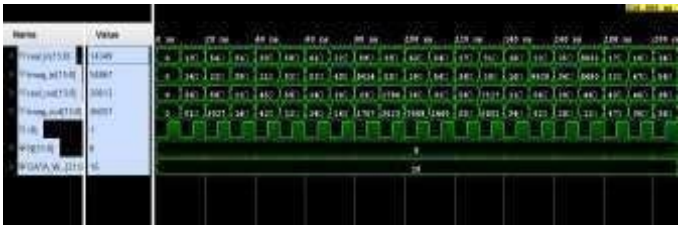


Figure 4: Proposed Simulation Result for N=8,DW=16

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5. CONCLUSION

The FFT revolutionized DSP by providing a highly efficient method for computing the DFT. Its algorithmic complexity of O(N log N) compared to the O(N^2) complexity of direct DFT computation enabled rapid analysis of large datasets, making real-time processing feasible across various fields. This efficiency, coupled with its accuracy, versatility, and wide-ranging applications, solidifies FFT as a cornerstone in modern signal processing. From audio and image processing to communication systems and scientific research, FFT plays a pivotal role in extracting meaningful information from signals, paving the way for advancements in technology and scientific discovery.

Despite its computational efficiency, implementing FFT algorithms requires careful consideration of factors such as data size, memory constraints, and desired precision. Choosing the appropriate FFT variant, such as radix-2, radix-4, or mixed-radix algorithms, depends on the specific requirements of the application and the available computational resources. Additionally, optimizing FFT implementations for specific hardware architectures, such as CPUs, GPUs, or specialized signal processing units, further enhances performance and scalability. By leveraging these optimizations and advancements, developers can harness the full potential of FFT for tackling complex signal processing tasks in diverse domains.

Looking ahead, the continued evolution of FFT algorithms and implementations promises even greater efficiency, scalability, and versatility. Research efforts focus on further reducing computational complexity, exploring parallel and distributed computing techniques, and integrating FFT with emerging technologies such as machine learning and quantum computing. As FFT continues to underpin innovations in signal processing and data analysis, its importance in modern technology landscapes remains undeniable, shaping the future of DSP and scientific exploration.

The FFT stands at the forefront of signal processing and data analysis, with a promising future scope poised for further advancements. As computational capabilities continue to expand, one area of focus lies in optimizing FFT algorithms for high-performance computing (HPC) architectures. Researchers are exploring parallel and distributed computing techniques to leverage the increasing computational power of supercomputers, clusters, and cloud platforms. By developing highly efficient parallel FFT implementations, the scope for real-time analysis of massive datasets across diverse domains, including scientific research, telecommunications, and financial markets, is greatly enhanced.

Integration with machine learning represents another exciting frontier for FFT. As machine learning algorithms become increasingly prevalent in data analysis workflows, there is growing interest in leveraging FFT for feature extraction, classification, and anomaly detection tasks. Future developments involve creating hybrid algorithms that combine FFT with deep learning techniques, enabling more robust and interpretable models for predictive analytics and pattern recognition. By harnessing the power of FFT within machine learning frameworks, researchers aim to unlock new insights from complex and high-dimensional datasets across various applications.

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