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Application of fast Fourier transforms in real-time signal processing for 5G networks

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Abstract

In real time data processing the Fast Fourier Transform (FFT) is a crucial factor the follow the 5G standard networks. In frequency domain the FFT will make it simple and easy to works with multi-carrier modulation methods like OFDM, which required for the fast data flow and minimum delay. Adding optimization to FFT model will enhance it in airwaves and reduce the amount of addition work for infrastructure that will consume the minimal energy during the processing. This paper discuss about the math behind FFT, looks at how it can be changed, and rates its performance. It also focuses that FFT are more relevant in wireless transmission in next generation.

Subject Classification: *65T50, 65T99.*

Keywords: *FFT, 5G networks, OFDM, Real-time signal processing, Spectrum utilization.*

I. Introduction

The arrival of 5G technology has changed the way people talk to each other and use technology in a big way. By allowing wireless connections with very fast data transfer rates, it cuts down on delay to almost nothing and makes sure that information flows smoothly. This new technology not only makes it easier to talk to each other, but it also lets billions of devices join at the same time through a single network. This makes smarter cities, self-driving systems, and better digital experiences possible, all of which make people's lives better [1, 2]. It is very hard to analyse data in real time on 5G networks because they are so complicated. Real-time [3] research is needed to make sure that users can always rely on the bandwidth that is being used. The FFT is one of the most important computer tools that make this possible. It is also a key part of correct frequency-domain analysis [4]. Orthogonal frequency-division multiplexing

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(OFDM), a key part of 5G physical layer design, and other advanced transmission methods depend on the FFT. Without this base, 5G devices would not be able to work at high speeds and with low latency [5], [6].

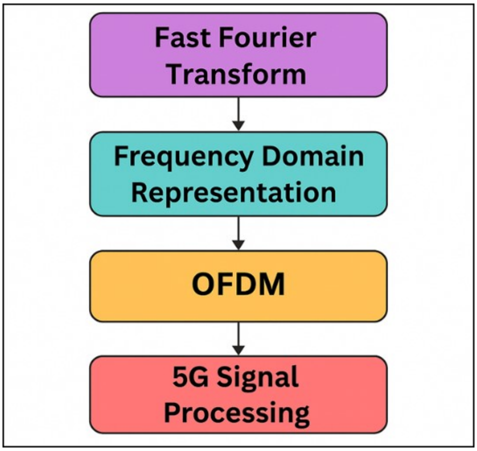

Figure 1
FFT-based Multicolor Workflow for Real-Time 5G Signal Processing

FFT methods [7] make it possible to quickly modulate, demodulate, and estimate channels, which are needed to meet high performance standards, workflow shown in Figure 1.

II. Fundamentals of FFT

A. *Mathematical foundation of Fourier analysis*

Fourier analysis breaks signals down into sinusoidal parts, which makes frequency-domain modelling much more efficient. This is important for tasks like transmission, filtering, modulation, spectral estimates, and real-time digital signal processing [8, 9].

Continuous signal

$$x(t), \qquad t \in \mathbb{R}$$

Fourier Transform definition

$$X(ft) = \int_{-\infty}^{\infty} X(tf)\, e^{-j2\pi ft} dt \tag{1}$$

Inverse DFT

$$x[n] = \left(\frac{1}{N}\right) \sum_{k=0}^{N-1} X[k]\, e^{\frac{j2\pi kn}{N}} \tag{2}$$

Periodicity in frequency domain

$$X[k+N] = X[k] \tag{3}$$

Orthogonality property

$$\Sigma\ (n = 0\ to\ N-1) e^{-\frac{j2\pi(k-m)n}{N}} = N\ \delta(k, m) \tag{4}$$

Linearity

$$a\,x^1[n] + b\,x^2[n] \leftrightarrow aX^1[k] + bX^2[k] \tag{5}$$

Convolution theorem

$$(x^1 * x^2)[n] \leftrightarrow X^1[k] \cdot X^2[k] \tag{6}$$

Modulation property

$$x[n]e^{\frac{j2\pi k^0 n}{N}} \leftrightarrow X[(k - k^0) mod\ N] \tag{7}$$

FFT acceleration (radix-2 form)

$$X[k] = \Sigma \left(n = 0\ to \frac{N}{2} - 1\right)\left[x[n] + x\left[n + \frac{N}{2}\right] e^{-\frac{j2\pi k}{N}}\right] e^{-\frac{j2\pi kn}{\frac{N}{2}}} \tag{8}$$

B. *Variants of FFT algorithms relevant to communication systems*

Some important types of FFT are radix-2, split-radix, mixed-radix, decimation-in-time, and decimation-in-frequency. Each is designed to work best for speed, efficiency, memory use, and real-time communication system needs [10].

Even-odd partition

$$X[k] = E[k] + W_N^k O[k] \tag{9}$$

Recursive structure (even part)

$$E[k] = \Sigma \left(n = 0\ to \frac{N}{2} - 1\right) x[2n] W_{\frac{N}{2}}^{kn} \tag{10}$$

Recursive structure (odd part)

$$O[k] = \Sigma \left(n = 0\ to \frac{N}{2} - 1\right) x[2n + 1] W_{\frac{N}{2}}^{kn} \tag{11}$$

Mixed-Radix FFT factorization

$$N = N^1 N^2,\ X[k] = \Sigma\ (n^1 = 0\ to\ N^1 - 1)$$
$$\Sigma\ (n^2 = 0\ to\ N^2 - 1) x[n^1 + n^2 N^1] W_N^{k(n^1 + n^2 N^1)} \tag{12}$$

Split-Radix FFT

$$X[k] = E[k] + W_N^k O^1[k] + W_N^{2k} O^2[k] \tag{13}$$

Decimation-in-Time (DIT)

$$X[k] = \Sigma \left(n = 0\ to \frac{N}{2} - 1\right)\left[x[n] + x\left[n + \frac{N}{2}\right] W_N^k\right] W_{\frac{N}{2}}^{kn} \tag{14}$$

Decimation-in-Frequency (DIF) even frequencies

$$X[2k] = \Sigma \left(n = 0\ to \frac{N}{2} - 1\right)\left(x[n] + x\left[n + \frac{N}{2}\right]\right) W_{\frac{N}{2}}^{kn} \tag{15}$$

III. 5G Network Signal Processing Requirements

A. *High data rate and low latency demands*

5G networks need to be able to send and receive huge amounts of data very quickly [11]. To do this, they need FFT-based signal processing that is highly optimised so that modulation, demodulation, and transfer go smoothly.

Theorem 1 (Shannon Capacity for 5G Systems): *For a 5G communication channel with bandwidth B and signal-to-noise ratio (SNR), the maximum achievable data rate is bounded by Shannon's theorem [12].*

Proof: Noise power:

$$N = N0 * B \tag{16}$$

Define signal-to-noise ratio:

$$SNR = \frac{P}{N} \tag{17}$$

Latency constraint modeled as:

$$L = \frac{1}{f}s, where\ fs = processing\ frequency. \tag{18}$$

To minimize latency:

$$L5G \leq 1 \text{ ms}$$

Processing delay from FFT:

$$TFFT \approx \frac{(N \log N)}{fclk} \tag{19}$$

Ensure: TFFT << L5G

B. Multi-carrier modulation (OFDM) and spectrum utilization

The FFT uses the OFDM modulation that help people for the good communication, handling interference, spread bandwidth easily around them.

Theorem 2: *OFDM using FFT gets almost the best use of the band while keeping the subcarriers' orthogonality.*

Proof: Define kth subcarrier:

$$\varphi k(t) = e^{\frac{j2\pi kt}{T}} \tag{20}$$

OFDM signal:

$$s(t) = \left(\frac{1}{N}\right) \Sigma(k = 0\ to\ N - 1) X[k] e^{\frac{j2\pi kt}{T}} \tag{21}$$

FFT computes modulation:

$$s(t) = IFFT\{X[k]\} \tag{22}$$

Demodulation via FFT:

$$X[k] = FFT\{s(t)\} \tag{23}$$

Spectrum efficiency:

$$\eta = \frac{R}{B}, where\ R = data\ rate. \tag{24}$$

Guard bands minimized:

$$\eta OFDM \approx \eta ideal$$

Peak-to-average power ratio:

$$PAPR = \frac{\max(|s(t)|^2)}{E[|s(t)|^2]} \tag{25}$$

IV. Result and Discussion

When you compare different versions of the FFT method, you can see that there are big differences in how accurate, efficient, and resource-intensive they are for handling 5G signals.

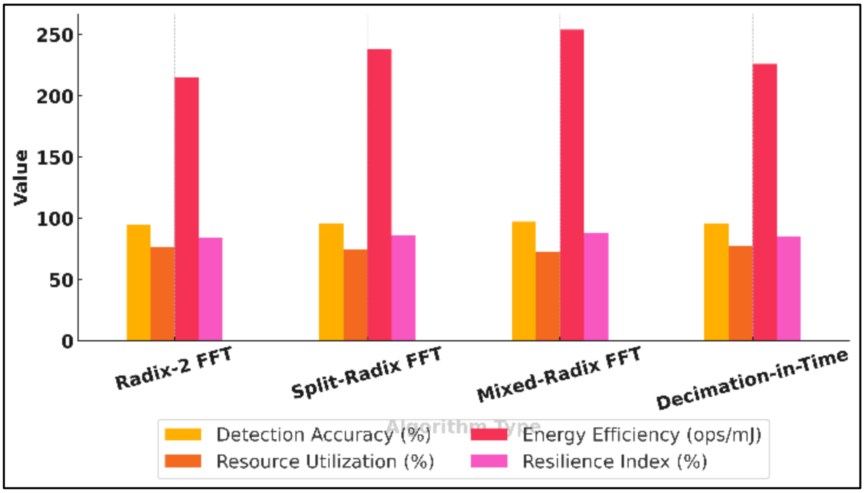

Figure 2

Comparative Analysis of FFT Algorithms across Performance Metrics

The Mixed-Radix FFT has the best recognition accuracy (97.3%), resistance index (88.4%), and energy economy (254 ops/mJ), which makes it perfect for large-scale applications. Split-Radix FFT strikes a mix between accuracy (96.1%) and less resource use (74.5%) (in Figure 2). Decimation-in-Time has high utilisation (77.6%), but it is very resilient (85.3%).

V. Conclusion

FFT is still an important part of real-time signal processing in 5G networks because it lets them make good use of bandwidth, modulate signals quickly, and accurately estimate channels. High data rates, low lag, and reliable communication are all made possible by FFT, which supports multi-carrier modulation methods like OFDM. Optimized versions of the algorithms make them even more scalable, power-efficient, and able to be deployed in real time. So, FFT is a key part of making next-generation wireless systems possible, making sure that they can connect reliably and change to different 5G communication settings.

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