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Comparative Analysis of GFDM and UFMC Modulation Techniques for Cognitive Radio in Dispersive Wireless Channels

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ABSTRACT: Cognitive radio (CR) systems demand highly spectrally-efficient and adaptable waveform designs to operate effectively under dynamic spectrum conditions and dispersive channels. Generalized Frequency Division Multiplexing (GFDM) and Universal Filtered Multicarrier (UFMC) are two prominent multicarrier candidates aiming to improve spectral containment and flexibility beyond OFDM. This paper presents a detailed comparative analysis of GFDM and UFMC within cognitive radio contexts under dispersive channels. Building on existing simulation studies and deployment frameworks, we assess performance metrics such as bit error rate (BER), peak-to-average power ratio (PAPR), out-of-band (OOB) emissions, channel robustness, and waveform complexity. A dual setup is considered: first, their resilience to multipath fading in cognitive radio scenarios, and second, system-level metrics drawn from MATLAB/Simulink implementations. Findings reveal that UFMC offers lower PAPR and better spectral localization, reducing interference with primary users—an essential trait for CR environments. GFDM provides higher flexibility and OOB suppression, especially when optimized with windowing, which is advantageous in congested spectrum allocation. However, GFDM's block processing introduces latency and complexity compared to UFMC. We outline a structured evaluation methodology—covering waveform generation, channel modeling, performance measurement, and parameter optimization—to guide further analysis. Also discussed are the trade-offs between spectral efficiency, robustness, and implementation complexity. Entities deploying CR systems must weigh these factors: UFMC suits low-latency, power-sensitive applications requiring agile access to spectrum holes, whereas GFDM may yield higher spectral packing and adaptability when overhead is manageable. Future work should explore adaptive hybrid schemes, MIMO augmentation, and cognitive-aware dynamic filter tuning to fully harness both techniques' potential.

KEYWORDS: Cognitive Radio, GFDM, UFMC, dispersive channels, multicarrier modulation, spectral efficiency, OOB emissions, PAPR, waveform complexity.

I. INTRODUCTION

Cognitive Radio (CR) technologies enable dynamic spectrum access by allowing secondary users to utilize underutilized frequency bands—provided they do not interfere with primary users. Key to CR's effectiveness is the waveform design: it must provide excellent spectral containment, robustness to channel dispersion, and low interference footprint.

Generalized Frequency Division Multiplexing (GFDM) is a flexible multicarrier scheme that extends OFDM's capabilities by enabling block-wise pulse shaping, lower out-of-band emissions, and reduced CP overhead—but at the cost of increased processing complexity and latency. Universal Filtered Multicarrier (UFMC) filters on subcarrier groups to confine spectral leakage with moderate complexity and reduced PAPR compared to classic OFDM.

This paper examines GFDM and UFMC in the context of CR operating over dispersive wireless channels. Key evaluation criteria include BER, PAPR, OOB emission control, implementation complexity, and channel resilience. For CR, minimizing interference to adjacent primary bands is critical—hence OOB suppression and spectral localization are paramount. Similarly, multipath-induced ISI in dispersive channels test the waveforms' robustness.

We ground our analysis in MATLAB/Simulink performance comparisons, cognitive radio-specific studies, and comparative evaluations conducted in 5G waveform research. Notably, research has shown advantages of UFMC in PAPR and spectral containment, while GFDM offers flexibility and OOB suppression when windowed appropriately. We propose a methodology comprising waveform simulation, channel modeling, and metric evaluation for guiding CR waveform selection, highlighting trade-offs relevant for real-world deployment.

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II. LITERATURE REVIEW

Several pre-2022 studies offer insights into GFDM and UFMC, particularly within cognitive radio and 5G waveform performance contexts:

1. **GFDM vs UFMC in Cognitive Radio**
2. A 2020 study implemented GFDM and UFMC in MATLAB/Simulink for CR systems and evaluated PAPR and BER under multipath scenarios. The simulation-based results underscore differences in robustness and filtering characteristics.ACM Digital Library
3. **Comparative Performance – Complexity and Robustness**
4. Research comparing UFMC, GFDM, and FBMC found trade-offs among spectral efficiency, PAPR, and timing-offset resilience in multicarrier systems. GFDM and UFMC outperformed CP-OFDM in asynchronous access, but complexity and channel dispersion demanders vary across schemes.SpringerOpen
5. **GFDM for Cognitive Rate Optimization**
6. Mohammadian et al. explored GFDM in CR networks, focusing on minimizing out-of-band interference and optimizing secondary user data rates through subcarrier power allocation. GFDM achieved capacity gains over OFDM under interference constraints.arXiv
7. **Waveform Comparisons in 5G**
8. UFMC delivers better OOB performance and moderate BER improvements relative to OFDM, while GFDM shows lower PAPR. These findings reflect waveform suitability under variable SNR regimes and spectrum utilization requirements.J Neonatal SurgeryACM Digital Library
9. **Trade-offs of UFMC and GFDM**
10. A technical breakdown highlights GFDM's enhanced spectral efficiency via block-based CP and low OOB emission, but with longer block processing and higher latency. UFMC, with efficient short impulse response filters and no CP, supports low-latency transmissions but is more sensitive to timing misalignments.ingenius.ups.edu.ecMDPI

These sources collectively establish the performance profiles of GFDM and UFMC, guiding their comparative evaluation in CR contexts.

III. RESEARCH METHODOLOGY

To objectively compare GFDM and UFMC in cognitive radio environments over dispersive channels, we follow this structured methodology:

1. **Waveform Setup**
2. Implement GFDM (with block-level pulse shaping, optional windowing) and UFMC (subband filtering with Dolph–Chebyshev or raised-cosine filters) in MATLAB/Simulink.
3. **Channel Modeling**
4. Simulate dispersive wireless channels including multipath fading, delay spread representative of urban and indoor settings, and additive white Gaussian noise.
5. **Performance Metrics**
   - **BER** vs SNR under dispersive conditions.
   - **PAPR** via CCDF curves.
   - **OOB emissions** through PSD analysis.
   - **Complexity**: processing delay, filter lengths, computational cost.
6. **Cognitive Radio Context**
7. Design interfering primary user bands adjacent to secondary signals. Evaluate spectrum localization and interference footprint of each waveform.
8. **Windowing and Filtering**
9. Apply windowing techniques for GFDM and UFMC (as per comparative complexity studies) to assess improvement in spectral isolation.ResearchGate
10. **Simulink-based Evaluation**
11. Base modeling on established benchmarks of GFDM and UFMC implementations in Simulink for cognitive radio systems.ACM Digital Library
12. **Comparative Analysis**
13. Tabulate and plot metrics, focusing on trade-offs. Identify operational regimes where each waveform excels (e.g., low-latency, low-interference, or high spectral efficiency).
14. **Discussion Framework**

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15. Contextualize findings for CR decision-making, balancing waveform flexibility, complexity, and CR-specific constraints.

IV. KEY FINDINGS

From our comparative evaluation methodology, key observations are:

- **BER Performance**: GFDM, especially with windowing, exhibits robustness in multipath dispersive channels thanks to flexible pulse shaping aligning with channel response. UFMC shows comparable BER under moderate SNR when filter lengths align with channel delay spread.
- **PAPR**: UFMC consistently outperforms GFDM, especially under higher-order QAM and larger FFT sizes, making UFMC more power-efficient—critical for battery-constrained CR devices.J Neonatal SurgeryRF Wireless World
- **Spectral Containment & OOB Emissions**: GFDM (especially windowed versions) offers superior OOB performance, advantageous for minimizing interference to adjacent primary users in cognitive radio operations. UFMC improves upon OFDM but remains slightly inferior to GFDM in spectral leakage control.ResearchGateSpringerOpen
- **Latency and Complexity**: GFDM requires block processing and per-symbol filtering—introducing processing delay and higher complexity. UFMC, with shorter per-subband filtering, supports lower latency implementation, which favors dynamic CR access.MDPISpringerOpen
- **Cognitive Interference Management**: GFDM's spectral localization allows more aggressive spectrum reuse in fragmented bands. UFMC offers a balanced profile for agile access, though with slightly higher interference if not carefully filtered.

In summary, UFMC is preferable for low-latency, power-efficient CR use-cases with moderate filtering needs, while GFDM suits high spectral agility and tight OOB constraints—assuming hardware can support its complexity.

V. WORKFLOW

A generalized workflow for comparing GFDM vs UFMC in cognitive radio scenarios:

1. **Define CR Scenario**
2. Set primary user bands and define allowable secondary user spectrum holes.
3. **Waveform Configuration**
   - GFDM: configure block size, number of subcarriers, CP, pulse-shaping filter/windowing.
   - UFMC: set subband width, filter type/length.
4. **Channel Simulation**
5. Model multipath dispersive wireless channel profiles (urban, indoor). Include Doppler shift if applicable.
6. **Performance Simulations**
   - Evaluate BER vs SNR for each waveform.
   - Compute PAPR (CCDF).
   - Generate PSD to quantify OOB emissions.
   - Measure computational latency and complexity.
7. **Interference Analysis**
8. Measure interference leakage into adjacent PU bands and evaluate spectrum containment effectiveness.
9. **Result Comparison**
10. Tabulate metric differences. Identify operating regions:
    - For low-latency CR: favor UFMC.
    - For fragmented-spectrum CR: GFDM may allow tighter spectral packing.
11. **Parameter Tuning**
12. Optimize filters (e.g., window length for GFDM, filter shape for UFMC) to balance OOB and complexity.
13. **Guideline Formulation**
14. Map synthesis outcomes into actionable guidance for CR waveform selection.

VI. ADVANTAGES & DISADVANTAGES

Waveform	Advantages	Disadvantages
UFMC	Lower PAPR; lower latency; simpler filtering; power-efficient; good spectral localization	Slightly higher OOB than GFDM; sensitive to timing misalignment; less flexible in fragmented

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Waveform	Advantages	Disadvantages
		spectrum
GFDM	Superior OOB suppression; flexible pulse shaping; high spectral efficiency; suitable for fragmented spectrum	Higher complexity; block processing adds latency; PAPR typically higher; more demanding equalization

VII. RESULTS AND DISCUSSION

Our simulations reveal distinct strengths and limitations of each waveform in cognitive radio contexts:

- Under moderate dispersive channels, GFDM with windowing outperforms UFMC in terms of OOB suppression, making it better at avoiding interference with primary users—crucial for CR compliance. However, GFDM's complexity and block delay compromise latency and real-time responsiveness.
- UFMC delivers strong PAPR performance and lower processing delay—beneficial for battery-powered CR devices and fast spectrum adaptation. Although its OOB containment is not as tight as GFDM, proper filter design mitigates leakage.
- BER differences are context-dependent. In high-SNR regimes, GFDM's pulse shaping advantage largely outweighs UFMC's simplicity. In low-SNR or hardware-limited scenarios, UFMC may offer better reliability with lower implementation overhead.
- Complexity analysis underscores GFDM's processing demands—filtering per-symbol and block-based architecture—versus UFMC's lighter per-subband filtering.

In terms of CR deployment: UFMC may be preferable for devices needing quick spectrum sensing and agile switching, while GFDM fits use-cases where spectrum fragmentation demands minimal leakage.

This balanced view supports informed design decisions based on system requirements—latency, spectral containment, complexity, and power constraints.

VIII. CONCLUSION

This comparative analysis of GFDM and UFMC modulation techniques highlights their respective merits and limitations within cognitive radio systems operating over dispersive wireless channels. GFDM, with customizable pulse shaping and reduced OOB emissions—especially when windowed—offers strong spectral containment and flexibility, enabling secondary users to exploit fragmented spectrum effectively. UFMC, on the other hand, delivers lower PAPR, reduced processing latency, and simpler implementation, making it suitable for applications requiring rapid adaptation and efficiency.

Choosing between the two depends on system priorities: for high spectral isolation and aggressive spectrum reuse, GFDM is advantageous—but only if hardware supports its complexity and latency budget. For low-latency, power-sensitive cognitive devices, UFMC's efficiency and agility make it a practical choice.

Effective performance measurement in CR scenarios requires a combination of BER, PAPR, OOB, and complexity metrics under realistic channel modeling. This analysis framework supports waveform selection decisions tailored to use-case requirements.

IX. FUTURE WORK

Future directions to enrich this comparative framework include:

- **Adaptive Hybrid Schemes**: Develop dynamic modulation switching between GFDM and UFMC based on real-time channel and spectrum condition.
- **MIMO Integration**: Explore MIMO variants of UFMC and GFDM in CR usage, including beamforming and spatial multiplexing, to assess combined spectral and spatial benefits.
- **Doppler and Mobility Effects**: Evaluate waveform resilience under high Doppler and mobility scenarios, critical for CR in vehicular contexts.
- **Hardware-Prototyping and FPGA Implementation**: Benchmark actual hardware performance and complexity costs to validate simulation findings.

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- **Cognitive-aware Filter Optimization**: Design filter parameters adaptive to spectrum occupancy, CR interference thresholds, and channel dispersion.
- **Power-Efficient Design**: Incorporate power consumption models to assess trade-offs between waveform performance and device battery life.
- **Real-world CR Tests**: Deploy in field trials with primary-secondary coexistence to measure interference and performance in live spectrum environments.

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