Project Summary: Application of 5G New Radio for Satellite Links with Low Peak-to-Average Power Ratios

1. Introduction

1.1 Background and Motivation

The integration of satellite communication (SATCOM) and 5G New Radio (NR) systems represents a critical evolution in global telecommunications infrastructure. This paper by Saarnisaari and de Lima addresses one of the most significant challenges in this integration: the high peak-to-average power ratio (PAPR) of 5G NR signals, which severely limits the efficiency of satellite power amplifiers.

Satellite systems traditionally operate with very low power amplifier back-off values (0 dB for DVB-S2 with QPSK/8PSK), while terrestrial 5G systems typically require 6-10 dB back-off. This discrepancy creates a fundamental incompatibility that must be resolved for successful integration. The paper demonstrates that through careful system design and appropriate reference symbol density configuration, 5G NR can operate at 2 dB back-off with minimal performance degradation.

1.2 Key Performance Parameters and System Configuration

The study employs a comprehensive simulation framework with the following specifications:

- **Waveform Parameters**: OFDM with 4,096-point FFT, 3,300 active subcarriers
- **Subcarrier Spacing**: 60 kHz (scalable to other 5G NR numerologies)
- **Modulation**: QPSK (chosen for robustness at low SNR)
- **Channel Coding**: Rate 1/2 LDPC for data blocks (1,024 information bits)
- **PAPR Reduction**: Iterative Clipping and Filtering (ICF) with 3 iterations
- **Target Clipping Level**: 2 dB at 10^{-2} CCDF
- **Power Amplifier Model**: SSPA with smoothness parameter a = 3
- **Channel Model**: Single-path AWGN (representing highly directional satellite links)

2. System Performance Analysis

2.1 PAPR Reduction Performance

The Iterative Clipping and Filtering method demonstrates exceptional performance in reducing the 5G NR signal's dynamic range. The original OFDM signal exhibits a PAPR of approximately 10 dB at the 10^{-2} CCDF point. Through the ICF process:

Clipping Process Parameters:

- Clipping ratio: A = 2 dB
- Number of iterations: 3 (1 initialization + 2 refinements)
- Oversampling: Standard 5G NR zero-padding at band edges
- Out-of-band nulling: Applied after each clipping iteration

The ICF method introduces clipping noise with power approximately 15 dB below the signal level for 2 dB clipping. This noise power increases to about 25 dB below signal level for 6 dB clipping, demonstrating the aggressive nature of the 2 dB target.

2.2 Reference Symbol Density Analysis

The paper reveals a critical relationship between demodulation reference signal (DMRS) density and system performance under severe PAPR constraints. The study examines various configurations:

Time Domain Configurations:

- T1: DMRS in 1 symbol per slot (7.14% overhead)
- T2: DMRS in 2 symbols per slot (14.28% overhead)
- T4: DMRS in 4 symbols per slot (28.57% overhead)
- T7: DMRS in 7 symbols per slot (50% overhead)

Frequency Domain Configurations:

- F6: DMRS every 6th subcarrier (16.67% overhead)
- F12: DMRS every 12th subcarrier (8.33% overhead)
- F24: DMRS every 24th subcarrier (4.17% overhead)

The total RS overhead for configuration TxFy = $(x/14) \times (1/y) \times 100\%$

2.3 BER and BLER Performance Results

Synchronization Signal Block Performance: The SS block, containing PSS, SSS, and PBCH with DMRS every 4th subcarrier, demonstrates robust performance:

- Error-free reception above -2 dB SNR/RE
- Initial synchronization successful despite ±720 kHz Doppler (LEO)
- Multi-arm receiver with frequency spacing of 1/(2T_sig) handles large CFO

Data Channel Performance at BER = 10^{-4}:

- Reference (no PAPR reduction): 3.2 dB SNR/RE
- T7F6oneT (optimal RS): 4.0 dB SNR/RE (0.8 dB penalty)
- T4F6oneT (moderate RS): 5.5 dB SNR/RE (2.3 dB penalty)
- T2F6oneT (minimal RS): 7.2 dB SNR/RE (4.0 dB penalty)
- T7F6allT (time averaging): 4.5 dB SNR/RE (not recommended due to CFO)

2.4 Power Amplifier Efficiency Analysis

The reduction in required back-off translates directly to improved DC-to-RF conversion efficiency:

SSPA Efficiency Model:

- Efficiency η ∝ $\sqrt{\frac{P_{out}}{P_{sat}}}$ for Class AB operation
- At 6 dB back-off: $P_{out} = \frac{P_{sat}}{4}$, efficiency ≈ 25%
- At 2 dB back-off: $P_{out} = \frac{P_{sat}}{1.58}$, efficiency ≈ 55%
- Improvement factor: 2.2× or 30% absolute increase

This efficiency improvement is crucial for satellite systems where prime power is limited by solar panel capacity and battery storage.

2.5 Satellite-Specific Adaptations

Doppler Frequency Shift Compensation: The paper addresses extreme Doppler shifts in satellite systems:

- LEO (600 km altitude, 2 GHz): ±48 kHz shift, -544 Hz/s rate
- LEO (600 km altitude, 30 GHz): ±720 kHz shift, -8.16 kHz/s rate
- MEO (10,000 km altitude, 30 GHz): ±225 kHz shift, -90 Hz/s rate

Timing Advance Extensions: Standard 5G NR supports only 2 ms timing advance, insufficient for satellite delays:

- LEO: 0.5-7 ms one-way delay
- MEO: 7-120 ms one-way delay
- GEO: 120 ms one-way delay Solution: Common minimum delay approach with 12+ bits for TA transmission

3. Data Representation and Analysis

3.1 PAPR Reduction Effectiveness

The ICF method successfully reduces PAPR while maintaining spectral mask compliance:

Metric	Original Signal	After ICF	After HPA
PAPR @ 10^{-2} CCDF	10.2 dB	2.0 dB	2.0 dB
PAPR @ 10^{-3} CCDF	11.5 dB	2.8 dB	2.8 dB
PAPR @ 10^{-4} CCDF	12.3 dB	3.5 dB	3.5 dB
EVM	<1%	<3%	<8%

3.2 Performance vs. RS Density Trade-off

Configuration	RS Overhead (%)	SNR @ BER=10^{-4} (dB)	Penalty vs. Ideal (dB)	Throughput Efficiency
T7F6oneT	8.33%	4.0	0.8	91.67%
T4F6oneT	4.76%	5.5	2.3	95.24%
T2F6oneT	2.38%	7.2	4.0	97.62%
T7F12oneT	4.17%	4.3	1.1	95.83%
T7F24oneT	2.08%	5.8	2.6	97.92%

3.3 Satellite Orbit Comparison

Parameter	LEO (600 km)	MEO (10,000 km)	GEO (35,786 km)
One-way Delay	2 ms	33 ms	120 ms
Max Doppler @ 2 GHz	±48 kHz	±15 kHz	~0 Hz
Max Doppler @ 30 GHz	±720 kHz	±225 kHz	~0 Hz
Doppler Rate @ 30 GHz	-8.16 kHz/s	-90 Hz/s	~0 Hz/s
Footprint Diameter	~2,000 km	~8,000 km	~18,000 km

4. Conclusion

4.1 Summary of Key Findings

This comprehensive study demonstrates the feasibility of operating 5G NR waveforms over satellite links with aggressive PAPR reduction to 2 dB. The critical enabler is the use of dense reference symbol patterns, particularly the T7F6 configuration, which limits performance degradation to less than 1 dB while enabling a 30% improvement in power amplifier efficiency.

The research conclusively shows that:

1. Standard 5G NR signals can be adapted for satellite use without fundamental waveform changes
2. The ICF PAPR reduction method maintains spectral compliance while achieving 2 dB PAPR
3. Dense RS allocation compensates for channel estimation degradation due to clipping noise
4. Multi-arm receivers can handle the extreme Doppler shifts of LEO satellites
5. Simple standard modifications (TA extension, RS configuration) enable satellite operation

4.2 Practical Implications

For satellite operators, these findings suggest that 5G NR integration is technically feasible with:

- Existing SSPA technology (no linearization required)
- Standard 5G NR chipsets (with firmware modifications)
- Minimal impact on link budgets (<1 dB with proper configuration)
- Significant OPEX savings from improved power efficiency

4.3 Future Research Directions

The paper identifies several areas requiring further investigation:

1. Extension to higher-order modulations (16-QAM, 64-QAM) with low PAPR
2. Optimal RS power allocation under satellite power constraints
3. Advanced PAPR reduction techniques targeting <2 dB operation
4. Multi-user scheduling for satellite OFDMA with varying CFO
5. Integration with advanced features (massive MIMO, beamforming)