POLITECNICO DI TORINO

Master Degree course in Communications Engineering

Master Degree Thesis

Performance Evaluation of NOMA and OFDMA in LEO Satellite Constellations

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Thesis Summary

Low Earth Orbit (LEO) satellite constellations are emerging as a cornerstone of next-generation communication infrastructures, and their significance for Internet of Things (IoT) ecosystems continues to grow steadily. LEO satellites operate at considerably lower orbital altitudes, thereby mitigating signal propagation delays and significantly reducing communication latency. The adoption of advanced multiple access techniques is indispensable, as they have to manage scarce spectral resources while supporting the exponential growth in the number of connected devices. Such techniques are required not only to enhance spectral efficiency and maximize achievable throughput but also to ensure robust and reliable connectivity in highly dynamic and interference-prone LEO environments. Consequently, the selection and design of multiple access schemes represent a critical factor in determining the overall performance, scalability, and quality of service of LEO-based communication systems. This thesis investigates the performance of Non-Orthogonal Multiple Access (NOMA) and Orthogonal Frequency Division Multiple Access (OFDMA) in LEO satellite communication networks. A heuristic-based software simulation environment is developed to model a satellite constellation system in Walker Delta form and evaluate the comparative performance of these two multiple access techniques. The study primarily focuses on Signal-to-Interference-plus-Noise Ratio (SINR), system capacity, data rates, spectral efficiency, and varying satellite constellation network conditions. By conducting comprehensive simulations, this research aims to provide insights into the suitability of NOMA and OFDMA for LEO constellations for IoT applications and high-speed internet service in Ka-band. The findings contribute to the ongoing efforts to enhance access strategies for next-generation satellite networks.

The thesis under the title of Performance Evaluation of NOMA and OFDMA in LEO Satellite Constellations investigates the comparative performance of two next-generation multiple access technologies in the context of LEO satellite communications. It is triggered by the sudden growth of the LEO constellations and their now more prominent role in providing global broadband communications and high-scale IoT applications. They are used in the Ka-band in which effective spectrum use and the capability of supporting thousands of connections in parallel are of salience. The work is targeted at the evaluation of NOMA and OFDMA whose high research activity in terrestrial wireless networks does not translate in a straightforward way in terms of performance for the very different challenges presented by the orbital dynamics and Doppler effect and interference in the context of LEO satellite constellations.

The monograph begins in a theoretical section in which the basics of the access methods are mathematized. For NOMA, mathematical details are given for the superposition of the User Terminal (UT) signals in the power domain and extraction by Successive Interference Cancellation (SIC). SINR expressions for individual UTs are derived taking account of power allocation factors and channel fading and noise variance. These are generalized for the computation of total system capacity and spectral efficiency. Modelling for OFDMA pays special attention to the allocation of subcarriers orthogonally in the UT's domain and the occurrence of inter-carrier interference (ICI) by the effect of Doppler frequency shifting and co-channel interference (CCI) by the overlap of coverage. Theoretical expressions are derived connecting UT SINR and throughput and aggregate

capacity and how resource allocation policy impacts overall system performance.

Following the theoretical part, a simulation context is conceptualized and programmed in Python 3.10. The simulator is based on an object-based design and takes advantages of the Poliastro library for orbital mechanics, Cartopy for map projections, and general scientific packages such as NumPy and Matplotlib for computations and visualizations. The Walker Delta constellation model is employed for simulating the network of satellites, and the satellites' quantity, the UT density and the subcarrier quantity are defined as the independent variables. The satellites' and the UT's representation is done by ideal 50 dBi fixed gain parabolic antennas, and the communications links are affected by Rayleigh Fading Channel in order to consider the multipath propagation. The simulations are carried out in the Ka-band under 100 MHz bandwidth by satellite at 28 GHz frequency, and the performance assessments are done in the context of Monte Carlo experiments during 20 random generations by scenario.

Simulation stage proceeds step by step. First comes the creation of orbital configuration and the dispersion of the UTs across the European coverage area. Following this, the link budgets are calculated and the SINR values obtained for each UT under the NOMA and OFDMA scenarios. In NOMA, SIC residue serves as a parameter in accounting for imperfect deletion of SIC, while for OFDMA the emphasis is placed on the effect of ICI and CCI. The spectral efficiency is then computed by the normalization of aggregate throughput by bandwidth. Finally, the overall system capacity and the data rates per UT are attained, making possible a comparative study of the two access schemes under the same network and environmental conditions. SIC implementation in NOMA simulations are kept simplified, since the actual waveforms are not considered in the scope of this work.

The results give valuable trade-off information for the two strategies. In SINR terms, NOMA shows distinct advantages when SIC is ideally realistic, with the higher SINR levels under heavy data per UT loads. Optimal conditions were observed for scenarios in which approximately five hundred UTs were covered by two hundred and sixty satellites by a trade-off of having good coverage and manageable interference. OFDMA performance was good for scenarios of low Doppler effect but worsened as the subcarrier orthogonality was eliminated by mobility and also as CCI became significant by increasing concentration of UTs. Spectral efficiency results confirmed the NOMA superiority by realizing up to 7.46 bit/s/Hz compared to OFDMA's 5.84 bit/s/Hz. The advantage was subject, however, to accurate UT grouping and was observed to diminish even when more than a few UTs were grouped in a single satellite system while OFDMA's efficiency took a nose dive as the user-terminal-to-subcarrier ratio was high.

In terms of system capacity, NOMA revealed the potential of sustaining 1.3 Tbps under nearly ideal SIC circumstances but plummeted upon the onset of SIC residues. OFDMA peaked at 473.5 Gbps upon the employment of two hundred and fifty-six subcarriers but was offset by more significant Doppler-related loss at high allocations in terms of subcarriers. Per-user-terminal data rate analysis also corroborated these findings. In a constellation of two hundred and sixty satellites, NOMA supported average rates exceeding 260 Mbit/s under perfect interference circumstances and OFDMA peaked at 191

Mbit/s upon the employment of sixty-four subcarriers. The increase in the satellites benefited consistently in terms of improvement in fairness and throughput but in OFDMA, excessive subcarriers did more harm than good. These results highlight the overriding significance of interference control and wise resource allocation in terms of determining possible performance in the context of LEO systems.

The thesis work deduces that NOMA is a highly promising technique for maximizing the use of spectrum in LEO constellations in applications for massive connectivity and high rates. It is very good in terms of multiplexing the UT in the power domain and in cancelling interference using SIC. However, the performance is highly sensitive in terms of interference cancellation quality and without near-perfect SIC the benefits can deteriorate very rapidly. OFDMA, while less effective is more robust in some cases, notably those wherein fairness and probable performance across the UT set are of concern. It is a potential candidate for LEO services requiring ease of implementation and balanced resource allocation. The research sheds light on the fact that none of the schemes is universally supreme and the choice simply relies upon the interaction of efficiency, complexity and service imperatives. It also points the way for heterogeneous schemes of combining NOMA and OFDMA as a bright line of work for the near future. The thesis adds in the current debate regarding strategies for multi-access and next-generation satellites by yielding theoretical and real-life implications for the system design and implementation in the near future.