Regional CubeSat Communication and Constellation Design Evaluation

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Abstract—**In the rapidly evolving landscape of space networks, CubeSats have emerged as pivotal components facilitating cost-effective networks, supporting many applications, including monitoring, surveillance, and in-space backhauling. Besides, the forthcoming Emirati Interplanetary Mission in 2028 underscores the imperative of efficient constellation designs, particularly in remote and challenging areas. However, developing such intricate systems from the ground up is beset with formidable costs and technical complexities. In response to these challenges, our project aims to create a simulator of small satellite constellations that will, in advance of their deployment, serve as a proactive measure to mitigate potential issues and curtail the risk of costly satellite failures. We perform the link budget analysis and provide simulations of various regional constellations, showcasing their dynamic orbital mobility and providing a cost-effective platform for comprehensive performance testing, focusing on vulnerability assessment. The proposed simulator will validate the optimality of satellite constellation design and highlight the manifold terrestrial benefits of CubeSats, substantially elevating performance metrics such as the link budget. The transformative potential of our methodology lies in its capacity to significantly reduce production costs while concurrently bolstering the efficiency of CubeSat communication systems. This, in turn, positions our approach as a formidable contender in the competitive market landscape, poised to reshape the future of satellite technology.**

Index Terms—**CubeSats, constellations, link budget analysis, backhauling.**

I. Introduction

Ensuring equitable access to the digital world is paramount in our increasingly interconnected global society. Unfortunately, a significant disparity persists between regions with robust internet connectivity and those grappling with limited or no access. To promote resilience and inclusivity globally, we must make concerted efforts to bridge this digital divide. As of the close of 2019, projections from the International Telecommunication Union (ITU) indicate that approximately 3.6 billion individuals still lacked access to the internet, underscoring the magnitude of this challenge [1]. This issue is particularly acute in the least developed countries, where only two out of every ten people are privileged to be online. Space-related technology has become increasingly captivating, with space research offering new frontiers. Among these frontiers, miniature satellite constellations, commonly called CubeSat constellations, have emerged as a desirable prospect [2]. What distinguishes them is their versatility, design, deployment cost-effectiveness, and capacity to support a wide range of applications [3]. These applications encompass everything from remote sensing, aiding in the understanding and monitoring of the Earth's surface and atmosphere, to space exploration missions that expand our knowledge of the cosmos and even provide internet connectivity in remote and underserved areas. However, the practical deployment of CubeSat mega-constellations to meet the anticipated demand presents formidable real-world challenges [4]. This challenge is partly due to the substantial time and effort required for conceiving, designing, and assembling these satellite systems. Moreover, it is essential to ensure a robust and reliable design while rigorously assessing the feasibility of a mission before deploying these costly satellites. This prudent approach is critical for mitigating the significant risks of mission failure and the potential degradation of expensive satellite assets [5]. Besides, despite the growing interest in CubeSats to perform different missions, research on designing their digital twin or a simulator remains limited due to the lack of feasibility of the essential metrics of CubeSat design. Also, open-source design applications – like STK and GMAT – lack critical design parameters, such as revisit time and inter-satellite links. Moreover, it is near impossible to design a perfect digital twin as there is always a possibility of micrometeoroids or orbital debris collisions and noise and crosstalk from other neighboring satellites [6]. Moreover, no studies investigate real-time link budget analysis using digital twins. With real-time link analysis, we can continuously monitor the bit error rate using various mathematical models in [7]. Our approach stands poised to improve the small satellite constellation landscape by delivering substantial reductions in production costs, all while elevating the operational efficiency of communication systems to new heights. Our seamless integration of virtual and real-world techniques via the proposed simulator empowers us to proactively harness data insights, ensuring continuous system monitoring, early issue mitigation, minimal downtime, and discovery of novel applications. In this way, our mission is to profoundly contribute to the ongoing growth and evolution of the space technology sector in the UAE while concurrently narrowing the digital divide problem and performing environmental monitoring.

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II. Proposed Simulator Design

The design of a simulator for mega-constellations of CubeSats is critical, ensuring the reliable transmission of data between space and Earth, Earth to space, or through intermediary communication relays. International entities govern the allocation of frequency bands for specific functions, such as space-to-Earth, Earth-to-space, and inter-satellite communication [8]. In the case of CubeSats, uplink frequencies are typically kept higher than downlink frequencies to minimize signal attenuation and reduce power requirements [9]. Existing studies have predominantly focused on the analysis of VHF (144 - 146 MHz) and UHF (435 - 438 MHz) amateur bands, which are commonly employed in different missions [10]. Nevertheless, some investigations have delved into Ka-band, X-band, S-band, and L-band frequencies [11], [12]. In the design of these communication links, factors such as range, throughput, and received signal quality assume paramount importance for communication engineers. Hence, the comprehensive analysis provided by a link budget is indispensable, as it accounts for all gains and losses within the communication link. According to [13], employing the free-space propagation model, we can evaluate the normalized signal-to-noise ratio (γ) at the ground station to determine the link budget for the satellite duplex link:

$$\gamma = \frac{E_b}{N_\circ} = \frac{P_t G_t G_r}{kTLR_b} \tag{1}$$

Here, E_b represents the energy-per-bit, $N_\circ$ denotes the noise spectral density, P_t signifies the transmit power, G_t corresponds to the transmitter antenna gain, G_r represents the receiver antenna gain, k stands for the Boltzmann constant, T reflects the system temperature noise, L encompasses the total loss, and R_b relates to the desired data rate. The total path loss L is equal to:

$$L = L_{FS} L_{atm} L_{POL} L_{FTx} L_{FRx} L_{DTx} L_{DRx}. \tag{2}$$

All these different types of losses are defined in Table II. By simplifying (2), we consider $L_{FTx} = L_{FRx} = L_F$ and $L_{DTx} = L_{DRx} = L_D$.

$$\begin{aligned} L(dB) = L_{FS}(dB) + L_{atm}(dB) + L_{POL}(dB) \\ +2L_F(dB) + 2L_D(dB). \end{aligned} \tag{3}$$

With path loss in (3), link reliability is assessed by calculating the Bit Error Rate (BER) based on the signal-to-noise ratio. The BER calculation based on SNR is given in Table I for some of the well-known digital modulation schemes.

Moreover, for effective CubeSat utilization in LEO, distinct parameters necessitate design considerations due to their smaller footprint compared to medium Earth orbit (MEO) and geostationary orbit (GEO) satellites. This difference is primarily influenced by satellite altitude, with higher altitudes yielding larger footprints. To achieve global coverage, we adapt in this paper the Walker Constellation model with symmetric CubeSats (having the same inclination angle and altitude) for the local coverage in UAE as shown in Fig. 1

TABLE I: BER formulas for different modulation techniques.

Coherent Modulation Technique	**BER** (P_b)
BPSK	$0.5(\sqrt{\frac{E_b}{N_\circ}})$
M-PSK	$\frac{1}{m} \times (\sqrt{\frac{mE_b}{N_\circ}} \times \sin(\frac{\pi}{M}))$
M-QAM	$\frac{2}{m}(1 - \frac{1}{\sqrt{M}}) \times (\sqrt{\frac{3m}{2(M-1)}} \times \frac{E_b}{N_\circ})$

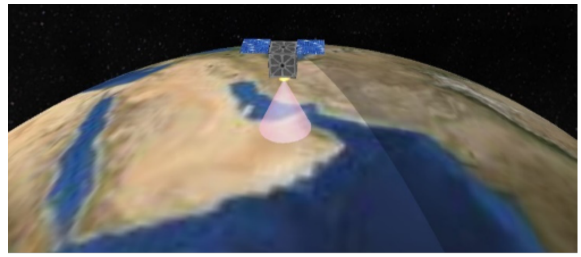

Fig. 1: Satellite orbital trajectory.

Using (4), we can calculate the orbital period T:

$$T = \sqrt{\frac{4\pi^2 R^3}{GM}}, \tag{4}$$

where R is the average radius of the orbit, the universal gravitational constant $G = 6.6726 \times 10^{-11} Nm^2/kg^2$, $M_{earth} = 5.98 \times 10^{24} kg$, $R_{earth} = 6.37 \times 10^6 m$. Then, we can find the six initial Keplerian elements of the CubeSat:

1) Semi-major axis (a):

$$a = \sqrt[3]{\frac{P^2 GM}{4\pi^2}}, \tag{5}$$

where P is the orbital period, and M is the combined mass of primary and secondary bodies.

2) Eccentricity (e):

$$\vec{e} = \frac{\vec{v} \times \vec{h}}{\mu} - \frac{\vec{r}}{r}, \tag{6}$$

where v is orbital speed, $\vec{h}$ is angular momentum vector, μ is standard gravitational parameter, and r is orbit radius.

3) Inclination angle (i):

$$\cos(i) = \frac{\hat{Z} \cdot \vec{h}}{|\hat{Z}||\vec{h}|}. \tag{7}$$

where Z is the angular momentum vector.

4) Right Ascension of Ascending Node (Ω):

$$\cos(\Omega) = \frac{\hat{I} \cdot \vec{n}}{|\hat{I}||\vec{n}|}, \tag{8}$$

where Ω is the angle from the vernal equinox to the ascending node. The satellite passes through the equatorial plane through the ascending node, moving from south to north.

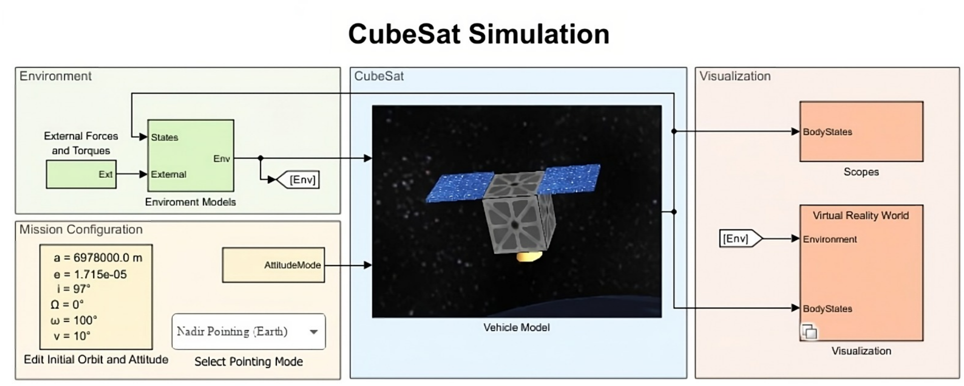

Fig. 2: Block diagram on Simulink.

5) Argument of Perigee (ω):

$$\cos(\Omega) = \frac{\vec{n} \cdot \vec{e}}{|\vec{e}||\vec{n}|}, \tag{9}$$

where Ω is the angle from the ascending node to the eccentricity vector, n is a vector pointing toward the ascending node.

6) True mean anomaly (M):

$$\cos(v) = \frac{\vec{e} \cdot \vec{r}}{|\vec{e}||\vec{r}|} \tag{10a}$$

$$\tan(\frac{E}{2}) = \sqrt{\frac{1-e}{1+e}}\tan(\frac{v}{2}) \tag{10b}$$

$$M = E - e\sin(E) \tag{10c}$$

where E is an eccentric anomaly. Table 2 shows the Keplerian elements found using equations (2-8) for a simple orbit design for our target location. Next, we will simulate the satellite-to-ground link's constellation design and communication link budget.

III. Numerical Results

We utilized the "Aerospace Block set" Simulink Toolbox to analyze Expo City's mission geometry for Dubai's coverage, defining the CubeSat vehicle model and its mission parameters aligned with the initial design parameters. The Simulink block diagram is depicted in Fig. 2, and the satellite trajectory over a 3D globe is shown in Fig. 1. This analysis used the initial parameters in Table II. Additionally, we simulated the orbit design in MATLAB Simulink through the CubeSat Simulation Project Toolbox, which offers a pre-configured CubeSat for simulation and visualization via Simulink 3D Animation. A MATLAB graphical user interface (GUI) was also employed to simulate the three-dimensional orbit of the satellite, requiring input for defining the orbit trajectory and CubeSat attitude. Given that a majority of Low Earth Orbit (LEO) satellites operate within the L-band frequency range of 1-2 GHz [14], we can reasonably assume that the Signal-to-Noise Ratio (SNR) at a typical ground station falls within the range of up to 20 dBs. Therefore, our simulation encompasses an SNR range from -5 to 20 dBs, in line with established guidelines [15]. Utilizing these SNR values, we conducted a comprehensive performance analysis of the CubeSat-to-ground link, depicted in Fig. 3 across various modulation schemes. Furthermore, to assess the practicality of our findings, we considered a specific scenario using the Simulink block diagram presented in Fig. 1. In this scenario, we evaluated the performance of a single CubeSat tasked with providing coverage to Expo City in Dubai. In Fig. 4, we present the Geodetic Latitude (depicted in Blue) and Geodetic Longitude (depicted in Red) of the CubeSat. The geodetic latitude of the CubeSat represents the angle formed between the equatorial plane and the perpendicular line intersecting the CubeSat's position on the Earth's surface. On the other hand, the Geodetic Longitude signifies the angle within the equatorial plane, defined by line 'a' connecting the

TABLE II: Initial input parameters.

Initial Parameters	**Value**
a: semi-major axis (km)	6978
e: eccentricity	0.00001715
i: inclination (deg)	97°
Ω: right ascension of ascending node (deg)	0°
ω: argument of periapsis (deg)	100°
v: true anomaly (deg)	10°
h: altitude (km)	500
Latitude (deg)	25.5°
Longitude (deg)	55.3°
L_{FS}: Free Space Loss (dB)	138.48
L_{atm}: Atmospheric Loss (dB)	0.2802
L_{POL}: Polarization Loss (dB)	2.31
L_D: Denoising Loss (dB)	0.0012
L_F: Feeder Loss (dB)	1

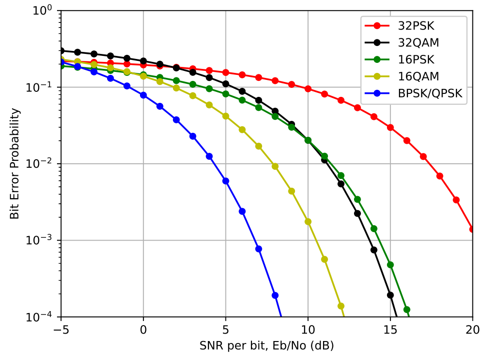

Fig. 3: BER vs. SNR per bit for different modulation techniques.

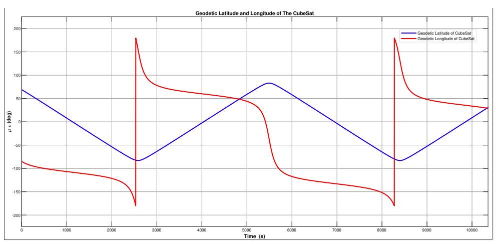

Fig. 4: Geodetic Latitude and Longitude of the CubeSat.

Earth's center to the prime meridian and line 'b' connecting the center to the meridian along which the CubeSat is situated. This information provides crucial insights into the CubeSat's position and orientation relative to the Earth's surface. In

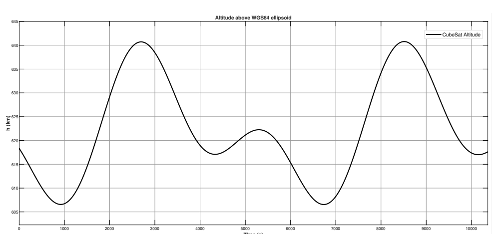

Fig. 5: Altitude above WGS84 of the CubeSat.

Fig. 5, we present the height above the CubeSat's WGS84 ellipsoid (referred to as HAE), representing a mathematical model of the Earth—an ellipsoid. To provide context, it's important to note that Fig. 4 and Fig. 5 together depict periodic signals of the CubeSat's Geodetic Latitude, Geodetic Longitude, and Altitude. This periodicity aligns closely with a period of approximately 5663 seconds. This period coincides with the orbital period of the CubeSat, a relationship that can be precisely calculated using (4).

IV. Conclusion

In conclusion, as we peer into the future of communication networks, we observe a shift toward fast broadband with the promise of 6G technology. However, we must embrace advanced modeling and simulation to address the ever-expanding coverage challenges of tomorrow's non-terrestrial networks. Developing a simulator for CubeSat constellations is a necessity and a strategic imperative. This tool enables us to overcome challenges and ensure satellite networks' cost-effective and successful deployment. Our study unveiled a sophisticated simulation platform tailored for advanced satellite networks. Through precise modeling of communication links and constellations and digital prototyping, we showcased CubeSat performance with real-time orbital motion and communication link analysis, focusing on regional coverage in the UAE. Future directions for research in this field involve fine-tuning the simulator for diverse geographical areas, designing mega-constellations, exploring adaptive communication protocols, and delving deeper into the optimization of CubeSat constellations to meet the evolving demands of global connectivity.

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