Analysis and Design of IoT over LEO Satellite: Uplink Performance Communication

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***Abstract*—As envisioned by the United Nations Sustainable Development Goals (SDGs), our sustainable future is heavily reliant on the potential use of the Internet of Things (IoT). The main challenge of seamless IoT integration is a need for more wireless connectivity, especially for IoT devices spread across a vast geographic region, including all rural and isolated locations. Therefore, designing and delivering cost-effective solutions to these locations is inevitable to enhance global connectivity's reliability, sustainability, and security.**

Low Earth Orbit (LEO) satellites have lately emerged as the preferred candidate to tackle this challenge due to their lower launching costs, simplicity of deployment, and minimal latency. Even though there is much research on LEO-based terrestrial communication in the literature, not all of them are applicable to supporting IoT network technologies.

I. Introduction

The IoT has a wide variety of applications, including agriculture development, equitable economic growth, climate change monitoring, affordable energy, accessible health care, equal education opportunity, and more [1], [2]. Many of these IoT applications are located or need to be located in rural and isolated areas; however, due to either environmental challenges or a lack of business profit, it is difficult to deploy terrestrial wireless networks.

Ongoing studies of integrating satellite-based IoT services go beyond current terrestrial communication and offer a promising solution to the above problems [3]. Soon, satellite-based IoT installations will become a reality, enhancing capacity in densely crowded megacities, not only in remote areas with insufficient coverage.

Furthermore, there is a shortage of analytical frameworks in the literature based on the uplink coverage for satellite-terrestrial hybrid networks. Our work presents an analytical approach to capture the uplink performance of the IoT over the LEO satellite network. Considered framework is based on stochastic geometry tools with its property of capturing the randomness inherent in wireless communication in all geographical locations rather than a specific location.

II. System Architecture and Main Results

Two communication scenarios, direct and indirect, are studied with the selection of appropriate point processes.

1) System Model: We investigate: (i) in scenario-1, the direct uplink communication of the IoT device with the LEO satellite, while (ii) in scenario-2, the communication link between the IoT device and the LEO satellite through the Gateway (GW), which can be considered a collocation of two networks (terrestrial and satellite). We model IoT devices as a Poisson Cluster Process (PCP), GWs as a Poisson Point Process (PPP) on the surface of Earth, and LEO constellation deployment as a Binomial Point Process (BPP) at some fixed altitude above the surface of Earth.

2) Channel Model: Adopting appropriate channel models is crucial for conducting a precise network performance analysis. Due to the hybrid communication of the terrestrial and satellite networks, we use Rayleigh and Shadowed-Rician fading, respectively, to obtain more accurate findings in each scenario.

3) Interference: The challenging part of uplink performance analysis is the characterization of interference. In this work, the aggregate interference - the total amount of interference brought on by all active interferers - is denoted using the $\mathcal{I}_{\text{agg}}$ notation. Because of the uncertainties in location and the number of active interferers, we employ stochastic geometry methods to derive the best manageable expressions for the uplink interference for each scenario.

4) Performance Analysis: We address the randomness caused by aggregate interference at a typical receiver for each link of all scenarios. Unlike the averaging interference power typically used in literature, we derive the most precise approximation of interference power using Laplace transform.

In the following theorem, we present our first key result, the Laplace transform of the interference of scenario-1, under the proper approximations.

Theorem 1 (Laplace Transform of $\mathcal{I}_{\text{agg}}^{\text{IoT-S}}$ for Scenario-1)**.** *The Laplace transform of the interference distribution at the serving satellite is*

$$\mathcal{L}_{\mathcal{I}_{\text{agg}}^{\text{IoT-S}}}(s) \approx \left(\int_{a_{\text{S}}}^{d_{\max}(\theta_c)} \left(1 + \frac{s\beta_s \rho_t^{\text{IoT}} c_0^2}{d_i^2}\right)^{-\alpha_s} f_{D_i}(d_i) dd_i + \int_{d_{\max}(\theta_c)}^{R_{\text{S}}+R_{\text{E}}} f_{D_i}(d_i) dd_i \right)^{N_{\text{S}}-1}, \quad (1)$$

where $f_{D_i}(\cdot)$ is the PDF of the interfering distance distribution and $d_{\max}(\theta_c) = \sqrt{R_{\text{E}}^2 + R_{\text{S}}^2 - 2R_{\text{E}}R_{\text{S}}\cos\theta_c}$.

Despite the complexity of the framework, we manage to compute the coverage probability in a relatively simple form.

Theorem 2 (Coverage Probability for Scenario-1)**.** *The uplink coverage probability for an arbitrarily located IoT device associated with the serving satellite under the tight bound of Gamma approximation of Shadowed Rician fading is*

$$P_{\text{cov}}^{\text{IoT-S}} \approx q \int_{L_0(a_{\text{S}})}^{L_0(d_{\max}(\theta_c))} \sum_{j=1}^{\alpha_s} \binom{\alpha_s}{j} (-1)^{j+1} \exp\left(-\frac{j\mu\tau}{\beta_s \rho_t^{\text{IoT}} l_0} \sigma_{\text{S}}^2\right) \times \mathcal{L}_{\mathcal{I}_{\text{agg}}^{\text{IoT-S}}}\left(\frac{j\mu\tau}{\beta_s \rho_t^{\text{IoT}} l_0}\right) f_{L_0}(l_0) dl_0, \quad (2)$$

where $q = 1 - \left(\frac{1+\cos\theta_c}{2}\right)^{N_{\text{S}}-1}$ *and* $\mathcal{L}_{\mathcal{I}_{\text{agg}}^{\text{IoT-S}}}(\cdot)$ *is stated in Theorem 1. The PDF of the path-loss function* L_0*,* $f_{L_0}(\cdot)$*, is derived from contact distance distribution.*

As stated earlier, scenario-2 consists of two collocated networks with different fading assumptions. As a result, the overall coverage probability is expressed as an association of IoT-GW and GW-S networks. Due to page constraints, we omit the theoretical results of scenario-2.

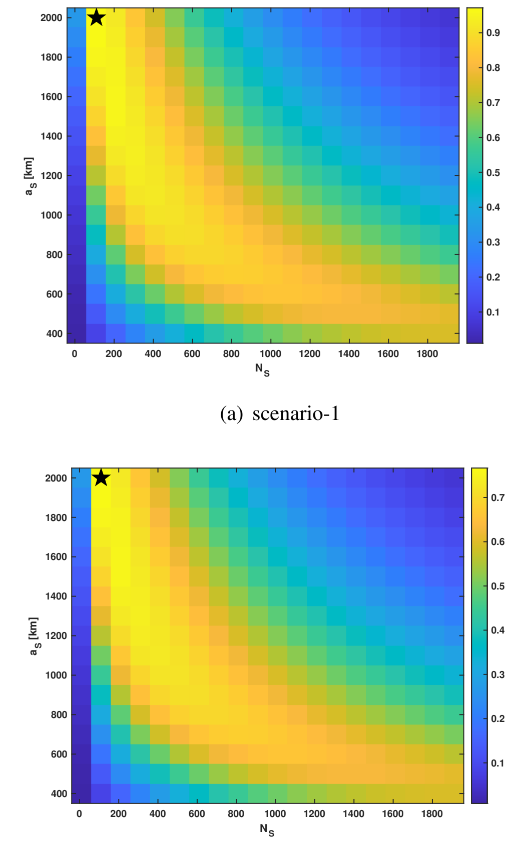
III. Results and Discussion

This framework offers insights into IoT's direct/indirect design over LEO satellite network infrastructures.

In Fig. 1, we present the joint optimization of both altitude and number of satellites in the LEO constellation to obtain the best feasible coverage probability, and the highest possible value is marked with a star. This optimization enables network providers to develop IoT over LEO satellite network growth plans. Our results show that direct communication outperforms the relay-based approach in terms of SINR coverage (see Fig. 1(a) and Fig. 1(b)).

Battery life is another essential criterion for IoT applications. Improving the lifetime helps us to avoid frequent battery replacements for IoT devices deployed in difficult-to-reach places and significant threats to environmental pollution. Fig. 2 illustrates the battery life of an IoT device versus different packet sizes against each communication link. As expected, reducing the packet size would result in longer battery life in all scenarios.

As shown in Fig. 2, one of the main findings of our framework is an intriguing trade-off: indirect communication has a longer IoT battery lifetime, while direct communication is superior in terms of coverage probability. Choosing the network settings that best balance high-performance requirements with extended battery life are vital.



(a) scenario-1

(b) scenario-2

Fig. 1: Heat map representing coverage probability of each scenario related to altitude against the number of satellites.

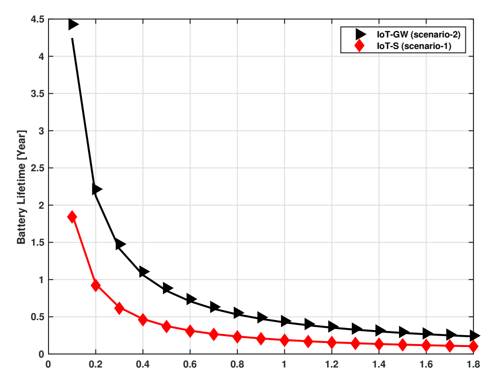


Fig. 2: Comparison of IoT-GW and IoT-S in terms of the lifetime of IoT device battery against the packet size. The estimation is based on a 5 Wh battery, which was also taken into account in the 3GPP calculations.

References

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