Analysis and Design of IoT over LEO Satellite:

Uplink Performance Communication based on Stochastic Geometry

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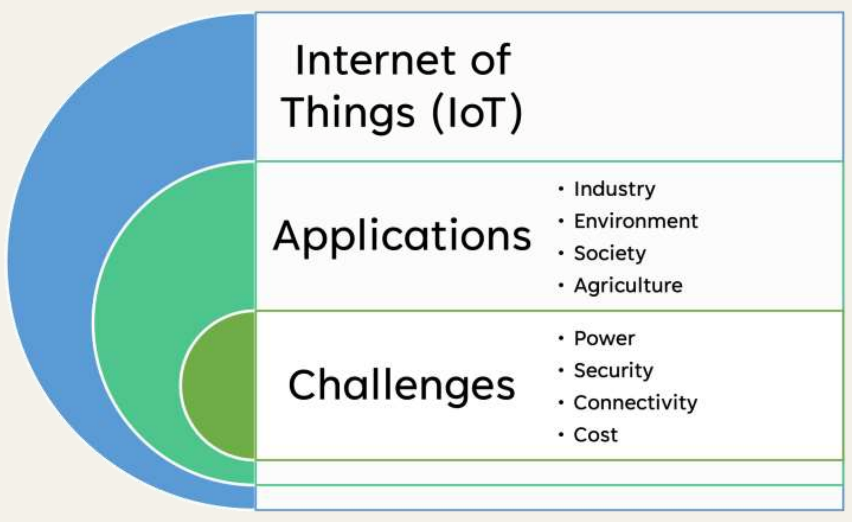
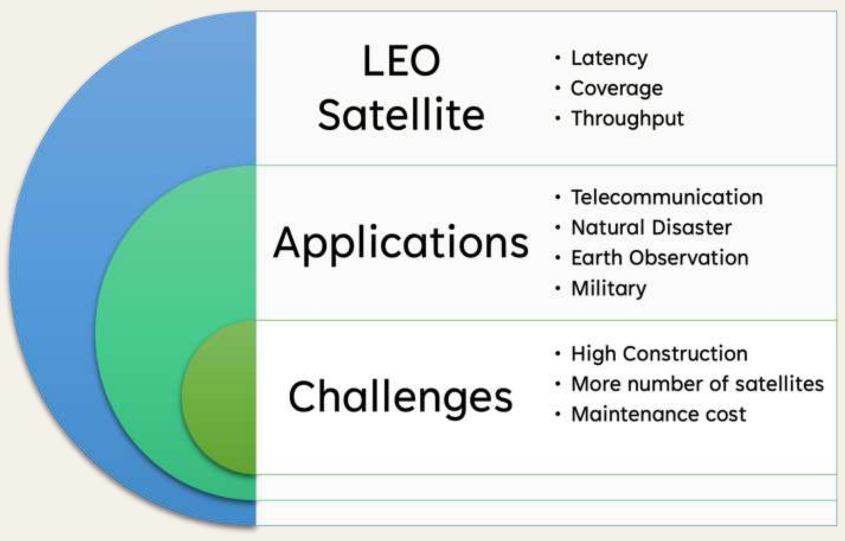
Introduction

❖ 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.



❖ 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.

❖ Our framework is based on the uplink coverage comparison of two proposed scenarios, as shown in Fig.1: direct and indirect network communication.

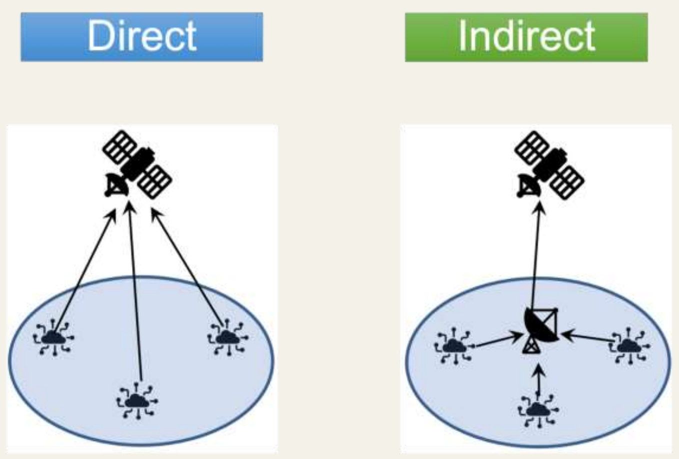


Fig. 1: General overview of the proposed framework.

➢ Scenario-1 models the direct uplink communication from a typical IoT device to a serving satellite.

➢ For scenario-2, the communication from a typical IoT device to a serving satellite is through a relay such as a Gateway (GW), which can be considered a collocation of two networks.

System Architecture

System Model:

❖ Direct Communication

➢ The deployment of LEO satellites follows a Binomial Point Process (BPP) with a given number of satellites at a fixed altitude above the Earth's surface.

➢ The associated IoT devices of each satellite are uniformly distributed within its beam on the surface of Earth.

❖ Indirect Communication

➢ Satellites follow the same distribution as in direct communication.

➢ We consider the Poisson Cluster Process **(**PCP) for terrestrial nodes, where GWs serve as parent points and IoT devices as offspring points.

Fig. 2: System model illustration of aerial link.

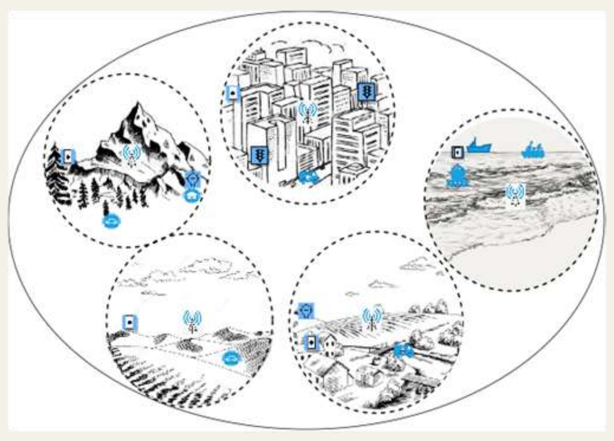


Fig. 3: System model illustration of terrestrial link for different environments.

Channel Model:

❖ Direct Communication

➢ Path-loss attenuation and Shadowed Rician fading are used to describe wireless channel propagation for direct communication.

❖ Indirect Communication

➢ For terrestrial links, we adopt the Rayleigh fading.

➢ Communication between GW and LEO satellites adopts the same channel as scenario -1.

Interference Characterization:

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.

For the visual representation of the interference area, refer to Fig. 4 and 5.

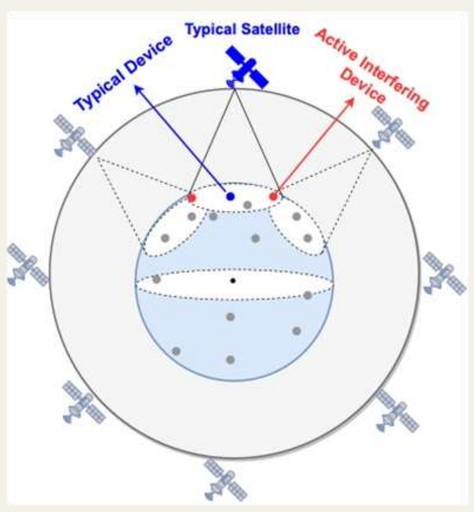


Fig. 4: Illustration of interference area for the aerial link.

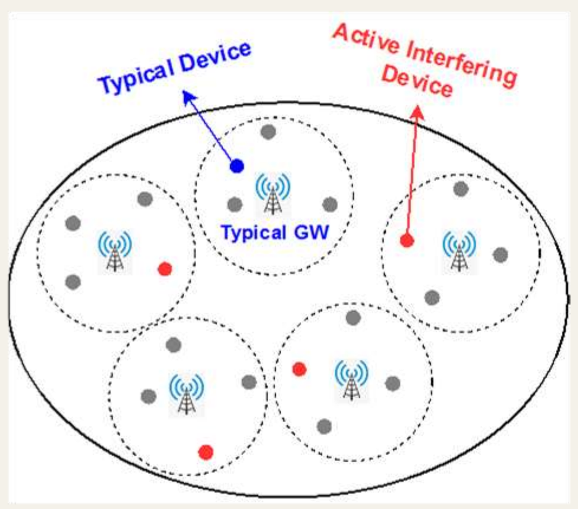
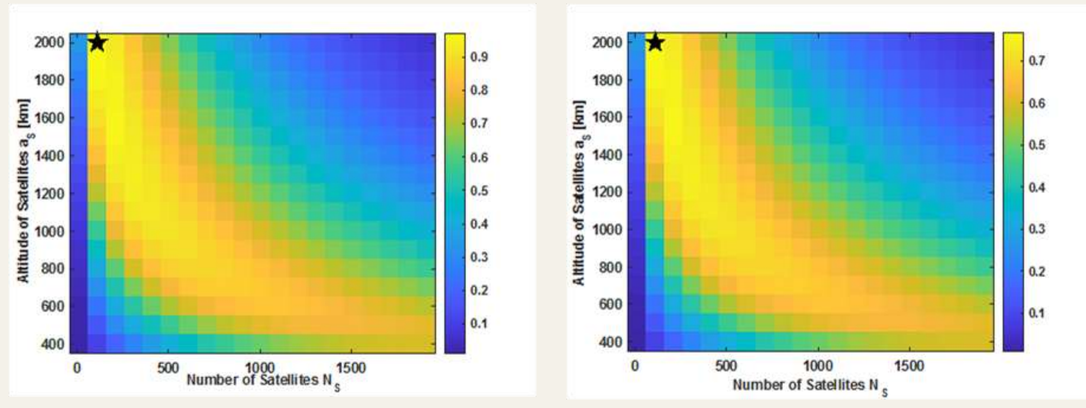


Fig. 5: Illustration of interference area for the terrestrial link.

Main Results and Discussions

❖ The performance of considered direct and indirect scenarios is analyzed and compared in terms of coverage probability. We derive the most accurate approximation of interference power by using Laplace transform, unlike the average of interference power typically used in literature.

➢ **How do the number of satellites and their altitude affect coverage?**

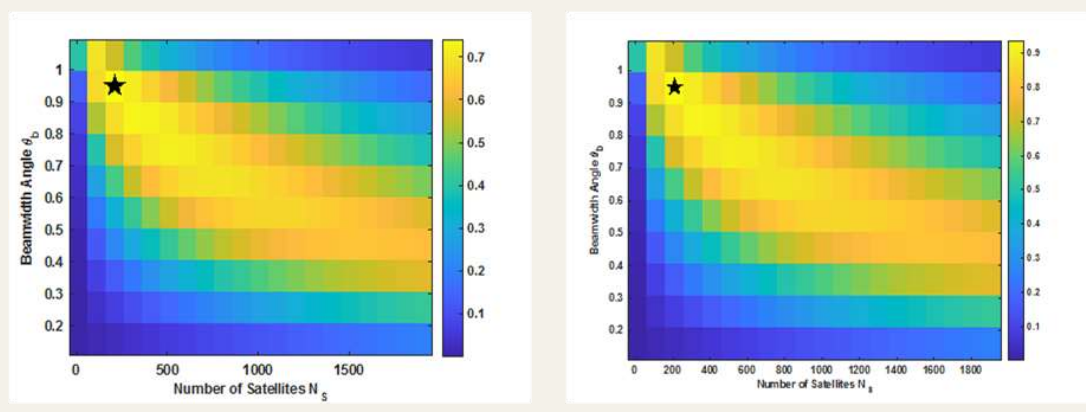


Direct Communication   Indirect Communication

Fig. 6: Joint optimization for best feasible coverage

We present the joint optimization of both altitude and number of satellites in the LEO constellation to obtain the best feasible coverage probability in Fig. 6. This optimization enables network providers to develop IoT over LEO satellite network growth plans.

➢ **What about effects of beamwidth angle over coverage?**



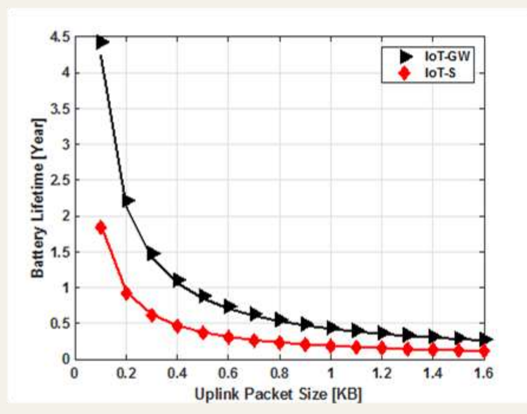
Direct Communication   Indirect Communication

Fig. 7: Contribution of beamwidth in coverage analysis.

According to the results of our simulations in Fig. 7, it is straightforward to conclude that increasing the number of satellites does not help to improve coverage as the beamwidth angle narrows. It is vital for both parameters to select optimal values to maximize coverage area.

❖ One of the critical requirements for IoT applications is battery life because we want to deploy IoT devices everywhere, especially in difficult-to-reach places.

➢ **Which scenario is better in terms of battery life?**



IoT-GW and IoT- S links are compared in terms of the lifetime of the IoT device battery against the packet size.

The estimation is based on a 5 Wh battery.

Fig. 8: Comparison of battery lifetime.

As expected in Fig.8, reducing the packet size would result in longer battery life in all scenarios. In contrast to what we showed in the previous figures, even though the direct communication scenario is the best choice in terms of coverage, it has a shortage in terms of battery life.

Energy usage, data packet size, packet transmission time, and the number of packet retransmissions are all factors that must be considered when calculating the expected battery life for a given use case.

Conclusion

❖ This work presents an analytical approach to evaluate the performance of an uplink network consisting of terrestrial IoT devices and a constellation of LEO satellites.
❖ The study's findings suggest that direct communication is more effective in achieving satisfactory SINR coverage than the relay-based approach.
❖ Energy usage factors must be carefully modeled to ensure that direct communication is the primary option; otherwise, indirect communication would be preferred for longer battery life.
❖ Overall, the framework presented provides valuable insights for designing IoT over LEO satellite network infrastructures.

References

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