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Handover strategies for satellite mega-constellations using semi-stochastic modelling

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Abstract

This paper uses semi-stochastic modelling to study inter-satellite handover strategies for coherent satellite communications between a ground user and a serving satellite from a mega-constellation. When a handover event occurs, the visible satellites are initialised using a non-homogeneous binomial point process. Thereafter, the chosen satellite persistently serves the user while following its deterministic orbit until it is no longer visible. This is a semi-stochastic model for persistent communications and is a refinement on stochastic models for non-persistent communications. Under Rician fading, the state-of-the-art nearest-satellite handover strategy—which is optimal for stochastic models—is enhanced with a handover strategy that chooses the satellite that maximises capacity across the visible orbit trajectory.

1 Introduction

Satellite mega-constellations consist of satellites moving in circular orbits around the Earth. Assuming no perturbations from external forces, which may be corrected for in practice, the satellite trajectories are completely determined by their initial positions. Empirical analyses typically initialise hundreds of satellites in a mega-constellation and project their orbits over many orbital periods. This deterministic model is very accurate, but it is intractable for theoretical analysis. Recently, this issue was addressed using stochastic models that independently model the satellite positions at discrete times using non-homogeneous point processes [1]. This approach prioritises tractability over accuracy. A hybrid approach is semi-stochastic modelling [2] that stochastically models the initial positions of satellites visible to the user and thereafter follows their deterministic trajectories until they are no longer visible. This approach improves the accuracy while retaining tractability.

Current state-of-the-art inter-satellite handover strategies choose a visible satellite to serve the user based on the link quality, propagation time, and handover rate [3]. The handover strategy that is typically employed is to choose the satellite link with the highest instantaneous SNR, maximising the channel capacity of stochastic models [4] since the satellite positions are modelled as independent at handover events that occur at consecutive time steps. On the other hand, semi-stochastic models include the subsequent trajectory of the visible satellites and thus provides a refined analysis of handover strategies.

2 Modelling satellite mega-constellations

The satellite mega-constellation considered here is a *Walker-Delta constellation* with N_{sat} satellites. Each satellite resides on the surface of a satellite sphere of radius R at an altitude h from the Earth sphere of radius r. There are $N_{\text{planes}} = 2\pi/s_{\text{orb}}$ orbital planes corresponding to circular orbits inclined by b radians relative to the equatorial plane. Each orbital plane has a reference point on the equatorial plane called the *ascending node* that corresponds to where satellites on this orbit are increasing in latitude. The ascending nodes are uniformly spaced around the equatorial plane by s_{orb} radians, with each orbital plane containing $N_{\text{orb}} = N_{\text{sat}}/N_{\text{planes}}$ satellites uniformly spaced by $2\pi/N_{\text{orb}}$ radians. The satellites are assumed to move at a constant speed of v_{sat} and thus an angular velocity of $\omega_{\text{sat}} = v_{\text{sat}}/R$.

Semi-stochastic modelling requires two components: the *stochastic component* that models the initial positions of visible satellites in the mega-constellation, and the *deterministic component* that models the satellite orbits while they remain visible to the user.

2.1 Stochastic component

Satellite position: Consider a satellite position at time $t = 0$ with spherical coordinates $(R, \theta(0), \phi(0))$, where $\theta(0)$ is the rotational angle and $\phi(0)$ is the polar angle. The rotational angle is stochastically modelled by approximating the uniformly spaced orbits as a continuous uniform random variable Θ on $[0, 2\pi]$. The polar angle is stochastically modelled by additionally approximating the uniformly spaced satellites on each orbital plane as a continuous uniform random variable on $[0, \pi]$; this results in a polar angle Φ with PDF [5, Lemma 2]

$$f_{\Phi}(\phi) = \frac{\sin(\phi)}{\pi\sqrt{\sin^2(\phi) - \cos^2(b)}} \tag{1}$$

for $\phi \in [\frac{\pi}{2} - b, \frac{\pi}{2} + b]$ and zero otherwise. The mega-constellation is modelled by taking N_{sat} i.i.d. realisations of the random spherical coordinates (R, Θ, Φ), forming a *non-homogeneous binomial point process (NBPP)*.

Visible satellites: Assume that a user at spherical coordinates $(r, \theta_{\text{u}}, \phi_{\text{u}})$ only has a line-of-sight with satellites that satisfy a minimum elevation angle $\psi_{\min}$ above the user's horizon plane. Then, the satellites visible to the user have positions in the random set $\mathscr{V} = \{(R, \Theta_k, \Phi_k)\}_{k=1}^{N_v}$ where N_v is the number of visible satellites. In practice, the mega-constellation is designed so that the number of visible satellites is at least one, the NBPP is conditioned on $N_v \geq 1$ going forward.

Satellite direction: To set up the deterministic component to come, we additionally must specify whether a satellite is ascending $(+1)$ or descending (-1). Since every satellite spends an equal time ascending or descending, this is stochastically modelled by a discrete uniform random variable A on $\{-1, +1\}$.

2.2 Deterministic component

Starting at initial position $(R, \theta(0), \phi(0)) = (R, \Theta_k, \Phi_k)$, for some choice of k, the satellite follows a deterministic orbit trajectory with time-dependent positions $(R, \theta(t), \phi(t))$ and is ascending/descending according to a. Hence, the angle between the direction vector of the satellite and the latitude line at $\frac{\pi}{2} - \pi$ is $\beta_a(\phi(0)) = a\cos^{-1}(\cos(b)/\sin(\phi(0)))$. These positions can be computed by:

1. Initialise the satellite on a flat orbital plane at spherical coordinates $(R, \omega_{\text{sat}}t, 0)$;
2. Rotate counter-clockwise around the x-axis by satellite direction $\beta_a(\phi(0))$ radians;
3. Rotate clockwise around the y-axis by latitude $\frac{\pi}{2} - \phi(0)$ radians;
4. Rotate counter-clockwise around the z-axis by longitude $\theta(0)$ radians.

Hence, the time-dependent distance between the user and the satellite is $d(\theta(t), \phi(t)) = \sqrt{r^2 + R^2 - 2rR\cos\sigma(t)}$ where $\sigma(t)$ is the central angle between the user and the satellite. In addition, the satellite only has a line-of-sight with the user for a visibility time $T(\theta(0), \phi(0))$, in seconds, and is the time it takes for the elevation angle of the satellite to equal the min. elevation angle $\psi_{\min}$.

3 Persistent satellite channel

Let us model a coherent communication link between the user and a satellite as a discrete-time AWGN channel with block-fading. The channel outputs are

$$y_i = \sqrt{f_i g_i} x_i + n_i, \tag{2}$$

for $i = 0, 1, \ldots, N_s - 1$ with $N_s = \lfloor T_s/\Delta t \rfloor$ for serving time T_s and sampling interval Δt, where x_i is the input with transmit power P_t, f_i is the Rician fading coefficient, g_i is the satellite channel gain (inverse of path loss), and n_i is uncorrelated AWGN with power N_0.

At index $i = 0$, the set of visible satellites relative to a user (r, θ_u, ϕ_u) is the random set $\mathscr{V}$ according to the NBPP, from which the initial position of the serving satellite is chosen as $(R, \theta(0), \phi(0)) = (R, \Theta_s, \Phi_s)$. For indices $i > 0$, the serving satellite has positions $(R, \theta(i\Delta t), \phi(i\Delta t))$ according to its deterministic orbit trajectory for a serving time $T_s = T(\Theta_s, \Phi_s)$ seconds and $N_s = N(\Theta_s, \Phi_s) = \lfloor T(\Theta_s, \Phi_s)/\Delta t \rfloor$ samples. The channel gain g_i due to the serving satellite position on its orbit is

$$g_i = [d(\theta(i\Delta t), \phi(i\Delta t))]^{-2} \tag{3}$$

which is inversely proportional to the free space path loss. In addition, the fading coefficient f_i is i.i.d. distributed as the Rician-squared random variable F. Once the serving time is completed, a handover event is triggered to repeat the process above.

4 Persistent satellite capacity

The metric for evaluating the theoretical performance of the persistent satellite channel model is the persistent (satellite) capacity.

Theorem 1 (Persistent capacity [2]). *The capacity of the persistent satellite channel is*

$$C_{\text{pers}} = \frac{\mathbb{E}[C(\Theta_s, \Phi_s)]}{\mathbb{E}[N(\Theta_s, \Phi_s)]} \tag{4}$$

where the total orbit capacity is

$$C(\theta, \phi) = \sum_{i=0}^{N(\theta,\phi)-1} \mathbb{E}\left[\log\left(1 + \frac{F g_i P_t}{N_0}\right)\right] \tag{5}$$

with $(\theta(0), \phi(0)) = (\theta, \phi)$.

This capacity differs from the non-persistent capacity of the non-persistent satellite channel that only considers the satellites instantaneously at $i = 0$. Thus, the non-persistent capacity is only accurate when the handover rate is high or the time between handovers is small.

5 Handover strategies

Since the persistent capacity C_{pers} accurately represents the achievable information rate of the satellite mega-constellation, it is suitable for evaluating the relative performance of different handover strategies. To highlight the benefit of semi-stochastic models over stochastic models, we will firstly consider a handover strategy that is optimal in terms of non-persistent capacity, however, we will then consider an enhanced handover strategy made possible by the persistent capacity.

Nearest-satellite (NS) handover strategy: The nearest-satellite handover strategy chooses the satellite from $\mathscr{V}$ whose user-satellite distance achieves

$$\min_{1 \leq k \leq N_v} \{d(\Theta_k, \Phi_k)\}. \tag{6}$$

With only Rician fading, this handover strategy indirectly maximises the SNR at $i = 0$ and thus is optimal in terms of the non-persistent capacity. With shadowing, the analogous extension to this strategy would be to directly maximise the SNR at $i = 0$. This has been the state-of-the-art handover strategy for mega-constellations.

Max-orbit-capacity (MOC) handover strategy: The max-orbit-capacity handover strategy chooses the satellite from $\mathcal{V}$ whose orbit capacity achieves

$$\max_{1\le k\le N_{\mathrm{v}}} \left\{ \frac{C(\Theta_k,\Phi_k)}{N(\Theta_k,\Phi_k)} \right\}. \tag{7}$$

This handover strategy was heuristically chosen to improve upon the nearest-satellite handover strategy, which only maximises the instantaneous capacity at $i = 0$, by considering the average capacity over all i.

6 Numerical results

The following numerical results use a mega-constellation with parameters given in Table 1. These parameters are based on the first and fourth orbital shells of the Starlink mega-constellation, which have almost identical orbital inclinations and orbital spacings, except that the ascending nodes of the fourth orbital shell are shifted by 2.5° (half the orbital spacing for each individual shell). Thus, these two shells can be accurately approximated as one shell with a halved orbital spacing.

The persistent capacity C_{pers} for a user located in Sydney is given in Fig. 1. It is assumed that the visibility of the user is limited by objects in the surrounding environment such that they only have a line-of-sight with satellites with a minimum elevation angle of $\psi_{\min} = 30°$. The persistent capacity with NS handover is up to 0.1 dB higher with MOC handover. In addition, the average handover rate is reduced from 0.57 handovers/minute with NS handover to 0.38 handovers/minute with MOC handover. However, the average propagation time is increased from 2.01ms with NS handover to $2.36-2.37$ms with MOC handover. These results are expected since MOC handover attempts to increase the persistent capacity by choosing serving satellites that are earlier into their visible trajectories, which reduces the handover rate since the serving time is longer and increases the propagation time since the user-satellite distance is longer.

The accuracy of the semi-stochastic model is demonstrated by simulating all of the satellite orbits in the mega-constellation for 100 consecutive handovers, averaging the instantaneous capacities to compute the true persistent capacity. The true persistent capacity closely matches the persistent capacity of the tractable semi-stochastic model, motivating its use for simplified performance analyses.

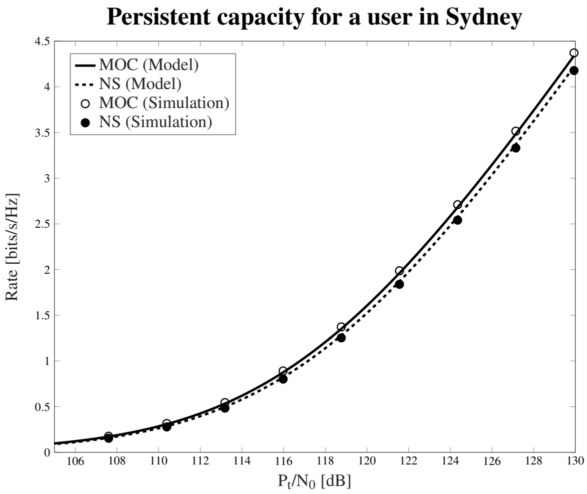

Figure 1. Persistent satellite capacity with respect to a user in Sydney $(\theta_{\mathrm{u}} = 151.2°, \phi_{\mathrm{u}} = 123.87°)$ with min. elevation angle $\psi_{\min} = 30°$. The persistent capacity of the channel model is computed using Monte Carlo integration of Eq. (4) with 10^3 samples from the NBPP. The persistent capacity of the LEO orbits is computed for 100 consecutive handovers. Both cases use a time interval of $\Delta t = 1$ second and Rician fading with unit power and Rician factor $K = 10$.

Parameters	
Satellite speed, v_{sat}	7.8 km/s
Altitude, h	550 km
Orbital inclination, b	53°
Orbital spacing, s_{orb}	2.5°
Num. of satellites per orbit, N_{orb}	22
Num. of orbital planes, N_{planes}	72
Num. of satellites, N_{sat}	3168

Table 1. Mega-constellation parameters based on the first and fourth shells of the Starlink mega-constellation [6].

References

[1] N. Okati and T. Riihonen, "Nonhomogeneous stochastic geometry analysis of massive LEO communica-

tion constellations," *IEEE Transactions on Communications*, vol. 70, no. 3, pp. 1848–1860, 2022.

[2] B. McBain, Y. Hong, and E. Viterbo, "Coherent capacity of satellite mega-constellations with persistence," *accepted at ICC'25, Montreal*, June, 2025.

[3] A. M. Voicu, A. Bhattacharya, and M. Petrova, "Handover strategies for emerging LEO, MEO, and HEO satellite networks," *IEEE Access*, vol. 12, pp. 31 523–31 537, 2024.

[4] N. Okati and T. Riihonen, "Coverage and rate analysis of mega-constellations under generalized serving satellite selection," in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2022, pp. 2214–2219.

[5] N. Okati, T. Riihonen, D. Korpi, I. Angervuori, and R. Wichman, "Downlink coverage and rate analysis of low Earth orbit satellite constellations using stochastic geometry," *IEEE Transactions on Communications*, vol. 68, no. 8, pp. 5120–5134, 2020.

[6] G. M. Capez, M. A. Cáceres, R. Armellin, C. P. Bridges, S. Frey, R. Garello, and P. Bargellini, "Characterization of mega-constellation links for LEO missions with applications to EO and ISS use cases," *IEEE Access*, vol. 11, pp. 25 616–25 628, 2023.