

Article

Jamming Analysis between Non-Cooperative Mega-Constellations Based on Satellite Network Capacity

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Abstract: Due to the openness of inter-satellite links (ISLs) in mega-constellations, the threat posed by jamming from non-cooperative constellations is becoming increasingly significant. Most of the existing approaches focus on the up/down link capacity between satellites and ground stations, which differs greatly from the situation whereby ISLs are subjected to non-cooperative jamming. Therefore, this work investigates the transmission rates of ISLs under jamming from non-cooperative mega-constellations. Based on this, a novel satellite network capacity calculation method is proposed to evaluate the mega-constellation network capacity when the transmission rates change dynamically. The simulation results show that the satellite number, jamming power and inclination of non-cooperative constellations have a significant influence on the network capacity. The optimal jamming efficiency occurs when the constellation inclinations are close.

Keywords: jamming analysis; mega-constellation; satellite network capacity; inter-satellite link; satellite communication



Citation: Zhang, Y.; Han, C.; Chu, F.; Xiong, W.; Jia, L. Jamming Analysis between Non-Cooperative Mega-Constellations Based on Satellite Network Capacity. *Electronics* **2024**, *13*, 2330. <https://doi.org/10.3390/electronics13122330>

Academic Editor: Christos J. Bouras

Received: 19 May 2024

Revised: 11 June 2024

Accepted: 13 June 2024

Published: 14 June 2024



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1. Introduction

With the rapid development of satellite communication technologies, non-geostationary-orbit (NGSO) constellations have become an essential supplement for space–air–ground integrated networks (SAGINs) [1]. However, the huge increase in the satellite number and service requirements have led to great challenges for mega-constellations [2]. Due to the openness of inter-satellite links (ISLs), ISLs are no longer absolutely secure [3–5]. Microwave ISLs can be threatened by malicious jamming from non-cooperative constellations, as shown in Figure 1. Ψ_A and Ψ_B denote the jammed and jamming constellations, respectively. The red region inside the cone is the main jamming region (MJR). In non-cooperative constellations, each ISL may be subjected to jamming. As a result, the entire constellation network is under an all-encompassing jamming threat, which will affect the overall network capacity.

The analysis of the satellite network capacity under non-cooperative jamming can improve the anti-jamming ability and quality of service (QoS) [6] in terms of capacity, latency [7] and security [8]. However, the impact of the jamming parameters and constellation configurations on the satellite network capacity is not clear at present. In mega-constellations, ISLs switch frequently, leading to dynamic changes in the link capacity. Thus, it is difficult to apply terrestrial network capacity analysis methods directly to mega-constellations [9]. Meanwhile, most of the existing approaches focus on the up/down link capacity between satellites and ground stations [10–12], which differs greatly from the situation whereby ISLs are subjected to non-cooperative jamming.

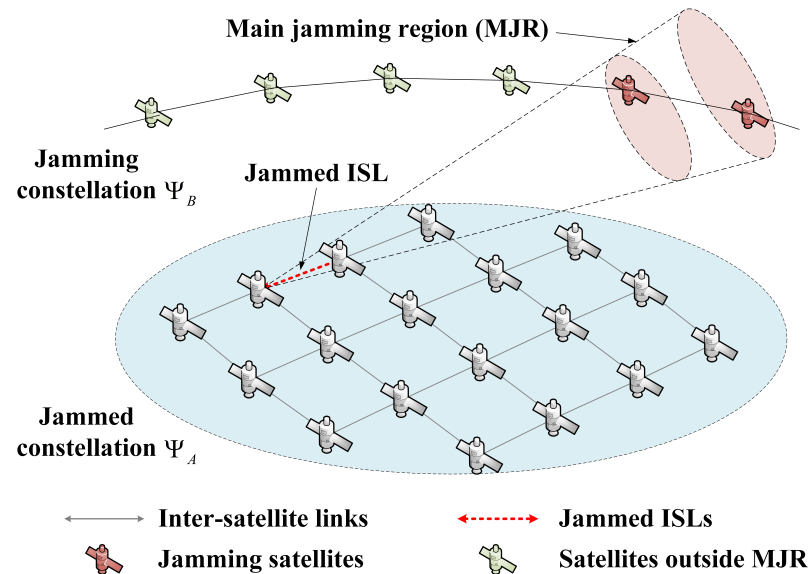


Figure 1. Scene diagram of jamming between mega-constellations Ψ_A and Ψ_B .

To address these issues, we define a typical non-cooperative jamming scenario [13,14] with two mega-constellations to analyze the impact of potential non-cooperative jamming on the satellite network capacity. Against this background, two questions remain to be answered: (1) How can we determine the impact of the jamming parameters on a single ISL's capacity? (2) How can we accurately measure the overall communication capacity of a mega-constellation network when the transmission rates of the ISLs are dynamically changing? To address the aforementioned challenges, we propose a calculation method for the satellite network capacity under non-cooperative jamming. We propose the main jamming region and propagation model to investigate the transmission rate under non-cooperative jamming. Based on this, a novel satellite network capacity calculation method is proposed to evaluate the network capacity of mega-constellations when the transmission rates change dynamically. The main determinants of the jamming effects are investigated to guide the anti-jamming design of mega-constellations. The main contributions of this paper are as follows:

- The concept of the main jamming region is defined in order to describe the jamming scene between mega-constellations;
- The transmission rates of ISLs in mega-constellations under jamming from non-cooperative constellations are calculated, and a novel satellite network capacity calculation method is proposed to evaluate the network capacity of mega-constellations when the transmission rates change dynamically;
- The simulation results show that the jamming power, constellation scale and inclination of non-cooperative jamming constellations have a significant influence on mega-constellations' network capacities.

The rest of the paper is organized as follows. In Section 2, we define the main jamming region and system model. In Section 3, we propose the satellite network capacity calculation method. In Section 4, the simulation results verify the effectiveness of our method. Section 5 concludes the paper.

2. System Model

In this section, the main jamming region is introduced. Then, we discuss the jamming scenario and propagation model. Finally, the transmission rate is calculated. Table 1 gives the summary of the mathematical notations.

Table 1. Summary of mathematical notations.

Notation	Description
Ψ_A	The jammed constellation
Ψ_B	The jamming constellation
$A(i, j)$	The j th satellite in the i th orbit
$\theta_{\max}$	The semi-cone angle of the main jamming region
G_t	The transmitting antenna peak gain
G_r	The receiving antenna peak gain
$L_{(i,j)}^{(i,j+1)}$	The ISL from satellite $A(i, j)$ to satellite $A(i, j + 1)$
$R_{i,j,t}^{\nearrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i,j+1)}$ with no jamming
$R_{i,j,t}^{\swarrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i,j-1)}$ with no jamming
$R_{i,j,t}^{\nwarrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i-1,j)}$ with no jamming
$R_{i,j,t}^{\searrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i+1,j)}$ with no jamming
$d_{i,j,t}$	The distance between $A(i, j)$ and $A(i, j + 1)$ at time slot t
$\tilde{R}_{i,j,t}^{\nearrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i,j+1)}$ under jamming
$\tilde{R}_{i,j,t}^{\swarrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i,j-1)}$ under jamming
$\tilde{R}_{i,j,t}^{\nwarrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i-1,j)}$ under jamming
$\tilde{R}_{i,j,t}^{\searrow}$	The maximum transmission rate of ISL $L_{(i,j)}^{(i+1,j)}$ under jamming
$R_{(i,j)}^{(i,j+1)}$	The maximum transmission rate of intra-plane ISL $L_{(i,j)}^{(i,j+1)}$
$R_{(i,j)}^{(i,j-1)}$	The maximum transmission rate of intra-plane ISL $L_{(i,j)}^{(i,j-1)}$
$R_{(i,j)}^{(i+1,j)}$	The maximum transmission rate of inter-plane ISL $L_{(i,j)}^{(i+1,j)}$
$R_{(i,j)}^{(i-1,j)}$	The maximum transmission rate of inter-plane ISL $L_{(i,j)}^{(i-1,j)}$
R_o	The transmission rate of intra-plane ISLs
R_h	The transmission rate of inter-plane ISLs
C_A	The network capacity of Ψ_A
H	The total hop count of Ψ_A

2.1. Main Jamming Region

The jamming effect between non-cooperative constellations is affected by the angle θ between the jamming and jammed satellites. θ is the angle between the jammed satellite's pointing antenna and the jamming satellite–jammed satellite connection line. For an arbitrary ISL, the jamming effect will decrease as θ increases. Therefore, we mainly consider the jamming effect within a certain pinch range (e.g., $\theta_{\max}$), i.e., the main jamming region (MJR). The MJR is the cone formed with $\theta_{\max}$ as the half-cone angle. The MJR in a geocentric rectangular coordinate system is shown in Figure 2. For jammed ISLs, the MJR is the region where the jamming satellites can effectively interfere with the target ISLs.

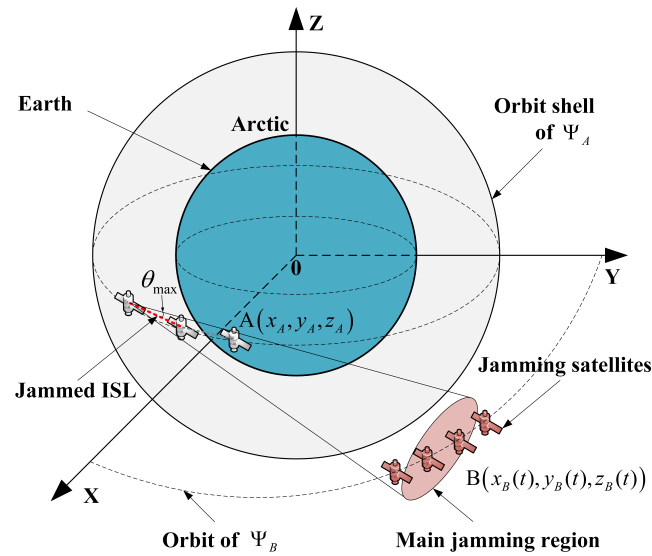


Figure 2. Schematic diagram of main jamming region in geocentric rectangular coordinate system.

In mega-constellations, $A(i, j)$ denotes the j th satellite in the i th orbit. The MJR is constructed as follows: take $A(i, j)$ in the jammed constellation Ψ_A as the vertex, take the jammed ISL $L_{(i,j)}^{(i,j+1)}$ as the central vertical line and form a cone with $\theta_{\max}$ as the semi-cone angle. The region where the cone intersects the orbits of jamming constellation Ψ_B is defined as the MJR. The satellites in the MJR are the corresponding jamming satellites of $L_{(i,j)}^{(i,j+1)}$. According to the above definition, we can construct the MJR for each ISL in Ψ_A . For ISLs in the same orbit, if $\theta_{\max}$ is small enough, the MJRs of each ISL will not overlap. Taking a single ISL as an example, we analyze the influence of the jamming parameters on the transmission rate.

2.2. Jamming Scenario

Assume that both the jammed constellation Ψ_A and non-cooperative jamming constellation Ψ_B are Walker constellations. Since the jamming effect is closely related to the relative positions of the satellites, we first define the satellite coordinates of Ψ_A and Ψ_B in the Cartesian coordinate system.

Let the radius of Earth be R_e . The Walker constellation determines the positions of satellites by seven parameters, i.e., $Z/N/F/h/\mu/\Omega_0/\varphi_0$, where Z denotes the satellite number in the constellation, N denotes the satellite orbit number, F is the phase factor, h is the orbital altitude, μ denotes the orbital inclination, Ω_0 is the initial right ascension of the ascending node (RAAN) and φ_0 is the initial true anomaly. On this basis, we define the spatial dynamic coordinates of all satellites as well as Earth stations.

Assume that the parameters of the jammed constellation Ψ_A are $Z_A/N_A/F_A/h_A/\mu_A/\Omega_{A0}/\varphi_{A0}$. The coordinates of the j th satellite in the i th orbit of Ψ_A can be expressed as

$$A(i, j, t) = (x_A(i, j, t), y_A(i, j, t), z_A(i, j, t)) \quad (1)$$

$$\begin{cases} x_A(i, j, t) = (R_e + h_A)(\cos \Omega_A \cos(\varphi_A + \omega_A t) - \sin \Omega_A \sin(\varphi_A + \omega_A t) \cos \mu_A) \\ y_A(i, j, t) = (R_e + h_A)(\sin \Omega_A \cos(\varphi_A + \omega_A t) + \cos \Omega_A \sin(\varphi_A + \omega_A t) \cos \mu_A) \\ z_A(i, j, t) = (R_e + h_A) \sin(\varphi_A + \omega_A t) \sin \mu_A \end{cases} \quad (2)$$

where $\omega_A = \sqrt{\frac{GM}{(R_e + h_A)^3}}$, G denotes the gravitational constant, M denotes the mass of the Earth and $\Omega_A = \Omega_{A0} + i \times (2\pi/N_A)$, $\varphi_A = \varphi_{A0} + 2\pi(i \times \frac{F_A}{Z_A} + j \times \frac{N_A}{Z_A})$.

Assume that the parameters of Ψ_B are $Z_B/N_B/F_B/h_B/\mu_B/\Omega_{B0}/\varphi_{B0}$; the satellite coordinates in Ψ_B are similar to those of Ψ_A .

2.3. Propagation Model

The free space propagation model is utilized to calculate the channel gain between satellites. Assume that the distance between the jamming satellite and jammed satellite is d , and the free space attenuation of the signal is

$$L_d = \left(\frac{\lambda}{4\pi d} \right)^2 \quad (3)$$

According to ITU-R S.1528 [15], when the satellite antenna's off-axis angle is φ , the receiving antenna peak gain $G_r(\varphi)$ is

$$G_r(\varphi) = \begin{cases} G_r^{\max}, & \text{if } \varphi \leq \varphi_b \\ G_r^{\max} - 3\left(\frac{\varphi}{\varphi_b}\right)^2, & \text{if } \varphi_b < \varphi \leq Y \\ G_r^{\max} + L_s - 25 \log\left(\frac{\varphi}{Y}\right), & \text{if } Y < \varphi \leq X \\ L_F, & \text{otherwise.} \end{cases} \quad (4)$$

where $G_r^{\max}$ is the maximum receiving antenna peak gain. $X = Y(10)^{0.04(G_r^{\max} + L_s - L_F)}$, $L_F = 0$. For LEO satellites, $L_s = -6.75$, $Y = 1.5\theta_b$. According to the reciprocity theorem, the transmitting antenna peak gain $G_t(\varphi)$ equals $G_r(\varphi)$.

2.4. Transmission Rate Calculation

Denote the transmission rate of ISL $L_{(i,j)}^{(i,j+1)}$ from satellite $A(i, j)$ to satellite $A(i, j+1)$ in Ψ_A at time slot t as $R_{i,j,t}^{\nearrow}$. When $L_{(i,j)}^{(i,j+1)}$ is not jammed, $R_{i,j,t}^{\nearrow}$ is calculated as follows:

$$R_{i,j,t}^{\nearrow} = \log_2 \left(1 + \frac{p_A G_t^{\max} G_r^{\max} \left(\frac{\lambda}{4\pi d_{i,j,t}^{\nearrow}} \right)^2}{KTW} \right) \quad (5)$$

where $d_{i,j,t}^{\nearrow} = \|A(i, j, t) - A(i, j+1, t)\|$.

Satellites in the MJR corresponding to $L_{(i,j)}^{(i,j+1)}$ satisfy the following conditions:

$$\begin{cases} B(t) = (x_B(t), y_B(t), z_B(t)) \\ \langle A(i, j, t) - A(i, j+1, t), B(t) - A(i, j+1, t) \rangle < \theta \end{cases} \quad (6)$$

Assume that, at time slot t , the number of satellites satisfies Equation (6) is $J(t)$. Denote the above satellite coordinates as $B_j(t), j = 1, 2, \dots, J(t)$. Thus, we obtain the data transmission rate $\tilde{R}_{i,j,t}^{\nearrow}$ of $L_{(i,j)}^{(i,j+1)}$ under non-cooperative jamming.

$$\tilde{R}_{i,j,t}^{\nearrow} = \log_2 \left(1 + \frac{p_A G_t^{\max} G_r^{\max} \left(\frac{\lambda}{4\pi d_{i,j,t}^{\nearrow}} \right)^2}{\sum_{k=1}^{J(t)} p_B G_r^{\max} G_t \left(\theta_{i,j,t}^{\nearrow}(k) \right) \left(\frac{\lambda}{4\pi D_{i,j,t}^{\nearrow}(k)} \right)^2 + KTW} \right) \quad (7)$$

where

$$\begin{aligned} D_{i,j,t}^{\nearrow}(k) &= \|B_k(t) - A(i, j+1, t)\| \\ \theta_{i,j,t}^{\nearrow}(k) &= \langle A(i, j, t) - A(i, j+1, t), B_k(t) - A(i, j+1, t) \rangle \end{aligned} \quad (8)$$

Similarly, we can calculate the transmission rate $R_{i,j,t}^{\swarrow}, R_{i,j,t}^{\nwarrow}, R_{i,j,t}^{\searrow}$ of $L_{(i,j)}^{(i,j-1)}, L_{(i,j)}^{(i-1,j)}$ and $L_{(i,j)}^{(i+1,j)}$ under jamming-free conditions, as well as the transmission rate $\tilde{R}_{i,j,t}^{\swarrow}, \tilde{R}_{i,j,t}^{\nwarrow}, \tilde{R}_{i,j,t}^{\searrow}$ after jamming.

In summary, for satellite $A(i, j)$ in Ψ_A , the inter-satellite link rates of $A(i, j)$ are $(R_{i,j,t}^{\swarrow}, R_{i,j,t}^{\nwarrow}, R_{i,j,t}^{\searrow}, R_{i,j,t}^{\swarrow})$ and $(\tilde{R}_{i,j,t}^{\swarrow}, \tilde{R}_{i,j,t}^{\nwarrow}, \tilde{R}_{i,j,t}^{\searrow}, \tilde{R}_{i,j,t}^{\swarrow})$ under jamming-free and non-cooperative jamming conditions, respectively.

3. Satellite Network Capacity Calculation Method

Assume that the number of orbits and the number of satellites in each orbit in Ψ_A are N and M , respectively. The ISLs are connected in the “+Grid” mode, as shown in Figure 3. In Ψ_A , the link rates of $A(i, j)$ are $(R_{i,j,t}^{\swarrow}, R_{i,j,t}^{\nwarrow}, R_{i,j,t}^{\searrow}, R_{i,j,t}^{\swarrow})$, respectively. $A(i, j)$ sends data equally to all other satellites, i.e., the traffic rates sent by $A(i, j)$ along the four directions are $\frac{R_{i,j,t}^{\swarrow}}{NM-1}, \frac{R_{i,j,t}^{\nwarrow}}{NM-1}, \frac{R_{i,j,t}^{\searrow}}{NM-1}, \frac{R_{i,j,t}^{\swarrow}}{NM-1}$, which can be denoted as $\tilde{R}_{i,j,t}^{\swarrow}, \tilde{R}_{i,j,t}^{\nwarrow}, \tilde{R}_{i,j,t}^{\searrow}, \tilde{R}_{i,j,t}^{\swarrow}$, respectively. The network capacity C_A of Ψ_A equals the total transmission rate R divided by the average hop count $E(H)$.

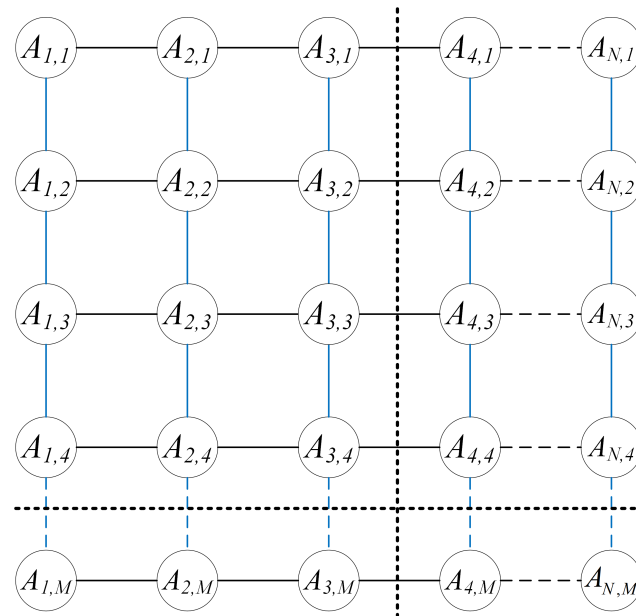


Figure 3. +Grid topology of mega-constellation network.

3.1. Transmission Rate

In the inclined-orbit constellation Ψ_A , the intra-plane ISLs and inter-plane ISLs have similarities; therefore, we only give the proof of the intra-plane ISLs' transmission rate here.

When M is odd, for any intra-plane ISL $L_{(i,j)}^{(i,j+1)}, L_{(i,j)}^{(i,j-1)}$ will be passed through when $A(i, j)$ sends data to $A(i, (j+1) \bmod M), A(i, (j+2) \bmod M), \dots, A(i, (j + \frac{M-1}{2}) \bmod M)$. Therefore, $L_{(i,j)}^{(i,j+1)}$ is used $\frac{M-1}{2}$ times. The maximum transmission rate of $A(i, j)$ is $\tilde{R}_{i,j,t}^{\swarrow}$. Meanwhile, $L_{(i,j)}^{(i,j+1)}$ will also be passed through when $A(i, (j-1) \bmod M)$ sends data to $A(i, (j+1) \bmod M), A(i, (j+2) \bmod M), \dots, A(i, (j + \frac{M-1}{2} - 1) \bmod M)$. $L_{(i,j)}^{(i,j+1)}$ is passed through $\frac{M-1}{2} - 1$ times. The maximum transmission rate under the jamming condition from $A(i, j-1)$ to $A(i, j)$ is $\tilde{R}_{i,(j-1) \bmod M,t}^{\swarrow}$. By analogy, $L_{(i,j)}^{(i,j+1)}$ will still be passed through until $A(i, (j - (\frac{M-1}{2} - 1)) \bmod M)$ sends data to $A(i, (j+1) \bmod M)$. Under this

condition, $L_{(i,j)}^{(i,j+1)}$ is used once. The maximum transmission rate is $\tilde{R}_{i,(j-\frac{M-1}{2}) \bmod M,t}^{\nearrow}$. Therefore, the actual maximum transmission rate of $L_{(i,j)}^{(i,j+1)}$ is

$$\begin{aligned} R_{(i,j)}^{(i,j+1)} &= \sum_{k=0}^{(M-1)/2-1} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow} \\ &= \sum_{k=0}^{(M-1)/2} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow} \end{aligned} \quad (9)$$

When M is even, $L_{(i,j)}^{(i,j+1)}$ will be passed through when $A(i,j)$ sends data to $A(i, (j+1) \bmod M)$, $A(i, (j+2) \bmod M)$, ..., $A(i, (j + \frac{M-2}{2}) \bmod M)$. $L_{(i,j)}^{(i,j+1)}$ is utilized $\frac{M-2}{2}$ times. When $A(i,j)$ sends data to $A(i, (j + \frac{M}{2}) \bmod M)$, both forward and reverse ISLs can be used; therefore, $L_{(i,j)}^{(i,j+1)}$ is passed through $\frac{1}{2}$ times. The maximum transmission rate is $\tilde{R}_{i,j,t}^{\nearrow}$. When $A(i, (j-1) \bmod M)$ sends data to $A(i, (j+1) \bmod M)$, $A(i, (j+2) \bmod M)$, ..., $A(i, (j + \frac{M}{2} - 1) \bmod M)$, $L_{(i,j)}^{(i,j+1)}$ will be passed through $\frac{M-1}{2} - 1$ times. The maximum transmission rate is $\tilde{R}_{i,(j-1) \bmod M,t}^{\nearrow}$. By analogy, $L_{(i,j)}^{(i,j+1)}$ will still be passed through until $A(i, (j - \frac{M}{2}) \bmod M)$ sends data to $A(i, (j+1) \bmod M)$. Under this condition, $L_{(i,j)}^{(i,j+1)}$ is used $\frac{M}{2} - \left(\frac{M}{2} - 1 \right) - \frac{1}{2} = \frac{1}{2}$ times. The maximum transmission rate is $\tilde{R}_{i,(j-\frac{M-2}{2}) \bmod M,t}^{\nearrow}$. Therefore, the actual maximum transmission rate of $L_{(i,j)}^{(i,j+1)}$ is

$$\begin{aligned} R_{(i,j)}^{(i,j+1)} &= \sum_{k=0}^{(M-2)/2} \left(\frac{M-2}{2} + \frac{1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow} \\ &= \sum_{k=0}^{(M-2)/2} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow} \end{aligned} \quad (10)$$

In summary, the maximum transmission rate of intra-plane ISL $L_{(i,j)}^{(i,j+1)}$ is

$$R_{(i,j)}^{(i,j+1)} = \begin{cases} \sum_{k=0}^{\frac{M-2}{2}} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow}, & M = 2n \\ \sum_{k=0}^{\frac{M-1}{2}} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow}, & \text{otherwise} \end{cases} \quad (11)$$

Similarly, the maximum transmission rates of intra-plane ISL $L_{(i,j)}^{(i,j-1)}$, inter-plane ISL $L_{(i,j)}^{(i+1,j)}$ and $L_{(i,j)}^{(i-1,j)}$ are $R_{(i,j)}^{(i,j-1)}$, $R_{(i,j)}^{(i+1,j)}$ and $R_{(i,j)}^{(i-1,j)}$, respectively.

$$R_{(i,j)}^{(i,j-1)} = \begin{cases} \sum_{k=0}^{\frac{M-2}{2}} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j+k) \bmod M,t}^{\swarrow}, & M = 2n \\ \sum_{k=0}^{\frac{M-1}{2}} \left(\frac{M-1}{2} - k \right) \tilde{R}_{i,(j+k) \bmod M,t}^{\swarrow}, & \text{otherwise} \end{cases} \quad (12)$$

$$R_{(i,j)}^{(i+1,j)} = \begin{cases} \sum_{k=0}^{\frac{N-2}{2}} \left(\frac{N-1}{2} - k \right) \tilde{R}_{(i-k) \bmod N,j,t}^{\searrow}, & N = 2n \\ \sum_{k=0}^{\frac{N-1}{2}} \left(\frac{N-1}{2} - k \right) \tilde{R}_{(i-k) \bmod N,j,t}^{\searrow}, & \text{otherwise} \end{cases} \quad (13)$$

$$R_{(i,j)}^{(i-1,j)} = \begin{cases} \sum_{k=0}^{\frac{N-2}{2}} (\frac{N-1}{2} - k) \tilde{R}_{(i+k) \bmod N, j, t}^{\searrow}, N = 2n \\ \sum_{k=0}^{\frac{N-1}{2}} (\frac{N-1}{2} - k) \tilde{R}_{(i+k) \bmod N, j, t}^{\searrow}, otherwise \end{cases} \quad (14)$$

Therefore, the transmission rates of intra-plane ISLs R_o and inter-plane ISLs R_h are, respectively,

$$R_o = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (R_{(i,j)}^{(i,j+1)} + R_{(i,j)}^{(i,j-1)}) \quad (15)$$

$$R_h = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (R_{(i,j)}^{(i+1,j)} + R_{(i,j)}^{(i-1,j)}) \quad (16)$$

The total transmission rate R of Ψ_A is

$$R = R_o + R_h = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (R_{(i,j)}^{(i,j+1)} + R_{(i,j)}^{(i,j-1)}) + \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (R_{(i,j)}^{(i+1,j)} + R_{(i,j)}^{(i-1,j)}) \quad (17)$$

3.2. Average Hop Count

The topology of an inclined orbit constellation has symmetry. Take the center node as the source node (e.g., $(\frac{N}{2}, \frac{M}{2})$ if N and M are even). Either of the other nodes is equivalent to $(\frac{N}{2}, \frac{M}{2})$ because either node can be rotated to the center by rotation. Take the example that both N and M are even. When $(\frac{N}{2}, \frac{M}{2})$ sends data to other nodes, the total hop count is

$$\sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \quad (18)$$

The topology of Ψ_A can be divided into four regions, i.e., the lower left, lower right, upper left and upper right, as shown in Figure 3. The hop counts for each region are H_{ll} , H_{lr} , H_{ul} and H_{ur} , respectively.

$$\begin{cases} H_{ll} = \sum_{i=0}^{N/2} \sum_{j=0}^{M/2} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \\ H_{lr} = \sum_{i=N/2}^{N-1} \sum_{j=0}^{M/2} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \\ H_{ul} = \sum_{i=0}^{N/2} \sum_{j=M/2}^{M-1} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \\ H_{ur} = \sum_{i=N/2}^{N-1} \sum_{j=M/2}^{M-1} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \end{cases} \quad (19)$$

Therefore, the total hop count H is

$$\begin{aligned} H &= H_{ll} + H_{lr} + H_{ul} + H_{ur} \\ &= \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \left(\left| i - \frac{N}{2} \right| + \left| j - \frac{M}{2} \right| \right) \\ &= \sum_{i=0}^{N-1} \left| i - \frac{N}{2} \right| + \sum_{j=0}^{M-1} \left| j - \frac{M}{2} \right| \\ &= \frac{NM^2 + N^2M}{4} \end{aligned} \quad (20)$$

Thus, the average hop count $E(H)$ of each ISL is

$$E(H) = \frac{NM^2 + N^2M}{4(NM - 1)} \quad (21)$$

The above is the case when both N and M are even. Other cases are similar. Thus, the average hop count of each ISL is, respectively,

$$E(H) = \begin{cases} \frac{NM^2 + N^2M}{4(NM - 1)}, N = 2n, M = 2n \\ \frac{N(M^2 - 1) + N^2M}{4(NM - 1)}, N = 2n, M = 2n + 1 \\ \frac{NM^2 + (N^2 - 1)M}{4(NM - 1)}, N = 2n + 1, M = 2n \\ \frac{N(M^2 - 1) + (N^2 - 1)M}{4(NM - 1)}, N = 2n + 1, M = 2n + 1 \end{cases} \quad (22)$$

Therefore, we obtain the network capacity C_A of Ψ_A by dividing the transmission rate R by the average hop count $E(H)$.

$$C_A = \frac{R}{E(H)} \quad (23)$$

Thus, when the link rates in Ψ_A change dynamically, the network capacity C_A is defined as follows:

$$C_A = \begin{cases} \frac{4}{N+M} (R_o + R_h), N = 2n + 1, M = 2n + 1 \\ \frac{4(NM - 1)}{NM^2 + N^2M} (R_o + R_h), N = 2n, M = 2n \\ \frac{4(NM - 1)}{NM^2 + (N^2 - 1)M} (R_o + R_h), N = 2n + 1, M = 2n \\ \frac{4(NM - 1)}{N(M^2 - 1) + N^2M} (R_o + R_h), N = 2n, M = 2n + 1 \end{cases} \quad (24)$$

where R_o and R_h denote the sums of the actual transmission rates of intra-plane and inter-plane ISLs, respectively.

$$R_o = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \sum_{k=0}^{\frac{M-1}{2}} \left(\frac{M-1}{2} - k \right) (P + Q) \quad (25)$$

$$R_h = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \sum_{k=0}^{\frac{N-1}{2}} \left(\frac{N-1}{2} - k \right) (U + V) \quad (26)$$

where $P = \tilde{R}_{i,(j-k) \bmod M,t}^{\nearrow}$, $Q = \tilde{R}_{i,(j+k) \bmod M,t}^{\nwarrow}$, $U = \tilde{R}_{(i-k) \bmod N,j,t}^{\searrow}$, $V = \tilde{R}_{(i+k) \bmod N,j,t}^{\swarrow}$.

In summary, network capacity C_A is a function of the satellite transmission rate. Denote the network capacity function as Γ ; then, $C_A = \Gamma(R_{i,j,t}^{\nearrow}, R_{i,j,t}^{\nwarrow}, R_{i,j,t}^{\searrow}, R_{i,j,t}^{\swarrow})$. Therefore, the network capacities under jamming-free conditions and non-cooperative jamming conditions are $C_A = \Gamma(R_{i,j,t}^{\nearrow}, R_{i,j,t}^{\nwarrow}, R_{i,j,t}^{\searrow}, R_{i,j,t}^{\swarrow})$ and $\tilde{C}_A = \Gamma(\tilde{R}_{i,j,t}^{\nearrow}, \tilde{R}_{i,j,t}^{\nwarrow}, \tilde{R}_{i,j,t}^{\searrow}, \tilde{R}_{i,j,t}^{\swarrow})$, respectively. $|C_A - \tilde{C}_A|$ portrays the effect of non-cooperative jamming on the network capacity of Ψ_A . Based on the network capacity obtained from the calculation method, we analyze the trend of the jamming effects of various jamming parameters of Ψ_B .

4. Simulation Results

In the simulation, we consider a fundamental scenario with two mega-constellations: Ψ_A and Ψ_B . The altitude of Ψ_A is 500 km, which is jammed by Ψ_B at an altitude of 1000 km. The simulation ranges from 1 January 2024 04:00:00 to 10 January 2024 04:00:00. The simulation results are averaged over this period. The antenna models of Ψ_A and Ψ_B are both ITU-R S.1528. The parameter settings in the simulation are shown in Table 2.

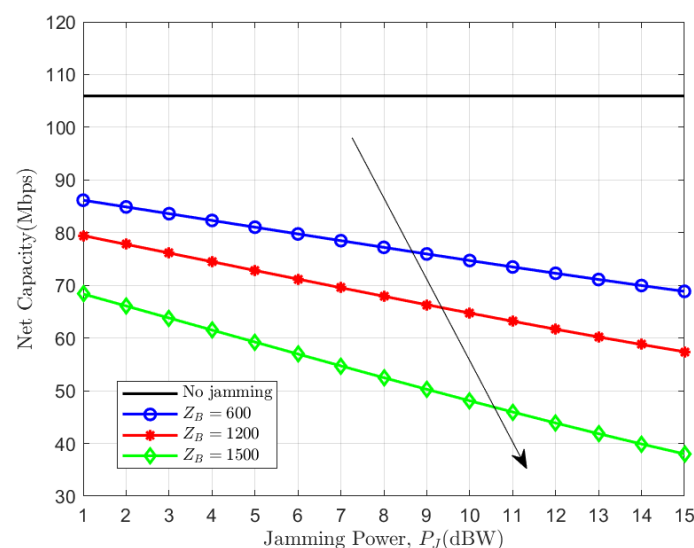
Table 2. Simulation parameters [16–18].

Parameters	Ψ_A	Ψ_B
Orbit prediction model	Two body	Two body
Altitude h /km	500	1000
Inclination $\mu/(^{\circ})$	60	70
Number of orbits N	30	30
Satellites per orbit M	40	20
Phase factor F	1	1
Satellite antenna model	ITU-R S.1528	ITU-R S.1528
Transmitting power/dBW	7	7
Communication frequency/GHz	27.075	27.075
Communication bandwidth/MHz	50	50
Transmitting antenna peak gain/dBi	39.9	39.9
Receiving antenna peak gain/dBi	37	37
Transmitting antenna HPBW/ $(^{\circ})$	5	3.5
Receiving antenna HPBW/ $(^{\circ})$	5	3.5
Temperature of terminal/K	200	200

We analyze the impact of the jamming power P_J and constellation scale Z_B of Ψ_B on the network capacity of Ψ_A , as shown in Figure 4. An increase in both the jamming power and constellation scale can lead to an increased jamming intensity, which will finally decrease the overall network capacity.

The constellation configurations of Ψ_B also have a significant impact on the jamming effects. We analyze the network capacity of Ψ_A when the inclination μ_B of Ψ_B changes within $[50^{\circ}, 68^{\circ}]$, as shown in Figure 5. In our simulation, $\mu_A = 60^{\circ}$. The network capacity of Ψ_A is minimized when μ_A and μ_B are close. The probability of satellites in Ψ_B appearing in the MJR of Ψ_A will increase due to the proximity of μ_A and μ_B , leading to an increased jamming intensity.

Besides the inclination, we also analyze the impact of the altitude on the network capacity C_A , as shown in Figure 6. It can be seen that there is no clear trend in C_A when h_B varies. As h_B varies, so does the jamming angle. Both of the above factors have an effect on the jamming intensity. We also investigate the influence of the phase factor on C_A . Compared to μ_B and P_J , the effect of the phase factor is negligible, as shown in Figure 7.

**Figure 4.** Network capacity of Ψ_A under different P_J and Z_B .

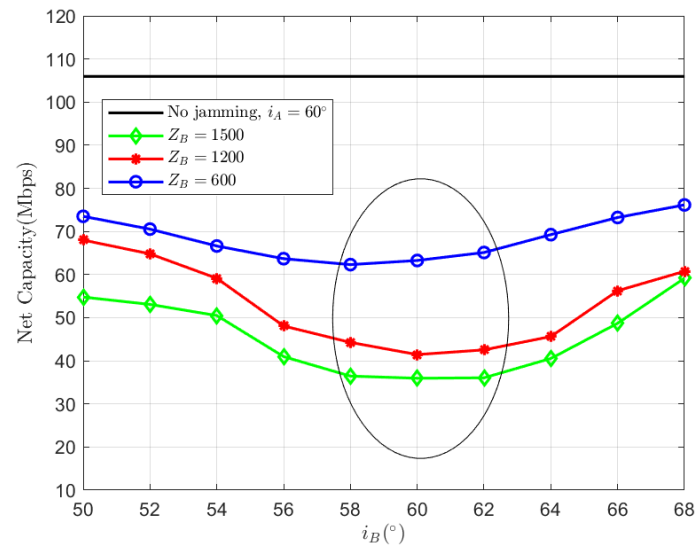


Figure 5. Network capacity of Ψ_A under various μ_B .

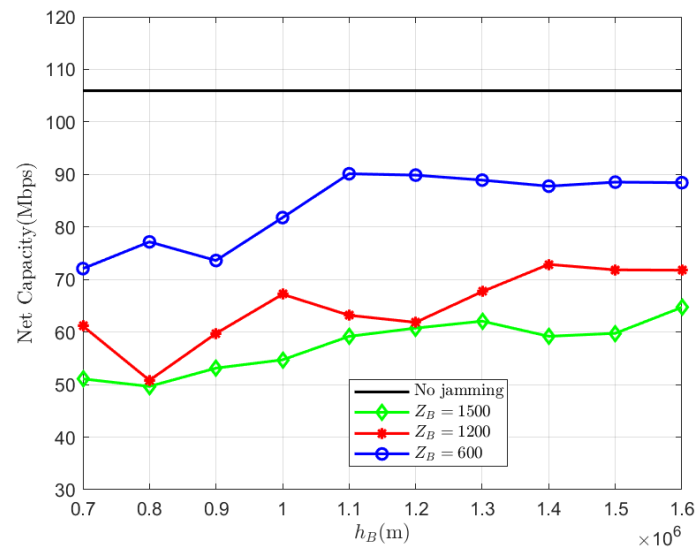


Figure 6. Network capacity of Ψ_A under various h_B .

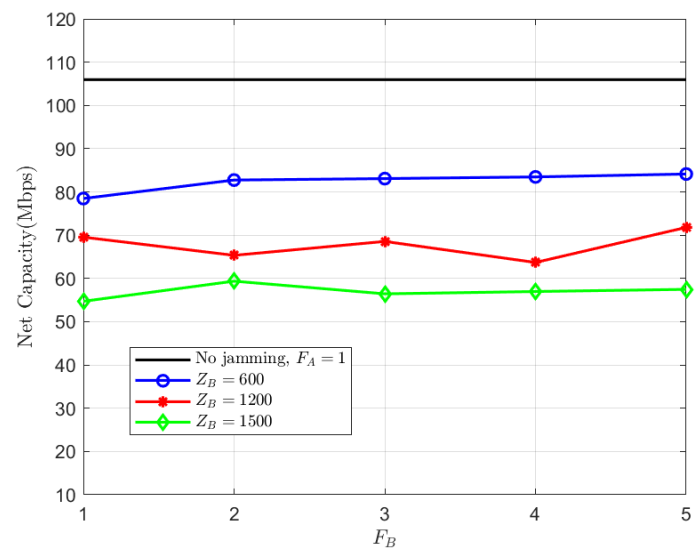


Figure 7. Network capacity of Ψ_A under various F_B .

5. Conclusions

In this work, we investigate the transmission rates of ISLs in mega-constellations under jamming from non-cooperative constellations and propose a novel satellite network capacity calculation method to evaluate the network capacity of mega-constellations when the transmission rates change dynamically. The experimental results illustrate that the jamming power, constellation scale and inclination of non-cooperative jamming constellations have a significant influence on mega-constellations' network capacities. The optimal jamming efficiency occurs when the constellation inclinations are close. It should be noted that the proposed method is also applicable to free space optical (FSO) communication. The difference is that the beamwidth of FSO is relatively narrow; thus, the MJR needs to be set at a smaller $\theta_{\max}$.

Author Contributions: Data curation, W.X.; Formal analysis, Y.Z.; Investigation, F.C.; Methodology, Y.Z.; Software, C.H.; Writing—original draft, Y.Z.; Writing—review and editing, W.X. and L.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China under Grant 61901523.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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