Interference Analysis Method Based on Link-Building Pattern in the Moving Non-geostationary Satellites

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Abstract. The frequency interference is becoming a serious problem because of the coexistence scenarios of Non-Geostationary orbit constellation systems. By studies the relative position of Non-Geostationary orbit satellites and ground stations, one interference analysis method was proposed to calculate the moving large amount satellites. This method classified the link-building status by logical operation between the interfering link and interfered link, constructed the link-building pattern, and optimized the calculation progress, thereby, improved the simulating efficiency. Considering the case of two single satellites like the flying DAMPE and HXMT satellites and two different constellation systems like the ITU-registered Oneweb and Telesat systems, a simulation scenario was established. The experiment results showed that this proposed method can improve the simulation efficiency higher than the full link simulation. That can be an adaptive technology for the interference calculation analysis of the Non-Geostationary orbit systems no more than 2000 satellites.

1. Introduction

With the rapid development of spatial information network technology in recent years, a variety of constellation systems consisting of Non-Geostationary Orbit (NGSO) satellites emerge in a bursting situation, such as Space X’s StarLink constellation system, OneWeb’s L5 constellation system [1], etc. Thereby, the spectrum scarcity is a crucial problem. In order to solve this spectral coexistence problem, traditionally, the satellite system was controlled at the system design stage through static constraints such as frequency isolation, time isolation, spatial isolation, and power limit.

However, due to the huge amount and large coverage of the NGSO constellation systems, the orbit construction and motion mode are complex, and the frequency overlap and interference phenomena are prominent. The existing frequency co-existence calculation analysis methods and support tools are mostly based on static scenarios. So, it is difficult to meet the requirements of frequency compatibility analysis when the amount is more than 1000 satellites dynamical working simultaneously [2, 3]. Therefore, it is necessary to explore the adaptive interference calculation and analysis method between moving NGSO satellite systems.

This paper focused on the studies of interference analysis method based on link-building pattern, and took single case like the flying Dark Matter Particle Detection Scientific Satellite (DAMPE) and Hard X-ray Modulation Telescope Satellite (HXMT) satellites and two different constellation systems case like the ITU-registered Oneweb and Telesat as the experiments to verify the performance of the proposed method.
2. Communication Calculation Model

Due to the orbital and motion characteristics of the NGSO satellite systems, the positional relationships between the satellites and earth stations are time-varying. The theoretical coverage time depends on the relative position information and running speed between the running satellite and the earth station [4], which can be regarded as the time-varying motion of a plurality of different space objects in their respective coordinate systems.

Assuming that the earth station had been calibrated in the true north direction, the azimuth starting point of the antenna coincides with the X’ axis of the Station Centric Coordinate System (SCCS), pointing to the east direction, and the starting point of the elevation angle coinciding with the X'O'Y' plane, the positive direction pointing to the north. According to the ITU-R SA, 609-2 recommendation [5], the condition for the normal establishment of the communication link is that the satellite and the earth station are visible and the margin is above 3 dB.

The scenario was shown in figure 1. When the communication link was initially established, assume the satellite located at point A, then flight to point B when the communication link disconnected. According to the orbit data, the coordinate data can be got in ECI and SCCS systems.

![Figure 1. Communication link between satellites and ground station.](image)

By setting the angular velocity of the satellite relative to the earth station is \( \omega \), the time interval \( \Delta t \) from point A to point B can be calculated. This time was the actual contact time of the link under normal communication conditions, as shown in equation (1):

\[
\Delta t = \frac{1}{\omega} \left( \begin{bmatrix} x_B' \\ y_B' \\ z_B' \end{bmatrix} - \begin{bmatrix} x_A' \\ y_A' \\ z_A' \end{bmatrix} \right)
\]

(1)

For point A and B, their coordinates in ECI were \( S_A(x_A, y_A, z_A) \) and \( S_B(x_B, y_B, z_B) \), also in SCCS, \( S'_A(x'_A, y'_A, z'_A) \) and \( S'_B(x'_B, y'_B, z'_B) \). If the communication distances between satellites to ground station are \( d_A \) and \( d_B \) at this two fixed time, the azimuth angle \( \theta_A \) and \( \theta_B \), also the elevation angle \( \gamma_A \) and \( \gamma_B \), can be calculated as equations (2) and (3).

\[
\begin{align*}
\theta_A &= \arctan \frac{x_A'}{y_A'}, \quad -90° \leq \theta_A \leq 90° \\
\gamma_A &= \arcsin \frac{z_A'}{d_A}, \quad 0° \leq \gamma_A \leq 90° \\
\gamma_B &= \arcsin \frac{z_B'}{d_B}, \quad 0° \leq \gamma_B \leq 90° \\
\theta_B &= \arctan \frac{y_B'}{x_B'}, \quad -90° \leq \theta_B \leq 90°
\end{align*}
\]

(2)

(3)

Due to the time-varying character of position, the coordinates and communication distance of the satellite in SCCS O'(X', Y', Z') were time variables, every elevation and azimuth angle of the earth station antenna during the whole coverage time can be obtained. So, the assembles are established as equations (4) and (5).

\[
\gamma(t) = \{ \gamma_0, \gamma_1, \gamma_2, \ldots, \gamma_n \}, \quad n = \frac{\Delta t}{t_{step}}, \quad 0 < t < \Delta t
\]

(4)
\[ \theta(t) = \{\theta_0, \theta_1, \theta_2, \ldots, \theta_n\}, \quad n = \frac{\Delta t}{t_{\text{step}}}, \quad 0 < t < \Delta t \]  

(5)

3. Interference Calculation Model

The evaluation parameters of the interference signals between the two communication links include various forms, such as interference-to-noise ratio (I/N), carrier-to-interference ratio (C/I), carrier-to-interference and interference noise ratio (C/(I+N)), power flux density (PFD), equivalent power flux density, equivalent noise temperature increment percentage \( \Delta T/T \) [6-9]. In this paper, the interference-to-noise ratio \( I/N \) method was used to evaluate the parameter between NGSO satellite systems.

3.1. Interference Calculation Model of Single Satellite

The interference scenario of two single satellites has been shown in figure 2.

![Down link interference diagram between NGSO satellites](image)

**Figure 2.** Down link interference diagram between NGSO satellites.

When the two satellites Sat1 and Sat2 were simultaneously flying in orbit, the satellite Sat1 and the earth station GS1 had a normal communication link L1 within the coverage time, and the satellite system Sat2 and the earth station GS2 had a normal communication link L2 within the coverage time. When there were overlapping frequency bands in the downlink communication channels of these two systems, part of the transmit power of Sat2 has been captured by the receiving antenna of the earth station GS1, forming the interference link L21 of “Sat2-GS1”.

As shown in figure 3, assuming that the power spectrum density of the interfering signal was evenly distributed within the bandwidth, the interfering signal power within the overlapping bandwidth can be calculated by equation (6):

\[ P'_2 = P_2 \frac{W_{\text{overlap}}}{W_2} \]  

(6)

\( P_2 \): the transmitting power of Sat2  
\( P'_2 \): the transmitting power of Sat2 within the overlapping band  
\( W_2 \): the signal band of Sat2  
\( W_{\text{overlap}} \): the overlapping band of Sat1 and Sat2 in the downlink channel

![Overlapping frequency bands of satellites](image)

**Figure 3.** Overlapping frequency bands of satellites.
The calculation method of the interference signal power \(I_{21}\) at the receiver’s input of the earth station GS1 was as follows:

\[
I_{21} = P_2' \cdot G_2(\varphi_2) \cdot G_1(\varphi_1) \left[\frac{\lambda_{21}}{4\pi d_{21}}\right]^2
\]  

(7)

- \(G_2(\varphi_2)\): the transmitting antenna gain of Sat2 in the GS1 direction
- \(G_1(\varphi_1)\): the receiving antenna gain of GS1 in the Sat2 direction
- \(d_{21}\): the distance of the down interfering link
- \(\lambda_{21}\): the down link wave length of the Sat2

Then the equivalent noise power at the receiving end of the GS1 earth station can be calculated by equation (8):

\[
N_1 = k \cdot T_1 \cdot W_1
\]  

(8)

- \(T_1\): the equivalent noise in the GS1 receiving end, K
- \(W_1\): the signal band in the GS1 receiving end, Hz
- \(k\): Boltzmann constant, J/K

Then the interference-to-noise ratio at the receiving end of the GS1 can be calculated by equation (9):

\[
\frac{I_{21}}{N_1} = \frac{P_2' \cdot G_2(\varphi_2) \cdot G_1(\varphi_1) \left[\frac{\lambda_{21}}{4\pi d_{21}}\right]^2}{k \cdot T_1 \cdot W_1}
\]  

(9)

### 3.2. Interference Calculation Models of Constellation Systems

In fact, the constellation systems that generate interference are not simple single satellite systems, which composed of multiple satellites. The co-channel interference caused by the constellation systems is much more complicated than single satellite systems [10-12]. In this paper, only the downlink communication channels were considered, which would be interfered by the integrated interference signals from the constellation systems.

In figure 4, the normal communication link \(L_1\) from NGSO Sat1 was interfered by the interfering link \(L_{ij}\) from NGSO Sat2, here, \(i \in \{1,2,3 \ldots, n\}\), that was the satellite number of the constellation system Sat2, the total number was \(n\). \(j \in \{1,2,3 \ldots, m\}\), was the beam number of the antenna onboard the satellite, which had the same amount beams \(m\).

Then, the integrated \(I/N\) experienced by the receiver of the satellite earth station GS1 can be calculated by equation (10):

\[
\left(\frac{I}{N}\right)_\Sigma = \frac{1}{N} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{I_{ij}}{N} = \frac{1}{N} \sum_{i=1}^{n} \sum_{j=1}^{m} I_{ij}
\]  

(10)
(I/N)Σ: the integrated I/N in the receiving end of Sat1 system
N: the equivalent noise power in the receiving end of Sat1 system
I_ij: the interfering signal power from interfering link j on satellite i of Sat2 constellation system to the receiving end of the Sat1 system

3.3. Interference Evaluation Parameters
For a single satellite system, the criterion for judging whether interfered by other satellites is to calculate the interference-to-noise ratio, if it exceeds the tolerance threshold during the current contact period that will be harmful. But, for the constellation systems, the source of the interference signals may come from different communication links in different satellites. The criterion for judging whether or not being interfered is the integrated interference-to-noise ratio received by the receiving end. If that exceeds the tolerance threshold, the receiving system is considered to be interfered.

The interference evaluation criteria between two NGSO satellite systems can be referred to ITU-R S.1432-1 and ITU-R S.1324 [13, 14]. Where I/N=-12.2 dB has been looked as the threshold for harmful interference assessment.

The probability distribution of interference can be expressed by the Cumulative Distribution Function (CDF) curve, which can visually reflect the probability distribution of the overrun time. The CDF curve reflects the global value of the system’s performance, but for each simulation step, the I/N ≥ (I/N)th will be the criteria.

4. Interference Analysis Method Based on Link-Building Pattern
For two NGSO constellation systems, due to the large amount of satellites, the combinations of the establishment and maintenance of the interfering link and the interfered link are very complicated. If the I/N value of the entire time and whole links are to be calculated, and the real-time decision of tolerance status are to be judged simultaneously, that will result in a huge amount of computation and low efficiency under the entire simulation scenario.

In order to improve the efficiency of calculation, in this paper, an analysis method based on link-building pattern was proposed. The basic idea was that in the process of distributed calculation, the computational cluster operated the link-building calculation, and the interference evaluation module operated the simulation analysis of the built link parallelly.

After the computational cluster generated a link-building pattern table according to the calculation result of the communication link, the interference evaluation module dynamically queried state ‘1’ in the communication link list and established linked table. Then the link-building matrixes were constructed according to the linked table. By the logical operation of the interfering matrix state and interfered matrix state, the interference combinations were classified into three types: interference-free, single-interference, and mutual interference. Furthermore, the single-interference link can be classified into A interfering B or B interfering A.

Finally, only those links would be calculated whose status were ‘1’ in the matrix and relating to the current evaluation object, and other non-attention links would be ignored. Thereby, the amount of calculation link was reduced and the efficiency of analysis was improved. The calculation process was described below.

First, the link building calculation was performed according to the conditions for establishing the downlink communication in Section 2 [15-17]. In order to meet the requirement of the bit error rate $BER \leq 10^{-5}$, the carrier-to-noise ratio $C/N$ of the downlink should be greater than a certain threshold value $C/N_{th}$. The equation is as follows:

$$
\left[ \frac{C}{N} \right]_D = [EIRP]_S - [L_D] + [G_{RE}] - 10 \log (K T_E B_E)
$$

(11)

$[EIRP]_S$: effective radiated power
$[L_D]$: total downlink loss
\[ G_{re} \]: the receiving antenna gain of the earth station

\[ T_{e} \]: the equivalent noise temperature

\[ B_{e} \]: the receivers’ bandwidth of the earth station

For the two constellation systems shown in figure 4, the communication link calculations between the satellites and the earth stations were performed separately, and if the calculation results satisfied \( C/N \geq (C/N)_{th} \), it was considered that the communication link can be established.

For Sat1 system, assuming that the satellites total number was \( S \), the beams per satellite was \( K \), the earth stations total number was \( L \), and randomly distributed. So, the communication link table \( TA \) of the Sat1 system has been established as shown in figure 5. Here, ‘X’ indicated a link-building state, \( X = '1' \) indicated a link that successfully established, and \( X = '0' \) indicated a link that didn’t have a communication condition.

\[ I_{N} \geq (I/N)_{th} \], the interference link table \( TBA \) of the Sat2 satellite system to the Sat1 earth station can be established, as shown in figure 6. Similarly, the interference link table \( TAB \) of the Sat1 satellite system to the Sat2 earth station can be established. Wherein, ‘Y’ indicated the interference link state, \( Y = '1' \) indicated that the interference signal exceeded -12.2dB threshold, and \( Y = '0' \) indicated that the interference condition was not be met.

Then, by performing matrix-based logic operations on the communication link tables \( TA \), \( TB \) and the interference link table \( TAB \), \( TBA \), the interference situation of the target can be obtained, as shown in the equation (12).

Since the movement of the NGSO satellite system relative to the earth station has certain regularity and repeatability, the communication link table and the interference table also show certain repetition regularity. When the number of satellites, orbits, and earth location of the two NGSO constellation systems are conformed, the link-building diagram between the two constellation systems can be defined and becomes a relatively fixed pattern. In the process of interference simulation and calculation, as long as the constellation configuration of the two satellite systems and the topology between the satellites do not been changed, it is generally only necessary to query those links with
state ‘1’ in the two pattern tables, and calculate the mutual or single interference links meeting the condition of equation (12).

\[
\begin{align*}
T_{AB} & \& T_{BA} = '1' & \text{mutual interference} \\
T_{AB} & \& T_{BA} = '1' & \text{no interference} \\
T_{AB} & \& T_{B} = \begin{cases} '1' & A \text{ interfering } B \text{ and } B \text{ had link} \\ '0' & A \text{ uninterfering } B \text{ or } B \text{ without link} \end{cases} \\
T_{AB} & \& T_{A} = \begin{cases} '1' & A \text{ interfering } B \text{ and } A \text{ had link} \\ '0' & A \text{ uninterfering } B \text{ or } A \text{ without link} \end{cases} \\
T_{BA} & \& T_{B} = \begin{cases} '1' & B \text{ interfering } A \text{ and } B \text{ has link} \\ '0' & B \text{ uninterfering } A \text{ or } B \text{ without link} \end{cases} \\
T_{BA} & \& T_{A} = \begin{cases} '1' & B \text{ interfering } A \text{ and } A \text{ has link} \\ '0' & B \text{ uninterfering } A \text{ or } A \text{ without link} \end{cases}
\end{align*}
\]

5. Performance Analysis
In order to verify the feasibility of the above-mentioned calculation method in the co-channel interference analysis, two scenarios were constructed. One was the interference simulation between two single satellite systems, which used the orbital data and communication link parameters of the DAMPE and the HXMT satellites, also the Kashi earth station. The other scenario was the interference simulation between the two constellation systems, which used the orbital data and communication link parameters of the ITU-registered OneWeb and Telesat constellation systems [18, 19].

5.1. Interference Analysis of Two Single Satellite Systems
The DAMPE is a circular orbit with a height of 500 km and an inclination angle of 97.4°. The HXMT satellite is a circular orbit with a height of 550 km and an inclination angle of 43°. The selected earth station was the Kashi station whose geographic information is (75.9E, 39.5N, 1307 m). Among them, DAMPE was the interfering system and HXMT was the interfered system. The parameters of these two downlink communications have been shown in table 1.

| Parameters                                      | HXMT | DAMPE |
|------------------------------------------------|------|-------|
| Peak gain of earth station (dBi)                | 57   | 57    |
| Beam width of the receiving earth station antenna (°) | 0.2  | 0.2   |
| Transmitting power of satellites (dBW)          | 23   | 23    |
| Peak gain of the transmitting antenna on satellites (dBi) | 3    | 0     |
| Half power beam width of transmitting antenna on satellites (°) | 120  | 100   |
| Communication bandwidth (MHz)                   | 375  | 375   |
| Communication frequency (GHz)                   | 8.212| 8.212 |
| System noise temperature of the earth station receivers (K) | 138  | 138   |
| Polarize mode                                   | RHCP | RHCP  |

The simulation period was 2 years, the step length was 60s, and the starting time was 20:00 on January 1, 2020. The simulated scenario of the design was shown in figure 7.

Through simulation, the coordinates of the two satellite systems and the distance between the satellites and the earth stations have been obtained. By put these orbital and communication into the SCCS, the actual contact time CT_DAMPE and CT_HXMT in the case of normal communication conditions were calculated. The overlapping contact time of the two satellite systems from October to November 2020 can be shown in figure 8.
Figure 7. The simulation scenario of 2 NGSO satellites.

Figure 8. Contact time of communication links.

It can be seen from the results that during the two years simulation, DAMPE will have 32 overlapping coverages for HXMT, and the maximum $I/N$ was -3.327dB and the minimum value was -40.883dB. The percentage time when $I/N$ exceeds -12.2 dB was 0.00185%, which was lower than the interference threshold of 0.0125%, and no actual harmful interference occurs. The CDF curve was shown in figure 9.

Figure 9. CDF curve of DAMPE and HXMT.

5.2. Interference Analysis of Two Constellation Systems
The interference analysis between two NGSO constellation systems is more complicated.

After establishing the interference analysis scenario in the simulation platform, the focus was on large amount computational analysis around the interference evaluation parameters. In this paper, the Oneweb system and the Telesat system were taken as examples to analyze the interference between downlink channels of two constellation systems in Ka band.

Among them, Oneweb was the interfering system and Telesat was the interfered system. The orbital parameters and communication link parameters of these two constellation systems can be...
shown in tables 2 and 3. The simulation and calculation method was the link-building pattern established in the fourth part of this paper.

**Table 2.** Oneweb & Telesat orbit parameter.

| Constellation systems | Orbital height (inclination) | Plane amount | Satellites per plane | Total amount of satellites |
|-----------------------|-----------------------------|--------------|----------------------|---------------------------|
| OneWeb                | 1200km (87.9°)              | 18           | 40                   | 720                       |
| Telesat               | 1000km (99.5°)              | 6            | 12                   | 72                        |

**Table 3.** Oneweb & Telesat downlink parameter.

| Parameters                                      | Oneweb | Telesat |
|------------------------------------------------|--------|---------|
| Peak gain of earth station (dBi)                | 61     | 61      |
| Beam width of the receiving earth station antenna (°) | 0.15   | 0.15    |
| Transmitting power of satellites (dBW)          | 5      | 5       |
| Peak gain of the transmitting antenna on satellites (dBi) | 27.3   | 27.3    |
| Half power Beam width of transmitting antenna on satellites (°) | 5.2    | 5.2     |
| Communication bandwidth (MHz)                   | 250    | 250     |
| Communication frequency (GHz)                   | 18     | 18      |
| System noise temperature of the earth station receivers (K) | 138   | 138     |
| Polarize mode                                   | RHCP   | RHCP    |

The simulation start time was 20:00 on January 1, 2019, the period was 3 days, and the step was 60s. According the simulation data, the interference noise ratio \( I/N \) of the Oneweb system to the downlink communication link of the Telesat system was 4.312 dB during the simulation period of 3 days, and the corresponding time point was 10:37 on January 2, 2019. The time probability that the \( I/N \) exceeds -12.2 dB threshold was 0.0078%, and the CDF curve can be shown in figure 10.

![Cumulative Distribution Function](image)

**Figure 10.** Downlink \( I/N \) CDF curve from Oneweb to Telesat system.

6. **Conclusion**

In this paper, the calculation and analysis method for co-frequency and dynamical scenarios between two large NGSO constellation systems has been studied. An interference calculation technology of the spectral co-existence based on the link-building pattern has been proposed. Furthermore, one dynamical interference simulation scenario has been provided. And the data of verify the performance of this proposed method has been presented with two single satellites and two constellation systems.
actually registered in ITU. The results show that the proposed method is adaptive to the interference simulation of the co-channel communication link between NGSO constellation systems when the satellite amount is no more than 2000. Also, it can be used as a reference of co-existence interference analysis for huge NGSO constellations.

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