LEO Satellite Networks: When Do All Shortest Distance Paths Belong to Minimum Hop Path Set?

Quan Chen, Lei Yang, Deke Guo, Bangbang Ren, Jianming Guo, and Xiaoqian Chen

***Abstract*—Low-Earth orbit (LEO) satellite constellation network (SCN) has become a promising solution for non-terrestrial networks (NTNs). In LEO-SCNs, the shortest distance path (SDP) and minimum hop path (MHP) are two types of important paths.This paper focuses on the proposition that all the SDPs belong to the MHP set and studies the conditions when the proposition holds or not. Based on the topological regularity and link distance variation patterns, this paper proves several simplified equivalent propositions and derives a discriminant function to judge if the proposition holds in an arbitrary constellation. Simulations verify the judging method and find that all the SDPs belong to the MHP set in constellations with small inclinations (less than 68 deg) or large phasing offsets. The propositions can help to simplify the calculation of SDP.**

***Index Terms*—LEO satellite networks, constellation, routing, inter-satellite link, shortest path, minimum hop path**

I. Introduction

Low-Earth orbit (LEO) satellite constellation networks (SCNs), especially mega-constellation networks, have become an emerging technology for providing low-latency, broadband, and wide-area network services [1], [2]. Studies have shown that the LEO-SCNs have low-latency advantages over ground networks in many scenarios [3].

The delay in LEO-SCN is mainly determined by the path distance, thus many routing strategies search for the *shortest distance paths* (SDPs) [4] which can be solved by classical shortest path algorithms, e.g., Dijkstra algorithm [5]. The minimum hop-count path (MHP) is also an important type of path that has the least possible hops between two nodes [6]. In general wireless networks, it is difficult to find an explicit relation between SDP and MHP if the links have irregular or random lengths. Between two nodes, an SDP may have more hops than the MHP. However, in LEO-SCN, it is possible that all SDPs belong to the MHP set because of the regularity and symmetry of the constellation topology and the periodic variation of inter-satellite links (ISLs) [4]. If this proposition holds, then the SDP calculation in the constellation can be greatly simplified and limited to a smaller sub-graph.

Generally, the LEO-SCN has a mesh-like topology [3], and thus the calculation of MHP in LEO-SCN is much simpler than SDP. Moreover, since those MHPs define a local subgraph, if SDP is strictly proved to belong to the MHP set, the solution of SDP can be simplified to within the subgraph, which greatly lowers the complexity especially in mega-constellations.

Qu et al. [5] summarize the SDP and MHP and their applications in routing strategies. Chen et al. [7] assume all SDPs are also MHP and adopt the MHP instead of SDP as the routing metric for low-latency. Also, some researchers have investigated if all SDPs belong to the MHP set. Ekici et al. [6] find the SDP is in the MHP set in some special cases, then they exploit the latitude information to simplify the shortest path calculation. But this algorithm only applies to polar constellations with zero phasing offset. Duan [8] proposes a judging condition for all SDPs belong to the MHP set in polar constellation networks. But the condition is sufficient but not necessary and only applies to limited cases. Therefore, a general and analytical judging approach is needed.

This paper aims to provide a general method for judging if all SDPs belong to the MHP set in a given LEO-SCN. The original proposition is equivalently converted and simplified. Then an explicit discriminant function is derived to judge if the proposition holds or not. The judging condition is sufficient and necessary. Finally, numerical simulations verify the method. The main contributions are summarized as follows:

- In the typical constellation network topology, judging if all SDPs belong to the MHP set is equivalently simplified to judge the single-hop vertical detour case.
- Based on the ISL variation, a discriminant function and analytical criterion are proposed to judge if all SDPs in a given constellation network belong to the MHP set or not.
- Simulations verify the proposed judging method and the results show that whether the proposition holds mainly depends on the orbit inclination and phasing factor. All SDPs belong to the MHP set in constellations with small inclinations (less than 68 deg) or large phasing offsets.

II. Constellation Network Model

A. Satellite Constellation and ISLs

The LEO-SCN typically adopts the Walker constellation [5] that is formally expressed by α: $N_S/N_P/F$, where α is the orbit inclination, $\alpha \in (0, \pi)$, N_S is the total satellite number, N_P is the number of orbit planes, and F is a phasing factor. N_P orbit planes with the same inclination and altitude are regularly distributed along the equator, and these orbits are evenly spaced by $\Delta\Omega = 2\pi/N_P$. M_P satellites are also evenly distributed in each plane, $M_P = N_S/N_P$. The satellite position within the plane is specified by the satellite phase angle u ($u \in [-\pi, \pi]$). The phase angle differences of adjacent

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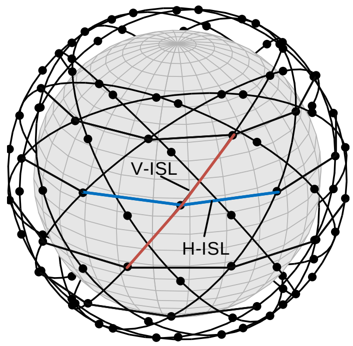

Fig. 1. Constellation topology and ISLs. All V-ISLs have equal and constant distances, while H-ISL distances are different and vary with satellite phase u.

satellites within the plane and between adjacent planes are $\Delta\Phi = 2\pi/M_P$ and $\Delta f = 2\pi F/N_S$, respectively.

Fig. 1 shows the classical ISL connecting mode [4]. Each satellite maintains four ISLs: two vertical (intra-plane) ISLs (V-ISLs) with adjacent satellites within plane; two horizontal (inter-plane) ISLs (H-ISLs) with satellites in adjacent orbits.

B. ISL distance variation

Because of the regularity and symmetry of the Walker constellation, the ISL variation pattern of any satellite applies to all the satellites in the constellation. The ISL distance is

$$d = \sqrt{2}\,(R_E + h_s)\sqrt{1 - \cos\Theta} \tag{1}$$

where R_E is the Earth radius, h_s is the orbit altitude, and Θ is the Earth-centered angle between the two satellites. Θ of V-ISLs is $\Delta\Phi$, while Θ of H-ISLs can be calculated by

$$\cos\Theta = c_1 - c_2\cos(2u + \Delta f) \tag{2}$$

where $c_1 = \left(\cos^2(\Delta\Omega/2) - \cos^2\alpha\sin^2(\Delta\Omega/2)\right)\cos\Delta f - \cos\alpha\sin\Delta\Omega\sin\Delta f$, $c_2 = \sin^2\alpha\sin^2(\Delta\Omega/2)$. Based on (1) and (2), the ISL distances have two characteristics:

- All the V-ISLs are of the same and constant distances;
- H-ISL distances are different and vary with satellite phase u.

In terms of H-ISLs, the derivative of d is

$$\frac{\mathrm{d}d}{\mathrm{d}u} = -\frac{\sqrt{2}\,(R_E + h_s)}{\sqrt{1 - \cos\Theta}}c_2\sin(2u + \Delta f) \tag{3}$$

Since $c_2 > 0$, $\sqrt{1 - \cos\Theta} > 0$, the sign of $\frac{\mathrm{d}d}{\mathrm{d}u}$ is determined by $\sin(2u + \Delta f)$. The H-ISL distance reaches the minimum at $u' = \frac{2k+1}{2}\pi - \frac{\Delta f}{2}$ and the maximum at $u'' = k\pi - \frac{\Delta f}{2}$. The distance variation has a period of π and is symmetrical about $u = \frac{k\pi}{2} - \frac{\Delta f}{2}$, as later shown in Fig.6.

III. Notations and Definitions

With the four-ISL connecting pattern, the virtual topology of the constellation network is mesh-like or torus-like [3], [9] (see Fig. 2). Each satellite S can be identified by a virtual address (v_S, h_S) indicating the v_S-th satellite in the h_S-th orbit plane. Any two satellites in the network are reachable via a multi-hop path P. The vertical, horizontal, and total hop-counts of P are denoted by $N^v(P)$, $N^h(P)$, and $N(P)$, respectively. The physical distance of P is $d(P)$.

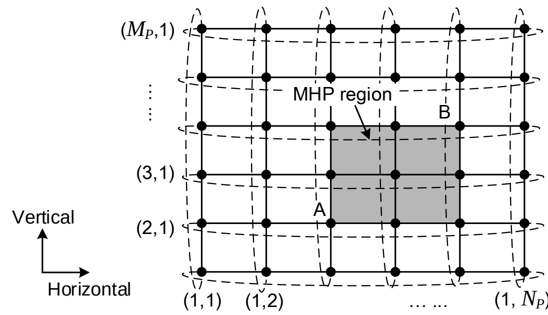

Fig. 2. The mesh-like virtual topology of constellation. The SDP calculation can be simplified to the MHP region if all SDPs belong to MHP set.

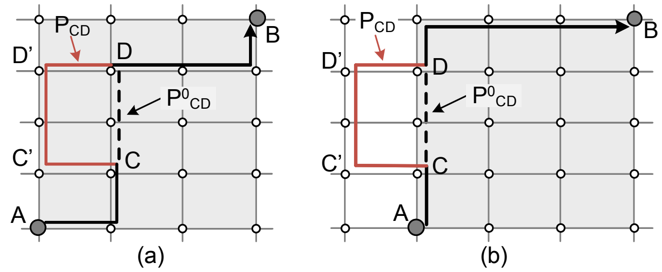

Fig. 3. Examples of the horizontal detour. The dashed line indicates the corresponding minimum hop path.

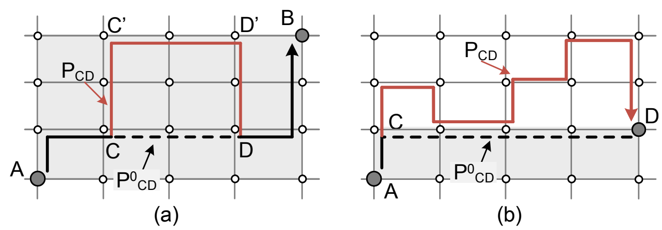

Fig. 4. Examples of the vertical detour. The dashed line indicates the corresponding minimum hop path.

Definition 1. ***Minimum Hop Path (MHP).*** In the mesh-like topology, the path from satellite $A(v_A, h_A)$ to $B(v_B, h_B)$, P_{AB}, is not unique. The MHP between A and B is defined as $P^0_{AB} = \arg\min_{P\in\{P_{AB}\}} N(P)$. The set of all MHP P^0 between all node pairs is denoted by $\mathcal{P}^0$.

Although each satellite has four ISLs, any satellite on P^0_{AB} has at most two forwarding directions [6]. The next-hop node on P^0_{AB} is always closer to B in terms of hop-count. The required minimum hop-count of P^0_{AB} can be given by $N(P^0_{AB}) = N^v(P^0_{AB}) + N^h(P^0_{AB})$, where $N^v(P^0_{AB}) = \min\{|v_A - v_B|, M_P - |v_A - v_B|\}$ and $N^h(P^0_{AB}) = \min\{|h_A - h_B|, N_P - |h_A - h_B|\}$ [1].

Definition 2. ***Horizontal and Vertical Detour.*** A non-minimum hop path contains one or multiple detours. P_{CD} is a *horizontal detour* if $h_C = h_D$ and $N^h(P_{CD}) > 0$, as shown in Fig 3. Similarly, P_{CD} is a *vertical detour* if $v_C = v_D$ and $N^v(P_{CD}) > 0$, as shown in Fig 4. Due to the mesh-like topology, a detour P_{CD} has more hops than P^0_{CD}. $N(P_{CD}) - N(P^0_{CD}) = 2k$, $k \in \mathbb{Z}^+$.

Definition 3. ***Minimal Vertical Detour (MVD).*** If P_{CD} is a

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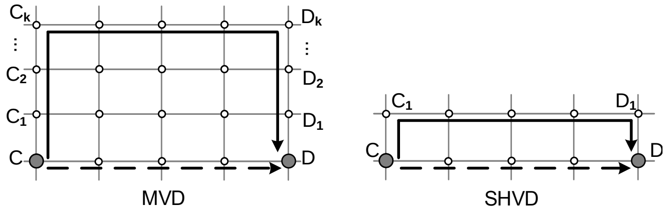

Fig. 5. Minimal vertical detour(MVD) and single-hop vertical detour(SHVD).

vertical detour and all horizontal hops of P_{CD} are successively taken, then P_{CD} is defined as an MVD (see Fig. 5) and $\mathcal{P}^{\mathrm{MVD}}$ denotes its set . Note that each vertical detour contains at least one MVD. If $P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$, then $N^v(P_{CD}) = 2k$, $k \in \mathbb{Z}^+$.

Definition 4. ***Single-Hop Vertical Detour (SHVD).*** If $P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$ and $N^v(P_{CD}) = 2$, then P_{CD} is defined as an SHVD (see Fig. 5). $\mathcal{P}^{\mathrm{SHVD}}$ denotes the SHVD set, $\mathcal{P}^{\mathrm{SHVD}} \subseteq \mathcal{P}^{\mathrm{MVD}}$.

Definition 5. ***Shortest Distance Path (SDP).*** The SDP between A and B is defined as $P^*_{AB} = \arg\min_{P\in\{P_{AB}\}} d(P)$. Let P^* denote an SDP between any given node pair.

IV. Equivalent transformation of propositions

The core proposition that all the SDPs belong to the MHP set in an LEO-SCN can be expressed as $\mathbf{P1}$: $\forall P^* \in \mathcal{P}^0$. This paper aims at judging the conditions for the establishment of $\mathbf{P1}$. Based on the above definitions, we derive several simplified necessary and sufficient conditions for $\mathbf{P1}$, and propose a discriminant function to judge if $\mathbf{P1}$ holds or not.

Proposition 1. *An SDP has no horizontal detour.*

Proof. If P_{CD} is a horizontal detour, as shown in Fig. 3, then $h_C = h_D$, $N^h(P_{CD}) > 0$, while $N^h(P^0_{CD}) = 0$. Since all the V-ISLs have the same physical distance d^V, $d(P_{CD}) = N^v(P_{CD}) \cdot d^V + \sum_{i=1}^{N^h(P_{CD})} d^H_i$, where $d^H_i > 0$ is the distance of i-th H-ISL; while $d(P^0_{CD}) = N^v\left(P^0_{CD}\right) \cdot d^V$. Since $N^v(P_{CD}) \geq N^v(P^0_{CD})$, then $d(P_{CD}) > d(P^0_{CD})$, the horizontal detour must be longer than the corresponding MHP. Because any segment of the SDP should also be an SDP, the horizontal detour cannot be included in an SDP. □

Note that the distances of H-ISLs are different and vary with the satellite location. Although vertical detour introduces extra vertical hops, if vertical detour reaches the location with shorter H-ISLs and the saved distance of H-ISLs can make up for the extra vertical hops, then the detour is shorter than the MHP. Therefore, the vertical detour is possible in an SDP.

Proposition 2. *A necessary and sufficient condition for* $\forall P^* \in \mathcal{P}^0$ *is that* $\forall P_{CD} \in \mathcal{P}^{\mathrm{MVD}}, d(P_{CD}) > d(P^0_{CD})$.

Proof. (1) Necessity: If $P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$, then $v_C = v_D$ and P^0_{CD} is unique. Given $\forall P^* \in \mathcal{P}^0$, thus $P^*_{CD} = P^0_{CD}$. Since $\mathcal{P}^{\mathrm{MVD}} \cap \mathcal{P}^0 = \varnothing$, if $P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$, then $P_{CD} \notin \mathcal{P}^0$ and $P_{CD} \neq P^0_{CD} = P^*_{CD}$. Thus $d(P_{CD}) > d(P^*_{CD}) = d(P^0_{CD})$.
(2) Sufficiency: If $\exists P^* \notin \mathcal{P}^0$, then P^* has at least one detour. According to *Proposition 1*, the detour must be a vertical detour. Then there must be an MVD on the detour, and we take it as P_{CD} . Since any segment of P^* is also the shortest, then $P_{CD} = P^*_{CD}$, $d(P_{CD}) \leq d(P^0_{CD})$. That is, if $\exists P^* \notin \mathcal{P}^0$, then $\exists P_{CD} \in \mathcal{P}^{\mathrm{MVD}}, d(P_{CD}) \leq d(P^0_{CD})$. The contrapositive proves the sufficiency of the original proposition. □

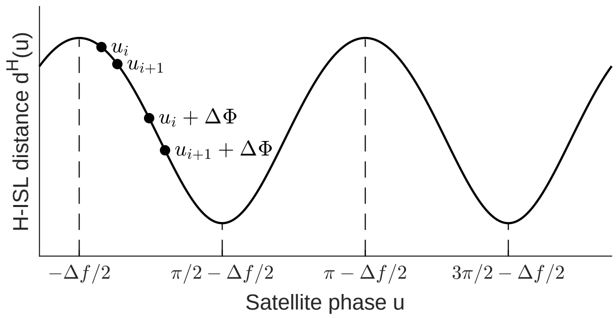

Fig. 6. H-ISL distance variation pattern.

Proposition 3. *A necessary and sufficient condition for* $\forall P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$, $d(P_{CD}) > d(P^0_{CD})$ *is that* $\forall P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) > d(P^0_{CD})$.

Proof. (1) Necessity: Since $\mathcal{P}^{\mathrm{SHVD}} \subseteq \mathcal{P}^{\mathrm{MVD}}$, the necessity is obvious.
(2) Sufficiency: As shown in Fig. 5, given $P_{CD} \in \mathcal{P}^{\mathrm{MVD}}$, then $N^v(P_{CD}) = 2k$, $k \in \mathbb{Z}^+$, and $d(P_{CD}) = d(P^0_{C_kD_k}) + 2k \cdot d^V$. If $\forall P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) > d(P^0_{CD})$ is given, since $(P_{CC_1} + P^0_{C_1D_1} + P_{D_1D}) \in \mathcal{P}^{\mathrm{SHVD}}$, then $d(P^0_{C_1D_1}) + 2d^V > d(P^0_{CD})$. Similarly, $d(P^0_{C_2D_2}) + 2d^V > d(P^0_{C_1D_1})$, ..., $d(P^0_{C_kD_k}) + 2d^V > d(P^0_{C_{k-1}D_{k-1}})$. Then $d(P_{CD}) = d(P^0_{C_kD_k}) + 2k \cdot d^V > d(P^0_{CD})$. The sufficiency is proved. □

Combining *Proposition 2* and *3*, to judge if $\forall P^* \in \mathcal{P}^0$ is simplified to judge if $\forall P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) > d(P^0_{CD})$. Note that the above propositions apply to all LEO-SCNs with the four-ISL pattern and mesh-like topology. Although H-ISL distances vary with time (or satellite phase u), these propositions apply to cases at all times.

As shown in Fig. 5, if $P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) = d(P^0_{C_1D_1}) + 2d^V$. The H-ISL distance varies with u and can be expressed as $d^H(u)$. Let the satellite phase of C be u_1, then u of the i-th node along P^0_{CD} is $u_i = u_1 + (i-1)\,\Delta f$, and u of the corresponding i-th node along $P^0_{C_1D_1}$ is $u_i \pm \Delta\Phi$. Due to the symmetry of $d^H(u)$, analysis of solely $u_i + \Delta\Phi$ will suffice. Let $g(u_i) \triangleq d^H(u_i) - d^H(u_i + \Delta\Phi)$. Assume $N^h(P^0_{CD}) = m$, then the distance difference between P^0_{CD} and P_{CD} is $G(u_1, m) \triangleq d(P^0_{CD}) - d(P_{CD}) = \sum_{i=1}^{m} g(u_i) - 2d^V$, where $u_i = u_1 + (i-1)\Delta f$ and $m = \{1, 2, ..., \lfloor \frac{N_P}{2} \rfloor\}$.

Proposition 4. *A necessary and sufficient condition for* $\forall P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) > d(P^0_{CD})$ *is that* $\forall u_1 \in [\frac{-\Delta f - \Delta\Phi}{2}, \frac{\pi - \Delta f - \Delta\Phi}{2}]$, *we have the Discriminant Function* $G_M(u_1)$, *and* $G_M(u_1)$ *should satisfy*

$$G_M(u_1) \triangleq \sum_{i=1}^{M} d^H(u_i) - d^H(u_i + \Delta\Phi) - 2d^V < 0 \quad (4)$$

where $M = \min\{\lfloor \frac{N_P}{2} \rfloor, \lfloor \frac{\pi - \Delta\Phi - 2u_1}{2\Delta f} + \frac{1}{2} \rfloor\}$ *and* $u_i = u_1 + (i-1)\Delta f$.

Proof. If $\forall P_{CD} \in \mathcal{P}^{\mathrm{SHVD}}$, $d(P_{CD}) > d(P^0_{CD})$, then $\forall u_1, m$, $G(u_1, m) < 0$. The above two propositions are equivalent.

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TABLE I
RELATIONSHIP OF SDP AND MHP IN TYPICAL CONSTELLATIONS

Constellation	Parameter	$\forall P^* \in \mathcal{P}^0$
GlobalStar	52°: 48 / 8 / 0	Yes
Iridium-a	86.4°: 66 / 6 / 2	Yes
Iridium-b	86.4°: 66 / 6 / 0	No
OneWeb	87.9°: 648 / 18 / 0	No
Starlink-I	53°: 1584 / 72 / 39	Yes

Next, let $G^{\max}$ be the maximum of $G(u_1, m)$, we search for $G^{\max}$ and further narrow the range of u_1 and m.

Given u_1, $G(u_1, i) - G(u_1, i-1) = g(u_i)$. Let $g(u_i) \geq 0$, i.e., $d^H(u_i) \geq d^H(u_i + \Delta\Phi)$, based on the monotonicity and symmetry of $d^H(u)$ as discussed in Section II-B and shown in Fig. 6, u_i should satisfy $-\frac{\Delta f}{2} \leq \frac{u_i+(u_i+\Delta\Phi)}{2} \leq \frac{\pi}{2} - \frac{\Delta f}{2}$. Let u_i be u_1, we obtain $\frac{-\Delta f - \Delta\Phi}{2} \leq u_1 \leq \frac{\pi - \Delta f - \Delta\Phi}{2}$; let u_i be u_m, we obtain $m \leq \frac{\pi - \Delta\Phi - 2u_1}{2\Delta f} + \frac{1}{2}$. Besides, in the mesh-like topology, $m \leq \lfloor \frac{N_P}{2} \rfloor$ [1]. Thus to keep $g(u_i) \geq 0$, the maximum of m is $M = \min\{\lfloor \frac{N_P}{2} \rfloor, \lfloor \frac{\pi - \Delta\Phi - 2u_1}{2\Delta f} + \frac{1}{2} \rfloor\}$. Then $G(u_1, m)$ reaches $G^{\max}$ at $m = M$, and $G(u_1, M)$ is taken as the discriminant function and denoted by $G_M(u_1)$. The above constraints of u_1 and m also specify the conditions when $G(u_1, m)$ reaches $G^{\max}$. Meanwhile, if $G_M(u_1) < 0$ with u_1 in the specified range, then $G^{\max} < 0$ and $\forall u_1, m$, $G(u_1, m) < 0$. Thus, the ranges of u_1 and m are narrowed. □

$G_M(u_1)$ actually means the maximum distance gap between the SHVD and MHP at u_1. Note that since near-polar constellations (e.g., $\alpha \in [80, 100]$ deg) are π-type [7], related values should be modified by $\Delta\Omega = \pi/N_P$ and $M = \min\{\lfloor N_P - 1 \rfloor, \lfloor \frac{\pi - \Delta\Phi - 2u_1}{2\Delta f} + \frac{1}{2} \rfloor\}$ in near-polar constellation cases.

Proposition 4 offers an analytical criterion to judge if **P1** holds or not. Based on (1) and (4), whether **P1** holds depends on four constellation parameter α, N_P, M_P, and F, but not h_s.

In addition to the theoretical value, **P1** helps to simplify the calculation of SDP. In a graph with n nodes, to solve the SDP between two nodes, traditional methods need to traverse all the n nodes. But if **P1** holds, the SDP calculation only needs to search the MHP region. Averagely, only $1/16$ computations are needed [7], saving over 93% computations.

V. SIMULATIONS AND RESULTS

Based on *Proposition 4* and the *discriminant function*, we examine if **P1** holds or not in some typical constellations, as listed in Table I. Based on Table I, we also test the *Proposition 4* by Monte Carlo simulations which are independent of the above formulations. For each constellation in which **P1** holds in Table I, we randomly generate 1×10^6 node pairs at different time and calculate the shortest path and its hop-count between each pair, then check if it equals the minimum hop-count. The results support the conclusion that in these constellations all SDPs belong to the MHP set. The establishment of **P1** also means that the calculation of SDP in these constellations can be simplified and only the MHP sub-region is needed.

We further study the effects of the four factors α, N_P, M_P, and F by examining if **P1** holds with all the possible parameter combinations. $N_P, M_P = [6, 7, ..., 100]$, $F = [0, 1, ..., N_P - 1]$, $\alpha \in (0, 120]$ deg and is discretized by 0.5 deg. Results show that **P1** always holds for any inclined constellations with $\alpha \leq 68$ deg. When $\alpha > 68$ deg, the establishment of **P1** is mainly affected by α and F rather than N_P or M_P.

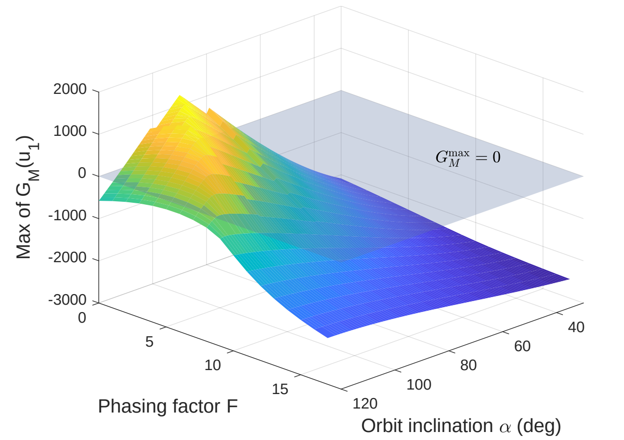

Fig. 7. The maximum of the discriminant function with different α and F (at fixed $N_P = 18$, $M_p = 36$). $G_M^{max} = 0$ is the critical plane. G_M^{max} below the plane means **P1** holds in the corresponding constellation.

Fig. 7 gives an example of $N_P = 18$, $M_p = 36$. **P1** holds in most cases, but the surface above the critical plane indicates that **P1** does not hold when α approaches 90 deg and F is small. Based on $d^H(u)$, when α approaches 90 deg, $|\frac{\mathrm{d}d}{\mathrm{d}u}|$ and $g(u_i)$ are greater, then G_M^{max} is greater; Similarly, a smaller F allows greater M, which also leads to a greater G_M^{max}. In these cases, **P1** does not hold, i.e., it is possible to find a path with vertical detour that has a shorter distance than the MHP.

VI. CONCLUSION

This paper derives some simplified equivalent propositions when all SDPs belong to the MHP set and provides a discriminant function to judge if the proposition holds or not. Theoretical model and simulations show that the proposition holds in constellations with small inclinations (e.g., less than 68 deg) or large phasing offsets.

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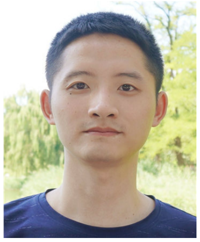

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