Direct to Cell VLEO SatCom System Provide Low E2E Latency in STIN

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Abstract. Large scale low earth orbit (LEO) satellite constellations provide global Internet services for mobile terminals. In this paper, we first give an architectural model of the Direct to Cell satellite communications(SatCom) system. Then we analyze the terrestrial coverage and Doppler shift of the very low earth orbit (VLEO) satellites based on the abstracted geometric architecture. In particular, we simplify the Doppler shift closure expression compared to the conventional expression. We compare the end to end (E2E) latency of Satellite Terrestrial integrated network (STIN) and traditional terrestrial networks (TN). According to the different scenarios, we propose suitable location known and altitude known E2E transmission schemes. The proposed E2E transmission strategy based on maximum inter satellite links (ISLs) requires the least number of satellites and provides lower E2E transmission latency, with a 28% improvement over traditional terrestrial E2E transmission, which fully illustrate the E2E latency advantage of STIN. Finally, we obtain the areas of lower E2E latency for D2C VLEO SatCom transmissions.

Keywords: VLEO · STIN · Doppler shift · E2E latency · ISLs

1 Introduction

With the rapid development of the global economy, the realization of seamless communication on a global scale has become an essential requirement for future mobile communications [1]. One of the visions of 6th generation (6G) communication system is aiming to provide global coverage to support ubiquitous and seamless communications. STIN make seamless connection possible. The Direct to Cell(D2C) satellite communications(SatCom) system is a representative technology for global coverage and seamless communications in next generation communication systems [2]. Compared to terrestrial networks, satellites offer a broader coverage range [3]. Moreover, the 3rd Generation Partnership Project (3GPP) has explored several study items in Releases 15 and 16 [4,5] to examine the support about new radio non-terrestrial networks (NR-NTN), especially for SatCom issues. Subsequently, work items has been approved for the

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standardization of 5G NR-NTN in Release 17 [6], giving priority to the satellite scenario, focusing on the transparent forwarding scenario of LEO, and further discussing the coverage enhancement and mobility enhancement of NTN. From early study items to recent work items, research on NTN has gained increasing attention. Previously, terrestrial fiber optic E2E transmission latency is high, which affects the delay sensitive services such as finance and intelligent medical care. The leading starlink GEN1 constellations have shortened the E2E latency [7], but they do not provide different strategies for different transmission distances in STIN. However, our proposed E2E transmission strategy based on maximum ISLs reduces the number of satellites and further shortens the end to end transmission delay on this basis.

The main contributions of this paper are summarized as follows. Firstly, in large scale VLEO SatCom systems, we analyze the terrestrial coverage and Doppler shift of VLEO communication satellite under the STIN architecture. In particular, we simplify the Doppler shift closure expression compared to the conventional expression in 3GPP [4]. Then, we compare the E2E latency between STN and TN. Appropriate low latency E2E transmission strategies for different situations have been determined for any given two points with least number of satellites, effectively highlighting the advantages of E2E latency through ISLs in D2C VLEO SatCom systems.

The rest of this paper is organized as follows. Section 2 analyzes the main parameters of the D2C VLEO SatCom systems. In Sect. 3, we introduce our proposed E2E transport latency and strategy. Section 4 provides the numerical results and compares the E2E latency between SatCom and TN. Finally, we conclude this paper in Sect. 5.

2 Main Parameters of SatCom System

2.1 Satellite Coverage

The geometric model of the SatCom system is given in Fig. 1. The coverage area of a single satellite R_{cover} is related to the orbit altitude h and the minimum elevation angle of the terrestrial terminal α as shown in Fig. 1. The coverage of the satellite R_{cover} can be further obtained by just figuring out the geocentric angle γ corresponding to the coverage. The simplification to obtain the geocentric angle γ can be defined as follows

$$\gamma = \arccos(\frac{r_E}{r_E + h}\cos\alpha) - \alpha \tag{1}$$

where r_E is the radius of Earth, h is the altitude of the satellite. Due to the limitations of the mechanical attitude, α represents the minimum elevation angle of the terrestrial terminal antenna. The terrestrial coverage of a single satellite can be expressed by the following equation

$$R_{cover} = 2r_E \cdot \gamma = 2r_E \cdot \left[\arccos\left(\frac{r_E}{r_E + h}\cos\alpha\right) - \alpha\right] \tag{2}$$

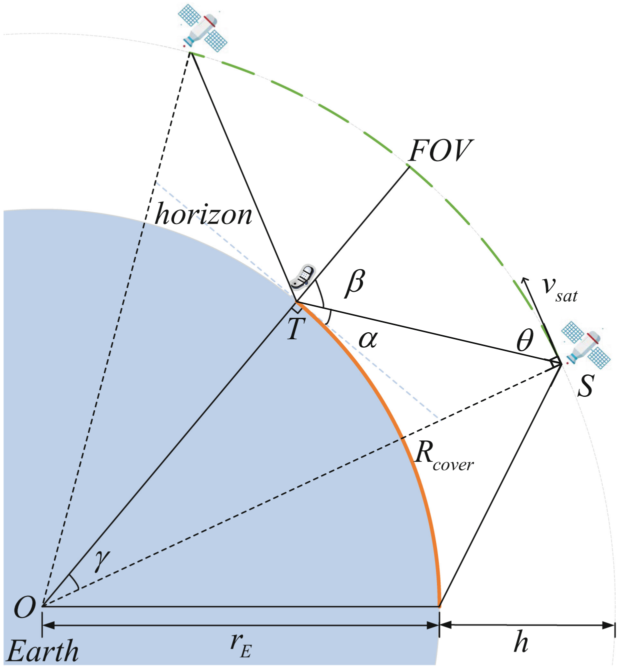

Fig. 1. The SatCom system geometric model.

Although the VLEO satellites are close to the Earth's surface and have low orbital altitudes, resulting in small communications coverage of a single satellite, it can be compensated by deploying large scale VLEO constellation and ISLs can be used to achieve wide coverage and make up for the small coverage area of a single D2C VLEO satellite.

2.2 Doppler Shift

Doppler shift is also one of the very real and difficult issues we need to consider [8]. Firstly, according to the cosine theorem we can calculate the distance between the satellite and the terrestrial terminal d_{ST} by Eq. (3)

$$d_{ST}^2 = (r_E + h)^2 + r_E^2 - 2r_E(r_E + h)\cos\gamma \tag{3}$$

Then according to the sine theorem we can get another representation of d_{ST} in the following equation

$$\frac{\sin\gamma}{d_{ST}} = \frac{\sin(\frac{\pi}{2} - \theta)}{r_E} \rightarrow d_{ST} = \frac{r_E \sin\gamma}{\cos\theta} \tag{4}$$

where θ is the angle between satellite velocity and terrestrial communications equipment. Bringing (4) back to (3) gives the relationship between θ and γ as shown in the following equation

$$\cos\theta = \frac{\sin\gamma}{\sqrt{1 + (\frac{r_E+h}{r_E})^2 - 2(\frac{r_E+h}{r_E})\cos\gamma}} \tag{5}$$

And since the geocentric angle γ is unknown, it is further expressed using the terrestrial equipment elevation angle α to represent the geocentric angle γ by bringing (1), which then gives the relationship between θ and α, enables to calculate the Doppler shift.

The Doppler shift f_d due to satellite movement is formulated as follows

$$\begin{aligned} f_d &= f_c v_{sat} \cos\theta / c \\ &= \frac{f_c v_{sat}}{c} \cdot \frac{\sin\gamma}{\sqrt{1 + (\frac{r_E+h}{r_E})^2 - 2(\frac{r_E+h}{r_E})\cos\gamma}} \\ &= \frac{f_c}{c} \cdot \sqrt{\frac{GM_E}{r_E+h}} \cdot \frac{\sin\left[\arccos(\frac{r_E}{r_E+h}\cos\alpha) - \alpha\right]}{\sqrt{1 + (\frac{r_E+h}{r_E})^2 - 2(\frac{r_E+h}{r_E})\cos\left[\arccos(\frac{r_E}{r_E+h}\cos\alpha) - \alpha\right]}} \end{aligned} \tag{6}$$

where f_c is the frequency of carrier and c is the speed of light in vacuum. The higher the transmission frequency, the larger the Doppler shift will be. So we choose the lower frequency band of the S band, and the Doppler shift is also smaller. The relationship between θ and α is also derived in the 3GPP protocol [4]. However, we further found that the relationship between θ and α can be obtained directly through the sine theorem without the need for the intermediate variable geocentric angle γ to convert, as follows

$$\frac{\sin(\frac{\pi}{2} - \theta)}{r_E} = \frac{\sin(\frac{\pi}{2} + \alpha)}{r_E + h} \rightarrow \cos\theta = \frac{r_E}{r_E + h}\cos\alpha \tag{7}$$

Bringing (7) back to (6) gives a direct relationship as follows

$$f_d = f_c v_{sat} \cos\theta / c = \sqrt{\frac{GM_E}{(r_E + h)^3}} \cdot f_c r_E \cos\alpha / c \tag{8}$$

This greatly simplifies the computational complexity of solving the Doppler shift f_d, and numerical simulations show that the results of the two computational approaches (6) and (8) are consistent.

3 End to End Transport

3.1 Maximum ISL

We also consider the case where the ISL is blocked by the atmosphere, and the maximum ISL for a VLEO satellite can be easily calculated using the formula

$$ISL_{max} = 2\left(\sqrt{(r_E + h)^2 - (r_E + a)^2}\right) \tag{9}$$

where a is the height of the atmospheric layer above the surface of Earth, generally taken as $a = 80\,\text{km}$ [9]. The maximum ISL corresponding to the maximum geocentric angle γ_{max} can be expressed as

$$\gamma_{max} = 2\arccos(\frac{r_E + a}{r_E + h}) \tag{10}$$

3.2 End to End Transport Latency

Due to the different travel speeds of light in different media, when to choose SatCom and when to choose terrestrial communication in STIN is also a discussable point, and we will quantitatively analyze the effect of transmission distance on this.

First, we consider the case of a direct link with the least number of satellite. Let d_E represent the shortest transmission distance for E2E communication, not a physically true straight line, but the great circle surface distance of the shortest arc between two points around the Earth as a sphere. The distance between any two points on Earth is usually calculated using the Haversine Formula as follows

$$d_E = 2r_E \arcsin\left(\sqrt{\text{hav}(\varphi_2 - \varphi_1) + \cos(\varphi_1)\cos(\varphi_2)\text{hav}(\lambda_2 - \lambda_1)}\right) \tag{11}$$

where $\text{hav}(x) = \sin^2\left(\frac{x}{2}\right)$ is the semipositive vector function, λ_1, λ_2 are the longitudes and φ_1, φ_2 are the latitudes of the two points.

In the single hop scenario when $d_E \leq R_{cover}$, user data can be transmitted directly from one satellite to another terrestrial gateway or terminal, without the need to relay flows on multiple satellites, this mode is also known as the bent pipe mode. However, if the operation is located on a GEO satellite, then the bent pipe mode can cause a large latency. And this is one of the advantages of the D2C VLEO SatCom system. Due to the movement of the satellite, the transmission between the satellite terrestrial link is constantly changing. The transmission latency is minimized when the distance between the satellite and the two users is equal. Assuming that the satellite needs to be switched to provide optimal network performance, the transmission latency is largest when the satellite is located directly above a user.

In the multi hop scenario, we assume that traffic relaying is completed by multiple satellites in the satellite network. The distance d_E needs to satisfy $R_{cover} < d_E \leq \pi r_E$ and corresponding to the geocentric angle is $\gamma_E = d_E / r_E$. Because d_E should be less than half of the Earth's perimeter. Divide γ_E into parts according to γ_{max} and calculate the minimum number of satellites needed to connect any two points

$$\begin{cases} n_{\gamma_{max}} & = \lfloor \frac{\gamma_E}{\gamma_{max}} \rfloor \\ \gamma_f & = \gamma_E - n_{\gamma_{max}} \times \gamma_{max} \end{cases} \tag{12}$$

where $\lfloor x \rfloor$ represents a downward rounding integer, $n_{\gamma_{max}}$ represents how many integer γ_{max} are contained in γ_E and γ_f is the remainder of γ_E divided by γ_{max}.

From this we obtain the minimum number of satellites required as $n_{\gamma_{max}} + \lceil \gamma_f \rceil + 1$. The distance of the last segment of ISL corresponding to γ_f is

$$ISL_f = 2\,(r_E + h)\,sin(\gamma_f/2) \tag{13}$$

For computational comparison, based on the scenario where the satellites are directly above the gateway or the terminal, the E2E transmission latency with the minimum number of satellites is shown below

$$\begin{aligned} t_{n_\gamma} &= d_{n_\gamma}/c = \left(n_{\gamma_{max}} ISL_{max} + ISL_f + 2 \times h\right)/c \\ &= 2\left[\,n_{\gamma_{max}}\sqrt{(r_E + h)^2 - (r_E + a)^2} + (r_E + h)sin(\gamma_f/2) + h \quad\right]/c \end{aligned} \tag{14}$$

where d_{n_γ} denotes the E2E transmission distance using the minimum number of satellites.In the next section, t_{n_γ}also represents the E2E delay of our proposed strategy. Assuming the suitable density of satellites to be deployed in the ultra large scale constellations, satellite paths are composed of a series of point to point free space ISLs. The length of this series of connected links is approximately equal to the length of an arc in a sphere with a radius of the Earth's radius plus the altitude of the satellite. The corresponding E2E transmission latency for this scenario can be calculated by the following equation

$$t_{arc} = d_{arc}/c = \left(ISL_{arc} + 2\,h\right)/c = \left[d_E\,(r_E + h)\,/r_E + 2h\right]/c \tag{15}$$

where d_{arc} denotes the E2E transmission distance in this scenario and ISL_{arc} denotes the approximate arc length of ISLs. Compared to terrestrial fiber optic networks, latency is lower when the additional distance is shorter using a satellite network. However, the additional latency caused by this extra distance can be easily offset by communicating over long distances at the vacuum speed of light via satellite networks. The E2E transmission latency of the terrestrial network in the fiber optic can be expressed as

$$t_{TN} = d_E/v_{op} = d_E \cdot n_{op}/c \tag{16}$$

where v_{op} is the speed of light in optical fiber, n_{op} is the refractive index and $v_{op} = c/n_{op}$. This is the shortest transmission latency of the terrestrial fiber optic network in the most ideal case, since in practice it is not possible to lay fibers continuously over the most direct paths. We then consider the case $t_{arc} < t_{TN}$ where the E2E transmission latency in STIN is less than the minimum E2E transmission latency in the terrestrial fiber optic network. Given the terrestrial E2E communication distance d_E, the ISLs strategy for SatCom is chosen to have lower latency than the terrestrial fiber optic network when the orbital altitude h satisfies the following equation

$$h < \frac{(n_{op} - 1) \cdot r_E \cdot d_E}{d_E + 2r_E} \tag{17}$$

Bringing the previous maximum terrestrial E2E communication distance $d_{E_{max}} = \pi r_E$ into the above equation yields

$$h_{max} = \frac{(n_{op} - 1) \cdot r_E \cdot d_{E_{max}}}{d_{E_{max}} + 2r_E} = \frac{\pi \cdot (n_{op} - 1) \cdot r_E}{\pi + 2} \tag{18}$$

When the satellite orbit altitude is higher than $h_{max} = 1829\,\text{km}$, SatCom loses its advantage in E2E transmission latency. When the satellite altitude h is given and the E2E communication distance d_E satisfies the following equation, the SatCom ISL latency is smaller than the terrestrial fiber optic network

$$d_E > \frac{2h \cdot r_E}{(n_{op} - 1)r_E - h} \tag{19}$$

where satellite orbit altitude $h < (n_{op} - 1)r_E$. The above analyses are all based on scenarios where the satellite is directly above the gateway or terminal. It should be noted that the actual total path length will likely be shorter. Ideally, the line from the gateway or terminal to the satellite is inclined at an angle to the terrestrial while $d_{ideal} = (r_E + h)d_E/r_E$ and t_{ideal} also can be calculated. However, it also depends on the relative location of the terrestrial gateway or terminals and the density of satellites. Due to the motion of the satellite with respect to the terrestrial gateway or terminal, the minimum latency occurs only briefly. The latency perceived by the user is subject to change, and the period of change is related to the altitude of the satellite. Still, we can estimate the minimum latency more accurately from this. Given any two points on Earth and the satellite altitude, the propagation latency of the satellite path can be calculated and compared to the terrestrial fiber path. Another variable is the satellite altitude, at a given distance between two points, we can determine whether satellite transmissions located at different altitudes are conducive to lowering the latency by comparing the terrestrial and satellite transmission latency.

3.3 End to End Transport Strategy

Based on the above analysis we give two different E2E transmission strategies, which are E2E transmission strategy based on given location and E2E transmission strategy based on given satellite altitude as shown in Algorithm 1 and Algorithm 2.

In Algorithm 1, after giving the latitude λ_1, λ_2 and longitude φ_1, φ_2 of the two points for E2E transmission, the E2E transmission distance d_E can be calculated. If the orbit altitude h of the satellite to be launched satisfies (17), we select the SatCom transmission strategy and give the corresponding E2E transmission latency t_{n_γ}, otherwise we select the TN transmission strategy and give the corresponding E2E transmission latency t_{TN}.

In Algorithm 2, given the orbit altitude h of the satellite to be launched, if the E2E transmission distance d_E satisfies (19), then we select the SatCom transmission strategy and give the corresponding E2E transmission latency t_{n_γ}, otherwise we select the TN transmission strategy and give the corresponding E2E transmission latency.

4 Simulation Results

The simulation parameters are shown in the Table 1. First, we analyze the Doppler shift of LEO satellite in dependence of the elevation angle α for

Algorithm 1 Location Known E2E strategy

```
Input: E2E transmission longitudes $\lambda_1, \lambda_2$, latitudes $\varphi_1, \varphi_2$, Earth radius $r_E$, light speed $c$, atmospheric height $a$, refractive index $n_{op}$.
Output: E2E strategy and E2E latency.
Calculate $d_E$ by (11);
if altitude $h$ meet (17) then
    Calculate $n_{\gamma_{max}}$ and $\gamma_f$ by (12);
    Calculate $t_{n_\gamma}$ by (14);
    return SatCom strategy and E2E latency $t_{n_\gamma}$.
else
    Calculate $t_{TN}$ by (16);
    return TN strategy and E2E latency $t_{TN}$.
end if
```

Algorithm 2 Altitude Known E2E strategy

```
Input: Orbit altitude $h$, Earth radius $r_E$, light speed $c$, atmospheric height $a$, refractive index $n_{op}$.
Output: E2E strategy and E2E latency.
if E2E distance $d_E$ meet (19) then
    Calculate $n_{\gamma_{max}}$ and $\gamma_f$ by (12);
    Calculate $t_{n_\gamma}$ by (14);
    return SatCom strategy and E2E latency $t_{n_\gamma}$.
else
    Calculate $t_{TN}$ by (16);
    return TN strategy and E2E latency $t_{TN}$.
end if
```

Table 1. Simulation Parameters

System Parameters	Values
Earth radius r_E	6371 km
Orbit altitude h	550 km
Minimum elevation angle α	30°
Gravitational constant G	$6.6743 \times 10^{-11} N \cdot \mathrm{m}^2/\mathrm{kg}^2$
Earth mass M_E	$5.9722 \times 10^{24} kg$
Speed of light in vacuum c	$299,792,458\,\mathrm{m/s}$
Refractive index n_{op}	1.4675

different carrier frequency f_c and different orbit altitudes h according to (6) and (8) as shown in Fig. 2. We selected Gen1 and Gen2 Starlink user downlink frequencies and three different orbit altitude. From this figure, it is easy to see that the frequency selection has a much greater effect on the Doppler shift than the orbit height selection. Doppler shift f_d increases with increasing carrier frequency f_c. And Doppler shift f_d decreases with increasing orbit altitude h. The maximum Doppler shift happens when the satellite rises or sets since the relative velocity between the satellite and the terrestrial equipment is

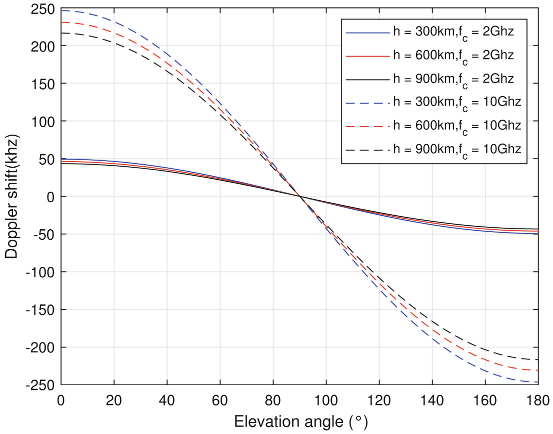

Fig. 2. Doppler shift of LEO satellite in dependence of the elevation angle α for different carrier frequency f_c and different orbit altitudes h.

maximized. The Doppler shift is minimized when the satellite passes over the top of the terrestrial equipment, where the angle between the terrestrial equipment and the direction of satellite motion is orthogonal. And since satellite motion is periodic, the change in Doppler shift is also periodic. Thus we can regularly estimate and pre-compensate for the Doppler shift due to satellite motion at the communication terminals. Obviously, the frequency shift caused by the satellite Doppler shift is much larger than that of the cellular network. After that we compare the E2E transmission latency of different schemes as shown in Fig. 3, where the ideal E2E transmission latency is the shortest. The satellite network in the comparison scenario uses the parameters of the SpaceX Gen1 Starlink constellation, i.e., an orbit altitude $h = 550\,\text{km}$ and a uniform spacing angle $\gamma_{Gen1} = 5°$ between the 72 satellites in the orbital plane [10]. Short distance communication while d_E is slightly smaller using terrestrial fiber optic networks with a slightly smaller transmission latency than STIN. When $d_E = 2900\,\text{km}$, the communication latency of terrestrial fiber network and STIN is almost the same. However, as the communication distance increases, the advantages of STIN slowly show up. The longer the communication distance, the more latency is shortened, and the more obvious the advantages of STIN will be. The latency of our proposed scheme is slightly lower than the E2E latency of SpaceX Gen1 Starlink Constellation and uses fewer satellites. If we use the proposed scheme to transmit from New York to London by the shortest path, using the speed of light in a vacuum as the transmission speed, we can achieve a latency as low as 46 ms, which would take 59 ms even if we use fiber optic cables to take the shortest route, which is a 28% drop in speed. For the financial markets in both cities, millions of dollars can be transferred in a fraction of a second, and lower latency will provide a huge advantage in capitalizing on price volatility. These companies are already looking for technological solutions such as high-speed communication networks to reduce latency, and VLEO SatCom system may provide the perfect solution.

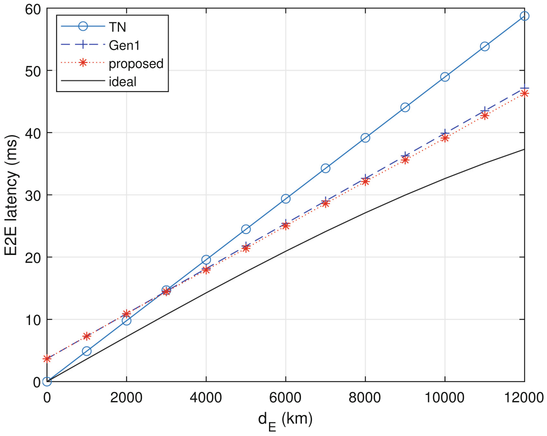

Fig. 3. Comparison of E2E transmission latency of different schemes.

Finally, the simulation analysis of Algorithm 1 and Algorithm 2 to obtain the areas of lower E2E latency for D2C VLEO SatCom transmissions is shown in Fig. 4. The parts above the blue curve are where our proposed solution is better in terms of E2E latency. For Algorithm 1, the transmission distance d_E is given, the E2E latency of SatCom strategy using ISLs is smaller while the orbit altitude h is lower than the blue curve meeting (17). For Algorithm 2, the orbit altitude h is given, the E2E latency of SatCom strategy using ISLs is smaller while the transmission distance d_E is longer than the blue curve that satisfies (19). Considering the limit cases, the lower the orbit altitude h, the longer the communication distance d_E, and the shorter the E2E latency, the more obvious the advantage of SatCom strategy with ISLs.

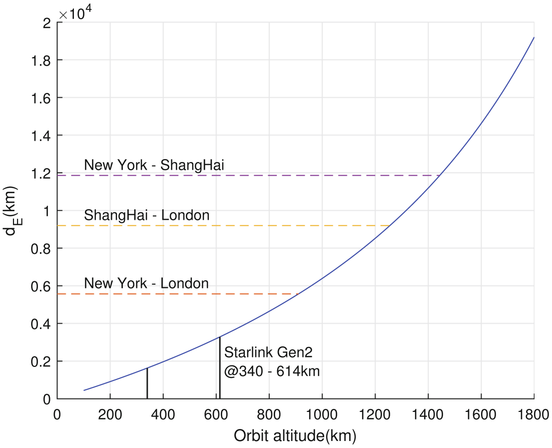

Fig. 4. Areas of lower E2E latency for VLEO SatCom transmissions.

5 Conclusion

In this paper, we analyze the terrestrial coverage and Doppler shift of D2C VLEO SatCom system to provide global coverage and low latency in STIN, especially simplify the closed expression for the Doppler shift compared to traditional methods. We also provide appropriate low latency E2E transmission strategies for different situations. The proposed E2E transmission strategy based on maximum ISLs requires fewer satellites and provides lower E2E transmission latency, which is 28% better than the conventional terrestrial E2E transmission, fully demonstrating the E2E latency advantage of the D2C VLEO SatCom system.

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