Directed Percolation Routing for Ultra-Reliable and Low-Latency Services in Low Earth Orbit (LEO) Satellite Networks

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***Abstract*—With tens of thousands Low Earth Orbit (LEO) satellites covering Earth, LEO satellite networks can provide coverage and services that are otherwise not possible using terrestrial communication systems. The regular and dense LEO satellite constellation also provides new opportunities and challenges for network architecture and protocol design. In this paper, we propose a new routing strategy named Directed Percolation Routing (DPR), aiming to provide Ultra-Reliable and Low-Latency Communication (URLLC) services over long distances. Given the long propagation delay and uncertainty of LEO communication links, using DPR, each satellite routes a packet over several Inter-Satellite-Links (ISLs) towards the destination, without relying on link-layer retransmissions. Considering the link redundancy overhead and delay/reliability tradeoff, DPR can control the size of percolation. Using the Starlink as an example, we demonstrate that with the proposed DPR, the inter-continent propagation delay can be reduced by about 4 to 21 ms, while the reliability can be several orders higher than single-path optimal routing.**

1. Introduction

Thanks to the reusable rocket technologies and the development of small-size, light-weight, and low-cost satellites, launching Low Earth Orbit (LEO) satellites becomes more economical. With tens of thousands of LEO satellites covering Earth, LEO satellite networks can provide coverage and services that are otherwise not possible using terrestrial communication systems [1]. How to provide Ultra-Reliable and Low-Latency Communication (URLLC) services over long distances has been one of the most challenging and profitable networking problems. For instance, in high-frequency trading (flash trading), the opportunity to realize a profit may be available for only a few to a fraction of a millisecond before parity is achieved. Since the propagation speed of light in the space is about 50% higher than that in fiber optical links, using LEO as the backbone for long-distance communication is anticipated to save tens of milliseconds for inter-continent transmissions. URLLC services thus are critical to the profitable operation of LEO networks.

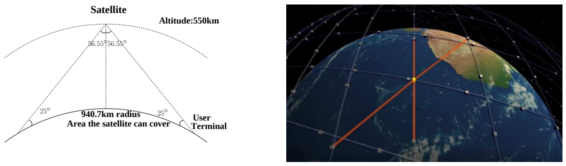
However, the current Internet architecture and TCP/IP protocol stack were designed to provide best-effort connectivities for arbitrary network topologies, and they do not take the advantages of the regular and dense LEO satellite constellation, and cannot well-support URLLC services. For instance, routing strategies on the Internet are based on various ways to implement shortest-path routing, so the optimal path can be used to minimize the metrics such as the number of hops, delay, or other link costs [2], [3]. The reliability of transmissions highly depends on link-layer retransmissions using the automatic repeat request (ARQ) protocols. In LEO, the distance between satellites are hundreds to thousands of km away, so propagation delay over a single link can take up-to tens of ms, harmful to URLLC services. Furthermore, satellites at different locations may experience severely uneven loads.

In the literature, several new routing strategies have been proposed for LEO satellite networks, aiming to balance the load or taking multi-path to enhance the throughput [2], [3], [4]. How to using redundant satellite links for URLLC services remains an open issue, which motivates this work.

Given the large bandwidth of inter-satellite optical communication links, we aim to achieve URLLC by directed percolation (DP) of packets in the network. Since the LEO network exhibits a grid structure, packets can take many possible links to reach the destination, so long as the next hop is closer to the destination. For example, Toronto is in the northeast of San Francisco, so the packet from San Francisco can be delivered towards north/east to reach Toronto. DP is a fundamental problem heavily investigated by Physics, Chemistry, Material Science, etc. To the best of our knowledge, this is the first application of DP for backbone networks supporting URLLC services.

The main contributions of this paper are three-fold. First, we propose a new routing strategy, named Directed Percolation Routing (DPR), where each satellite routes a packet over several output links towards the destination. The reliability and latency of the service can be ensured given the redundant transmissions, instead of relying on link-layer retransmissions. Second, we develop a performance analysis framework to quantify the reliability and latency of DPR, when different numbers of links are used for packet transmission. Third, using the Starlink constellation as an example, we conduct extensive simulations to obtain the delay distribution and reliability performance of DPR, compared with the optimal shortest-path routing and multi-path routing. Simulation results show that with the proposed DPR, the inter-continent propagation delay can be reduced by at least 4 to 21 ms, while the reliability can be several orders higher than single-path optimal routing. The analysis and simulation results reveal the tradeoff between the transmission cost and the service quality in terms of delay and reliability, which can be used to set DPR system parameters according to the service requirements.

The rest of the paper is organized as follows. Sec. 2 presents the system model. The proposed DPR protocol is described in Sec. 3. The analytical framework is presented in Sec. 4. The performance evaluation based on the Starlink constellation is given in Sec. 5, followed by concluding remarks and further research issues in Sec. 6.



(a) Satellite-to-Earth (b) Inter-Satellite-Links (ISLs)

Figure 1. Satellite communication links

2. System Model

We consider an LEO satellite network that has a global coverage and can provide inter-continent networking services. The Starlink project by SpaceX is leading the development of such LEO networks, and we use Starlink's planned constellation as an example. The proposed solution can be applied to other similar LEO networks. In the first phase, the Starlink constellation has 1,584 satellites in 72 orbital planes, and 22 satellites in each plane. Each plane has a $53°$ inclination and the orbit is 550 km above Earth [5]. Each satellite is essentially a flying, solar-powered wireless router. They provide global broadband Internet access.

Each satellite can use phased array antennas to exchange data with earth stations, by steering multiple narrow beams electronically. Phased-array antennas on the earth-facing side of the satellite can thus link to user terminals. The oft-described "pizza box" earth stations will provide Internet services to a group of nearby users on the ground. Each satellite can cover an area as shown in Fig. 1(a). Given the thousands of satellites flying above Earth, all stations can be covered all the time. The structure is similar to the cellular networks, while the satellite-to-earth links replacing terrestrial cellular up/down-links to/from the base stations.

Different from the traditional cellular systems where base stations are connected to the Internet with wired backbone, in the LEO system, satellites using Inter-Satellite-Links (ISLs) to form a satellite backbone network. Links between satellites in the same orbital plane are named Satellite-Link (SL) and those between satellites in neighbour orbital planes are Orbit-Link (OL) [10]. Both SL and OL are laser optical links with the following channel model.

We apply the method from [11] to present the line-of-sight (LOS) power level at the receiver. The receive power P_r is given by $P_r = AP_t$, where P_t is the transmitted power, and A is the channel attenuation. We have

$$A = \eta_t \eta_r G_t G_r L_t L_r \left(\frac{\lambda}{4\pi d} \right)^2, \tag{1}$$

where η_t (η_r) are the optical efficiency of the transmitter (receiver), G_t (G_r) are the gain of the transmitter (receiver), L_t (L_r) are the transmitter (receiver) pointing loss factor, λ is the operating wavelength, and d is the distance between the transmitter and receiver. The transmitter gain G_t is given by $G_t = (\pi D_t/\lambda)^2$, where D_t is the transmitter telescope diameter. Similarly, we can obtain the receiver gain G_r using D_r, the receiver's telescope diameter. The transmitter pointing loss factor $L_t = \exp(-G_t\theta_t^2)$, where θ_t is the transmitter pointing error; the receiver pointing loss factor $L_r = \exp(-G_r\theta_r^2)$, where θ_r is the receiver pointing error.

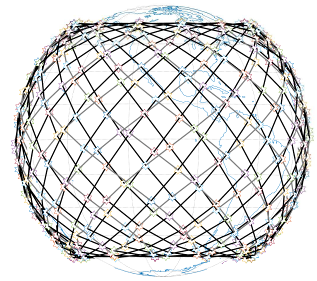


Figure 2. LEO network topology

The optical link's signal-to-noise ratio is given by $\mathrm{SNR} = P_r/\sigma_{th}^2$, where σ_{th}^2 is associated with the Gaussian-distributed thermal noise with zero mean. The noise power is $\sigma_{th}^2 = \left\langle i_{th}^2 \right\rangle / T$, where $\left\langle i_{th}^2 \right\rangle$ represents the average of the thermal noise power spectrum density and T is the reciprocal of bandwidth. We have $\left\langle i_{th}^2 \right\rangle = kT_0$, where k is the Boltzmann's constant and T_0 is the temperature of the system in Kelvins. Note that given the other system parameters, the SNR and thus link reliability largely depend on the link distance, as shown in (1).

Given the LEO topology and ISL link characteristics, the routing problem in the satellite backbone is the focus of this work. Specifically, once a message enters the LEO network and reaches a satellite, how to deliver it to the satellite that covers the destination earth station through multi-hop ISL paths needs to be determined. We name the satellite taking the packet from the earth-station and that sending the packet to the destination earth-station as source/destination satellite, respectively. Given the many multi-hop paths between the source/destination satellites, the objective is to choose the transmission links/paths that can ensure high-reliability and low-latency.

3. Directed Percolation Routing (DPR)

Note that the LEO backbone is drastically different from the traditional Internet backbone. First, all satellites are flying with high speed but at a predefined orbit and speed. Satellites in the same orbital plane have a low relative speed, while those in different orbital planes have a high relative speed. Each satellite maintains relatively stable SL links and highly dynamic OL links. Second, the locations of all satellites at any time instant are known and they form a grid topology, as shown in Fig. 2. Also, the distance and link capacity of all ISLs at any time instant can be estimated. Third, each ISL can be up-to thousand km long, which results in high propagation delay. Fourth, depending on the current locations, the traffic volumes to different satellites are highly un-even. These prominent features and the needs to support URLLC services request a re-visit to the network architecture and routing protocol design.

Traditional Internet routing aims to find a shortest path to minimize the end-to-end path cost, using centralized or distributed algorithms. In LEO, ISL links are of long distance and highly dynamic, and using link-layer retransmissions to ensure per-hop and then per-path reliability will lead to large delay variation, not desirable for URLLC services. On the other hand, given the grid topology of satellites, there are many paths between a pair of satellites with similar cost or latency. It is desirable to take the advantage of the grid topology and the many available links in the network for URLLC services.

Given the same angular velocity of the satellites with the same orbit altitude, the satellites in the same orbital plane are almost static relatively, and each uses two SL links to connect to their neighbors in the same orbital plane. Each satellite can connect to its nearest satellites in the two neighbour orbital planes for a certain period of time, as shown in Fig. 1 (b).

A simple method is to use directed flooding to send the packet over the whole grid between the source/destination satellites. If the grid starting from the source satellite and ending at the destination satellite is of size $m \times n$, directed flooding means that each satellite (acting as a router in the LEO backbone network) will relay any packet to the neighboring satellite who is closer to the destination of the packet. Using the Starlink constellation as an example, each satellite maintains four ISL links, two with the neighboring satellites in the same orbital plane and two with those in the neighbor orbital planes, as shown in Fig. 1 (b). Given the high connectivity of the LEO backbone, such a flooding strategy is prohibitively costly, as the destination may receive up to $\binom{m+n}{n}$ copies of the same packet, as there are $\binom{m+n}{n}$ paths in the $m \times n$ grid.

To avoid such flooding cost, we can ensure that each packet is transmitted only once per link, so packets will percolated in the grid towards the destination. Thus, we name it Directed Percolation Routing (DPR). Using DPR, each router in the grid will forward a packet to each of its neighbor satellites which are closer to the destination once. Since the same packet may reach a satellite through more than one links, each satellite needs to store the identity of packets being transmitted for a period of time, i.e., a timer is set for a packet identity stored, and it will be removed from the buffer when the timer expires. Meanwhile, when a satellite receives a packet from its neighbor, it will be compared with the stored packet identities. If the new arrival finds a match, the new arrival will be dropped and no further action is needed; otherwise, the new arrival's identity will be stored, and the packet will be sent to the neighbor satellite(s) who is (are) closer to the destination. According to our analysis, a timer of 50 ms is sufficient, so the storage and comparison cost introduced by DPR is limited.

With DPR, considering the $m \times n$ grid where each satellite has four ISLs, each satellite will receive at most two copies of the same packet, and it will send at most two copies out. DPR's total transmission cost of a packet in an $m \times n$ grid equals the number of links, $2mn + m + n$, which is much more affordable compared to flooding. The load is also evenly distributed to all links in the grid. Even if the movement of the satellites may lead to topology change from time to time, the location-based DPR routing can make the decision based on the current locations of neighboring satellites. Thus, the DPR routing based on locations is simple and robust.

A major benefit of DPR is that, given the redundant but evenly distributed transmissions, the end-to-end reliability can be substantially improved, without relying on link-layer retransmissions. It is particularly desirable in LEO networks for URLLC services as the link-layer retransmission is very time-consuming. When random node or link failure occurs, the redundant transmissions from the other part of the network can maintain the URLLC services.

Furthermore, the DPR can be flexibly configured to reduce the transmission cost by removing some overly-congested or undesirable ISLs from the percolation paths to make a tradeoff between transmission cost and service quality. Such a tradeoff relies on a thorough analysis of DPR performance given the network topology and each ISL's characteristics. In the following section, we will develop the analytical model to study the DPR performance.

4. DPR Performance Analysis

To quantify the performance of DPR, we first analyze the network topology using Starlink parameters. The topology can determine the SL and OL link distance and propagation delay. Then, based on the path loss model, we can obtain the link reliability. Applying the directed connectivity analytical model [7], [8], the end-to-end DPR reliability can be obtained.

4.1. LEO Topology

As satellites' movement is predictable, the LEO topology is predictable. The orbital period is $T = 2\pi\sqrt{r^3/\mu}$, where $\mu = 398600.441\ \mathrm{km}^3/\mathrm{s}^2$ on Earth, and r is the radius of Earth plus the altitude of the orbit. For Starlink, we have the period of satellites equal to 5738.82 s. Since each packet can live in the LEO backbone network for at most several hundred milliseconds, the topology of satellite networks is assumed static during the lifetime of a packet. According to the movement patterns of satellites, any source satellite can easily estimate the network topology at any time.

The LEO topology is shown in Fig. 2, where the hexagram symbol denotes satellite. The black lines are SLs and the gray lines are OLs. Starlink has 72 orbital planes, while we draw 24 here for a clear illustration. Assuming the satellites are evenly distributed in an orbit, the length of each SL is $2r\sin(\pi/m_s)$, where $m_s = 22$ (for Starlink) is the number of satellites in an orbital plane.

As shown in Fig. 3(a), for circular orbits of Earth, there is an intersection line of any two orbits (red orbit and green orbit) through the geocenter. The two intersection points of the two orbits are denoted by I and I'. Denote the 22 satellites in the green orbit by $B_1^1, B_2^1, B_3^1, ..., B_{22}^1$, marked in blue hexagram. Their projections on the red orbit are denoted by $B_1'^1, B_2'^1, B_3'^1, ..., B_{22}'^1$, marked in green diamond, where $\angle IOB_{1n} = \angle IOB'_{1n} (1 \leq n \leq 22)$. In arcs $\widehat{B_n'^1 B_{n+1}'^1} (1 \leq n \leq 21)$, the middle point in arc $\widehat{B_{22}'^1 B_1'^1}$ is M_{22}. To minimize the average distance of OLs, the most suitable satellite in the neighbour orbital plane should be in arcs $\widehat{M_n M_{n+1}} (1 \leq n \leq 21)$ or $\widehat{M_{22} M_1}$.

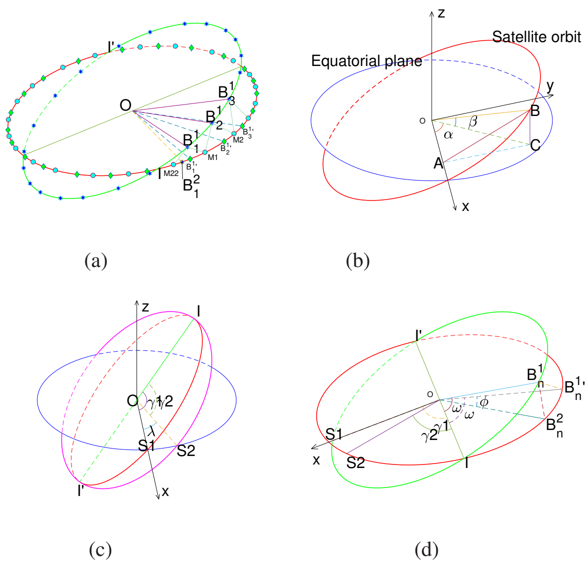


Figure 3. Distance model of satellites in neighboring orbital planes

Only one satellite will be located in each arc when the satellites are evenly distributed in the orbital plane, denoted by $B_1^2, B_2^2, B_3^2, ..., B_{22}^2$. Satellite B_n^1 and B_n^2 are the matched satellites in the neighbour orbital planes and their links are OLs. Next, we calculate the distance between two satellites and the OL distance.

4.2. Satellite Distance

We first define a convenient coordinate system for satellites to calculate their distance. Let the geocenter (point O) be the origin. The x-axis is on the lines of intersections between the equatorial plane and the satellite orbit plane. The z-axis is perpendicular to the equatorial plane. The y-axis is perpendicular to x- and z-axes, constituting the right-handed system. Satellites are located in the spherical surface whose sphere center is O and the radius is r. The longitude ranges from 0 at the meridian, which passes through the forward x-axis, to π eastward and $-\pi$ westward, and the latitude ranges from 0 at the Equator to $\pi/2$ at the North Pole and $-\pi/2$ at the South Pole.

Each satellite's altitude and latitude are affected by the inclination of its orbit. As shown in Fig. 3(b), for a satellite located at point B, set its longitude and latitude angles as α and β. Point C is the projection of B in the equatorial plane (the blue circle). Line BA is perpendicular to OA, so CA is also perpendicular to OA. In $\triangle OBC$, $\angle BOC = \beta$, $|OB| = r$, so $|OC| = r\cos\beta$, $|BC| = r\sin\beta$. In $\triangle ABC$, the inclination of the satellite orbit is $\angle BAC = \theta$. In Starlink, $\theta = 53°$ in all orbits, so $|AC| = r\frac{\sin\beta}{\tan\theta}$. In $\triangle OAC$, $\angle AOC = \alpha$, so $\sin\alpha = \frac{\tan\beta}{\tan\theta}$. In $\triangle OAB$, set $\angle AOB$ as the initial phase angle γ, $\sin\gamma = \frac{\sin\beta}{\sin\theta}$.

In our coordination system, the coordinate of B is $(r\cos\alpha\cos\beta, r\frac{\sin\beta}{\tan\theta}, r\sin\beta)$. For any two satellites with altitude and latitude angles of (α_1, β_1) and (α_2, β_2), respectively, their distance $L = r[(\cos\alpha_1\cos\beta_1 - \cos\alpha_2\cos\beta_2)^2 + (\sin\alpha_1\cos\beta_1 - \sin\alpha_2\cos\beta_2)^2 + (\sin\beta_1 - \sin\beta_2)^2]^{1/2}$.

4.3. Distance of OLs

Point I is an intersection of two orbits. As shown in Fig. 3(c), γ_1 (γ_2) is the angle between OI and OS_1 (OS_2). We denote the latitude angle of I by β_I and the longitude angle by α_I. We have $\sin\alpha_I = \sin(\alpha_I - n\lambda)$ for ($n = 1, 2, ..., m_o - 1$), where $m_o = 72$ is the number of orbital planes and $\lambda = 2\pi/m_o$. If two orbits are neighbours, $n = 1$. Then $\alpha_I = (\pi + \lambda)/2$. Set $\angle IOS1 = \gamma_1$ and $\angle IOS2 = \gamma_2$. We have $\gamma_2 = \arcsin[\sin(\arctan(\sin(\frac{\pi-\lambda}{2})\tan\theta))/\sin\theta]$ and $\gamma_1 = \pi - \gamma_2$.

For a satellite in the green orbital plane, B_n^1, its coordinate is (α_1, β_1), and its matched satellite in the red orbital plane, B_n^2, has the coordinate of (α_2, β_2). Define $\angle IOB_n^1 = \omega$, so $\angle IOB_n'^1 = \omega$ $(0 \le \omega < 2\pi)$. Define the angle between the two orbital planes as $\angle B_n'^1 OB_n^2 = \phi$, in the range of $-\frac{2\pi}{2m_s} < \phi \le \frac{2\pi}{2m_s}$. Next, we have $\angle IOB_n^2 = \omega + \phi$. As shown in Fig. 3(d), $\sin(\gamma_1 + \omega t) = \sin\beta_1/\tan\theta$ and $\sin(\gamma_2 + \omega t + \phi) = \sin\beta_2/\tan\theta$. Next, we have $\sin\alpha_1 = \tan\beta_1/\tan\theta$ and $\sin(\alpha_2 - \lambda) = \tan\beta_2/\tan\theta$ (keep α_1 and $\gamma_1 + \omega t$ in the same quadrant, and α_2 and $\gamma_2 + \omega t + \phi$ in the same quadrant). Finally, plugging in the formula of distance between two satellites in Sec. 4.2, we can calculate the OL distance.

4.4. Bond Probability and End-to-End Reliability

In Starlink, the satellite height is 550 km above Earth, still inside the atmosphere, so we can use the propagation channel model in Sec. 2. Given the OL and SL link distances obtained, and plugging into the channel model in Sec. 2, we can obtain the SNR of each ISL.

The demodulation error probability with M-ary pulse-position modulation is given by [12]

$$P_e = \frac{(M-1)}{(\pi\mathrm{SNR})^2}\exp(-\mathrm{SNR}/4). \tag{2}$$

The bit error rate is related to P_e by

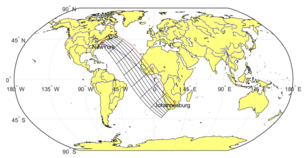
$$\mathrm{BER} = 2^{k-1}P_e/(2^k - 1), \tag{3}$$

where $k = \log 2M$. Finally, the packet loss rate in the link can be expressed as

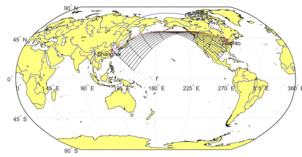
$$P_l = \exp\left(N\log(1 - P_e)\right), \tag{4}$$

where N is the packet length.

In percolation theory, each link is called a bond, and the probability that a link is connected is called the bond probability, p. Since with DPR, each packet is transmitted over a link once, the packet loss rate of a link thus equals one minus the bond probability. Given the lattice grid and the bond probability of each link, the end-to-end reliability (or connectivity) can be calculated using the recursive numerical method given in [7], [8]. Based on the end-to-end reliability analysis, we can further tune on/off links in the network to make a tradeoff of transmission overhead and performance. Such a tradeoff can be observed from the performance evaluation below.



(a) New York-Johannesburg



(b) Toronto-Shanghai

Figure 4. Quadrilateral grid

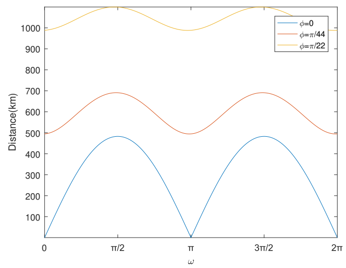


Figure 5. OL link distance

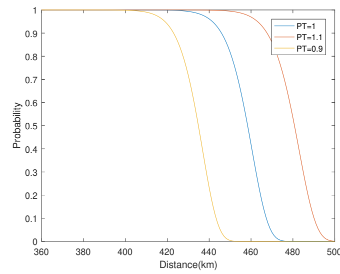


Figure 6. Probability of bonds

TABLE 1. SIMULATION PARAMETER SETTINGS

Parameters	Values
bandwidth (GHz)	400
pulse-position modulation	1024-ary
operating wavelength (nm)	1550
transmit power (dBm)	20
transmitter/receiver aperture diameter (mm)	150
transmitter/receiver optics efficiency	0.8
transmitter/receiver pointing error (μrad)	1.1
temperature (Kelvin)	289.85

5. PERFORMANCE EVALUATION

To evaluate the performance of DPR in LEO networks and validate the analysis, we conducted simulations using Starlink system parameters, and considered a few important inter-continent source-destination pairs.

Starlink covers the whole Earth except the Arctic and Antarctic, so all cities are always covered. Given the location of two cities (e.g., New York to Johannesburg and Toronto to Shanghai), at any time, we can easily identify the satellites covering the corresponding earth-stations. The quadrilateral satellite grid between New York and Johannesburg is plotted in Fig. 4(a), while the grid between Toronto and Shanghai contains a fold, as shown in Fig. 4(b). The blue line is the trace as the crow flies. The red line in the quadrilateral networks is a shortest path in the LEO network.

OL Distance – Following the analysis in Secs. 4.2 and 4.3, the distance of OLs can be calculated with a fixed gap ϕ. Fig. 5 shows the distance of OLs. Obviously, a smaller gap ϕ always has a shorter distance. Thus, $\phi = 0$ will lead to the shortest distance and the highest reliability.

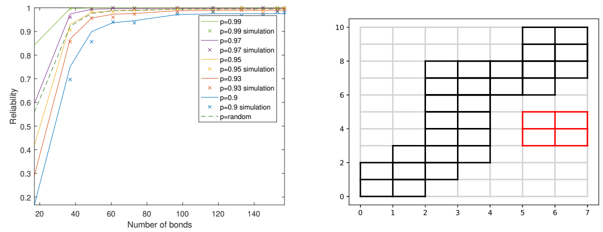
Bond Probability – By calculating the distance of the SLs and OLs, we can obtain the bond probability (p) of each link using the formula in Sec. 4.4. The parameters are given in Table 1. The hardware parameters are from [6].

Fig. 6 shows the relationship between distance and bond probability with a fixed transmit power. From the figure, p is very distance sensitive. When the distance is above a threshold, p quickly drops to zero when the distance is further increased by 50 km. If we use a high transmit power, the system may waste energy substantially; if we use a low transmit power, some links with long distances can hardly deliver any message successfully. To achieve reasonable performance, transmit power should be adjusted for different ISLs to keep p in a reasonable range. In the following, we set $0.9 \leq p \leq 0.999$.

Reliability – To investigate the tradeoff of link cost and performance, we can activate a part of ISLs in a grid. Given the nature of DPR, we use the number of active bonds (links) instead of path number for performance comparison. Here, the number of active bonds is proportional to the communication cost.

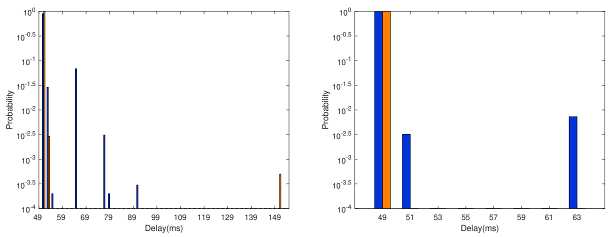
We consider the 10×7 quadrilateral grid network between Toronto and Shanghai as an example, where there are in total 157 links (bonds) in the grid. To deliver a packet from the source to destination, the least number of active bond number is 17 when a single 17-hop path is used. We chose the optimal single-path to obtain the path-reliability and tuned p for all links from 0.9 to 0.99, and we also investigated the scenario where the bond probability of each link is randomly chosen between 0.9 and 0.99. As shown in Fig. 7(a), using single-path routing, even when $p = 0.99$, the end-to-end reliability is only 0.85, not desirable for URLLC. On the other hand, with the increase of the bond number, DPR achieves a higher reliability. When $p = 0.99$, using 61 active bonds can achieve a close to one reliability, so we can turn off the rest 97 to save cost. In the situation of congestion, we can inactivate those bonds with higher traffic loads. When p is as low as 0.9, we can still achieve above 0.98 end-to-end reliability when we activate about 100 bonds. Fig. 7(a) also shows that the simulation results match the analysis well. The dotted line shows DRP in heterogeneous bond probability (average of 0.95). We can found the performance is similar to the homogeneous bond probability case ($p = 0.95$) when there are more than 37 active bonds. Fig. 7(b) shows a simple example of selecting bonds to avoid busy bonds (those in red). The black bonds are active and the rest are inactive. How to avoid congestion and ensure load balancing remains an open issue.

Delay – Next, we simulated the shortest path routing and DPR to evaluate the delay performance. For shortest single-path routing, we chose the path with the smallest delay between the two cities, and the lost packet will be retransmitted in the link layer. On the other hand, for the



(a) Reliability (b) Avoiding congestion

Figure 7. Active bond number vs. reliability, Toronto to Shanghai



(a) $p = 0.99$ (b) $p = 0.999$

Figure 8. Delay distributions, single path (blue) vs. DPR (orange)

proposed DPR, the packet will be retransmitted only if timeout (when zero copy is reached in the destination and no end-to-end ACK is received by the source). For each setting, $10,000$ packets were transmitted and their delays were measured.

The resulting delay distribution when $p = 0.99$ and $p = 0.999$ are shown in Fig. 8(a) and (b), respectively, where the blue bars are for single-path and the orange bars for DPR. From the figures, not only the average delay of DPR is smaller, more importantly, using the shortest-path routing, about 10% of packets suffering a delay jitter more than 20 ms when $p = 0.99$, while only 0.02% of packets suffering delay outage using DPR. When $p = 0.999$, about 1% of packets suffering a delay jitter around 14 ms using the shortest-path routing, and all packets can reach the destination within 50 ms using DPR. Thus, DPR is more desirable for URLLC services.

We also chose four inter-continent pairs of Johannesburg and Rio de Janeiro, Shanghai and Toronto, Tokyo and Paris, and New York and Canberra to compare the performance in Table 2. To ensure URLLC services, we have $p = 0.999$, and no link-layer or end-to-end retransmission is used. From Table 2, with DPR, the reliability crossing the LEO backbone is about 99.9998%. Furthermore, since the light propagation speed over the air is about 50% higher than that in fibre optical cables, even using the direct distance to under-estimate the propagation distance of fibre cables, the inter-continent backbone in LEO can still save at least 4 to 21 ms one-way propagation delay, making LEO a game changer for time-sensitive applications such as flash trading.

6. Conclusions

In this paper, we developed the Directed Percolation Routing (DPR) for LEO backbone. First, we abstract the network into a quadrilateral topology. Each packet can be

TABLE 2. RELIABILITY AND DELAY PERFORMANCE

	Johannesburg – Rio de Janeiro	Shanghai – Toronto	Tokyo – Paris	New York – Canberra
Direct distance (km)	7100	11537	9887	16303
LEO path distance (km)	9405	14164	12096	18225
LEO grid	3×13	7×10	6×9	9×7
Loss rate with DPR	$2.0e-6$	$2.0e-6$	$2.0e-6$	$2.0e-6$
Min delay reduction (ms)	4	11	9	21

directly percolated in an $n \times m$ grid network to reach the destination. Furthermore, we can inactivate some ISLs to control the size of percolation to avoid congestion or reduce the transmission cost. From the analytical and simulation evaluation, the reliability and delay performance of DPR can support inter-continent URLLC services.

Given the unique features of LEO satellite backbone, there are many open issues beckoning further investigation. For DPR, bonds can be heterogeneous and some bonds are more critical than the others, e.g., the two connecting to the source and the two to the destination. How to apply a random forwarding probability in different part of the networks to reduce overhead, ensure load balancing, and avoid congestion, while maintaining the service quality needs further investigation.

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