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Networking in Interstellar Dimensions: Communicating with TRAPPIST-1

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***Abstract*—The recent discovery of potentially habitable planets orbiting the TRAPPIST-1 system intensified interest in interstellar exploration. In these challenging mission concepts, communication protocols would need to cope with unprecedented signal propagation delays. In this work, we propose and explore Delay Tolerant Networking (DTN) technologies and analyze in a case study based on the TRAPPIST-1. Results suggests that DTN protocols features could become a valuable means to achieve data delivery in future interstellar networks.**

***Index Terms*—Space Networking, Interstellar Networking, Delay/Disruption Tolerant Networking, TRAPPIST-1**

I. Introduction

A total of 2858 stars are known to have orbiting planets, 632 of which are multiplanetary systems with at least two confirmed planets [1]. Among these, the TRAPPIST-1 system has gained significant attention from the community since February 2017, after astronomers announced that three of its seven planets orbit in the so-called habitable-zone [2]. Although the discovery renewed public interest in interstellar exploration, the fundamental problem of interstellar flight is still of course distance, which imposes significant challenges (yet unresolved) to the spacecraft's power supply, propulsion and braking systems. Flight kinematics have been the main focus of interstellar research; however, the supporting communication architecture of such missions also demands attention as it would need to cope with unprecedented signal attenuation and propagation delays.

A reliable communication architecture would be needed in order to control, operate, and troubleshoot future interstellar endeavors, be they small probes, satellites, or manned missions. As discussed in [3] and in the present paper, the immense interstellar distances argue for an autonomous multi-hop relay strategy instead of a direct point-to-point link. Networked multi-hop transmission of information happens on an everyday basis on Internet, but interplanetary and near-Earth space environments certainly impose different communication challenges [4], [5]. In particular, the large signal propagation time, the effect of planet rotation, and on-board power restrictions result in severe communication delays and frequent disruptions. These conditions contraindicate traditional Internet protocol operations, which are largely based on virtually instant and reliable flow of information between sending and receiver nodes.

As a result, the Delay/Disruption Tolerant Network (DTN) architecture has been considered as an alternative to extend Internet boundaries into space [5]–[8]. Even though DTN protocols have been widely studied [9]–[12] and validated in orbit [13]–[15], they have not been assessed beyond the solar system. Indeed, while interplanetary delays are typically on the order of hours, the interstellar propagation time is generally on the order of years. In this paper, we present an analysis of how DTN protocol principles could drive advances in networking infrastructure to communicate with remote areas of the galaxy. To this end, we analyze and simulate an appealing case study based on an interstellar DTN-based relay system connecting the Earth with the TRAPPIST-1 planetary system. Besides a brief reference to the idea of the authors in [16], this is the first time that DTN has been proposed and studied at interstellar scale.

This paper is structured as follows. In Section II we provide an overview of the interstellar dynamics and current technologies. Section III presents a general overview of DTN and discusses how its features can facilitate communications in an interstellar environment. A thorough analysis of simulations based on the TRAPPIST-1 case study is presented in Section IV and further discussed in Section V. Section VI closes this article by presenting the conclusions and future perspectives.

II. Interstellar Environment

A. Interstellar Dynamics

The nearest star, Proxima Centauri, is about 1.3 pc (parsecs[1]), equivalent to 4.2 light-years from the Sun [17], while the TRAPPIST-1 star is located approximately 12.1 pc or 39.5 light-years away. While the absolute positions of stars such as Proxima and TRAPPIST-1 are governed by the galactic potential, simulations (comparisons between numerical integrations of an isolated N-body system and the same system of non-interacting particles each moving under the acceleration of the galactic potential) show that all the stars of the solar neighborhood move with constant relative speed over any given interval of, say, a hundred thousand years [18]. Furthermore, over realistic interstellar travel times (a few decades or a few hundred years), the stars within the local star neighborhood

[1]A parsec is equal to about 3.26 light-years (31 trillion kilometers).

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can generally be assumed at rest. Thus, our main discussion is focused on the interaction of a spacecraft in a mostly static interstellar environment.

Besides the relative immobility of nearby stars, the analysis in [18] demonstrated that the force environment in which a spacecraft would travel on an exploration mission is simpler than expected. The reason is that an interstellar traveling object can be affected by the gravitational forces of stars, or star systems, only when it approaches them closely. In particular, when the spacecraft leaves the influence of its departure system (i.e., the solar system), it flies solely under the forces induced by the galactic potential. The gradient of this potential is so small that the spacecraft can be assumed to be affected by no forces at all. Figure 1 shows the Laplace spheres of influence [19] of the stars that populate the solar neighborhood within 7 pc of the Sun (the radii of the spheres were computed assuming a value of 2×10^{11} solar masses for the mass of the Galaxy [20]). For example, at the surface of the Laplace sphere of the Sun the gravitational acceleration due to the stars within 7 pc is close to $10^{-11} m/s^2$. In practice, this acceleration can be generally disregarded and the speed of the spacecraft can be considered virtually constant outside these spheres.

This has two important consequences: a) that by properly imparting velocity impulses, a spacecraft can be stably positioned anywhere outside the gravitational domain of the stars, and b) that travel between the stars can occur on rectilinear orbits. Furthermore, an interstellar spacecraft can also be conveniently stationed within the area of influence of a star system. One possibility is to perform an orbit transfer toward the remote star or to a free-floating planet (a planet that is not bounded to any star; such planets are known to be present throughout the galaxy [21]). In the case of a multi-star system, a spacecraft could also rest with minimal station-keeping maneuvers at the libration points (a.k.a Lagrange points) where the gravitational effects of the stars are balanced.

As a result, there seems to be no theoretical impediment nor difficulty in accurately deploying both fixed and mobile spacecraft in the interstellar medium. That said, gravitational effects aside, the interstellar space remains a generally unknown environment for humankind. Moreover, several technological challenges to efficiently power and propel an object across such immense distances remain unmet.

B. Interstellar Propulsion and Power Technologies

Pioneer 10 and 11 (launched towards Jupiter in 1972 and 1973 respectively) have reached escape velocity and will penetrate into interstellar space. Unfortunately, both have fallen silent due to the expected aging of their power sources (Radioisotope thermoelectric generators, or RTGs) [22]. Voyager 1 and 2 (twin spacecraft launched in 1977) are still transmitting data and Voyager 1 became the first probe to pass through the heliopause, and enter interstellar space in 2012. Voyager 1 also has the highest asymptotic speed of any spacecraft leaving the solar system: around 3.6 AU (Astronomical Unit[2]) per year. Additionally, if the New Horizons mission continues as scheduled, then it will become the fifth human-made object to reach interstellar space, albeit at the much lower velocity of 2.5 AU per year.

[2]An Astronomical Unit is equal to 1.495979×10^8 km, the mean distance from the Sun to the Earth.

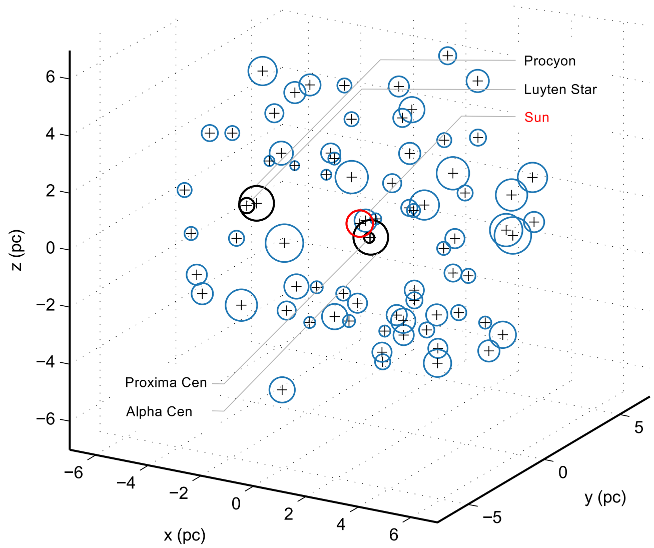

Figure 1. Sphere of influence of nearby stars (retrieved from [18])

Even at its record-setting speed, the Voyager 1 spacecraft would take around 74,000 years to reach Proxima Centauri and almost 690,000 to reach the TRAPPIST-1 system (assuming constant speed and a direct course). In order to reduce interstellar travel time, several projects have been undertaken with the objective of advancing the state-of-the-art of propulsion systems. The Daedalus project [23] (and its successor Icarus [24]) studied nuclear fusion as a means to achieve a cruise speed of 12% of the speed of light. Another popular concept that reports a possible cruise speed of 20% of the light speed is the microwave sail, which is similar to a solar sail in concept but is powered from a man-made source through huge microwave lenses [25]. Alternative approaches were analyzed by the Realistic Interstellar Explorer project which proposed a deep fall from Jupiter to the Sun, where a large propulsive maneuver would propel a probe on a high-energy, ballistic escape trajectory of 20 AU per year [26]. The same project also suggested extremely slow-decaying RTG configurations to support electric propulsion and power supply to probes with multi-decade lifetimes.

In general, the sustained interest of the research community in efficient propulsion and long-lasting power supply alternatives suggests that small unmanned probes could be launched into interstellar voyages within the next few decades [27]. However, such enthusiasm is not shared within the communication community, which has not yet provided a comprehensive analysis of how protocol strategies could cope with the challenges of the interstellar domain.

C. Interstellar Communications

Communication signals from the Voyager spacecraft get weaker as they travel away due to the inverse square law of

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signal power. To extract such feeble signals, high-gain ground station antennas are being continuously re-engineered [28]. Similarly, scientists have sought signals transmitted by extraterrestrial life located outside the Solar System for years. Studies on these receiving systems showed that antenna arrays are a cost-effective solution for receiving signals from a few hundred light years from Earth [29]. However, the larger the distance, the more significant the challenge in obtaining a suitable sensitivity in the receiver system.

In order to extend the range of interstellar communications, alternative methods have been studied. For example, an optical link could allow a higher concentration of energy in a laser beam. However, the optical downlink would require extremely accurate pointing unattainable with current orientation determination and control technologies [30]. As a result, more exotic methods of communication have also been explored. For example, gravitational wave emissions would supposedly enable a drastic increase in communication distances due to their immunity to the interference of intervening matter [31]. However, these methods remain open research topics and their practical implications and implementation characteristics are still unknown. If we are only considering current technologies, scalability limitations will eventually become prohibitive in direct long-range point-to-point communication systems.

To avoid concentrating all signal decoding effort in a point-to-point ground facility, Khan [3] suggested the deployment of repeaters at appropriate locations as the mother spacecraft traverses interstellar space. In the proposed method, the spacecraft would send information directly to the nearest repeater, which would amplify the received signal and retransmit it to the next repeater. Although this strategy is analogous to repeaters widely used in wired and wireless technologies, its applicability in space requires special attention. In this regard, Khan proposed an appealing architecture and a suitable physical layer for an interstellar multi-hop repeater communication system. However, the study disregarded channel errors and, thus, did not consider higher level protocols that could guarantee correct data delivery. Indeed, to the best of the authors knowledge, none of these higher-level features have yet been analyzed in the multi-hop interstellar domain.

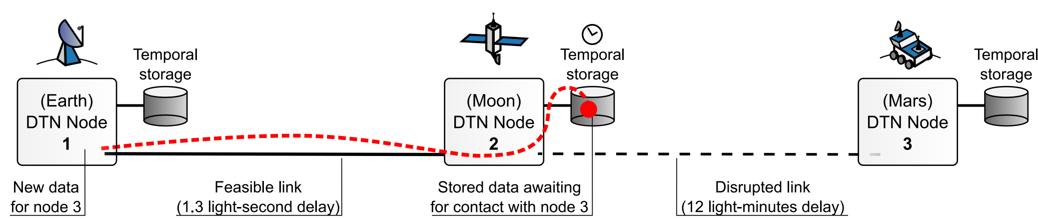
III. Delay/Disruption Tolerant Networks

A. DTN Overview

In order to overcome high signal delays, the Delay/Disruption Tolerant Network (DTN) architecture assumes that end-to-end feedback messages, widely exploited in Internet protocols, may no longer be continuous nor instantaneous [5], [6]. In other words, the transmission of data must not be interrupted nor affected while waiting for a confirmation of reception from the next hop [32]–[34]. In order to tolerate disruptions, local memory in intermediate relay nodes is typically exploited to temporarily store in-transit data [35]. As a result, the DTN architecture enables the network to reliably forward information in a store-and-forward fashion without assuming the next-hop node will instantly be available to respond [7]. While delay is the predominant phenomenon in interstellar communications, both high-delay links and network disruptions are addressed by the same principles of store-and-forward transmission and minimal end-to-end control messages.

Similar to the scenario analyzed in [36], [37], Figure 2 illustrates an interplanetary DTN where node 1, located on Earth, sends data to a rover on Mars (node 3). Since there is no direct communication between the source and destination nodes, data needs to go through intermediate node 2 orbiting the Moon. However, the visibility between nodes 2 and 3 does not allow establishing the link yet (the rover might be in the other side of Mars). Thus, node 2 decides to retain in-transit data in its local storage until the contact with node 3 becomes available after the planet rotates. In this context, DTN feedback messages are minimized due to both high channel delays (i.e., a signal traveling at light-speed from the Moon to Mars takes 12 minutes on average) and the lack of a stable end-to-end path. Furthermore, node 2 can become a *custodian* of the stored data in order to guarantee its successful delivery. The core idea is to hand over a bundle to a node together with a request to guarantee delivery of the data. If this request is confirmed by the next node on the path, the local copy of the bundle can be deleted due to the given delivery guarantee.

Custody transfer procedures are part of the reliability features of DTN, and given their particular relevance in the interstellar domain, they will be separately discussed in Section III-B.



	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Avg. Distance to Sun (UA)	0,38	0.72	1.00	1.52	5.21	9.54	19.18	30.11
Latency	3 min	6 min	8 min	**12 min**	43 min	1h20	2h40	4h10

Figure 2. Store, carry and forward in DTN

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During the last decade, DTN technology has received significant attention from the communication community. In particular, the Bundle protocol has been proposed [9], several routing strategies have been studied [10], and diverse software stacks have been publicly released (e.g. the ones described in [11], [12]). In general, these DTN solutions are proposed as overlay layers on top of existing protocols (i.e., Internet protocols, space links, wireless sensor networks, etc.). Most recently, the Internet Engineering Task Force (IETF) standardization community and the Consultative Committee for Space Data Systems (CCSDS) are both pursuing the standardization of these DTN advances. DTN protocols have been successfully validated in near-Earth [13] spacecraft operations, and are presently operational on the International Space Station (ISS) [14]. Moreover, NASA's DINET experiment successfully demonstrated the applicability of DTN technology over long-range interplanetary deep-space links (distances between 40 and 80 light seconds) [15]. This remarkable experiment confirmed that DTN principles can pave the way toward autonomous networks in the interplanetary domain.

B. Towards Interstellar DTN

In this work, we push DTN applicability from interplanetary to the interstellar domain. Table I summarizes and compares the magnitude of the expected delays between direct communication partners (thus, hop-by-hop) and the reasons of possible disruptions in the near-Earth, interplanetary (i.e., solar system), and interstellar environments. In general, DTN principles can be generalized towards a drastic latency increment. However, the storage resources required to implement technological solutions in such a vast domain require further analysis. Indeed, the latter is a main objective of the present paper.

In DTN, primary responsibility for reliable data delivery is moved from the end-to-end to the hop-by-hop domain: end-to-end feedback on the order of several years is of no use for the communication architecture. To this end, DTN nodes may optionally provide *custody transfer*. Accepting a message and acknowledging custody transfer for it implies promising not to delete it until it can be reliably delivered to another DTN node providing custody transfer (or to the message's destination), to the best of the ability of the forwarder [38]. Therefore, custody transfer enables the protection of in-transit data, so that end hosts no longer need to keep a copy of data that has been custodially transfered to a next hop. Furthermore, custody transfer serves as a resource and congestion mitigation, as nodes with consumed buffers may reject custody while still forwarding the message to the next hop.

Table I
PREDOMINANT HOP-BY-HOP DELAY AND DISRUPTION EFFECTS

	Delay	Disruption
Near-Earth	On the order of milliseconds	Due to Earth occlusion
Inter-planetary	On the order of minutes or hours	Due to planets occlusion
Interstellar	On the order of days, months, or years	Due to attitude-related constraints.

Given the immense distances and the potential degradation of data in the resource-constrained communication systems of future interstellar probes, a reliability mechanism is mandatory. In this context, DTN custody transfer strategies can be effectively implemented on top of interstellar relay networks as discussed in Section II-C. Indeed, these reliability features can complement the physical layer measures proposed in [3].

IV. INTERSTELLAR DTN RELAY NETWORK ANALYSIS

To evaluate interstellar custody transfers, we propose to deploy a relay network with mobile relays every few light-hours. By this approach, retransmissions in the case of data loss can be performed by the previous relay to avoid 39.5-year retransmission cycles (at least if we assume a communication technology that renders transmission via such a distance possible). In order to provide estimates of the necessary buffer sizes and delay characteristics resulting from retransmissions, a general analysis has been conducted using this network of relays.

The overall trade-off in the proposed relay network is obvious: if on one hand only a few relays are placed between our solar system and TRAPPIST-1, the complexity and cost of single relays would be huge. The extreme path loss would result in enormous requirements to the deployed communication systems and huge delays would demand for very large buffers to store data until custody transfer has been acknowledged by the next relay. On the other hand, deploying a huge amount of relays results in enormous deployment as well as operational costs.

In the remainder of this section, first the feasibility of high-speed data transmissions between relays with light-hours distances is discussed, based on a coarse-grained analysis of the link budget. Secondly, an analytical model for required on-board storage and increased delays resulting from retransmissions based on the achieved packet error rate is presented.

A. Link budget analysis for interstellar relay networks

The predominant factor relevant to deep-space data transmissions is *free space path loss* resulting from the extreme distances involved. This significantly reduces the received signal power, depending on the distance to an amount which can barely be detected by state-of-the-art high-performance receivers. Based on [39], the received signal power[3] can be calculated using

$$P_r(dB) = P_t + G_t + G_r - L_{FS} - L_o. \quad (1)$$

The factors influencing the received signal power are the transmitter power P_t, the transmitter gain G_t, the receiver gain G_r, the free space path loss L_{FS}, and other losses such as transmission line losses, atmospheric losses, antenna polarization losses, and antenna pointing losses, summarized

[3]Note: All link equations are represented in *decibel (dB)* form in this paper. For the numerical form and more in-depth information, the reader is referred to [39].

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in the equation as L_o. The transmitter power of deep-space relays is limited by their power supply as well as the required cooling for the transmission systems, also depending on their efficiency. The transmitter gain G_t is determined by the available antenna. Parabolic reflector antennas are the most efficient type as they can produce a very focused beam. Their gain is influenced by the reflector diameter, the used radio frequency, and the aperture efficiency. Antennas also incur some losses, namely pointing and polarization loss. The former results from inaccurate pointing of the antenna beam, which has to be more accurate the more focused the beam is. The latter results from polarization mismatch and is typically very small for carefully engineered deep-space systems. It is assumed that the receiving and transmitting antennas are either the same or equivalent in terms of their gain and losses. Thus, the receiving antenna gain G_r and its pointing loss are assumed equal to the values calculated for the transmitter. The free space path loss L_{FS} can be calculated from the distance d and the signal wavelength λ using

$$L_{FS}(dB) = 20 \cdot log_{10}(\frac{4\pi d}{\lambda}). \quad (2)$$

In addition to the received signal power, the noise power at the receiver has to be determined. For deep-space systems the primarily relevant source of noise is thermal noise by incoming radiation as well as by the receiver system. The thermal noise can be represented as a single *system noise temperature* value, termed t_s. For the complete calculation, the reader is referred to [39]. The received noise power N can then be determined as follows,

$$N(dB) = k + 10 \cdot log_{10}(t_s) + 10 \cdot log_{10}(b) \quad (3)$$

where k is the Boltzman constant ($-228.6\ dBw/K/Hz$) and b is the system filter bandwidth (and, thus, the noise bandwidth) in Hz. The relation of the received signal and noise powers determines the *carrier-to-noise ratio (CNR)* of the system. Using that value, the achievable bit rate can be estimated. Every modulation and coding scheme has specific requirements regarding the CNR and results in a specific error rate based on that. For digital schemes, the main value of interest is the *energy-per-bit to noise density ratio (E_b/N_0)*. It is derived from the CNR using the signal bandwidth and the bit rate. This relation can also be employed to calculate an achievable bit rate, given a specific minimum value for E_b/N_0, using

$$br_{max} = b \cdot r_{coding} \cdot 10^{\frac{1}{10} \cdot (CNR-(E_b/N_0)_{min})} \quad (4)$$

where b stands for the signal bandwidth and r_{coding} is the code rate of the used coding scheme, i.e. the ratio of data bits to (transmitted) coded bits.

The discussed relations can be used to estimate achievable bit rates depending on the distance as well as on various other factors such as antenna diameter and transmitter power. For the analysis, a small Python-based calculation toolchain has been developed.[4] However, due to the vast amount of variable parameters, some assumptions had to be made. These are summarized below. The transmitter power is assumed to be 1 kW. Though currently this may seem impossible to realize, there are some developments of reactor-based power supplies for space probes (e.g. [40]) which may allow operation at several kilowatts of power over hundreds of years. Amplifiers operating at such power further need advanced heat dissipation and cooling systems which are also assumed to be implemented. The transmission frequency is assumed to be a common Ka-band frequency of 35 GHz. The antenna efficiency has been set to 70 % which is roughly equal to that of the current *Deep-Space Network (DSN)* antennas. The pointing accuracy was set to 1 arcsecond which is equal to the accuracy of current state-of-the-art start trackers that are the source of pointing data for space probes. Transmission and reception line losses, polarization loss and atmospheric losses are assumed very small and not exceed 2 dB in total. Thus, L_o is set to that value. The overall noise temperature of the receiver system is assumed to be 15 K. The noise temperature of the cosmic background is about 2.7 K. The overall noise temperature is primarily increased by the assumed temperatures of amplifiers and connection lines within the relay. It is assumed that these are very low, which can only be achieved by a cryogenic cooling system. The link bandwidth has been set to 500 MHz. A good near-Shannon-limit coding is assumed which provides a *bit error rate (BER)* of 10^{-6} at an E_b/N_0 value of 0.23 and has a code rate of 0.5, such as the code suggested by Chung et al. in [41].

The goal when choosing these parameters was to select reasonable values which may be realizable at a time when a relay network over a distance of 39.5 light-years can physically and economically be deployed. However, even if individual parameters vary significantly, the base model and, thus, the tendency of the results stays the same. The results of plotting the bit rate as function of the available antenna diameter and the relay distance are shown in figure 3.

As it can be seen from the figure, even with the assumed very powerful transmitter and receiver systems, positioning relays within distances approaching one or even several light-days results in very low performance in terms of achievable data rates. Considering the cost and feasibility of the required antennas alone, it might be more viable to deploy more relays within a shorter distance.

The next subsection will analyze the trade-off from another point of view: the required buffer sizes and retransmission delays in case of specific transmission failure rates.

B. Buffer size and retransmission delay analysis

As discussed above, communication between relays spaced several light-hours apart is feasible, however, the demands placed on the implemented systems grow exponentially with the relay distance. This section will shed light on a further

[4]The tools and their documentation are offered for download via https://www.upcn.eu/interstellar-dtn-2017.html

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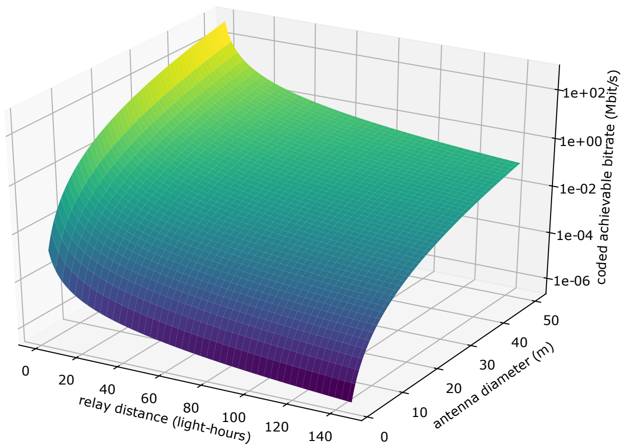

Figure 3. Achievable bit rate depending on distance and antenna diameter

issue: additional delays incurred by retransmissions of data as well as the resulting buffer size requirements at the relays.

Depending on the *bit error rate (BER)* resulting from the communication system characteristics, a part of the sent packets will be lost or damaged during transmission. This ratio, the *packet error rate (PER)*, can be calculated using

$$PER = 1 - (1 - BER)^{N_{bits}} \quad (5)$$

which takes the targeted packet size N_{bits} as a parameter.

Using the per-hop packet delivery probability (which is $P_{hop} = 1 - PER$) as input, it is possible to calculate the end-to-end delay and necessary buffer sizes. Bit rates on the links are arbitrarily assumed to be 1 GBit/s, but the linear scale of the problem enables buffer sizes for different bit rates to be easily extracted from the present analysis. Regarding the bit error rates, no human signal has yet been received by a human-made object over a distance of more than one light-day. Thus, firm knowledge about error rates and signal degradation in interstellar space backed up by practical experiences is not available. For this reason, a set of theoretically achievable packet error rates has been evaluated, in the range of 0.2 to 10^{-3}. For the sake of simplicity and considering its limited impact on the overall analysis, the packet error rates for the links between individual relays, between the earth and the first relay, and between the last relay and a station near TRAPPIST-1 have been assumed equal.

The number of relays in the path (n_{relays}) can be calculated based on the total distance d_{total} and the distance between relays d_{rel} by

$$n_{relays} = \lceil \frac{d_{total}}{d_{rel}} \rceil - 1. \quad (6)$$

In Table II, the number of relays has been calculated for a selected set of distance values. Besides distances selected to provide an estimate for different distance dimensions, the value of 19.1 light-hours is listed in the table. Based on data published by NASA[5], this value conforms to the current distance from Earth of *Voyager 1*, the most distant object created by mankind.

[5]http://voyager.jpl.nasa.gov/where/

Table II
RELATION BETWEEN DISTANCE AND AMOUNT OF RELAYS

Relay distance (light-hours)	Amount of relays
1	346,019
19,1	18,116
24	14,417
144	2,402
720	480

Based on the per-hop delivery probability P_{hop} and the distance between relays, the expected delay per hop τ_{hop} without any packet loss ($P_{hop} = 1$) can be calculated using

$$\tau_{hop} = \frac{d_{rel}}{c}. \quad (7)$$

However, when $P_{hop} < 1$, a more general equation modeling custody transfer retransmissions is required. In this case, the average delay per hop can be expressed by equation

$$\tau_{hop} = P_{hop}\Big(\frac{d_{rel}}{c} + \sum_{i=1}^{\infty}\big((2i+1)\frac{d_{rel}}{c} + i\Delta_{\tau_{ack}}\big)(1 - P_{hop})^i\Big) \quad (8)$$

which assumes that each relay accepts custody and attempts infinite retransmissions. As a retransmission is only plausible after waiting for a possible acknowledgment, each retransmission i increases the total transmission time by two times the transmission delay between two relays (d_{rel}/c). In particular, we assume the retransmission timer in each hop is set to $2 \cdot d_{rel}/c \cdot \Delta_{\tau_{ack}}$, where $\Delta_{\tau_{ack}}$ is a safe margin to avoid unnecessary retransmissions when the acknowledgment is delayed because of congestion on the return link. In general, $\Delta_{\tau_{ack}} \ll d_{rel}/c$ and can be disregarded when evaluating very long relay distances.

For the last relay, d_{rel} has to be calculated by equation

$$d_{rel,last} = d_{total} - d_{rel} \cdot n_{relays}. \quad (9)$$

Thus, the total delay of the delivery using the complete multi-hop relay path is provided by

$$d_{total} = \tau_{hop} \cdot n_{relays} + \tau_{hop,last}. \quad (10)$$

Because of the relation of relay distance and number of relays, it does not matter for the total delay how many relays are deployed and, thus, how far they are spaced apart. Table III lists selected values for the overall transmission delay over a total distance of 39.5 light-years, depending on the packet error rate (PER).

Table III
RELATION BETWEEN PACKET ERROR RATE AND DELAY

PER	Delay (years)
0.2	59.25
0.1	48.28
10^{-2}	40.30
10^{-3}	39.58

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In addition to the delay, the required relay buffer capacity can be calculated using the bit rate br, the distance between relays d_{rel}, and the delivery probability per hop P_{hop} using

$$C_{relay,min} = \frac{2P_{hop}^2 d_{rel} br}{8c} \cdot \sum_{i=0}^{\infty} (i+1) \cdot (1 - P_{hop}^2)^i. \quad (11)$$

It should be noted that this calculation is independent of the packet size. In Figure 4, the resulting buffer size requirements are plotted in dependence of the distance in which relays are deployed.

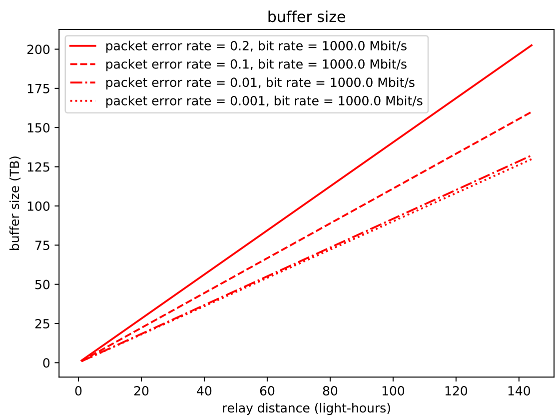

Figure 4. Relay buffer sizes depending on relay distance

As shown in Figure 4, the required buffer sizes increase linearly depending on the relay distance. Thus, equipping a relay with the necessary storage capacities to handle even high error rates in a relay network with huge relay distances seems technologically feasible in the future.

V. Discussion

The analysis presented in Section IV adresses the feasibility of deploying and operating a relay network consisting of hundreds of relays to avoid impracticable interstellar end-to-end delays caused by retransmissions. Assuming bit error rates on the order of 10^{-6} on individual links, deploying about 15,000 small sized DTN relays with an inter-relay distance of approximately one light-day seems reasonable at a first glance.

Current advances in directed energy propulsion as discussed in Section II may render possible a gigantic project like this one. If the relays can be constructed with small masses, bringing them to a productive state within a few hundreds, not thousands of years, is possible. However, deploying the proposed relay network will in any case be a multi-generation project whose duration will exceed even the construction times of cathedrals in medieval times (e.g. the construction of the Seville Cathedral took more than 100 years). Furthermore, there is no direct financial merit in such a project. These aspects may render the project implausible.

In order to address these issues, we propose an incremental deployment of the proposed relay network. The core idea is to establish the network not as a direct interstellar line of relays but instead via a sequence of intermediate solar systems forming a path to TRAPPIST-1. Thus, in the course of exploration of these increasingly distant solar systems, a communication infrastructure with the earth via all previously explored systems is constructed. For example, Figure 5 illustrates a possible path to TRAPPIST-1, passing 11 known stars. In this approach, the proposed topology would become a communication *backhaul* connecting subnetworks at the edge of the interstellar network. The resulting network is essentially a bus network with branches to solar systems on the path to TRAPPIST-1. The data paths can be managed by existing DTN routing protocols.

However, the core open issue mentioned above is still the nature of the interstellar space environment. Since this remains unknown, our analysis can only be based on general assumptions.

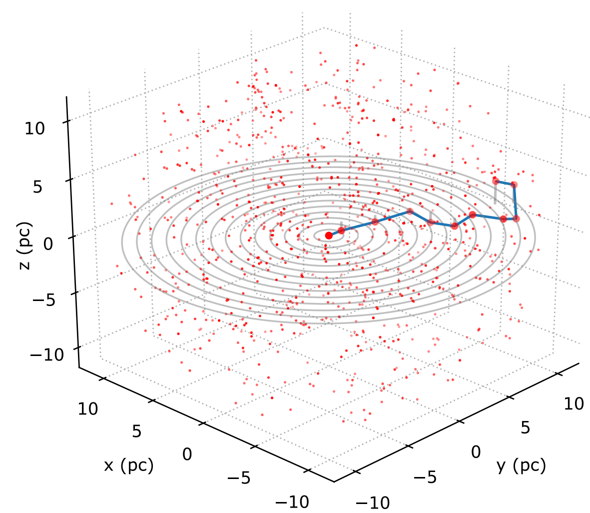

Figure 5. A Possible through-the-stars network topology to reach the TRAPPIST-1 system (red dots are all cataloged stars within the 13 pc from the Sun)

VI. Conclusions and Future Work

Based on the analysis presented in this paper, we consider the DTN architecture and protocols to be an essential component in building future interstellar networks. Due to the store-carry-forward principle underlying DTNs, they are a perfect fit to address issues resulting from both the anticipated physical conditions (high error rates) and the known physical conditions (long delays) characterizing interstellar space. In particular, we proved that DTN protocols can be conveniently combined with an infrastructure of interstellar relay systems to avoid retransmission of data via long distances and, thus, to achieve lower end-to-end delays while reducing required relay buffer capacities. As discussed in section II-A, besides non-trivial technological challenges, there is no theoretical impediment to positioning relays in interstellar space.

By proposing a simple model for the relay network, we have provided a first quantitative analysis of the impact of relay distances on achievable data rates, the delay, and buffer

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characteristics of an interstellar DTN. It has been shown that relatively large numbers of relays have to be deployed in order to achieve feasible end-to-end delays in communication with a very remote system such as TRAPPIST-1. Given the number of habitable-zone planets found in TRAPPIST-1, this system can be taken as a relevant case study for the vision of future interstellar DTN deployments. This analysis can thus provide some perspective for the construction of networks extending out to less distant solar systems.

Generally, with this paper, we would like to promote the core concept of interstellar DTN. Indeed, deploying instances of this class of networks may be a venture demanding the work and participation of several generations of humans. Specifically, the overall ideas sketched in this exploratory paper further motivate current work in the fields of energy generation, propulsion, and physical signal transmission for interstellar spacecraft. Furthermore, several DTN-related aspects can be derived as future work from the presented topics. For example, existing routing protocols and their topology information distribution mechanisms may be analyzed in the context of interstellar DTN. To this end, an accurate simulation environment for communication studies may be considered. Moreover, precise deployment strategies for incrementally realizing the network topology outlined here could be developed.

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