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Review

Delay and Disruption Tolerant Networking for Terrestrial and TCP/IP Applications: A Systematic Literature Review

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Abstract: Delay and Disruption Tolerant Networking (DTN) is a network architecture created basically to overcome non-continuing connectivity. There has been a great deal of research on this topic, from space communication to terrestrial applications. Since there are still many places on earth where there is no means of communication, the focus of this work is on the latest. A systematic literature review (SLR) was performed to know the main issues and advances related to the implementation of DTN for terrestrial and TCP/IP applications, especially in places where telecommunication infrastructure is lacking. The result is a classification of papers based on key aspects, such as architecture, performance, routing, and applications. A matrix of all the papers about these aspects is included to help researchers find the missing piece and concrete terrestrial solutions. The matrix uses three colors, green, yellow, and red according to the focus, either high, medium, or low, so that it is easy to identify specific papers.

Keywords: Delay and Disruption Tolerant Networking (DTN); performance; DTN architecture; DTN routing; Interplanetary Networking Special Interest Group (IPNSIG); Bundle Protocol (BP); systematic literature review (SLR)

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1. Introduction

Even though since July 2021, the United Nations established human rights on the Internet, including universal access and affordable and reliable connectivity, around the globe, many people still do not have any access (https://www.article19.org/resources/un-human-rights-council-adopts-resolution-on-human-rights-on-the-internet/ (accessed on 6 December 2023)).

The Interplanetary Networking Special Interest Group (IPNSIG) (https://www.ipnsig.org/ (accessed on 6 December 2023)) has established, as their mission, to procure Internet for everyone, everywhere, even in space. As part of this mission, they have developed several experimental protocols or Bundle Protocols (BPs), of which DTN is the main one. This protocol is designed to provide communication in contexts and environments where there is no way to ensure a response time that complies with networks, such as TCP/IP. The lack of connectivity in a TCP/IP network creates higher congestion due to the retransmissions of packets that time out.

As DTN has been tested in space communication and terrestrial applications, it could be a possible option for communication in rural areas around the world where there is limited or no connection. It would be interesting to evaluate to what extent this communication technology could be a solution that complies with what is considered a human right on the Internet. It is well known that people use the Internet mostly for TCP/IP applications. TCP/IP accounts for 95% of the worldwide networking traffic. Therefore, one can state that for DTN to be considered a solution for providing communication in rural areas, it must comply with TCP/IP.

Telecommunication infrastructure in rural areas, in general, if it exists, consists of satellite links and long-distance wireless connections of a low bandwidth. This infrastructure serves low-density population spread in regions with diverse topographic conditions where normal network transmissions are not always possible. DTN can fit in such a scenario, as application data are bundled and stored locally at each node and forwarded whenever there is an available node until it reaches the destination. This means it provides a custody-based retransmission service and stores data for long periods. This way, it is ensured that packets are not dropped or time-out in case of bandwidth delays or temporal breakups.

In rural areas where telecommunication infrastructure includes satellite links and wireless networks, the round-trip time (RTT), including routing and processing delays, can be quite high. In addition, there are operational conditions, such as mobility, weather conditions, and link obstructions, as well as other radio transmission aspects, such as modulation and coding. Here is where BP can play a role in supporting communication with these characteristics [1].

BP works with native Internet protocols through convergence layer adapters that can work over TCP (i.e., TCPCL), UDP (i.e., UDPCL), and other transport protocols. This architecture provides end-point identifiers and coarse-grained services, such as bundle transmission, bundle reception, session keeping, and passive listening. Bundles are data blocks with semantic information related to the application, which defines the services needed [2].

DTN has been already for a while and much research has been performed around this technology. It was first defined in 2004 by RFC 4838 (DTN Architecture definition); in 2007, in the RFC 5050, the BP was established; and then, in 2022, through RFC 9171, a new version was released, BPv7. However, we do not know for sure what is the state of it and to what extent it can work with TCP and UDP applications. Therefore, to obtain a complete picture of the state of the art of DTN for terrestrial applications, especially related to TCP and UDP, we performed an SLR.

This SLR aims to offer researchers an overview of this technology and whether it can evolve shortly for terrestrial applications or if, on the other hand, it is meant to die. We have defined three research questions that we believe can answer this interest and offer enough details to obtain a complete panorama of DTN about terrestrial applications. We want to know if DTN can be considered a feasible support for TCP and UDP applications in rural areas where the telecommunication infrastructure is considered extreme, as it is not always available. This research work has the intention of collecting, classifying, organizing, and studying works related to the DTN implementations of terrestrial and TCP/IP applications through an SLR. For that, we have defined the following three research questions.

RQ1: What are the trends in publications on terrestrial DTN?

RQ2: What are the main issues studied in the literature regarding implementing DTN in terrestrial applications?

RQ3: What are the trends in terrestrial applications of DTN?

2. Paper's Organization

This work is divided into six sections. The first section is a background where the concept of DTN is introduced, with its evolution, as well as the main features of this protocol. The second section describes, in detail, the research methodology, including the SLR protocol established to collect the data, organize it, and classify it. The third section is the results, which include the classification of the studies on DTN architecture, performance, routing, and applications. The fourth section is the discussion where an analysis of the findings is presented. The fifth section is the conclusions and future work. A matrix is added in Supplementary Material as an instrument to facilitate the work of other researchers interested in any of these specific topics around DTNs. This matrix is a valuable product that can save time for academics as they can easily find works with a focus on each of the four main topics listed before, DTN architecture, performance, routing, and applications. The colors used indicate whether the focus is high, medium, or low.

3. Related Work

Eleven review papers related to DTN were identified. Even though this paper is an SLR, it was considered relevant to include not only SLRs but also survey and review papers as they provide important elements and perspectives for a comprehensive understanding of this technology. Al-Fagih et al. present a survey to classify and organize routing schemes in DTN and map them with applications [3]. Chahal et al. center their SLR on routing, focusing on different algorithms and approaches [4]. Madni et al. performed an extensive survey on DNT and non-DTN routing for CubeSat communications [5]. Tornell et al. developed a survey on vehicular DTNs, focusing also on routing schemes and applications [6]. Xia et al. present a survey that relates social aware networking (SAN) with mobility patterns of mobile devices and the application of these concepts to DTN routing [7]. Kumar et al. focus their survey on the architecture of DNT and routing techniques, especially for natural disaster scenarios [8]. Wei et al. present a survey to classify technologies that support maritime communications, including hybrid satellite and terrestrial networks, and here, DTN plays an important role [9]. Sakthivel et al. study geographical routing for multi-hop wireless networks (MWNs), including MANET and DTN [10]. It focuses on mobility models as a major factor that influences the performance of geographical routing. Perumal et al. present an SLR about DTN for implementing internet connections in rural areas in Malaysia [11]. More et al. discuss issues that affect DNT performance, including routing protocols. The study also includes applications of DNTs [12]. Makawana et al. developed an SLR that mostly focused on paper objectives, citations, and paper types to provide a perception of this area of research [13].

Different from this work, most of these review papers were focused on routing. Perumal's work is somehow closer to the aim of this SLR; however, it is applied to a specific geographical region. Finally, Makawana's bibliometric study is related mostly to the interests of researchers behind the topic of DNTs. Our work is devoted to collecting and analyzing DTN works focused on terrestrial applications, to understand the main aspects and constraints to implement DTN, especially for services that use TCP/IP. Our work also aims to find the trends in DTN applications, as well as the main concerns of researchers around this protocol.

4. Contributions

This paper offers a review of a broad spectrum of papers especially dealing with the terrestrial applications of DTN, looking for the main issues around this technology. A concise list of the contributions of this paper are as follows:

→ A classification of papers based on four main aspects, architecture, performance, routing, and applications.
→ A matrix of all the papers studied, which is a reference to facilitate the work of researchers.

5. Methodology

To answer the research questions previously described, an SLR was implemented as it is a method that offers a formal and well-known process to dig into the literature and obtain results for the furtherance of DTN. An SLR was performed following Kitchenham's process for systematic reviews, including its three phases: planning, conducting, and reporting [14]. In the first stage, as suggested, the need for an SLR was identified, research questions were established, and a protocol was defined. The conducting stage consisted of implementing and executing the research questions and protocol established previously. This included a selection of database sources, search strategy, study screening, data extraction, analysis and classification, and quality assessment. This was the longest and most time-consuming process as it required going through each article several times. The search strategy required several adjustments to filter and obtain better search results. The classification of the information extracted from the studies allowed us to answer the research questions established.

The documenting phase was mainly reporting the results of the SLR through this paper. It also included reporting possible flaws of this study.

5.1. Planning the SLR

Even though DTN has been around for a while, the need for this SLR is to offer a complete package for the research community on how, if so, this protocol has been used with TCP/IP applications in areas of difficult access where an Internet connection is lacking.

Much has been written about DTN for space communication; however, the main interest of this SLR is to provide information about how DTN is used for terrestrial services and TCP/IP applications.

The first step was to define basic keywords for the search, which for this research included the following: "DTN", "protocol", "TCP/IP", "terrestrial", "delay tolerant network", "transmissions", applications", "networking".

The second step was to set up a string for the research. The basic search string defined was "terrestrial DTN". However, after several iterations, it was changed to "terrestrial DTN applications" to obtain more specific results. It was considered that this string was neither too broad nor too narrow. It did not include the words "TCP/IP" as this might narrow the results too much.

Third, it was the selection of search engines, which resulted in Google Scholar and IEEE Xplore, as they are two well-recognized sources for technical research and experimental reports in the academy and the industry.

5.2. SLR Protocol

Search string and temporal limitations

Initially, keywords, such as "DTN", "wireless networks", "performance", and "networking", were used for the search. However, these keywords were limiting the scope of the results. Another keyword that limited the results was "TCP/IP". From this point, we learned that a formula in the advanced search was required.

The first formula applied was terrestrial DTN app* OR simul* OR model* OR stud* OR eval* OR test* OR exp* "DTN" anywhere in the article. The time was set between 2000 to 2023. The result was 2990 documents. The second iteration used the formula DTN terrestrial application* application, OR terrestrial, OR delay, OR disruption "DTN" anywhere in the article. The time was set between 2000 to 2023. The result was 2320 documents. A third iteration was with the formula terrestrial DTN delay, OR disruption, OR terrestrial "DTN" anywhere in the article.

This string was set as the search for the two selected databases, Google Scholar and IEEE Xplore. The selection of these two databases was based on their recognition by the research community as trusted sources of academic and technical work. Mendeley was used to manage the documents, along with Microsoft Excel to process the data. The results from both databases were downloaded as csv files and then converted to Excel tables. As these data did not contain the same values, it was necessary to perform additional searches to manually add data to complete the information. The main values in the tables included the citation information, abstract, type of study, and paper category.

Inclusion criteria were as follows:

1. Studies available as open access;
2. Studies written in English;
3. Articles published after 2000;
4. Articles published in journals and books.

Exclusion criteria were as follows:

→ Articles where "DTN" stands for something different than delay-tolerant networks or networking.
→ Articles whose focus was mainly related to space communication.

5.3. Conducting the SLR

Database search

For Google Scholar, the string "DTN terrestrial applications" was set anywhere in the article as limiting it to only the title could leave many papers out. So, with that in mind, several iterations were tried. The results are shown below.

The first one was with the string DTN terrestrial applications, the exact phrase "DTN", at least application, terrestrial, delay, disruption, DTN anywhere in the article, which resulted in 172 articles. Then, a formula with all the words DTN terrestrial applications, with at least the word "DTN", the time for the retrieval was set to "2000 to 2023", review articles, and the language "English", resulted in 250 papers.

For IEEE Xplore, the search term was DTN OR delay disruption tolerant net* AND terrestrial all the fields in the abstract, and the period was set between 2000 to 2023. The result was 1610 documents, classified as 169 journals, 10 early access articles, 34 magazines, 1387 conferences, and 10 books.

Figure 1 shows each step of the SLR process in one simple and clear image to obtain the picture in one glimpse. First was the searching of the two databases, Google Scholar and IEEE Xplore, and the number of papers at that point. The second step, after applying the exclusion criteria, left 64 papers in Google Scholar and 179 in IEEE Xplore. The last step was reading the abstracts, which resulted in 63 papers in Google Scholar and 92 documents in IEEE Xplore, for a total of 155 papers for the review.

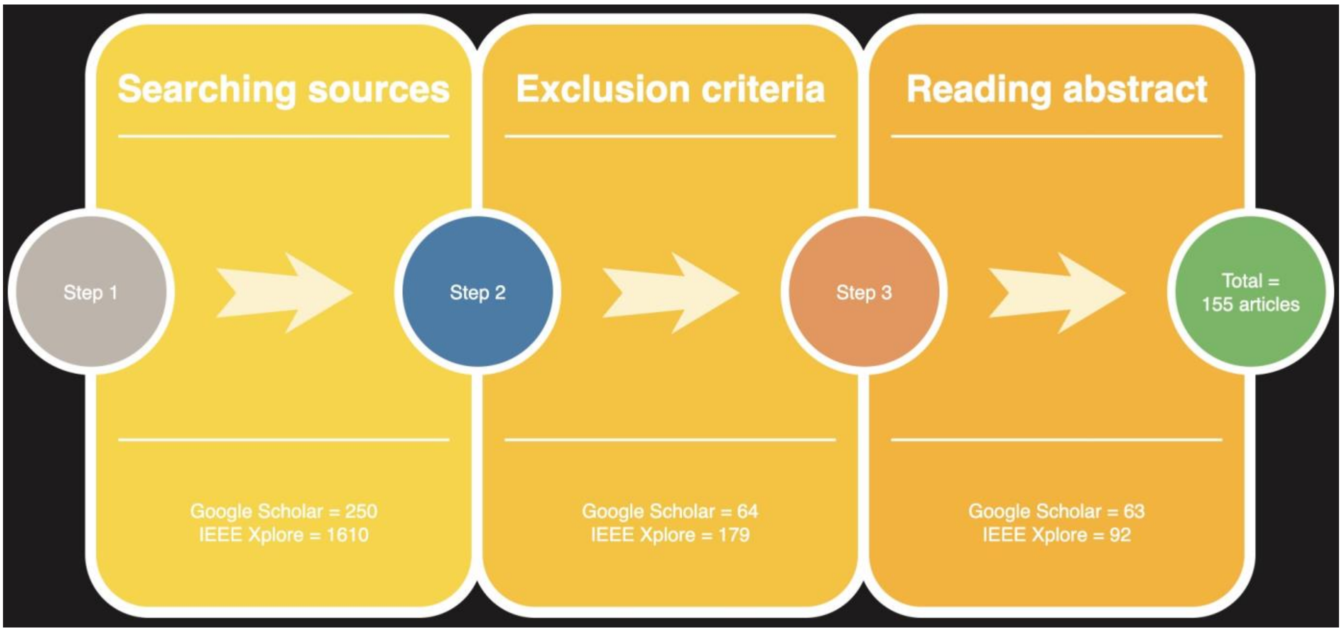

Figure 1. SLR process.

It is worth mentioning that, even though the exclusion criteria mention works related to space communication, several papers have important concepts of DTN, especially in terms of transport layer protocols and its connection with DTN, the Bundle Protocol, and terrestrial services supported by satellite communication, which was of interest of this work. Therefore, they were referenced.

Data extraction

Taking the results of the two search sources, Google Scholar and IEEE Xplore, a refining process began. To classify the papers collected in this research, a category was established based on the central topics found in most papers. These categories include the following topics:

→ DTN performance. This category includes papers that study any issue that might affect performance in DTN applications.

→ DTN routing. This category includes papers that discuss routing protocols, types of protocols, metrics, or any aspect of routing.
→ DTN applications. This category includes papers that propose applications either at the protocol level or implementations in real environments.
→ DTN architecture. This category includes mostly discussion papers that analyze aspects of the protocol and specific features.

It is important to notice that many papers involve more than one of these categories. In that sense, they had been classified in the category where they focus. It is worth mentioning that some papers focus on security; however, they do include aspects related to the listed categories.

6. Results

This section presents the results of analyzing the bibliometrics and content of the papers, including the classification made. The results are presented along with each of the research questions that were defined in the methodology.

RQ1: What are the trends of publications on terrestrial DTN?

The first question includes the number of publications per year found among the papers included in the SLR. A total of 155 papers were included from the period from 2004 to 2023. As it is shown in Figure 2, most of the publications were between 2010 and 2019, with 2014 having the highest number of papers. The main topics in that period revolved around security, sensors, cellular, and vehicular networks. This is a clear demonstration of the interest of finding ways to use this technology in new scenarios to penetrate the market of mobile and wireless technologies even in city areas where telecommunication infrastructure is present, clearly to reduce the costs of data transmission. A key aspect to overcome is to make the interoperability seamless for the final user.

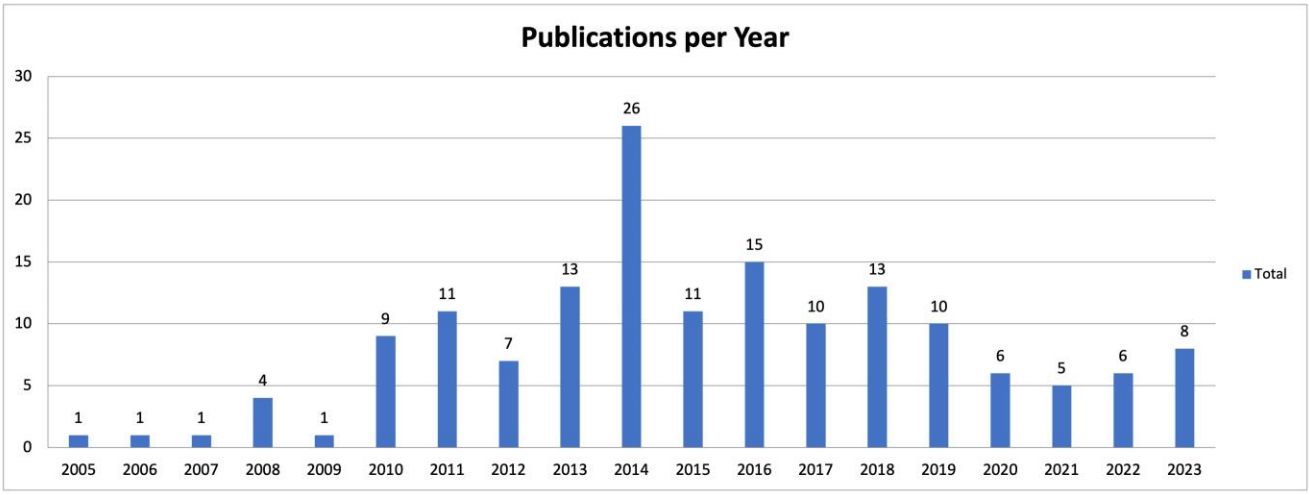

Figure 2. Publications per year.

RQ2: What are the main issues studied in the literature regarding implementing DTN in terrestrial applications?

The results show not only the main categories for the issues addressed in the papers, performance, routing, applications, and architecture but also include the papers that focused on security. Figure 3 below shows the number of papers per category.

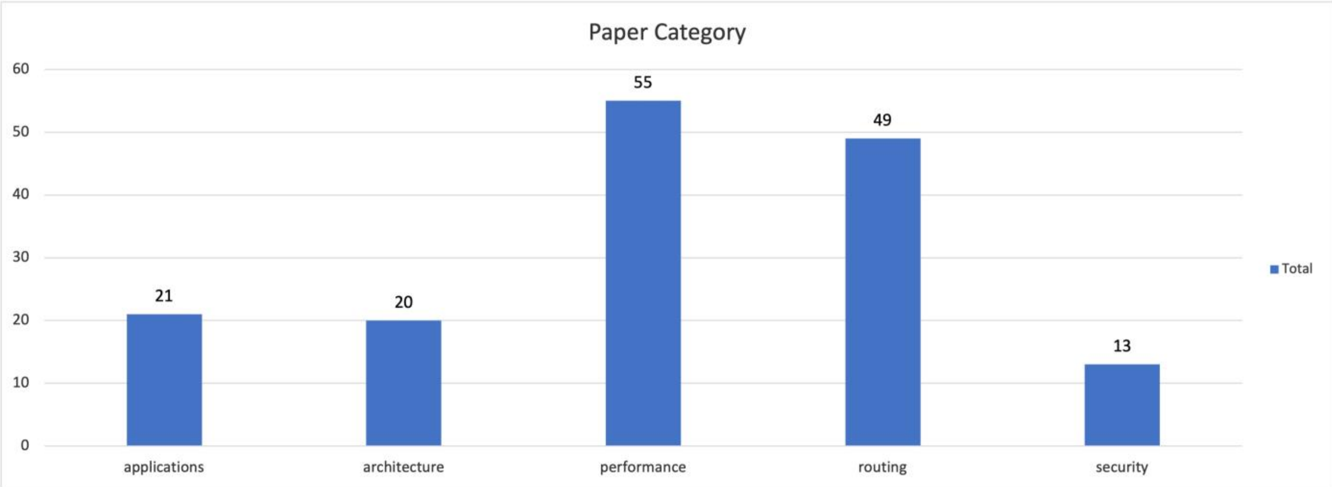

Figure 3. Paper categories.

An important number of research articles includes performance and routing as their main topic, but to get deeper into each of them, they were separated. The performance of DTN is a main issue, and so almost all the papers have a section about it, and the most recurrent topics were mobility, storage, processing capabilities, and energy.

This section addresses architecture, performance, and routing, whereas the results related to applications are presented in research question 3.

6.1. DTN Architecture

In terms of architecture, 20 papers discussed different elements of DNT, including the BP, topology, and how it differs from TCP/IP. In general, these works are intended to illustrate and describe how DTN works and its interaction with other layers, as well as to demonstrate that it can be used with different transport and data link protocols. From our point of view, here is not where the issues related to the performance of DTN lay, and so there are no works trying to make changes in terms of architecture.

DTN is a network architecture mainly designed for transmissions in harsh environments where there is no infrastructure for network communication, as it has been destroyed or is overloaded. Some of the characteristics of such a network are intermittent connectivity (never fully connected), limited resources (bandwidth, storage, energy supply), and variable delays. DTN is considered an opportunistic network because connections are intermittent and there is no guaranteed routing path between the origin and the destination. Scenarios for this topology include military connections, disaster areas, interplanetary transmissions, and rural communities with limited communication infrastructure [10].

The BP provides transport services for applications in larger packets than IP. Any layer, such as TCP, UDP, or LTP, can be used for transferring a bundle over a single hop. Bundles have a limited lifetime, TTL, after which it expires. Retransmission can happen in the origin or intermediate nodes [15]. The bundle layer and its BP are located between the application layer and the transport layer. It offers a message-oriented, store-carry-forward overlay network, and end-to-end connectivity. DTNs implement convergence layer adapters (CLA) to be able to provide functions for any protocol from different networks. BP data units are of variable sizes, so bundles are created depending on the situation. BP PDU consists of one or more blocks that contain metadata or application data. There is no error correction or detection [16].

The BP can use either TCP or UDP to transmit over a single hop given its feature of hop-to-hop reliability instead of end-to-end communication. After expiration, bundles can be retransmitted either by the origin or an intermediate node that keeps a copy of it. Too many copies can create congestion and lower performance [17]. BP can be implemented in a single process running on a general-purpose computer, a thread as a background process, an object on an object-oriented OS, or a special-purpose device [18].

BP interfaces with lower-layer protocols through CLA and provides features for custody transfer so that an intermediate node takes care of bundles, proactive and reactive bundle fragmentation to handle intermittent connectivity, and late binding so that the final hop resolves the DNS name. In TCP/IP, routers perform non-persistent (short-term) storage as continuous connectivity and short delays are assumed, so information is stored only at end nodes, whereas in DTN, persistent (long-term) storage is performed at intermediate nodes [19].

The BP in DTN defines how data are encoded and sent over the wire and might include mechanisms for reliability. As many DTN applications work with opportunistic contacts, a Discovery Protocol might take place so that neighbors might discover each other. Finally, the routing protocol itself has an impact on performance. Morgenroth refers to the DTN2 protocol stack, including Ethernet-based CL for wired communication between neighboring nodes without IP and/or TCP. uDTN is a BP implementation for wireless sensor networks (WSNs) running in 8-bit microcontrollers. PDUs are wrapped in IEEE 802.15.4 radio data frames and transported between nodes [20].

Unlike TCP/IP where there must be one or more links between the source and destination, DTN nodes receive messages and store them until another node is available to eventually reach the destination. The Bundle layer, between the application and transport layer, implements a custody transport mechanism through a message persistence store to reduce the impact of a link down during the transmission. Zhang states that to design a routing algorithm for DTN, one should consider the network topology dynamic change rate, communication link capacity, node cache capacity, and the average traffic volume between nodes [21].

DTN can interface any network protocol, through convergence layers, including TCP, UDP, Ethernet, Negative Acknowledgment-Oriented Reliable Multicast (NACK-NORM), AX.25, UCL, Licklider Transmission Protocol (LTP), and IEEE 802.15.4. Voyiatzis says that WSN can benefit from DTN as they are constricted by energy as is the case of Zigbee and 6LoWPAN—two key concepts in DTN. The first one is in network storage, which is provided for the application layer. The second one refers to being an agnostic network given the capacity of the protocol to integrate any kind of network protocol stack [22].

6.2. DTN Performance

A total of 55 papers focus on performance. This topic is quite large and involves different issues, including the computing and processing capabilities of nodes to receive and process packets and the storage and buffer capabilities of the node to be able to store packets until there is another node to forward them. This also involves the content dissemination capabilities of the nodes. An issue that is considered a great deal is energy consumption and capabilities in the nodes as this is vital for a route to be established from source to destination, especially when dealing with mobile devices. Mobility is another key aspect of performance, which also might involve node localization.

Mobility. An essential characteristic of multi-hop wireless networks (MWNs) is mobility as it makes path breakages in multi-hop and can produce more delay [10]. Moreover, the way DTN is implemented on an application does impact the achievable throughput. Elements that impact throughput are the duration and frequency of contacts, as well as the mobility of nodes. Longer contact and less mobility mean more data exchanged and higher network throughput [20]. The constant mobility of nodes can create the instability of network topology, long-term segmentation, asymmetrical and unstable node channels, or connection between nodes. This results in high packet loss, errors, and network delay uncertainty, among other issues [21]. From our perspective, mobility is an essential feature for nodes, and if DTN is based on the supposition of intermittent connectivity, then it does not make sense to consider this as a main concern for performance. The system must be able to perform in the presence of mobile nodes.

Storage capability. Storage is another issue that impacts performance. The disconnection due to dynamic mobility patterns and long queuing delays increase the need for the store to forward, no matter the node's limited resources (memory, processing, power) [23]. Content dissemination goes together with the storage capability of nodes, as information might have to be stored for long periods on each hop. Therefore, the performance of I/O and storage is a key component in the overall performance of DTN. Unlike the TCP/IP stack where end-to-end retransmissions of higher-level protocols prevent data loss, DTN requires data to be stored persistently (HDD, flash) to avoid data loss on node restarts, even before custody is accepted. Copying affects performance dramatically [20,21]. Mauldin found that link layer overhead and control messages overhead affect the protocol throughput, but message replication overhead is the largest impacting element [24]. For us, this should be the main concern for any DTN application due to the fact that the essence of DTN is "store" and forward; therefore, if nodes are not able to store packets, they are not doing any good in this kind of system.

Computing and processing capability. Performance metrics in DTN include the hop-to-hop throughput, end-to-end throughput, delivery delay, discovery latency, contact utilization, and bundle rate. Throughput is largely determined by the available computing or network resources and the quality of the protocol implementation.

Node connection creates a delay and depends on the capacity to process it. The delay is also influenced by the path choices of a routing algorithm, as well as by congestion control, which increases with low contact utilization. A high discovery latency affects contact utilization. This last is also affected by the bundle rate that includes processing to parse, generate, and forward bundles, which also depends on I/O and storage performance [4,20,25]. Computing and processing are, from our point of view, not only a feature solely based on the node but also on the lightness of the implementation. We found several implementations, such as IBR-DTN, DTN7, and ION-DTN. In consequence, here, there is room for research.

Energy constraints. Energy consumption is another element linked to DTN performance [4,25]. Some nodes are not able to keep the complex computations due to the energy consumption involved and the low capabilities they usually have [26]. As devices switch off the wireless chip to save energy, this reduces the chance of finding a direct neighbor through the discovery protocol [20]. From our point of view, just like mobility, this feature is expected in a DTN scenario as it is linked to intermittent connectivity; as a consequence, it should not be considered a main concern for performance.

6.3. DTN Routing

Routing is one of the main aspects that influences the performance of DTNs, and so, many authors have worked to tackle this topic. A total of 49 papers focus on routing. Most of the discussions revolved around route determination, the type of contact, whether the protocol sent only one copy or many, and the elements to design a routing protocol.

In DTN, end-to-end connectivity is a key factor as connectivity might be available only for short periods or not available at all. Each node that receives a message might store it in its buffer, carries it, and forwards it whenever it finds a neighbor that could potentially be part of the route to the destination. When the nodes are highly sparse or highly mobile, the routing path can be unavailable to meet the request time.

Contact type. One aspect largely studied concerning routing is the type of contacts. There are different kinds of contacts: persistent (always there), on-demand (when needed), scheduled, and opportunistic (found unexpectedly) [16]. Persistent contacts are always available, opportunistic contacts are random, scheduled contacts are established for a particular time and duration, and predicted contacts depending on the history and specific information can be guessed. Contact utilization is limited by the speed of the discovery mechanism. A lower contact utilization can influence end-to-end throughput and latencies.

A long connection time, frequent encounters, and a high message delivery ratio are preferred node qualities to improve routing performance. The link quality indicates the effectiveness of the connection between contacted nodes [27]. DTN is an opportunistic network, characterized by the lack of continuous connectivity and thus the need for store-and-forward mechanisms to ensure the delivery of data. However, due to the lack of end-to-end connectivity, routing in DTN suffers data loss and a low delivery ratio [28].

The most used routing protocols in DNTs are first contact, direct delivery, epidemic, spray and wait, and prophet [4]. Prophet outperforms epidemic content dissemination to achieve higher packet delivery rates and consumes less energy [29]. Mobile users' social characteristics can be used for routing decisions under the premise that they are less volatile. In this sense, social aware routing mechanisms group mobile users into communities and use information, such as the contact duration, node centrality, and data delivery preferences [30].

Number of copies. Another aspect related to DTN routing protocols is the number of copies they issue. It can be single-copy and multi-copy schemes. The first is resource efficient, but it has long delivery delays. Epidemic routing is a multi-copy scheme [16]. Madni categorizes DTN routing protocols into three classes: flooding-based, which makes replicas of packets according to the number of encountered nodes; quota-based establishes a fixed number of packet replicas; forwarding-based makes only a single copy of the packet throughout the network [5]. Stochastic routing floods the message to the node and does not know the network [23].

Route. The determination of the route might be deterministic by a predefined mobility pattern or non-deterministic modeled by a probability function. Deterministic routing can predict the future movement of nodes and connections based on some characteristics [23]. Intermittent connectivity makes the waiting time vary from seconds to days, which affects contact the schedule and thus performance.

Encounter-based routing protocols use the history of encounters between nodes to forward messages. They are divided into flooding and prediction based. Flooding does not take into consideration the encounter history, e.g., Epidemic and Spray and Wait. Prediction-based takes into consideration encounter information, using time metrics (interval, duration, inter-meeting time, or inter-contact time, etc.), with examples as follows: EBR (Encounter Based Routing) and Prophet. Infrastructure-based protocols use location information of nodes like routes or the distance between nodes: route or map-based, e.g., world model-based and MF; distance-based, e.g,. MOVE (movement of vehicle) uses the movement direction of nodes, and DAER (Direction Aware Epidemic Routing) uses the distance from the destination to evaluate the utility metric. Hybrid and others use more than one type of information to make decisions, e.g., PER (Predict and Relay), SimBet, and CAR [23].

The CNS algorithm uses the Markov model to predict the location of nodes, so there is a higher delivery probability. Because the algorithm uses contact history, the overhead will increase as the network grows. Comparing CNS with Epidemic, Spray and Wait, and Prophet for the scenario established, CNS had a better delivery ratio and less delay [28].

Chenji and Stoleru describe two main routing protocols for emergencies. Intercontact routing uses the recurrence of node movement to define delivery routes and Raven (Risk AversE routing in dtNs), which picks routes where jitter is lower. They also suggest that intercontact routing consumes less energy while keeping higher delivery rates by reducing the number of transmitted messages [31].

Hybrid MANET-DTN combines routing approaches. Whereas MANET assumes an available end-to-end path between the source and destination, in DTN, there is no end-to-end connection; therefore, many copies might be stored and forwarded. In MANET, when there is no end-to-end path, nodes might resend packets if they have not received an ACK [32]. Hybrid MANET-DTN routing protocols are categorized in DTN mechanisms inserted in MANET routing schemes, combining the DTN Bundle Protocol with MANET routing, and from scratch routing protocols for diverse networks [33]. The Hybrid DTN Routing Protocol (HDRP) combines flooding and forwarding mechanisms to find a balance and improve delivery rates. It is designed for IoT, drones (UAVs), and smart grid scenarios [34].

Prophet BSAS is a redesign of Prophet that allows for the transmission of higher amounts of data and reduces useless connections, based on a utility function that takes into consideration the transmission capacity, forwarding success rate, and the storage space of the nodes [35].

Context-aware adaptive routing (CAR) solves the problems of intermittent connectivity by estimating the next hop based on the prediction techniques of the Kalman Filter Algorithm and the utility function. It does not require nodes to keep track and store information on the history of encounters, which makes it suitable for networks with limited resources, such as CubeSat networks. Moreover, QoS techniques, including load balancing, dropping policies, and link recovery are suggested to enhance routing performance in such scenarios [5].

Wang simulates DTN time-space routing schemes, including Time-Expanded Graph (TEG) and Contact Graph Routing (CGR) [36]. Verma performs a simulation on The One comparing Epidemic, SNW, Prophet, EBR, CDBR (Contact Duration Based Routing), and ICR routing protocols. In smaller networks with fewer nodes, all give a comparable performance [23].

→ Number of nodes. With the higher number of nodes, (>60), SNW, Prophet, and ICR show comparable performance and outperform the others. Epidemic, Prophet, and CDBR suffer from high overhead because they rely on multiple copies of messages.
→ Buffer size. SNW, ICR, and CDBR are affected by an increased buffer size. ICR and SNW are good performers with high delivery ratios and low overheads.
→ Message size. For larger-size messages, all algorithms have low performance, but for smaller sizes, SNW and ICR outperform the others.

Design. Three limitations that should be taken into consideration when designing DTN routing protocols include disconnection that results from mobility and energy constraints, high latency, which varies from hours to days, and resource scarcity, which can affect store-and-forward features [27].

From our perspective, routing is definitely another crucial element to consider in the performance of DTN; however, there is no common agreement. The papers reviewed all focus in one or two algorithms for given scenarios. This variety of algorithms, as well as the diversity of contexts, makes it difficult to have a final statement in terms of which one is the best. It remains an opportunity to find a routing protocol that can be the standard.

RQ3: What are the trends of terrestrial applications of DTN?

DTN terrestrial applications are the focus of this SLR, and therefore, one research question was set for it. A total of 34 papers were found in this category. This includes implementations at the software or protocol level or applications in different case scenarios, such as communication in remote areas without network infrastructure, low-cost alternatives to satellite-assisted communication for sea applications, sensor applications for environmental purposes, and smart cities.

Rural remote areas and environment. Within the category of implementations for remote areas, there is Daknet, a low-cost DTN infrastructure for communication in rural areas in India [37]. KioskNet is another implementation of DTN for TCP/IP for rural areas that uses the cellular phone network [38]. Sámi is an implementation to provide communication to a remote population in Sweden [39]. ZebraNet and LUSTER are sensor networks based on DTN for wildlife and environment monitoring [40].

Smart cities. In the category of smart cities, there are different implementations. CarTel is a mobile sensor platform for traffic analysis [41]. DieselNet is a DTN network using WiFi nodes attached to buses to transfer data between them [42]. BikeNet is a mobile sensor that supports DTN and real-time sensing [43]. TrainNet is a DTN vehicular network where nodes and storage devices are attached to trains to transfer data between them [44]. DAPHNE, is a Delay Tolerant Application Proxy for e-health Network Environments [45]. An implementation of DTN in a smart city scenario running a Spray and Hop Distance

(SNHD) routing protocol shows that more tests are needed to evaluate the performance in IoT scenarios [46].

DistressNet is a platform for emergency responders' communications that implements DTN through networking equipment, including smartphones, routers, and sensors, which are carried by vehicles and mobile personnel acting as mules. The system also implements a cloud computing interface that works as Fog routers through Mikrotik RB433UAH devices, which allows users to share files. The platform also provides users with a social networking app to share their status or to message other users. All information is kept in the fog; therefore, regular synchronization with third-party services is required [31].

Protocol or software implementations. In the category of software or protocol implementations, several works were found. One of the issues of DTN is streaming, as applications require in-order delivery or full reliable services. Tetrys, an on-the-fly coding scheme, is a strategy for long-delay networks where missing packets are not possible with traditional retransmission mechanisms. It is based on an elastic encoding window updated dynamically using feedback information from the receiver. It generates repair bundles for every k-source bundle [47].

Zhang proposes a Software Defined Network (SDN) to separate the control function and the transmission function in mass sensor networks in satellite DTNs. Transmission requirements are translated into separate controls for satellite IoT. Zhang also states that satellite IoT, which combines satellite and IoT, is key for technologies, such as satellite manufacturing, satellite navigation, driverless, artificial intelligence, big data, wide-area narrowband low-power wireless communication, and 5G [26].

Srivastava proposes the use of throwboxes, cheap wireless storage devices used as dumping spots in fickle connections. The idea is to increase the message delivery ratio and decrease the message dropping, i.e., throwboxes forward messages. They can be placed where there is heavy traffic or for a sparsely populated network, at the point of contact with most nodes. It can be random or planned, fixed, or mobile. The mobile throwbox resulted in a higher delivery rate; less latency was found in the planned placement of the mobile throwbox and the same for contacts per hour [29].

Ad-hoc networks are not stable; therefore, they can take advantage of opportunistic contact to communicate. This can be applied in socially aware networking, especially because of the store-carry-and-forward capability and the need to make better predictions. Exploring the social relationships of people, animals, and vehicles carrying mobile devices can help predict mobility patterns and contact opportunities. Social Aware Networking (SAN), social opportunistic networks, vehicle social networks, and opportunistic Internet of Things (IoT) share the theory behind mobile nodes and social networks [7]. Using DTN-based robots with sensor localization can create topological maps as they work as relays for disconnected parts of the network [48].

As we can see, terrestrial applications for DTN are extensive and most important to point out is the smart cities' use. DTN has not only been experimented on in rural areas with limited or no telecommunication infrastructure but also in city environments together with other technologies. From our point of view, a user-friendly and common framework for this technology is lacking to pass the experimentation phase and be adopted massively.

6.4. Classification of Papers

A valuable contribution of this paper is the classification developed to categorize the 155 papers in the study into four main aspects: architecture, performance, routing, and applications. This classification corresponds to the central content found in the review. Supplementary Material is a matrix with all the papers in this SLR, which we believe is a useful tool for researchers. The matrix goes from reference number 50 until 204, which are the papers reviewed, whereas the first 49 documents were referenced in the paper itself.

To read this matrix, the first column is the Reference, so that it can be easily found in the bibliography. Then, there are four main columns for each of the categories mentioned before, architecture, performance, routing, and applications, which are distinguished each with a color. Each of the main categories includes subsections for more specific technical aspects of the paper. Within the aspect of performance, the most common elements found include computing/processing, storage/buffer, energy, and mobility. In the column of routing, the subsections include the most recurrent topics, such as the contact type, route determination, number of copies, and design. In the column of applications, the subsections include rural communication, environment, smart cities, and protocol, or software implementation. Furthermore, the matrix includes colors to facilitate finding papers. The colors correspond to the focus, where green means a high focus; yellow, medium; and red, low. As expected, some papers include the content of the four categories and so the colors help find the central aspects discussed.

7. Discussion

As shown in the results, most of the publications occurred between 2010 to 2019. However, in 2023, publications are still coming out, which means that the topic is of interest, moving from architecture and routing to applying DTN to new scenarios and technologies, such as IoT, 5G, and satellite technologies to support terrestrial communication. The most frequent topics in 2014, when the highest number of papers were found, include security, sensors, vehicular, and cellular networks. Given that this protocol sits between the application layer and the transport layer, it makes it possible to work with any underlaying protocol, especially in the data link layer.

It was shown in the results that most papers focus on aspects related to performance and routing. This makes sense as the purpose of DTN is precisely to ensure that packets are not dropped and can reach the destination in the presence of communication infrastructure limitations of different kinds, which has to do with routing. Also, we could see that most papers dealing with issues, such as security or applications, did include performance as part of their discussion or parameters to evaluate them.

Even though there has been a great amount of research work related to DTN routing, it continues to be one of the main interests, especially because of the conditions that make it different from traditional TCP/IP routing, where packets are dropped after a specific time. And, so, many different routing schemes were found in the literature, varying from how to choose a route depending on the type of contact, its social characteristics, or history. Others focus on the elements to design a routing protocol for these special conditions. However, still, there is not a strong word on the right combination of elements for a routing algorithm that gives an acceptable performance for different scenarios in the context of DTN. Therefore, here, there is an opportunity for further research.

An aspect that affects routing and performance in this type of network is the dynamicity of the topology. As nodes move around, disappearing from time to time due to energy constraints or mobility, routes change. This requires more computing resources for nodes to perform routing algorithms and calculate routes, which again comes to energy. Many papers discussed aspects, such as energy consumption and computing capabilities as elements that affect performance and that are directly linked to the routing capabilities of nodes, yet no overall solution has been found.

Even though a variety of routing algorithms are in the literature, it looks like each performs better in specific scenarios and not in all the possible situations. That is the case of algorithms like Intercontact, which is ideal for scenarios where nodes are mobile, but they have a recurrent path, and so they are recommended for emergency scenarios. Here, the focus of the algorithm is reducing energy consumption by reducing computation work to find routes. Routing algorithms based on society like CNS use the contact history to predict routes; as the network increases, so does the overhead. Likewise, Epidemic-based algorithms that flood the network with copies of messages have a lower performance as the network grows in nodes. There is the case of Hybrid MANET-DTN devoted to IoT, drones, and smart grid scenarios, which combines MANET with store-and-forward, and even there, different approaches perform differently. In this case, there are considerable computing and storage resources needed to make the calculations depending on which one must be applied in different times.

Regarding the design of DTN routing protocols, it seems that the biggest issues include the energy constrains of nodes, as well as storage limitations. In both cases, the performance is affected, as packets will take longer to reach their destination. Works intended to design light routing protocols that might consume less energy and computing resources were not found. It might be interesting to evaluate what would be the effect of applying federated machine learning techniques to make routing more efficient as the models can be updated locally. This does not solve the issue of storage.

From our perspective, high mobility and energy constraints create intermittent mobility, which is part of the features for which DTN is designed; therefore, performance evaluation should focus on storage and computing capabilities. This last aspect, as stated in the previous section, depends on how light the designs and implementations are made.

Finally, we did find several works on different applications to support agriculture, natural disasters, smart cities, and communication in rural areas. Some of them are over TCP. Nonetheless, most of the experiments did not dig deep into the transport layer itself but rather in the overall functioning and performance of the applications.

The projects that describe applications of DTN to support services, such as email, web caching, texting, and voice mail stated its feasibility. The positive side is the low cost of creating the infrastructure, which is a crucial element when it comes to providing Internet access to rural communities, especially of low income. In this sense, most of the experimental settings were performed in these kinds of scenarios. The negative side is the low throughput, not higher than 2.5 Mbps, which might be too low for a good user experience nowadays, even for asynchronous services. On top of this is the fact that the availability of the service for one depends on the cooperation and proper functioning of all the nodes in network. The presence of greedy nodes can affect the overall performance of the network.

Applications of DTN for environmental monitoring using massive sensors either applied to vegetation, climate, or fauna demonstrated its potential. In this case, the lower requirements in terms of data to be transferred and the energy consumption of sensors help to overcome some of the limitations of nodes, such as storage. Solutions for the lack of storage include implementations, like throwboxes [29] or the manual replacement of storage cards. This last one might be feasible if the size of the coverage area is manageable and if the necessary logistic is coordinated with the stakeholders. In cases of natural disaster, applications are somehow similar in terms of technical implementations, and so, it looks like a good fit for DTN, especially taking into consideration broken or a lack of infrastructure. In any of these cases, the best way to ensure that the communication is fully available requires a backbone of DTN nodes. This scenario raises the potential of using DTN combined with MANET, so that the first one takes over whenever the route to the destination is not available.

As mentioned in the previous section, the use of this technology in combination with other technologies in city areas where telecommunication infrastructure is not an issue does require a standard and user-friendly framework so that it can pass from the experimental phase to market adoption.

8. Conclusions and Future Work

As it was described at the beginning, the aim of this work is to offer an overview of the evolution of DTN technology as a support for terrestrial applications or if it is meant to die. The SLR performed demonstrates that there is much research interest in DTN technology, which varies in depth and mostly in four topics, architecture, performance, routing, and applications. Most of the papers related to applications are supported by experimental testbeds and simulations to prove the feasibility of the concept and to measure the performance of this protocol.

There is a tendency to combine DTN with new telecommunication technologies, such as 5G, 6G, and sensors. Still, there are many unsolved issues related to performance and routing, mainly linked to mobility, energy consumption, and the computing capabilities of nodes. Very few experiments focus on TCP itself but rather on the overall performance of applications. Nonetheless, this SLR does answer the main inquiry we had about whether DTN can be considered a support for TCP/IP applications or terrestrial applications.

DTNs for terrestrial applications, especially in areas where infrastructure is lacking, represent a feasible alternative. This is demonstrated by the many use cases collected in this SLR, which varies from communication in rural areas and agriculture, applications for the environment, including tracking animals and studies in the sea; smart cities, including transportation and natural disaster scenarios; and implementations in the architecture level or software.

This SLR offers a broad compendium of work on DTN, which has been classified using key and valid elements to study and evaluate a communication protocol and its architecture, performance, routing, and applications. The matrix developed in this SLR is a reference tool for researchers to easily find papers that have more content of their interest. Not only does it show the level of content classified based on the four main aspects of DTN, such as architecture, performance, routing, and applications, but it also shows more specific aspects related to these categories, which can be very valuable for researchers to speed up their experiments. In the performance category, computing and processing capabilities, storage and buffer, energy, and mobility are included. In the routing category the contact type, route determination, number of copies, and design were included. Even though routing also affects performance, it was organized this way to facilitate identifying works focused on any of these subcategories, and these were the more recurrent topics found in the revision. The colors that represent, green, high focus; yellow, medium; and red, low help to easily and quickly identify specific works.

Through this SLR, the main identified limitations of DTN include the scarcity of storage capabilities of nodes, energy constraints, and mobility. These three aspects affect finding routes to the destination and thus performance. As stated in the IPNSIG-SW's plan, still, there is space for research finding synergies between MANET and DTNs; therefore, this is a topic of interest as future work, more specifically testing it in different scenarios with TCP/IP [49].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/network4030012/s1 (references [50–204]).

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